

The Measurement of Sporting Performance using Mobile Physiological Monitoring Technology

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Abstract

Coaches are constantly seeking more ecologically valid and reliable data to improve professional sporting performance. Using unobtrusive, valid and reliable mobile physiological monitoring devices may assist in achieving this aim. For example, there is limited information regarding professional fast bowlers in cricket and understanding this role during competitive in-match scenarios rather than in simulated bowling events could enhance coaching and physical conditioning practices. The Bioharness™ is a mobile monitoring device and assesses 5 variables (Heart rate [HR], Breathing frequency [BF], Accelerometry [ACC], Skin temperature [ST] and Posture [P]) simultaneously. Therefore, the aims of this research were to assess the effectiveness of the Bioharness™ mobile monitoring device during professional sporting performance using fast bowlers in cricket and this was to be achieved in five research studies. Study 1 presented the physiological profile of professional cricketers reporting fitness data with other comparable professional athletes, with a specific interest in fast bowlers who were to be the focus of this work. The 2nd and 3rd study assessed the reliability and validity of the Bioharness™ through controlled laboratory based assessment. For validity, strong relationships ($r = .89$ to $.99$, $P < .01$) were reported for HR, BF, ACC and P. Limits of Agreement reported HR (-3 ± 32 beat.min⁻¹), BF (-3.5 ± 43.7 br.min⁻¹) and P ($0.2 \pm 2.6^\circ$). ST established moderate relationships ($-0.61 \pm 1.98^\circ\text{C}$; $r = .76$, $P < .01$). Reliability between subject data reported low Coefficient of Variation (CV) and strong correlations for ACC and P (CV $< 7.6\%$; $r = .99$, $P < .01$). HR and BF (CV $\sim 19.4\%$; $r \sim .70$, $P < .01$) and ST (CV 3.7% ; $r = .61$, $P < .01$), present more variable data. Intra and inter device data presented strong relationships ($r > .89$, $P < .01$, CV $< 10.1\%$) for HR, ACC, P and ST. BF produced weaker data ($r < .72$, CV $< 17.4\%$). Study 4 assessed reliability and validity of the Bioharness™ in a field based environment using an intermittent protocol. Precision of measurement reported good relationships ($r = .61$ to $.67$, $P < .01$) and large Limits of Agreement for HR (> 79.2 beat.min⁻¹) and BF (> 54.7 br.min⁻¹). ACC presented excellent precision ($r = .94$, $P < .01$). Results for HR ($r = \sim .91$, $P < .01$: CV $< 7.6\%$) and ACC ($r > .97$, $P < .01$; CV $< 14.7\%$) suggested these variables are reliable in the field environment. BF presented more variable data ($r = .46 - .61$, $P < .01$; CV $< 23.7\%$). In all studies, as velocity of movement increased (> 10 km.h⁻¹) variables became more erroneous. HR and ACC were deemed as valid and reliable to be assessed during in-match sporting performance in study 5. This final study sought to utilise and assess the Bioharness™ device within professional cricket, assessing physiological responses of fast-medium bowlers within a competitive sporting environment, collected over three summer seasons. The Bioharness™ presented different physiological profiles for One Day (OD) and Multi Day (MD) cricket with higher mean HR (142 vs 137 beats.min⁻¹, $P < .05$) and ACC (Peak acceleration (PkA) 227.6 vs 214.9 ct.episode⁻¹, $P < .01$) values in the shorter match format. Differences in data for the varying match states of bowling (HR, 142 vs 137 beats.min⁻¹, PkA 234.1 vs 226.6 ct.episode⁻¹), between over (HR, 129 vs 120beats.min⁻¹, PkA 136.4 vs 126.5 ct.episode⁻¹) and fielding (115 vs 106 beats.min⁻¹, PkA 1349.9 vs 356.1 ct.episode⁻¹) were reported across OD and MD cricket. Therefore, this information suggests to the coach that the training regimes for fast bowlers should be specific for the different demands specific to the format of the game employed. Relationships between in-match Bioharness™ data and bowling performance were not clearly established due to the complexities of uncontrollable variables within competitive cricket. In conclusion, the Bioharness™ has demonstrated acceptable validity and reliability in the laboratory and the field setting for all variables (Heart rate, Breathing frequency, Accelerometry, Skin temperature and Posture) but with limitations for heart rate and breathing frequency at the more extreme levels of performance. Furthermore, taking these limitations into account it has successfully been utilised to assess performance and provide further insight into the physiological demands in the professional sport setting. Therefore, this work suggests that coaches and exercise scientists working together should seek to utilise new mobile monitoring technology to access unique insights in to sporting performance which may be unobtainable in the laboratory or a simulated field based event.

Key words

Cricket, BioharnessTM, Fast-medium bowling, Reliability, Validity, Professional sport, Multi-variable,
Heart rate, Accelerometry

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Table of Contents

Abstract.....	ii
Key words.....	iii
Acknowledgements.....	iv
List of Publications and Presentations	ix
List of Figures, Tables and Equations	x
List of Abbreviations	xvi
Chapter 1 – Introduction.....	1
1.1. Science and Technology in Cricket	2
1.2 Research Aims and Studies	4
Chapter 2 - Review of Literature	5
2.1 Cricket and Exercise Science	6
2.2 Physical Demands of Cricket	8
2.2.1 <i>Physical Demands of Batting</i>	9
2.2.2 <i>Physiological Profiles of Batters</i>	10
2.2.3 <i>Physiological Responses of Batters</i>	10
2.2.4 <i>Batting Movement Patterns</i>	14
2.2.5 <i>Considerations for Future Research</i>	15
2.3. Physical Demands of Fielding.....	16
2.4.1 <i>Physical Demands of Fast-Medium Bowling</i>	17
2.4.2 <i>Physical Attributes Associated with Fast Bowling</i>	18
2.4.2.1 <i>Stature of Fast Bowlers</i>	18
2.4.2.2 <i>Bowling Arm Length</i>	19
2.4.2.3 <i>Upper Body Muscularity of Fast Bowlers</i>	19
2.4.2.4 <i>The Bowling Action and Technique</i>	20
2.4.2.5 <i>The Run Up</i>	21
2.4.2.6 <i>Front Knee Angle</i>	22
2.4.3 <i>Physiological Fitness Profile of Fast-Medium Bowlers</i>	23
2.4.3.1 <i>Physiological Responses of Fast Bowlers</i>	24

2.4.3.2 <i>In-Match Physiological Data</i>	26
2.4.3.3 <i>Limitations of Physiological Monitoring and Recommendations for Research</i>	27
2.4.3.4 <i>Summary</i>	28
2.4.4 <i>Movement in Fast Bowling</i>	31
2.4.5 <i>Bowling Accuracy</i>	32
2.4.6 <i>Summary of Cricket Literature</i>	34
2.5. <i>Reliability and Validity of Mobile Measuring Technology</i>	35
2.6 <i>Reproducibility and Precision of Measurement</i>	35
2.6.1 <i>Reliability and Validity</i>	36
2.6.2 <i>Methods to Assess Reliability and Validity</i>	37
2.6.3 <i>Laboratory versus Field Setting</i>	38
2.6.4 <i>Statistics used to Assess Reliability and Validity</i>	38
2.6.4.1 <i>Statistical Analysis to Assess Precision of Measurement</i>	38
2.6.4.2 <i>Relative Precision of Measurement</i>	40
2.6.4.3 <i>Absolute Precision of Measurement</i>	43
2.6.4.4 <i>Summary on Measurement of Reliability and Validity</i>	47
2.7 <i>Multi-Variable Monitoring Devices</i>	48
2.7.1 <i>Technological Development of Multivariable Devices</i>	48
2.7.2 <i>Classification of Mobile Monitoring Devices</i>	49
2.8 <i>Technology used within multivariable devices</i>	51
2.8.1 <i>Heart Rate Monitors</i>	51
2.8.1.1 <i>Technology Associated with Assessing Heart Rate</i>	51
2.8.1.2 <i>Research on the Precision of HRM</i>	55
2.8.2 <i>Breathing Frequency</i>	58
2.8.2.1 <i>Technology Associated with Assessing Breathing Frequency</i>	59
2.8.2.2 <i>Research on the Precision of Breathing Frequency Measurement</i>	60
2.8.3 <i>Accelerometry</i>	65
2.8.3.1 <i>Technology Associated with Assessing Accelerometry</i>	65
2.8.3.2 <i>Research on the Precision of Accelerometry</i>	67
2.8.4 <i>Posture</i>	70

2.8.4.1 Technology associated with Assessing Posture	70
2.8.4.2 Research on Precision of Posture Measurement	71
2.8.5 Skin Temperature	73
2.8.5.1 Technology Associated with Assessing Thermometry	74
2.8.5.2 Research on Precision of Thermometry (Infra-Red Devices)	76
2.8.6 Summary	82
Chapter 3 - Physiological Profile of Professional Cricketers.....	84
3.0 Abstract	85
3.1 Introduction	86
3.2 Methods	88
3.3 Results	92
3.4 Discussion.....	96
3.5 Conclusions	100
Chapter 4 - Validity of the Bioharness™ Monitoring System	102
4.0 Abstract	103
4.1 Introduction	104
4.2 Methods	106
4.3 Results	112
4.4 Discussion.....	119
4.5 Conclusion	123
Chapter 5 - Reliability of the Bioharness™ Monitoring System	124
5.0 Abstract	125
5.1 Introduction	126
5.2 Methods	127
5.3 Results	130
5.4 Discussion.....	136
5.5 Conclusion	140
Chapter 6 - Field Based Reliability and Validity of the Bioharness™ Monitoring System.....	141
6.0 Abstract	142
6.1 Introduction	143

6.2 Methods	145
6.3 Results	150
6.4 Discussion.....	161
6.5 Conclusions	165
Chapter 7 - Professional sporting performance and the use of the Bioharness™ monitoring device	166
7.0 Abstract	167
7.1 Introduction	168
7.2 Methods	170
7.3 Results	186
7.4 Discussion.....	202
7.5 Conclusions	219
Chapter 8 - Conclusions and recommendations	221
8.1 Conclusions	222
8.2 Recommendations	226
9. References.....	228
Appendices.....	241
Appendix 1 – Ethics confirmation	242
Appendix 2 – Hydration data for fast-medium bowlers (n = 30 matches).....	244
Appendix 3: Example Bioharness™ raw data output from bowling event	246
Appendix 4 – Descriptive data from consecutive overs analysis	247
Appendix 5. Heart rate and Accelerometry Correlations	252

List of Publications and Presentations

The following is a list of the 5 peer reviewed journal articles and 2 conference presentations which have been completed as a result of the PhD process.

Publications:

Johnstone, J.A. and Ford, P.A. (2010). Physiological profile of professional cricketers. *Journal of Strength and Conditioning Research*, 24, 11, 2900 - 2907.

Johnstone, J.A., Hughes, G., Ford, P.A., Watson, T. and Garrett, A.T. (2012). Part 1: Validity of the Bioharness™ monitoring system. *Journal of Sport Science and Medicine*, 11, 3, 400-408.

Johnstone, J.A., Hughes, G., Ford, P.A., Watson, T. and Garrett, A.T. (2012). Part 2: Reliability of the Bioharness™ monitoring system. *Journal of Sport Science and Medicine*, 11, 3, 409-417.

Johnstone, J.A., Hughes, G., Ford, P.A., Watson, T., Mitchell, A.C.S. and Garrett, A.T. (2012). Field based reliability and validity of the Bioharness™ multivariable monitoring device. *Journal of Sport Science and Medicine*, 11, 4, 643-652.

Johnstone, J.A., Hughes, G., Ford, P.A., Watson, T., Mitchell, A.C.S. and Garrett, A.T. (2014). The athletic profile of fast bowling in cricket: A review. *Journal of Strength and Conditioning Research*, 28, 5, 1465 – 1473.

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Johnstone, J.A., Hughes, G., Ford, P.A., Watson, T. and Garrett, A.T. (2011). Reliability of the Bioharness™ monitoring system, Presented 6th – 9th July, at the 16th Conference of the European College of Sports Sciences, Liverpool, UK.

List of Figures, Tables and Equations

Figures

- Figure 1. Total distance covered per hour by position in different formats of cricket (Petersen et al. 2010, p47). **p9**
- Figure 2. Comparison of aerobic physiological characteristics of South African international cricketers and rugby players (Noakes and Durrandt, 2000. p927). **p10**
- Figure 3. Mean and maximal heart rate (HR; $M \pm SD$) by position in Twenty20 cricket (Petersen et al., 2010, p49). **p13**
- Figure 4. The basic bowling action (Ferdinands et al., 2012, www.coachesinfo.com) **p20**
- Figure 5. Bowling actions; (a) Side on technique (b) Front on technique (c) Mixed action with hips more front-on than shoulders (d) Mixed action with hips more side on than shoulders (Portus et al., 2000, p1000). **p21**
- Figure 6. Heart rate response (mean \pm SD) recorded over 2 x 6 over spell (Duffield et al., 2009, p 31). **p25**
- Figure 7. Example of heteroscedastic data with increasing variance as values increase (Engineering Statistics 2012, <http://www.itl.nist.gov/div898/handbook/eda/section3/eda33q9.htm>). **p39**
- Figure 8. Scatter plot (a) Data from Borg et al (1993) with regression line (—), Scatter plot (b) with line of equality (----) added (cited Bland and Altman 2003, p86). **p41**
- Figure 9. Plot of difference against mean for the artificial data X and Y with mean difference and 95% limits of agreement indicated (Bland and Altman, 2003, p90). **p44**
- Figure 10. A typical data set, the measurement of systolic blood pressure by a test method, finger pressure and a standard method, arm blood pressure (Bland and Altman, 1986b, p1085). **p45**
- Figure 11. Diagram of the Bioharness™ and associated parts (Zephyr Technology, 2010, <http://www.zephyranywhere.com/products/>). **p50**

Figure 12. A typical ECG trace demonstrating the electrical activity HRM interpret (Tortora and Grabowski, 2003, p677). **p52**

Figure 13. Example schematic of typical HRM set up (Healthgoods.com, 2013, http://www.healthgoods.com/Acumen_Heart_Rate_Monitor_Strap_p/an-strap.htm). **p53**

Figure 14. Bland–Altman analysis of the pooled minute average data for breathing frequency (cited in Witt et al., 2006, p392). **p63**

Figure 15. Two piezo-electric configurations (Chen and Bassett, 2005, p491). **p66**

Figure 16. Differences between method pairs versus mean of the pairs in intensive care patients. Solid line represents mean (Stavem et al., 1997, p102). **p78**

Figure 17. Average temperature response of the 12 subjects. At $t = 0$ min, the subjects entered the warm chamber (30°C), coming from the cold chamber (10°C). At $t = 30$ min, the subjects started to exercise on a bicycle, at an external load of $1 \text{ W}\cdot\text{kg}^{-1}$ (Kitesmaker et al., 2006, p255). **p80**

Figure 18. Rectal temperature, IRTT and Sensor Touch data at all-time points during the experiment. The points indicate the median values, the boxes indicate the 25% to 75% range and the whiskers indicate the whole range, excluding outliers (individual circles) (Kistemaker et al., 2006, p259). **p81**

Figure 19: Schematic of testing protocol which participants progressed through. **p89**

Figure 20. Individual axes of accelerometer within the BioharnessTM (Zephyr Tech, 2012). **p107**

Figure 21. Picture of the BioharnessTM as worn by a subject participating in the testing process with skin thermistor attached. **p109**

Figure 22. Residual versus predicted plot demonstrating the relationship for (a) BF, (b) HR, and (c) ST. **p113**

Figure 23. Scatter plot demonstrating the relationship between (a) BioharnessTM BF and Criterion and (b) BioharnessTM HR and Criterion across all velocities on treadmill. Nb. line of identity (- -), regression line (—). **p114**

Figure 24. Trend in data between mean footsteps (-◇-) and mean VMU (-□-) per active stages of treadmill protocol (Nb. Treadmill stages 1 to 5 refers to 4 km.h⁻¹ to 12 km.h⁻¹ respectively).

p114

Figure 25. Residual versus predicted plot demonstrating the data spread for (a) HR and (b) BF.

p129

Figure 26. Profile of HR and BF data removal (%) at different velocities during data cleaning process.

p160

Figure 27. Schematic of HR data collection points linked to the associated hypotheses in Heart Rate 7.2.10. Each of numbers relates to a hypothesis and is representative of linked to one data capture which is then reassessed repetitively through the bowling spell.

p179

Figure 28. Schematic of ACC data collection points and associated hypotheses in Accelerometry 7.2.10 Each of numbers relates to a hypothesis and is representative of linked to one data capture which is then reassessed repetitively through the bowling spell.

p180

Figure 29. An example of screen shot of processed match data.

p182

Figure 30. HR (relative to age) for OD and MD matches during different match state.

p191

Figure 31. Trends for VMU and Vertical, Lateral and Sagittal values (a) during overs bowled and (b) during between over episodes.

p195

Figure 32. Median VMU over 7 consecutive (a) during bowling episodes and (b) between over episodes.

p196

Figure 33. Trends for relative HR values (age related %), Pre (HR_{10r}) and Post (HR_{60r}) HR markers (beats.min⁻¹) during consecutive bowling of overs.

p197

Figure 34. Mean HR (relative to age) and Min HR (relative to age) over 7 consecutive (a) between over episodes and (b) during bowling episodes.

p198

Figure 35. Scatter plot showing no significant relationship between (a) HR_{maxage} (%) and runs scored in subsequent over ($r = .10, P > .05, r^2 = 1\%$) and (b) VMU ($r = -.07, P > .05, r^2 < 1\%$) during bowling episodes.

p201

Tables

Table 1. Research reporting physiological responses of fast bowling for the past 25 years (from years 1987 – 2012).	p29
Table 2. Anthropometrical and body composition measures for professional cricketers.	p93
Table 3. Aerobic fitness, flexibility and speed measures for professional cricketers.	p94
Table 4. Bioharness™ data in comparison to the respective criterion measure.	p112
Table 5. Relationship of ACC data to the respective criterion measure (oxygen uptake, mL.kg ⁻¹ .min ⁻¹) and mean step counts per stage.	p113
Table 6. Heart rate (beat.min ⁻¹) data at varying intensities.	p115
Table 7. Breathing frequency (br.min ⁻¹) data at varying intensities.	p116
Table 8. Clean heart rate (beat.min ⁻¹) and breathing frequency (br.min ⁻¹) data at 10 and 12 km.h ⁻¹ .	p117
Table 9. Skin temperature (°C) data in hot, thermo-neutral conditions and combined data overview.	p117
Table 10. Relationship of ACC data to the respective criterion measure (oxygen uptake mL.kg ⁻¹ .min ⁻¹).	p118
Table 11. Bioharness™ reproducibility across whole data set.	p130
Table 12 Velocity specific reproducibility of HR (beat.min ⁻¹) data.	p131
Table 13. Velocity specific reproducibility of BF (br.min ⁻¹) data.	p131
Table 14. Clean HR (beat.min ⁻¹) and BF (br.min ⁻¹) data at 10 and 12 km.h ⁻¹ .	p132
Table 15. Reproducibility of Bioharness™ ACC data (Vector Magnitude Units, ct.sec ⁻¹).	p133
Table 16. Overview of intra device reproducibility of Bioharness™ device.	p134
Table 17. Overview of inter device reproducibility of Bioharness™ device.	p135
Table 18. Precision of HR (beat.min ⁻¹) and BF (br.min ⁻¹) data in comparison to respective criterion measure.	p151

Table 19. Relationship of ACC data to the respective criterion measure (oxygen uptake, mL·kg ⁻¹ ·min ⁻¹).	p152
Table 20. Reproducibility of the HR (beat.min ⁻¹) variable during simultaneous wearing of two devices.	p153
Table 21. Reproducibility of the BF (br.min ⁻¹) variable during simultaneous wearing of two devices.	p154
Table 22. Reproducibility of the ACC (VMU/ct.sec ⁻¹) variable during simultaneous wearing of two devices.	p155
Table 23. Reproducibility of the HR (beat.min ⁻¹) variable during a test-retest protocol.	p157
Table 24. Reproducibility of the BF (br.min ⁻¹) variable during a test-retest protocol.	p158
Table 25. Reproducibility of the ACC (VMU/ct.sec ⁻¹) variable during a test-retest protocol.	p159
Table 26. Physiological profile of 10 first-class fast/medium bowler participants (mean ± SD).	p170
Table 27. Run-up distance, time and velocity of 10 first class fast-medium bowler participants (mean ± SD).	p173
Table 28. Total number of competitive in-match hours and overs of fast-medium bowling data collected.	p173
Table 29: Objective normality tests completed on key data sets.	p184
Table 30. Descriptive statistics (median ± Inter quartile range) for bowlers' cumulative accelerometry data (ct.episode ⁻¹) in OD and MD cricket.	p186
Table 31. Descriptive statistics (median ± Inter quartile range) for cumulative accelerometry data (ct.episode ⁻¹) in OD and MD matches during bowling.	p188
Table 32. Descriptive statistics (median ± Inter quartile range) for cumulative accelerometry data (ct.episode ⁻¹) in OD and MD matches between over.	p188
Table 33. Descriptive statistics (median ± Inter quartile range) for cumulative accelerometry data (ct.episode ⁻¹) in OD and MD matches while fielding.	p189

Table 34. Descriptive statistics (mean \pm SD; 95% Confidence Intervals) for bowlers absolute (beat.min⁻¹) and relative (% of age) heart rate (HR) data across two match formats. **p191**

Table 35. Descriptive statistics (mean \pm SD; 95% Confidence Intervals) for absolute (beat.min⁻¹) and relative (% of age) heart rate (HR) data in OD and MD matches during bowling activity. **p192**

Table 36. Descriptive statistics (mean \pm SD; 95% Confidence Intervals) for absolute (beat.min⁻¹) and relative (% of age) heart rate (HR) data in OD and MD matches between overs. **p192**

Table 37. Descriptive statistics (mean \pm SD; 95% Confidence Intervals) for absolute (beat.min⁻¹) and relative (% of age) heart rate (HR) data in OD and MD matches during fielding activities. **p193**

Equations

Equation 1. Standard Error of Measurement. **p42**

Equation 2. Standard Error of Mean. **p42**

Equation 3. Calculation used for producing Bioharness™ VMU data (Zephyr Tech, 2012). **p106**

List of Abbreviations

ACC – Accelerometry

BATEX – Batting Exercise Test

BF – Breathing Frequency

CAAIS – Cricket Australia – Australian Institute of Sport

CMJ – Counter Movement Jump

COD – Coefficient of Determination

CV – Coefficient of Variation

ECG – Electro-cardiogram

EIT - Electrical Impedance Tomography

ES – Effect Size

f_R – Respiratory Frequency

GPS – Global Positioning Satellite

HR – Heart rate

HRM – Heart Rate Monitor

ICC – Intra Class Correlation

IFR – Infrared

Km.h^{-1} – kilometres per hour

LoA – Limits of Agreement

m.h^{-1} - Metres per hour

MD – Multi Day (cricket)

OD – One Day (cricket)

P – Posture

RIP – Respiratory Inductive Plethysmography

RPO – Runs per Over

Sec^{-1} - Seconds

ST – Skin Temperature

SJ – Static Jump

T20 – Twenty-twenty (cricket)

T_O - Temperature at Oesophagus

T_p – Temperature at Pulmonary Artery

T_R – Temperature at Rectum

V_I - Minute Ventilation

VO₂ – Volume of Oxygen

V_T - Tidal Volume

VMU – Vector Magnitude Units

Chapter 1 – Introduction

1.1. Science and Technology in Cricket

Despite its extensive history, the eclectic international environments it is played within, and now multi-million dollar rewards associated with high level performance, there is still limited depth of exercise science peer reviewed knowledge related to high level cricket performance (Bartlett, 2003, Bartlett, 2006, Duffield et al., 2009, International Cricket Council, 2009, Cricinfo, 2013). Moreover, at a cultural level, some elite cricket coaches have noted the slow progress of engagement with sports science research and associated technology within the game (Buchanan, 2008). With the increasing variations in the format of the game and financial incentives, there could be greater physical and psychological strain on performers. Recent increased interest in the sport has led to further professionalization of elite, or first-class performers who can play high numbers of matches (~100 days) in a calendar year (Noakes and Durandt, 2000, Engel, 2012,). With three established formats of the game, Twenty-twenty (T20) being a 3 hour match, One day (OD) match lasting 6-7 hours, and Multi-day (MD) matches played between 18-30 hours (3-5 days), differing physical qualities may be needed by performers. Therefore, exercise professionals and coaches alike require an in-depth understanding of the physical characteristics in order to optimise performance (Woolmer et al., 2008, Petersen et al., 2010, Petersen et al., 2011a). Whilst cricket may have started to fully embrace the associated exercise science research in recent years, there is a lag in relevant applied research being completed in order to enhance performance for both players and coaches (Kolt, 2012).

New physiologically based mobile monitoring technology is capable of recording everyday physical activity scenarios through to sporting performance, permitting data to be captured in increasingly ecologically valid situations (Achten and Jeukendrup, 2003, Brage et al., 2005, Jobson et al., 2009, Grossman et al., 2010). Monitoring technology, such as the Bioharness™ (Zephyr Technology Ltd, MD, USA), can simultaneously measures multiple physiological and activity related variables providing information for the coach or exercise scientist. Capturing more ecologically valid data, rather than simulated environments, may provide new knowledge for the exercise professional and ultimately improve players' performances.

There is a scarcity of in-match and longitudinal physiological assessment of performers within cricket, partly due to the aforementioned cultural issues in the game and also previous restrictions relating to suitable unobtrusive and precise mobile monitoring technology. These elements are being challenged in this research, in attempt to identify precision and reproducibility of data within a portable physiological monitoring device, understand players' physiological responses relative to actual performance and make this information accessible to players', exercise scientists and coaches.

This study is novel in that it will seek to use a new physiological monitoring system to inform coaches about performance based data, collected in-match at the professional sporting level.

1.2 Research Aims and Studies

The specific aim of this research is to assess the effectiveness of the Bioharness™ mobile physiological monitoring device in professional sporting performance. This research aim will be achieved through the completion of five studies;

Study 1: Physiological profile of professional cricketers

- The aim of this study is to assess the anthropometrical and physiological profile of a professional cricket team and identify differences between on-field playing positions.

Study 2: Validity of the Bioharness™ monitoring device

- The aim of this study is to assess the validity of each variable measured by the Bioharness™ in relation to credible criterion measures within a physically active laboratory situation.

Study 3: Reliability of the Bioharness™ monitoring device

- The aim of this study is to assess the reliability of each variable measured by the Bioharness™ device within a physically active laboratory situation.

Study 4: Field based reliability and validity of the Bioharness™ monitoring device

- The aim of this study is to assess the reliability and validity of each variable measured in the Bioharness™ in relation to criterion measures within a physically active field based setting.

Study 5: Professional sporting performance and the use of the Bioharness™ monitoring device

- The aim of this study are to;
 - (1) Develop a performance profile of professional cricket fast-medium bowlers across different forms of competitive cricket through measuring in-match physiological responses using the Bioharness™ mobile monitoring device.
 - (2) Investigate the relationship between cricket bowling performance and physiological data captured by the Bioharness™ mobile monitoring device from professional cricket fast-medium bowlers during competition.

Chapter 2 - Review of Literature

2.1 Cricket and Exercise Science

Cricket is embedded with tradition, regulations and cultural norms which have at times may have restricted the progression, development and the scientific understanding of the game (Woolmer et al., 2008, Buchanan, 2008). It has been widely reported that there is limited collections of peer reviewed research within cricket (Duffield et al., 2009) and in comparison to other sports cricket has been accused of being “backward” (Bartlett, 2006) and a “dinosaur” (Buchanan, 2008) in the way it has embraced sports science to enhance performance. Recently the importance of research is increasing and the development of an evidence base within cricket is needed as the physical demands associated with the sport increase (Kolt, 2012).

Much of the research within cricket has had a focus on biomechanics and injury prevention within bowlers (Elliott, 2000, Stuelcken et al., 2007, Kolt, 2012). A few studies have investigated physiological performance of this sport specific cohort but this has been restricted to controlled simulated bowling events (Gore et al., 1993, Devlin et al., 2001, Duffield et al., 2009). Though perhaps a dated view, it may be that cricket is not alone in the lack of physiological and performance related information being accessible for coaches. Some team sports in general have difficulties regards to field based studies and associated data collection (Devlin et al., 2001).

One of the first pieces of research published on the physical requirements of cricket may, inadvertently, have helped to perpetuate the indifferent attitude coaches and players currently have in relation to the specific understanding of the physiological requirements of the sport. The research in question, although with questionable assumptions on playing times made, suggested that cricketers do not expend much more energy than one would when walking (Fletcher, 1955). The research design has been questioned as Fletcher included time players spent watching the match in the calculations of energy spent within the game (Petersen et al., 2010). From this early work it can be assumed that research does influence practice, as the then leading governing body for the game, The Marylebone Cricket Club (MCC), presented their fitness guidelines to the (England) touring team of Australia and New Zealand in the 1950's; *“Each player is responsible for his own fitness. He must stay well rested and must not overstrain in practices. He should exercise only very mildly on “off days”, during which he may swim or play tennis or golf in the early mornings only; and he must stay out of the midday sun”* (Cited in Woolmer et al., 2008, p532).

Recent research has questioned these early findings, identifying much higher levels of physicality within cricket (Christie et al., 2007, Petersen et al., 2009c) and specifically bowling (Duffield et al., 2009). Importantly though, if Fletcher's (1955) study was considered the evidence base of that

historical era, it is not surprising that exercise science, coach education and resultant strategy has emphasised that physical conditioning is not a key aspect for cricket and skill alone is enough for success (Noakes and Durandt, 2000, Woolmer et al., 2008).

The historical lag in coaching strategy and player engagement with physical conditioning had moved slightly further forward 40 years later, with research on first-class South African players being reported (Stretch, 1991). The latter paper noted that performers engage in pre and early season conditioning regimes though when the competitive season starts emphasis is moved on to cricket skills and physical conditioning is limited. The general lack of physical conditioning in-season has been reported more recently and seems to relate to the volume of competitive cricket played which has increased exponentially in recent years leaving limited opportunities for physical training to occur (Noakes and Durandt, 2000, Petersen et al., 2011a, Houghton and Dawson, 2012). It is estimated that approximately 100 competitive games are scheduled each year for international performers, and for some, this figure does not include all domestic or the newer T20 competitions. In a report for Cricket Australia, cited by Peterson et al. (2010), a 9% decrement in performers "endurance fitness" through a first-class season was noted, which could be linked to this match-to-match orientated playing environment performers currently work within.

Even with the aforementioned time limitations, there is an emerging culture change occurring at the highest level of cricket performance, as players and coaches recognised the gap between teams who use and engage with sports science and those who rely on talent alone (Mansingh, 2006). Sports Science and Medicine (SSM) teams are the norm at the performance level of the game with an initial remit to reduce injury occurrence but now also directly to research and improve match performance (Woolmer et al., 2008, England and Wales Cricket Board, 2009). For example, even with the limited time available, the modern day performer is now embedded within well planned and progressed strength and conditioning programmes with some countries governing bodies adopting minimum standards of physical fitness to be considered for selection (Petersen et al., 2011a, Australian Cricket Board, 2012, England and Wales Cricket Board, 2012).

Moreover, with the increasing need for players to perform consistently in specific roles in a higher number of games, there is a clear paradox with the lack of depth of evidence in relation to the physiological requirements of performers across the different game formats. The outcome of this paradox is that there is only embryonic knowledge of conditioning practices, monitoring of match workload, fatigue mechanisms, recovery processes and understanding them in relation to performance.

To summarise, cricket has become a highly professional sport with more than 100 countries recognised by the International Cricket Council and high profile international competitions have seen a corresponding increase in interest in the game (International Cricket Council, 2009). The relationship cricket has with sports science research highlights that in this modern era of professional cricket there still appears to be a lack of scientific appreciation of certain fundamentals of the game; The position specific fitness demands of the game and fatigue related issues are poorly understood (Bartlett, 2006, Pyne et al., 2006). Historical research suggesting the idea of cricket as a leisurely activity is perhaps misleading though has helped to maintain the idea that skill alone is suffice for success in the sport (Payne et al., 1987, Woolmer et al., 2008).

With a slowly developing research base within the sport, Noakes and Durrandt (2000, p 921) present a thought that may well become more established in the psyche of coaches; *“...in cricketers of equal skill, physiological factors determine their fitness will ultimately predict their success and longevity in the sport”*. This lack of information on the physiological fundamentals of cricket could be limiting wider developments in conditioning training, injury prediction and identification, fatigue monitoring, talent identification and performance prediction.

2.2 Physical Demands of Cricket

If cricket is to progress players potential the specific physiological demands for the sport, and specific associated playing positions must be researched in order for coaches, exercise scientists and conditioning practitioners to optimise performance (Stretch et al., 2000, Vanderford et al., 2004). In comparison to other popular team sports, cricket still requires specific applied match related physiological understanding of the game. The physical demands have been extensively researched in other elite professional sports, including association football and rugby union (Reilly et al., 2000, Gabbett, 2002, Duthie et al., 2003, Drust et al., 2008) and cricket should strive to match this literature base benefitting players and coaches alike (Christie et al., 2007). Recent research (Petersen et al., 2010) has noted that different positions have assorted physical workloads (Figure 1) and this chapter will aim to briefly review the physical demands of batting and fielding and then present a more detailed picture of fast and fast-medium bowling.

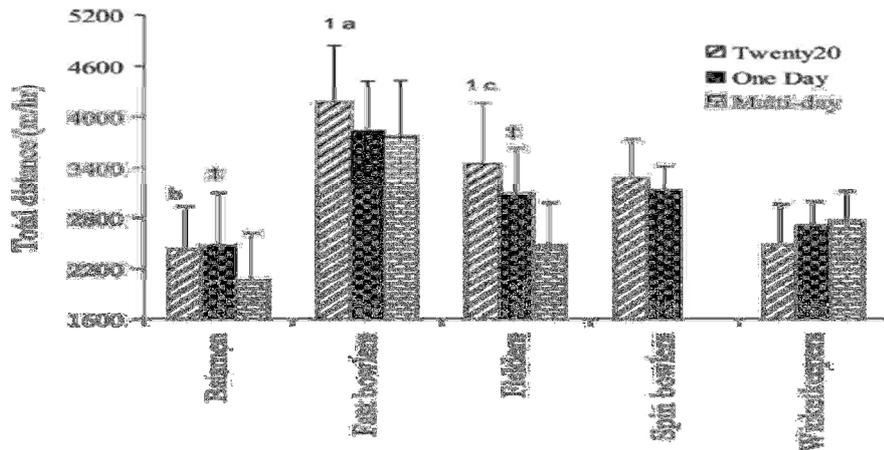


Figure 1. Total distance covered per hour by position in different formats of cricket.

¹Small magnitude of difference within position between Twenty20 and One Day cricket. ^a Small, ^b moderate, and ^c large magnitudes of difference within position between Twenty20 and multi-day cricket. Moderate magnitude of difference within position between One Day and multi-day cricket) (Petersen et al., 2010, p47).

2.2.1 Physical Demands of Batting

With the increasing volume of cricket being played and emergence of the faster shorter formats of the game, the physical preparation of all performers is increasingly important, though the evidence base for exercise scientist is sparse (Taliep et al., 2010). Until recently athletic demands on batters were based on supposition with Noakes and Durrandt (2000) hypothesising that if a batter scores a century in a match, with an assumption about the probable distribution of how the runs were scored, they would cover 3.2 km in approximately 8 minutes running at 24 km.h⁻¹. Considering the latter and the dimensions of the cricket pitch, there would also be at least 110 deceleration episodes in this time frame. Though this information seemingly provides an initial baseline of evidence for the exercise scientist these proposed data are anecdotal estimations. Interest in sprint performance of batters has been recently noted reiterating the lack of contemporary peer reviewed physiological evidence available for this playing position (Houghton et al., 2011, Lockie et al., 2013).

2.2.2 Physiological Profiles of Batters

The availability of objective physiological data linked to the batting role is poor with only a couple of papers noting this information. Moderate $\dot{V}O_2$ max values ($53.7 \pm 5.9 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) were reported for non-elite university performers (Christie et al., 2007) which is less than data presented ($\sim 60 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) (Figure 2) within a review on other elite batters (Noakes and Durandt, 2000). Clearly this chasm of evidence does not assist the exercise scientist in understanding the basic cardiovascular profile of the performer and should be rectified with future research.

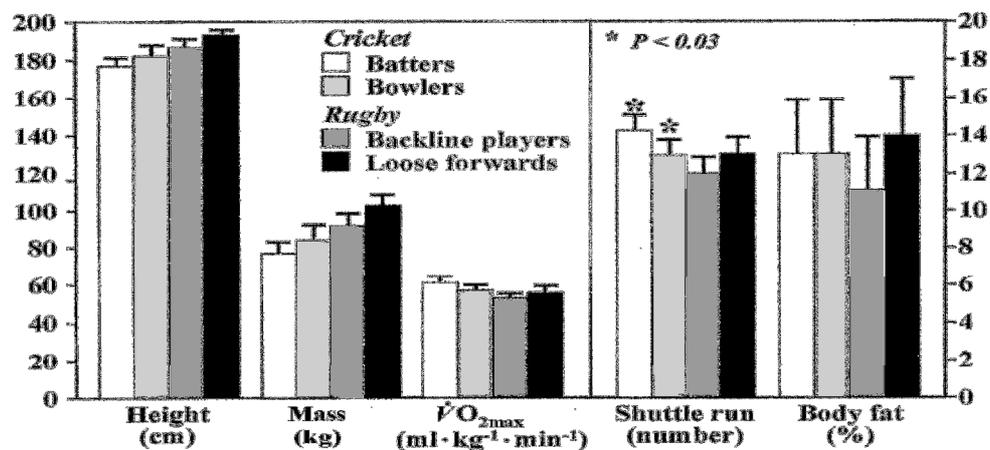


Figure 2. Comparison of aerobic physiological characteristics of South African international cricketers and rugby players (Noakes and Durandt, 2000. p927)

2.2.3 Physiological Responses of Batters

One paper appears to initiate further understanding of the physiological responses of this specific cricketing role through a simulated batting scenario where field based measures were taken (Christie et al., 2007). The batting protocol was developed after analysis of selected competitive OD matches, where >260 runs were scored in the innings. Based on the latter match analysis, participants completed a “typical OD innings” facing 7 overs (i.e. 1 delivery every 30 seconds with 1 minute between overs) and running intermittently (i.e. every 3rd ball) covering ~495 m over the whole process. Early increases in physiological responses were noted (Over 1, HR $126 \pm 14.1 \text{ beat}\cdot\text{min}^{-1}$; BF $26.2 \pm 2.6 \text{ br}\cdot\text{min}^{-1}$; $\dot{V}O_2$ $23.5 \pm 2.9 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) but these plateaued by the end of 3rd over (3rd Over, HR $145 \pm 19.9 \text{ beat}\cdot\text{min}^{-1}$; BF $29.9 \text{ br}\cdot\text{min}^{-1}$; $\dot{V}O_2$ $27.3 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$). In the latter section of the batting test, HR increased to 75% of age predicted maximum (mean $152 \text{ beat}\cdot\text{min}^{-1}$), $\dot{V}O_2$ consumption (mean $26.7 \pm 1.4 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) during test was moderate relative to $\dot{V}O_2$ max values presented ($53.7 \pm 5.9 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$). Clearly, the former moderate $\dot{V}O_2$ consumption value identified is influenced by the

stop-start nature of the protocol which aims to mimic a typical OD batting episode. This study was one of the first to attempt to quantify physiological responses during a simulated OD batting episode though wider application of the data is debatable. The test duration was relatively brief and work load set (i.e. running between the wickets) appeared to be consistent over-to-over as opposed to a more randomised running protocol, the latter of which may replicate more accurately a competitive situation. Moreover, the bowling which was delivered to the batting participants, which one would deem to be quite important to the validity of the data, did not appear to be well controlled as no indication of speed, type or length of delivery was provided, only that “an established cricketer” was used. Interestingly, though not surprisingly, estimated energy use of batters (2536 kJh^{-1}) from this current study was 4 times higher than Fletcher’s (1955) predictions (Christie et al., 2007) suggesting that the historical assumptions that were portrayed about cricket were misleading and further robust evidence is required to qualify the physical demands of modern day formats of the game.

A more recent attempt to simulate the batting environment, the batting exercise test (BATEX), claims to reproduce the OD work-rest environment in order to consider the physiological post-match fatigue (Houghton et al., 2011). The BATEX is a 6 stage match related test replicating a prolonged OD innings (2 hours 20 minutes). Based on previous research (Duffield and Drinkwater, 2008) and the analysis of ~88 matches, the work rate for participants increases as stages progress, as seen within actual competitive matches and unlike earlier simulation work of Christie et al. (2007). The BATEX focuses on OD batting though within the ~88 matches analysed to develop an ecologically valid work rate, peculiarly, the analysis included match data from T20 games which has different characteristics from other forms of cricket (Petersen et al., 2009a, Moore et al., 2012). Subsequent data may well have been affected by this T20 inclusion as the results from BATEX did not compare as accurately as hoped with GPS data (Petersen et al., 2010). Participants covered less total distance ($5.08 \pm 0.4 \text{ km}$) but completed higher sprinting activities ($25 \pm 3 \text{ h}^{-1}$) during the BATEX test when compared to GPS which was derived purely from OD competitive match data (distance $8.7 \pm 0.6 \text{ km}$; Sprints $13 \pm 9 \text{ h}^{-1}$). The authors suggested the reduction in distance was due to less walking within the BATEX protocol and felt the increased sprinting within the BATEX could be viewed as a “worst case scenario” by the exercise professional who would interpret the data. Moreover, the authors also highlighted the use of inferior 1 Hz GPS devices in comparison to 5 Hz devices used in the comparison study (Petersen et al., 2010) which may explain some of the variation in the data noted.

An additional aspect to the BATEX study (Houghton et al., 2011) was to ascertain if the simulated batting event resulted in muscular fatigue through the assessment of static jump (SJ) and countermovement jumps (CMJ). With relatively brief ($< 2 \text{ sec}^{-1}$) high intensity movements coupled with multiple rest intervals there would appear to be limited metabolic reasons for fatigue to occur

when batting (McArdle et al., 2009). An alternative fatigue hypothesis has been proposed linked to eccentric muscle action inducing biomechanical/neuromuscular fatigue due to repetitive acceleration-decelerations within longer batting episodes (Noakes and Durandt, 2000). Initial data pre-to-post BATEX reported a decrease in SJ with CMJ remaining the same (Houghton et al., 2011), when a reduction in CMJ has been noted within football up to 72 hours after performance (Magalhães et al., 2010). The validity of the test process might be in question, though there are no cricket specific competitive match pre-post data to compare, and in a follow-up study Houghton et al. (2012) did note decreased CMJ and SJ 24 hours post BATEX. It is worth noting, that although convenient in a field based study, CMJ and SJ movement patterns can vary if participants have little experience prior to testing (Bobbert et al., 1995, Powers and Howley, 2007). As noted by Houghton et al (2011; 2012) a familiarisation process for participants should be (and was) included within the methods but it appears to be limited by its brevity and perhaps further baseline jump data should be collected from participants in a physically fresh state. Confidence in the baseline jump data may improve the robustness of the research design, as not all performers will have the same exposure to the test with higher level players (i.e. Academy or Professional) probably experiencing jump testing more regularly. Overall, the results presented start to provide some valuable evidence on fatiguing mechanisms in batters. Jump testing could be a useful and straightforward assessment protocol for the exercise professional when planning conditioning programmes over the duration of season and protocols should be formalised for data comparisons to occur.

An embryonic evidence base of HR data for batting has been noted from both simulated events and in-match though as yet not captured within MD cricket. From the in-match data it is highest in T20 ($149 \pm 17 \text{ beat}\cdot\text{min}^{-1}$) in comparison to OD ($144 \pm 13 \text{ beat}\cdot\text{min}^{-1}$) (Petersen et al., 2010) with this trend also noted in a small study ($n=5$) from OD ($139 - 154 \text{ beat}\cdot\text{min}^{-1}$) and T20 ($149 - 167 \text{ beat}\cdot\text{min}^{-1}$) in English first-class cricket (Nicholson et al., 2009). The simulated OD batting environment appears to mirror the in-match values with Christie et al. (2007) OD batting test presenting mean HR of $145 \pm 10.5 \text{ beat}\cdot\text{min}^{-1}$ and Houghton et al. (2011) BATEX slightly lower HR mean of $130 \pm 16 \text{ beat}\cdot\text{min}^{-1}$. The limited HR data set suggest a moderate cardiovascular work load for batting, though mean HR values may occlude periods of higher work within an innings. Batters mean HR appears to be comparable to the mean HR of the bowlers (Figure 3) though the T20 data is captured over the duration of the involvement in the specific activity therefore bowling includes between-over rest episodes so probably lowering the final HR figure noted for bowlers (Petersen et al., 2010). Further exploration of in-match HR would be useful for exercise professionals to ascertain and capturing this data should be possible with the advancement of unobtrusive monitoring technology available (Petersen et al., 2009b).

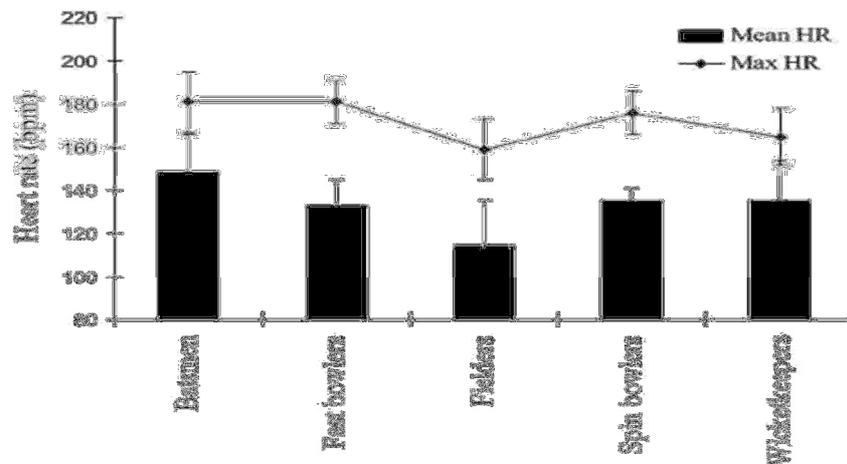


Figure 3 Mean and maximal heart rate (HR; M \pm SD) by position in Twenty20 cricket (Petersen et al., 2010, p49)

With the advent of popular shorter forms of cricket, research examining upper body strength has increased with the belief that stronger batters may score more runs quickly. Taliep et al. (2010) drew parallels to golf and baseball, where research suggested increases in 1 repetition maximum (RM) bench press lifts are linked to faster bat speed and therefore longer ball flight. Positive correlation ($r = .63, P = .05$) between 1RM and hitting distance were noted though no associations were made with actual match performance with OD or T20 strike rate and batting average. Even though participants ($n=18$) were elite performers, the data does not support the notion that greater upper body strength improves match performance. Critically, as seen with other batting simulations (Christie et al., 2007), there was a lack of control with regards “throw downs”, or the feeding of the ball for the batsman to strike. Coaching manuals and autobiographical anecdotes often cite the importance of placement and timing of hitting the ball is key within cricket rather than brute force alone (Woolmer et al., 2008, McGrath, 2010) further emphasising the need for research to consider this issue carefully within the research design process.

Batting performance has an additional element of protective clothing which can be up to 3 kg (dry weight) of additional load affecting running mechanics (Gore et al., 1993, Webster and Roberts, 2011). It is not clear how short or long term physiological performance is affected by movement wearing pads and other protective clothing, though it can be assumed, based purely on the additional load that there is a greater physiological cost to the performer. Conditioning practice should consider sprinting in pads in order for effective movement to be honed and the additional physical stress to be assessed.

2.2.4 Batting Movement Patterns

Even though objective physiological profiles are yet to be established for batters, time-motion analysis using retrospective video analysis and GPS technology has recently provided a further insight in to physical work completed in-match. Duffield and Drinkwater (2008) suggested batsmen's movement patterns during MD cricket and OD matches were similar, with the first and second sections of longer innings being relatively consistent with regards to movement completed which is somewhat counter to more recent GPS based data presented by Petersen et al. (2010). The variations, or lack of, in workload as an innings progressed are surprising as one would assume fatigue may occur over 2-3 hours not to mention the different tactical phases that occur within OD innings (Woolmer et al., 2008). The contrary results highlight the nuances of cricket and also could be attributed to more detailed time-motion data being captured through GPS technology as opposed to traditional time-motion methods used by Duffield and Drinkwater (2008).

Across differing formats of the game GPS technology has permitted further insights in to actual movement patterns, and therefore physical work, with batters reportedly covering greater total distances (mean \pm 90% CI) in MD (13.0 ± 0.2 km) in comparison to OD matches (8.7 ± 0.6 km) and T20 (3.5 ± 0.2 km) (Petersen et al., 2010). Clearly these distance data are linked to the unlikely assumption of players batting the full duration of the innings and the time associated with each match format influences the data set. When data are assessed relative to hours of play, MD cricket had the lowest distances covered per hour ($2.1 \text{ km}\cdot\text{h}^{-1}$), $0.4 \text{ km}\cdot\text{h}^{-1}$ lower than T20/OD cricket which both had similar values. These initial data indicate there is increased physical work (per hour) in the shorter formats of the game which is further supported when other aspects of player movement are noted. For example, for batters there were fewer sprint episodes per hour ($28 \pm 6 \text{ h}^{-1}$) and distance covered sprinting (86 ± 28 m) in MD cricket when compared to the other match formats. High intensity efforts of running 2's and 3's during the innings may last for 6 – 10 seconds and occur 6-14 times in an innings, which Duffield and Drinkwater (2008) claim was comparable to occurrences in Rugby Union and Field Hockey. At face value, these comparisons with other sports are useful though clearly cricket has many unique aspects, with it being played over a longer duration and more opportunities to recover for batters between physical efforts. Work to recovery ratio type data appears shortest in T20 (recovery ratio $38 \pm 13 \text{ sec}^{-1}$) in comparison to OD ($50 \pm 21 \text{ sec}^{-1}$) and MD ($61 \pm 10 \text{ sec}^{-1}$) cricket (Petersen et al., 2010), and this trend of increasing rest to work ratios from shorter to longer forms of cricket was mirrored elsewhere (Duffield and Drinkwater, 2008).

With respect to distance and velocity based data, new GPS technology supersedes the retrospective analysis through recorded match footage though both papers noted that stationary/walking

movement was the largest occurrence while batting and there were similar work to rest ratios (Duffield and Drinkwater, 2008, Petersen et al., 2010).

2.2.5 Considerations for Future Research

Access to the appropriate level performer is a common issue within exercise science research and it could be claimed this is also an issue for Christie et al. (2007) and Houghton et al. (2011; 2012). The number and performance level of the participants may have compromised comparisons and application of data to performance level cricketers with <10 non-elite (Christie, et al., 2007; Houghton, et al., 2011) and 6 Academy level performers used (Houghton & Dawson, 2012). Interestingly, when a higher level of performer was used in the second BATEX study, a difference in SJ/CMJ was seen pre-to-post perhaps reiterating the need for a homogenously experienced participant cohort.

Perhaps the most surprising criticism within batting focussed research papers is that, even if there is a physiological theme, bar basic anthropometrical information (i.e. stature and mass), most are devoid of any meaningful physiological characteristics related to the participants which must question the investigations robustness with regards to replication possibilities for other researchers (Taliep, et al., 2010, Houghton & Dawson, 2012). There appears to be a total lack of rudimentary evidence related to the physiological profile of batters at any performance level which must place exercise professionals on the back foot with regards to implementing bespoke conditioning programmes which could enhance players' athletic qualities.

Some variations between simulated tests in comparison to data from actual competitive matches are expected but it is unclear whether the differences noted are precise or if further refinement of the BATEX is required. Simulated tests would not be useful for the exercise professional if excessive differences between the test and match play data exist and a more accurate robust data set is probably required, may be through using unobtrusive mobile monitoring technology, before training programmes can be developed based on them.

To summarise the limited evidence base, with ample recovery periods between physical efforts, even in the shorter formats of the game, it would seem that short distance sprinting during batting is fuelled primarily by the phosphocreatine system, though when multiple back-to-back sprints occur in shorter formats of the game the body may draw on other anaerobic (lactic) mechanisms. For longer duration innings, when a number of kilometres (5 - 8 km) may be covered, batters could be susceptible to dehydration and possibly glycogen depletion unless in-match refuelling strategies are

implemented (Powers and Howley, 2007, Duffield and Drinkwater, 2008, Petersen et al., 2010). Biomechanical/neuromuscular fatigue may be evident when batters perform multiple acceleration and decelerations, though establishing this in the field has yet to be clearly evidenced in a batting population at the high performance level (Noakes and Durandt, 2000, Houghton et al., 2011, Houghton and Dawson, 2012). Even though there are common movement patterns required and therefore some standard physical characteristics for a cricket batsman, conditioning coaches could start to develop more bespoke training for specialist batters and consider how training could be manipulated to focus on different tournaments (e.g. T20 block of matches) as they occur through the season (Petersen et al., 2011b).

2.3. Physical Demands of Fielding

Except for the wicket-keeper, fielding is a role completed by all performers in the cricket team. Little is known about the physical characteristics of the role since the research focus that there has been within cricket, is on batting and bowling. Fielding related research in the area has mirrored those seen in bowling, assessing the mechanics of throwing (Freeston et al., 2007) and injury occurrence in performers (Saw et al., 2011).

Three papers have highlighted the physical workload within fielding through movement analysis during play (Rudkin and O'Donoghue, 2008, Petersen et al., 2011b, Petersen et al., 2010). Rudkin and O'Donoghue (2008) used traditional time-motion analysis techniques (i.e. observing motion real-time) whilst the two papers from Petersen et al. (2010; 2011) used GPS technology. The research by Petersen et al. (2010; 2011) investigated Centre of Excellence performers (i.e. non-first-class) in all three main formats of the game and MD/OD international matches versus Australian State first-class teams. Rudkin and O'Donoghue (2008) only collected data on English MD cricket. Interestingly, both sets of authors identified a similar mean total of ~15 km is covered in a full day of cricket (~100 over/6 hours a day) and this total distance is reduced in shorter formats of the game with performers from non-first class performance level covering 10.8 km and 4.6 km, in OD and T20 matches respectively (Petersen et al., 2010). Absolute OD distances covered by fielders increased at international level (12.0 ± 3.1 km) and in first-class matches (12.7 ± 1.8 km) perhaps suggesting different physical qualities are needed at the highest level of performance (Petersen et al., 2011b). For fielders, mean sprint distances were constant across all formats (~15 m) but T20 matches had the highest sprint load (Figure 1) with the greatest distance covered when sprinting (129 ± 91 m), highest number of efforts (i.e. >3 sprints in 60 sec) per hour (42 ± 20) and sprints per hour (8 ± 5) in

comparison to OD and MD formats (Petersen et al., 2010). In absolute values, MD has a greater physical load for fielders with 40-70% (5-10 km) more distance covered in a day in comparison to OD cricket which is valuable information for exercise scientists if planning optimal recovery strategies.

The specialist area of wicket-keeping was also reported by Petersen et al. (2010) with total distances covered being 16.6 km in MD, 9.5 km in OD and 2.2 km in T20. Similarly to fielding, it was noted that T20 is the more intense match format with a greater proportion of distance (T20 230 metres.hour⁻¹ [m.h⁻¹], OD 130 m.h⁻¹) covered at higher intensities (>12.6 km.h⁻¹).

As noted, the physical work related data are informative for conditioning and planning recovery but, importantly for coaches, the workloads for fielding are all less than those seen in fast bowlers and batsmen (Figure 1 and 3). Coaches need to calculate workload of players with differing roles in a team in order for the most appropriate conditioning programme to be developed during a season. Without considering this information it is unlikely optimal levels of physical performance will be maintained throughout the season.

From the evidence, it appears in comparison to the other main roles, fielding is the least intense aspect of cricket. Performers when fielding, bar wicket-keepers, cover less total distance (km), completing fewer sprints per hour in comparison to the other main positions, with the majority of their time spent walking (Rudkin and O'Donoghue, 2008). Petersen et al. (2010) note recovery between high intensity sprints is greater in MD (167 sec⁻¹), in comparison to OD (64 sec⁻¹) and T20 (51 sec⁻¹) which suggest that little metabolic fatigue should occur and the phosphocreatine system would adequately supply energy for the intermittent sprints. In temperate environments, physiological fatigue should not be accumulating when fielding in any form of the game though multiple acceleration and decelerations, involving repetitive eccentric muscle actions, through a day have been linked to reasons why fatigue may occur in some performers (Noakes and Durandt, 2000).

2.4.1 Physical Demands of Fast-Medium Bowling

Fast bowlers have attracted increased research interest as successful team performance is linked with these higher 'rated' individuals (Portus et al., 2000, Woolmer et al., 2008, Wormgoor et al., 2010). Whilst fast bowlers are a vital element in the cricket team, they typically have the shortest careers in comparison to their peers (Engel, 2007), and as such previous research in this population has had a biomechanical focus linked to injury avoidance and prevention (Bartlett et al., 1996, Elliott, 2000, Dennis et al., 2005). The lack of physiological performance related evidence has led to a hypothetical view of the fast bowler, with a "typical" fast bowler completing approximately 60

episodes of upper and lower body intense actions in a 10 over spell, covering approximately 1.9 km in 5.3 discontinuous minutes (Noakes and Durandt, 2000, Stretch et al., 2000). A move to address this lack of information has seen recent data presented in cross-sectional player anthropometric and physiological profile investigations (Pyne et al., 2006, Stuelcken et al., 2007), movement analysis papers (Duffield and Drinkwater, 2008, Petersen et al., 2011b) and initial investigations of the physiology of bowling (Burnett et al., 1995, Duffield et al., 2009, Minett et al., 2012a).

Within a “fast” bowling group, sub-divisions related to speed of delivery are commonly applied; fast, fast-medium, medium-fast. Glazier et al. (2000) reported, elite level fast bowlers deliver the ball between 36 – 40.5 m.sec⁻¹ (129 – 145.8 km.h⁻¹) or in rare “express” bowlers > 40.5 m.sec⁻¹ (> 145.8 km.h⁻¹). Though the aforementioned descriptors are often used, the lack of standardisation in this area makes cross-research data comparisons difficult.

Portus et al. (2000. p999) emphasised the issues that face the sports science professional working with bowlers;

“The prescription of fitness programmes for fast bowlers will continue to be based on educated guesses until we understand the role that certain physical characteristics play in fast bowling technique and performance”

Therefore, the incomplete evidence base for the fast bowler is leading to conditioning programmes and in-match advice being based on anecdotal or hypothetical data (Portus et al., 2000, Duffield et al., 2009).

2.4.2 Physical Attributes Associated with Fast Bowling

Effective fast bowlers need to maintain speed and accuracy of delivery during performance which has been linked to a number of factors including anthropometrics, body composition, bowling action, run up speed (Portus et al., 2000, Woolmer et al., 2008).

2.4.2.1 Stature of Fast Bowlers

Within the elite fast bowling population, fast bowlers’ possess a tall stature ranging between 1.83 – 1.92 m (Glazier et al., 2000, Pyne et al., 2006, Stuelcken et al., 2007, Duffield et al., 2009, Phillips et al., 2010) which is taller when compared to data on batsmen (1.76 – 1.85 m) (Christie et al., 2007, Houghton et al., 2011, Houghton and Dawson, 2012) and a comparable general male population (mean 1.77 – 178 cm) (Australian Bureau of Statistics, 1998, National Statistics, 2011). Tall statures

for fast bowlers could be perceived as a positive variable in terms of delivery release angle, bounce of ball from the pitch and force production (Norton et al., 1996, Glazier et al., 2000, Pyne et al., 2006, Stuelcken et al., 2007). It has been argued that a natural selection process has occurred (Norton et al., 1996) and data supports the evidence of the wider benefit of increased stature, as 80% of leading elite test match bowlers, categorised by number of wickets taken, are over 1.83 m (Engel, 2007, Cricinfo, 2008). Such applied information seems valuable to exercise scientists and coaches alike though with varieties of performers bowling technique has led to questions regarding the importance of this variable and its effect on performance (e.g. increase speed of delivery and/or variety of bounce) (Stuelcken et al., 2007, Wormgoor et al., 2010).

2.4.2.2 Bowling Arm Length

Glazier et al. (2000) suggested bowling arm length could be a key anthropometrical trait in relation to achieving high delivery speeds though subsequent contradictory research did not support this finding (Pyne et al., 2006, Stuelcken et al., 2007, Wormgoor et al., 2010). In theory, the findings of Glazier et al. (2000) should hold some credibility as the linear velocity of a point on a lever undergoing angular rotation is proportional to the angular velocity and the radius of rotation. Since the bowling arm may be considered a quasi-rigid lever during the bowling action, for a given angular velocity, a longer arm would produce a faster velocity of the wrist. Although the theory sounds logical, a longer arm will mean greater moment of inertia of that segment meaning greater resistance to rotation. Moreover, unlike the work of Pyne et al. (2006) and Stuelcken et al. (2007), Glazier et al. (2000) did not use first-class performers and the sample was relatively small (n=9) so questioning the credibility of their outcomes. Therefore, it appears that other variables may play a more important role in the generation of speed by the bowler (Stuelcken et al., 2007).

2.4.2.3 Upper Body Muscularity of Fast Bowlers

Within fast bowling, participants with higher ball release speeds have been shown to possess a greater anterior-posterior chest depth, a lean upper body and large arm girths (Stretch and Lambert, 1999, Portus et al., 2000, Pyne et al., 2006, Stuelcken et al., 2007). The bowling action involves humerus circumduction, utilising the pectorals major and latissimus dorsi and the deltoid muscles. The biceps brachii are active during the bowling action stabilising the elbow and glenohumeral joint, along with the rotator cuff muscles (Stuelcken et al., 2007). Force production from the upper body is one aspect of bowling technique and could account for between 36 – 45% of variance in bowling speed (Portus et al., 2000, Pyne et al., 2006, Stuelcken et al., 2007). Increased muscularity of the

upper body in performers stems from conditioning programmes and adaptation to the game demands. Training literature (Powers and Howley, 2007, McArdle et al., 2009,) notes a commonly held view of proportional relationship between muscle force production and cross-sectional area of a muscle confirming that bowling conditioning coaches should be aware of the importance of the role of lean muscle tissue in relevant musculature to help generate higher and more consistent bowling speeds.

2.4.2.4 The Bowling Action and Technique

Ferdinand (2012) describes the bowling action;

“During the delivery leap there is an initial trunk rotation and extension away from the intended direction of the ball. Once in delivery stride, the trunk begins to rotate and flex forwards pulling the bowling arm with it. However, there is a braking action on the trunk as it nears the end of its range of motion. By means of Newton's Third Law the braking action of the trunk segment further accelerates the bowling arm segments prior to ball release”

(http://coachesinfo.com/index.php?option=com_content&view=article&id=280:introduction&catid=84:cric ket-bowling&Itemid=159)



Figure 4. The basic bowling action from side-on view (Ferdinands et al. 2012, www.coachesinfo.com)

It is recognised that there are different classification of bowling actions which may affect the final speed of delivery. The actions noted within the literature relate to the bowlers body position and specifically degree of shoulder counter-rotation during the delivery. Portus et al. (2000) presented (Figure 5) an outline of the classification of bowling techniques into three main categories;

- (a) Side on (i.e. hip and shoulders aligned side ways to batter)
- (b) Front on (hips and shoulders front on to batter)
- (c) and (d) Mixed action (i.e. front on hip and side on shoulders or vice versa)

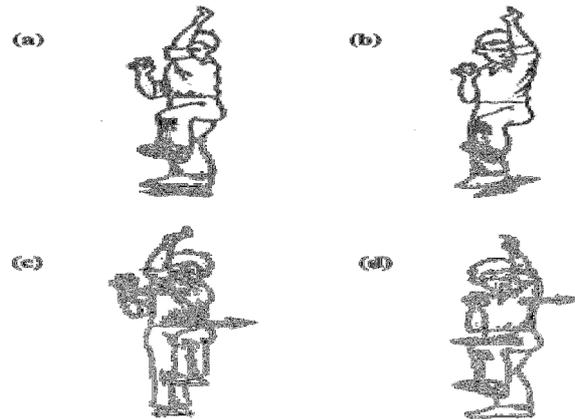


Figure 5. Bowling actions; (a) Side on technique (b) Front on technique (c) Mixed action with hips more front-on than shoulders (d) Mixed action with hips more side on than shoulders (Portus, Sinclair et al. 2000, p1000).

The position of the back foot in relation to the upper body on release of the ball is an indicator of bowling action type. Classification of bowling action can be subjective with an additional “semi-open” bowling action noted in some literature (Ferdinands et al., 2010). There are different definitions linked to amount of shoulder counter-rotation and how this categorises bowling action in the research literature. It is generally agreed though that a mixed action increases torsional load within the lumbar spine leading to injury (i.e. pars inter-articular stress fracture, intervertebral disc degeneration etc.) though in a cross section of sub-elite performers, a mixed-action was the most common noted (Portus et al., 2000, Ferdinands et al., 2010). Bowling action and speed of delivery have not been conclusively linked though technical elements within the bowling action do seem to be a factor and are discussed in the following sections.

2.4.2.5 The Run Up

Delivery speed can be affected by variations in the bowlers run-up speed, distance travelled and bowling action adopted (Wormgoor et al., 2010). Run up length has been associated ($r = .70$) with mean speed of the delivery and run up speed could have an effect of up to 16% on release speed (Duffield et al., 2009, Glazier et al., 2000, Elliott et al., 1986). Data is clouded by studies using both first-class and non-first-class fast bowlers which identifies run up lengths ranging between 15.2 - 17.7 m and mean run up velocity ranging between 17 – 21.6 km.h^{-1} with higher values recorded ($\sim 22 \text{ km.h}^{-1}$) in the last 5 m pre-delivery (Burnett et al., 1995, Duffield et al., 2009, Elliott et al., 1986, Stretch and Lambert, 1999). Performers who bowled at higher speeds seem to have a faster final 5 m of the

run up ($r = .72$) and evidence presented from performance level “nationally-contracted” performers suggests faster bowlers have a faster run up (Strath et al., 2000, Wormgoor et al., 2010). However, the relationship between bowling speed, run up length and bowling action are yet to be resolved. Somewhat conflictingly, run up speed must be balanced against the technical action, rhythm and momentum which influence the bowlers approach to the wicket (Duffield et al., 2009, Strath et al., 2000, Woolmer et al., 2008). Variations of bowling techniques has previously been reported (Portus et al., 2000, Ferdinands et al., 2010) with run up speed altering with the type of technique adopted. Bowlers with a front-on and mixed bowling action allow for higher approach speeds, which may be possible due to the position that the bowler can, or needs to adopt at the start of the delivery action (i.e. back foot impact) (Burnett et al., 1995, Elliott et al., 1986, Glazier et al., 2000). The uncertain intertwinement of technique and physical evidence may leave the technical and conditioning coach requiring more clarity on this issue to improve performance.

2.4.2.6 Front Knee Angle

It is documented that there could be a relationship between a straighter more extended front knee (e.g. $>150^\circ$) during ball release and higher delivery speeds (Loram et al., 2005, Pyne et al., 2006, Wormgoor et al., 2010, Strath et al., 2000). Portus et al. (2004) noted that during front foot contact a more extended front knee may allow for better transfer of kinetic energy, however, this favourable trait could also be associated with increased injury incidence as more impact force (e.g. 5 to 9 times body mass) is absorbed by soft tissues and the lower back (Portus et al., 2004, Portus et al., 2000). Effective lower body strength, specifically eccentric strength, could assist in maintaining an extended front knee and also assist in withstanding the impact forces that occur when the front foot lands during bowling (Elliott, 2000, Noakes et al., 1998). Bowlers possess increased levels of leg power with lower body power considered a partial predictor of bowling speed within first-class bowlers (Pyne et al., 2006). It is unclear if the increased levels of lower body strength noted are achieved through game play or planned conditioning, as if it is mainly the former there is more scope to develop this physical trait further. Optimum lower body strength qualities are yet to be confirmed, though may be a determining factor in achieving higher bowling speeds (Wormgoor et al., 2010).

The interrelated physical and technical attributes of the bowling action has led to multivariable models being developed in an attempt to predict performance, though collectively these models are inconclusive due to participant selection and varying methodologies used (Glazier et al., 2000, Loram et al., 2005, Pyne et al., 2006, Salter et al., 2007, Wormgoor et al., 2010). Clarity between key predictive variables needs establishing, to identify the most effective technical sequencing

(Ferdinands et al., 2010, Phillips et al., 2010, Strath et al., 2000) and physical (Pyne et al., 2006) attributes to include within a predictive multivariable model.

2.4.3 Physiological Fitness Profile of Fast-Medium Bowlers

In comparison to other team sports such as rugby (Duthie et al., 2003, Gabbett, 2002) and football (Reilly et al., 2000) there is limited information on fitness profiles from first-class bowlers and cricket players generally. Previously international cricket players have recorded similar aerobic and anaerobic fitness levels as professional international rugby union players (Bartlett, 2003, Noakes and Durandt, 2000) though a current full physiological profile of elite fast bowlers has yet to be established. When physiological data is noted, most investigators present this as secondary information and subsequently protocols used are not always explicit therefore limiting comparability of data. Examples of data on fast bowlers include; Predicted $\dot{V}O_{2\max}$ max between 50.6 – 62.7 mL.kg⁻¹.min⁻¹ (Duffield et al., 2009, Smith et al., 2007) which is similar to professional players in rugby union (Duthie et al., 2003) and football (Reilly, 2007) though the latter reported a higher upper range (75 mL.kg⁻¹.min⁻¹); Vertical jump values ranged 0.32 - 0.43 m (Duffield et al., 2009, Pyne et al., 2006), which are lower than values reported in football (0.48 to 0.60 m) (Reilly, 2007) and rugby union and rugby league (0.45 m to 0.56 m) (Duthie et al., 2003, Rennie et al., 2000) respectively; Bench press (9 kg) (75.1 ± 11.7 cm) and deltoid throws (50.5 ± 9.4 cm) using a Smith Machine (Pyne et al., 2006) have also been reported but have limited comparability. Though international teams are now subscribing to more formalised fitness screening procedures (England and Wales Cricket Board, 2012, Australian Cricket Board, 2012) these data are yet to appear in the public domain. Unlike in other sports (Duthie et al., 2003, Gabbett, 2002, Reilly, 2007) the intermittent depth of reporting of the methodology limits inter and intra sport comparisons, hindering the establishment of bowling-specific normative values which would be valuable for conditioning coaches when planning progressive training programs

Recent time-motion research capturing GPS data identifies fast bowlers cover ~22 km in a MD match, ~13 km in a OD match and ~5.5 km in a T20 match (Petersen et al., 2010). Moreover, in comparison to other members of the cricket team, fast bowlers have a greater number of high-intensity (> 14.4 km.h⁻¹) activities and less time to recover between these events in all formats of the game (Petersen et al., 2010, Petersen et al., 2011b, Petersen et al., 2009c). Current conditioning practices do not always match the physical intensity required (Petersen et al., 2011a) and without comprehensive long term fitness profiles of fast bowlers, exercise scientists and strength and conditioning coaches still have limited evidence to build bespoke programmes for players, limiting long term development.

2.4.3.1 Physiological Responses of Fast Bowlers

Investigations into physiological responses during fast bowling have revolved around participants bowling a pre-determined number of overs and then the maintenance of the bowling action, physiological fatigue and/or accuracy of the deliveries are monitored. Considering peer reviewed literature from the past 25 years, with an inclusion criteria of studies having ≥ 5 participants, a minimum of one physiological measure (e.g. heart rate, temperature) being collected, research examining physiological responses to fast bowling is limited to 8 studies (Table 1, p29). Considering the latter criteria, only one study (Petersen et al., 2010) does not use simulated (i.e. does use in-match) bowling events/environments to collect data. Bowling activity duration specified within the research has lacked consistency, with 12 overs (Burnett et al., 1995), 6 overs (Stretch and Lambert, 1999) and 2 x 6 over spells (Duffield et al., 2009) being arbitrarily applied and probably linked to anecdotal evidence from competitive matches. Confirmation of bowling spells from competitive match data is needed to corroborate the length of bowling events selected in future simulated research, which may improve the ecological validity of the data collected and therefore its application for exercise scientists working within the field (A fuller exploration of ecological validity is provided in section 2.5).

The most reported physiological measure, heart rate (HR), appears to respond to the intermittent increments, decrements and rest periods associated with the bowling activity as seen in Figure 6. Burnett et al. (1995) identified a heart rate range between 163 ± 11 beats \cdot min $^{-1}$ to a peak of 176 ± 12 beats \cdot min $^{-1}$, equating to 80.3% and 84.7% of theoretical maximum heart rate (i.e. $220 - \text{age}$), which was similar to data noted in first-class performers (Duffield et al., 2009). These peak heart rates are sustained for relatively short periods and relate to the high intensity physical work when bowling is occurring (Noakes and Durandt, 2000). Different heart rate data have previously been reported (Devlin et al., 2001, Gore et al., 1993, Stretch and Lambert, 1999) however, the participants, environmental conditions and lack of information with regards to bowlers run up (i.e. speed and length) and delivery speeds may partly explain the differences (Table 1).

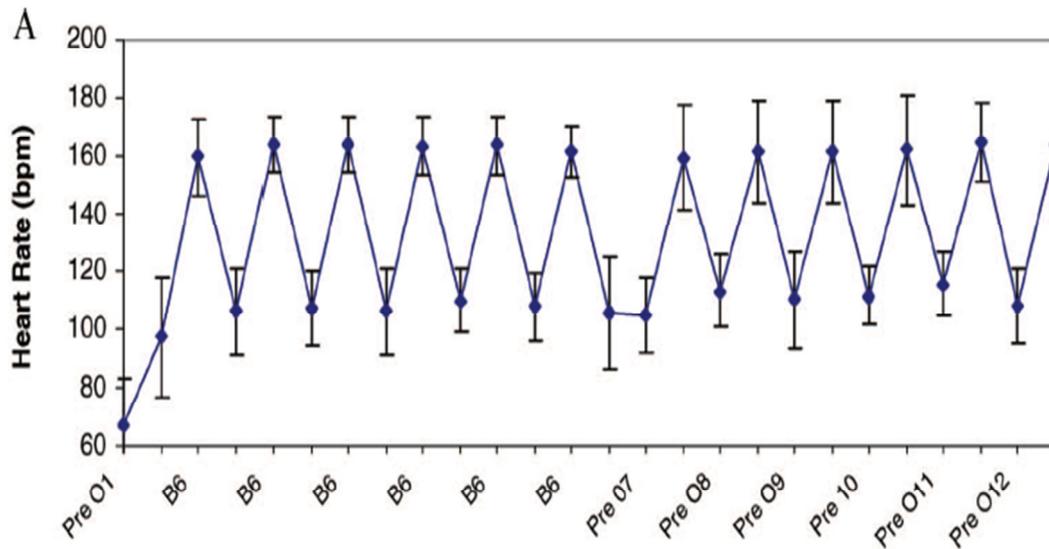


Figure 6. Heart rate response (mean \pm SD) recorded over 2 x 6 over spell (Duffield et al., 2009, p 31)
bpm = beats per minute

In the limited studies in which blood lactate was measured, a mean of 4.8 mmol.L^{-1} (Burnett et al., 1995) and a peak mean blood lactate of $5.0 \pm 1.5 \text{ mmol.L}^{-1}$ reported (Duffield et al., 2009). Duffield and colleagues (2009) suggest bowlers with longer run ups and/or faster run up speeds had higher lactate levels ($r = .60$) though blood lactate is not accumulating significantly during the bowling spell(s). Moreover, Duffield et al. (2009) also reported that blood glucose decreases ($6.3 - 5.5 \text{ mmol.L}^{-1}$) pre-test to the end of a second bowling spell intimating that specific nutritional support is required if high performance is to be maintained. Recently, Minett et al. (2012a; 2012b) have investigated cooling strategies on physiological responses (Table 1) of fast bowlers, suggesting a benefit from the process by reducing “thermal demands” on the body. There seems to be agreement that medium-fast bowling activity of up to 12 overs does not affect bowling speeds or accuracy in temperate environmental conditions (Burnett et al., 1995, Duffield et al., 2009, Minett et al., 2012a). This collection of results provides some evidence for exercise scientists and conditioning professionals to consider interventions pre, during or post bowling if high performance is to be maintained.

In summary, there appears to be bowling related increases in heart rate, suggesting substantial repeated intermittent cardio-vascular stress over the length of the bowling spell (Duffield et al., 2009). Though an increase in blood lactate is noted, no significant accumulation occurs suggesting the role of the anaerobic metabolic system is moderate, with both the ATP-PC and glycolysis

pathways contributing to the bowling event(s) (Burnett et al., 1995, Duffield et al., 2009, Stretch and Lambert, 1999). The between-over recovery and intermittent nature of the activity may explain the latter outcome, however the causes and specific markers of fatigue remain unclear. Noakes and Durandt (2000) debated the theoretical concept of physiological fatigue mechanisms within cricket and suggest the “classic models” of cardiovascular-anaerobic energy depletion model and energy supply-depletion do not explain the fatigue that may occur in cricket. Fast bowlers do enter repetitive high intensity acceleration-deceleration (i.e. eccentric muscle action) episodes which could lead to specific muscular fatigue due to altered muscle action, recruitment and firing, which may link to the loss of elastic energy element within muscle (Morgan and Allen, 2000, Duffield et al., 2009). Moreover, increased levels of markers associated with muscle damage (i.e. creatine kinase) and inflammation (i.e. C-reactive protein) have been reported post-bowling but this biochemical evidence is still in its infancy (Minett et al., 2012b). Without further research into this area, mechanisms of fatigue within the fast bowler will remain speculative.

2.4.3.2 In-Match Physiological Data

As physiological monitoring technology advances, devices have become more reliable, valid and unobtrusive to wear. Data that is captured during competitive matches could be considered to improve ecological validity of data (Petersen et al., 2009b). To date there appear to be only two studies which have completed physiological in-match monitoring of first-class performers; Petersen et al. (2010) monitored heart rate response in-match of fast bowlers, though the data was restricted to T20 cricket and was part of a wider time-motion study focussing on movement patterns (Table 1). Secondly, a conference paper also assessed heart rate response, focussing on OD cricket, though data was limited to only two first-class participants (Johnstone et al., 2008). Even though this limited novel data were collected in different formats of the shorter game, mean heart rates were similar, though peak heart rates reported were ~ 10 beats \cdot min $^{-1}$ higher in T20 cricket (Table 1). Considering the sparse data set, interestingly within the context of fast bowling, this in-match data notes similar peak heart rates but lower mean heart rates which are presented within the simulated bowling research (Burnett et al., 1995, Duffield et al., 2009). The differences noted in heart rate data between the in-match and simulated events may have wider implications on the ecological validity of data collected in the latter environment. Moreover, the varying match formats now played within cricket and match timings associated with each also require clarification within monitoring research. It could be argued, that basing conditioning programmes for fast bowlers on evidence collected from simulated data may not be appropriate with physical training programmes in cricket not matching

the game demands (Petersen et al., 2011a). Once a credible base of literature is developed which can corroborate the validity of simulated bowling events or a move occurs to use new technology within assessment of physiological responses in-match, exercise scientists may be able to draw more evidence based conclusions about physical demands on players and associated performance.

2.4.3.3 Limitations of Physiological Monitoring and Recommendations for Research

Simulated bowling research attempts to recreate a real match format, where access to performers within competitive first-class matches and unobtrusive monitoring technology has not seemingly been available. These simulated events use equivalent match timings (i.e. overs per hour) and require players to perform as per match conditions in an attempt to increase the ecological validity of the research setting, though some aspects of these methods used could be questioned. For example, after the participant has bowled one over from a set of overs, to replicate a real competitive match, between-over fielding activities were completed (Duffield et al., 2009). These between-over activities do not always note sufficient detail with regards to the actual activities and physical intensity participants worked at, as researchers crudely estimate this as there is little or no data reported from competitive matches for this period. Paradoxically, the physiological recovery available between-overs may be a crucial variable in relation to performance in the next over(s). Observations from matches suggest, between each over, fast bowlers are normally positioned in the field where it is least likely there will be significant fielding activity (i.e. physical work) in order to facilitate recovery for their next over. The value of this between-over, or *off the ball*, period is only now being considered in relation to recovery (Minett et al., 2012a) and could be an important research area to follow with regards to bowling performance.

The simulated bowling research has mainly focussed on short term performance and can only be applied to the shorter forms (e.g. OD/T20) of the game. An exception to this is Minett et al. (2012), who assessed data on bowling performance on two consecutive days. Gore et al. (1993) collected simulated data over 3 seasons though in the main little attempt due to logistical reasons, has been made to assess physiological responses in bowlers across MD bowling events/match. Even though MD cricket is still a key game format, considering the sports historical engagement with exercise science research (Buchanan, 2008) it is unsurprising the area of physical responses and bowling performance over MD remains unknown.

Research collated within the area of fast bowling has used a variety of participants linked to the speed of delivery these individuals can produce. As noted, elite level bowlers classed as “fast” have

been reported to deliver the ball $> 40.5 \text{ m}\cdot\text{sec}^{-1}$ ($> 145.8 \text{ km}\cdot\text{h}^{-1}$) (Glazier et al., 2000), though identifying and then accessing performers who fulfil, or partially fulfil, this latter bowling trait is difficult. When reviewing the available research, the quality of data is partially limited by the access to appropriately skilled participants who fulfil the bowling speed criteria which in turn, may restrict the results wider application and usefulness. At present, first-class/professional cricketers have been used in only three studies where bowling speeds were reported ($34.2 - 35.3 \text{ m}\cdot\text{sec}^{-1}$; $123 - 127 \text{ km}\cdot\text{h}^{-1}$) (Duffield et al., 2009, Minett et al., 2012b, Pyne et al., 2006). The utilisation of a lesser standard and/or skilled cricketers as participants has been common which produces lower bowling delivery speeds (i.e. $104.8 - 115.6 \text{ km}\cdot\text{h}^{-1}$) and therefore non first-class physiological performance data is reported (Burnett et al., 1995, Devlin et al., 2001, Glazier et al., 2000, Portus et al., 2000). Moreover, participant numbers within these studies are low ($n < 10$) except for Portus et al. (2000) ($n = 14$), Elliot et al. (1986) ($n = 15$) and Pyne et al. (2006) ($n = 24$). These issues highlight the difficulty of accessing elite performers which may not be unique to just cricket

In summary, the limited participant numbers, diverse skill level and broad disparity in bowling speeds noted across research may affect the quality of knowledge gained and therefore the application of the research to the higher levels of performance. If fast bowling is to be fully investigated and further advances are to be made in performance, accessing appropriate participants who operate at the highest level should be a key research aim.

2.4.3.4 Summary

Research has a great potential to influence the rapidly changing sport of cricket (Kolt, 2012) and fast bowling requires the confirmation of evidence related to performance at the highest level. Further work identifying key variables in order for more effective predictive multivariable models are required which will allow coaches to facilitate performance. Additionally, the advent of new unobtrusive monitoring should allow for more in-match monitoring of performance, so ecologically valid data can be captured allowing a more complete insight in to the physical requirements of fast bowling across different formats and on consecutive days. Research in this area should be a priority in order to help exercise scientists and coaches to optimise the selection of talented fast bowlers, improve performance and extend playing careers.

Table 1. Research reporting physiological responses of fast bowling for the past 25 years (from years 1987 – 2012)

Study	<i>n</i>	Mean ages (years)	Height and Mass	Methodology notes	Playing Standard ^(c)	Bowling type ^(d)	Mean run up speed (km.h ⁻¹)	Mean Heart rates (beats.min ⁻¹)	Bowling Velocity (metres.sec ⁻¹)	Other measures
Gore et al. (1993) ^(a)	12	19.5 ± 0.1 19.7 ± 0.6	187.4 ± 2.2 cm 81.3 ± 3.8 kg	Outdoor cricket nets, 3 seasons of data	First grade (AUS)	-	-	Cool 121 ± 1 Warm 122 ± 1	-	Sweat rate, Core temp
Burnett et al. (1995)	9	18.1 ± 1.0	1.85 ± 0.09 m 76.2 ± 10.0 kg	Outdoor cricket nets, 1 x 12 overs (28.1°C)	State development squad (AUS)	Fast	19.8	Over 1: 163 ± 11 Over 12: 172 ± 8	Range: 31.6 – 32.9	Bla, run up, Technique
Stretch and Lambert, (2000) ^(b)	J=11 S=10	J:11.6 - 13.3 S: 17.7 - 21.5	J:158.3 ± 5.8 cm J:45.6 ± 5.2 kg S:184.9 ± 5.3 cm S:78.0 ± 10.6 kg	Outdoor cricket nets, 1 x 6 overs, participants grouped by age (22.3°C)	Provincial Elite & potentially elite (SA)	Fast	-	J: 159 ± 12 S: 153 ± 10	-	Flexibility, Bowling accuracy
Devlin et al. (2001)	7	21 ± 1.0	- 89 ± 13 kg	Outdoor cricket pitch, 1 x 6 overs, (16°C)	Sub elite (AUS)	Med/ Fast	-	154 ± 15	Mean: 29.1	Accuracy, Hydration status
Duffield et al. (2009)	6	23 ± 3	185.6 ± 6.8 cm 86.9 ± 11.3 kg	Outdoor nets, 2 x 6 overs separated by 45mins, CAAIS FB ^(e) skill test (21-23°C)	First class (AUS)	Med/ Fast	19.9 ± 1.7 Final 5 m: 22.8 ± 1.9 ¹	Spell 1: 162 ± 9 Spell 2: 162 ± 12	Spell 1: 34.9 Spell 2: 34.8	Accuracy, Core body temp, Bla, pH, glucose
Petersen et al. (2010)	10	22.1 ± 2.8	1.81 ± 0.08 m 84.3 ± 8.7 kg	Competitive (n=7) international T20, in-match	Centre of Excellence (AUS)	Fast	-	133 ± 12 Peak 181 ± 10	-	GPS movement analysis study
Minett et al.	10	23 ± 8	189.8 ± 8.8 cm	Outdoor cricket square, 6	Senior club or	Med/	19.3 ± 3.81	Range:	Mean: 32.1	Core and skin

(2012a)				over, CAAIS FB skills test (31.9°C)	Junior state level (AUS)	Fast	Final 5m: 21.6 ± 2.3	160 - 170	Peak: 32.8	body temp, Urine gravity, Creatine kinase, Testosterone, Cortisol
Minett et al. (2012b)	8	23.3 ± 4.9	187.8 ± 5.9 cm	Outdoor cricket net, day 1: 10 over, Day 2: 4 over, CAAIS FB skills test (30.4°C)	State squad members (AUS)	Med/ Fast	20.3 ± 3.6 Final 5m: 20.9 ± 1.8	~150	Mean: 32.8 Peak: 34.7	Yo-Yo test, Core and skin body temp, Urine gravity, Creatine kinase, C- reactive protein

Tabular report: *n* = number of participants, *Data* reported verbatim from journal (a) Cool = 22°C, Warm = 30°C, (b) J = Junior, S = Senior, Only age ranges provided, (c) AUS=Australia, SA=South Africa, (d) Med = medium. (e) CAAIS FB = Cricket Australia Australian Institute of Sport Fast Bowling (skills test)

2.4.4 Movement in Fast Bowling

Monitoring the physical movement patterns of performers is now more accessible with the advent of GPS. Accurate assessment of movement patterns in cricket had yet to be evidenced until the use of GPS monitoring devices were utilised to identify workloads for high performance fast bowlers during competitive matches (Petersen et al., 2010, Petersen et al., 2009b). Across the different formats of the game fast bowler's total distance covered (mean+90% CI) was 5.5 ± 0.4 km for T20, 13.4 ± 0.7 km for OD match and 22.6 ± 2.1 km for MD cricket. Early single subject research noted that an international fast bowler during an OD match playing period (i.e. 3.5 hours fielding innings) covered a total distance ranging between 13.9 - 15.9 km which is similar to a fielder during a multi-day game (Petersen et al., 2009c, Rudkin and O'Donoghue, 2008). In comparison to the fielding data, the total distance by the fast bowler was completed in half the playing time (i.e. 3.5 hours vs 6 hours) providing first clear field based quantitative evidence of fast bowlers' higher workloads.

Further specific analysis of the total distance covered by fast bowlers during the OD international matches notes 69% (10.9 km) spent walking, 16% (2.5 km) jogging, 9% (1.3 km) running or striding, 7% sprinting (1.1 km). Physical efforts completed that were $> 12.6 \text{ km}\cdot\text{h}^{-1}$ totalled 191 lasting, on average, 2.7 sec^{-1} with 68 sec^{-1} recovery confirming the intermittent movement patterns completed by this player in this format of the game (Petersen et al., 2010).

Across the formats of cricket, in terms of hourly sprint distances completed by fast bowlers, the T20 format is 22% more intensive than OD and 43% more intense when compared to MD matches though MD matches had the higher total sprint distance (i.e. T20 24%, OD 59% of MD distance). Also only fast bowlers completed repeat sprint activities, which was defined as a minimum 3 sprints with $<60 \text{ sec}^{-1}$ recovery, during matches. Obviously these repeat sprint activities occur during bowling but also could occur between overs when fielding (Petersen et al., 2009a, Petersen et al., 2009c, Petersen et al., 2010, Petersen et al., 2011a). Overall this initial research within movement analysis confirmed that fast bowlers "*operated at the highest intensity (in comparison to other players) across all formats of the game*" (Petersen et al 2010. p50).

Historical research by Fletcher (1955) suggested cricket has little more energy expenditure achieved than when standing is clearly challenged by the current literature, though as Petersen et al. (2010) notes, may have reflected the physicality and culture of the game in the 1950's. Within the cricket team it appears players can have very different workloads depending on their role. It seems that the fast bowlers have highest workload of any cricket player, approximately twice the work load of a fielder. This information allows quantitative assessment of workload to be considered so conditioning coaches can develop bespoke training and recovery for players in the team.

2.4.5 Bowling Accuracy

Accuracy of the delivery is very important for the fast-medium bowler as it is crucial in a match scenario to restrict run scoring opportunities and create pressure on the batters (Woolmer et al., 2008, Phillips et al., 2012). Anecdotally, it is common practice to assess bowlers performance against the number of runs scored off their bowling or runs per over across a match (Pont, 2006, Woolmer et al., 2008). Within a research scenario, studies have attempted to assess accuracy and the effect of fatigue during a controlled simulated bowling event. This research area would be useful for the coach in order to understand the optimal number of overs a player should bowl before accuracy declines.

It has been debated across a number of sports if athletes' technical ability declines with an accumulation of physical fatigue during an on-going performance (McMorris and Graydon, 2000, Royal et al., 2006). Fatigue is multifaceted and can stem from a variety of sources linked to the sporting activity being completed (Powers and Howley, 2007; McArdle et al., 2009). Noakes and Durrant (2000) present cricket specific ideas on this theme describing a cardiovascular-anaerobic model, energy depletion model and a biomechanical (eccentric) model. The latter model of fatigue is claimed as being the more credible within cricketers and seems to be pertinent for fast-medium bowlers. The high incidence of accelerations and decelerations completed and the front foot contact period during bowling (i.e. ball release) produce large eccentric stress on the lower body. This area of eccentric muscle fatigue and bowling performance should be investigated further.

Fast-medium bowlers have a specific role within the cricket team and within cricket bowling studies currently it appears there is somewhat contradictory evidence with regards to bowling accuracy as a fast bowling spell continues (Stretch and Lambert, 1999, Devlin et al., 2001, Duffield et al., 2009). Portus et al. (2000), noted a change in technique within some bowlers, stating that a higher counter rotation of shoulders was significantly related ($r^2 = 29\%$) to bowlers being less accurate during overs 5 to 8 of an 8 over simulated bowling event. It was postulated that increased shoulder counter-rotation could mean increased instability of the head, and therefore eyes, leading to performers not being able to focus on the target which has been noted as important factor for accuracy. Hydration status (i.e. being mildly hypo-hydrated) was found to affect bowling accuracy (16% decrement) even though heart rate and speed of delivery remained unchanged (Devlin et al., 2001). Duffield et al. (2009) study found that their bowling participants, accuracy did not differ significantly ball-to-ball or between two 6 over spells of bowling (CV 4%) and was not associated with speed of delivery or physiological responses.

As noted previously, participants used within these latter pieces of research were of varying ability so their actual ability to execute the bowling skill with accuracy and consistency could be questioned.

The lack of equivalent standardised methods across these studies is also a limiting factor with a number of different protocols having been employed; subjective ball-by-ball observations from trained observers (Stretch and Lambert, 1999, Phillips et al., 2012), a pitch based target (Devlin et al., 2001), and a target next to the stumps (Portus et al., 2000) have all been utilised. Moreover, to further limit comparisons between data sets, all these studies had differing measuring mechanisms (i.e. scoring of accuracy). The most recent studies all use retrospective analysis after filming the bowling spell which introduces some quality control to the data collection (Devlin et al., 2001, Portus et al., 2000, Duffield et al., 2009). Portus et al. (2000) cite Stretch and Goslin (1987) Cricket Skills Test and Duffield et al (2009), uses the Cricket Australia-Australian Institute of Sport (CA-AIS) fast bowling skills test though it is unclear if the tests have been extensively validated or not. Assessing accuracy of bowling seems a logical and valuable performance variable to consider though methodological improvements need to be made before future research can confidently confirm or build on these initial findings.

A consistent theme among research which aims to identify key variables relating to bowling speed and accuracy is that there is an assumption that correct technical “temporal sequencing” of the bowling action is occurring (Pyne et al., 2006, Glazier et al., 2000, Phillips et al., 2012). More effective sequencing patterns of trunk and arm segments were identified in faster bowlers (Ferdinands et al 2002 cited in Stuelcken et al 2007) and coaching manuals often cite a rhythmical consistent smooth run-up and bowling action is preferred (Woolmer et al., 2008, McGrath, 2010). With limited information on this issue, whether participants have an effective “temporal sequencing” regarding their bowling action can at this current time, only be rationalised by their playing standard (i.e. first class performer or not). Research which uses the highest performance level of fast bowler delivering the ball at the fastest speeds should mean appropriate temporal sequencing is occurring and therefore individual or groups of predictors of performance could be considered which are applicable to equivalent types bowlers.

As noted, assessing accuracy of bowling performance in a simulated environment has its drawbacks and for real world value, more ecologically valid methods must be considered. In-match assessment of bowling accuracy has been made through performance analysis software mapping areas of the pitch where “good bowling” should occur (Petersen et al., 2009a, Moore et al., 2012). Objectivity and comparativeness of data is questionable as with varied match-to-match conditions (i.e. pitch, weather, format) and the interaction of the batter and bowler, formulating an evidence base on bowling accuracy is difficult to progress in competitive situations. Clearly in competitive match scenarios the bowler reacts to the current match situation which makes in-match accuracy data collection problematic. If regulations and technology permitted two-way communication to occur

with the bowler in-match further strides in ecologically valid accuracy research could be made. Ultimately it could be argued that the number of runs per over scored against the bowler is still the most cricket specific objective measure from competitive matches and is still cited by coaches and players alike (Woolmer et al., 2008).

In summary, there appears to be more work required to fully understand how bowling accuracy is affected over a series of overs or longer term day to day. Simulated accuracy bowling events provide technical insights for coaches and physiological data for conditioning coaches to continue to develop peak performance. Within the competitive nature of a match situation, accuracy of bowling performance is harder to confirm but can be related to runs scored per over unless other reliable and valid two-way monitoring technology is permitted in-match.

2.4.6 Summary of Cricket Literature

In comparison to other popular sports the literature base in cricket is still small. Further research is needed to enhance the evidence base across the whole sport especially as the three different formats of the game, and positions within them, become more specialised. Research within the area of fast-medium bowling mirrors the trend of the wider sport though this specific role is receiving more attention in the literature. The latter may stem initially from injury occurrence but now it is being acknowledged that further appreciation of physiological responses during bowling is required. Mobile monitoring technology may allow the fast-tracking of evidence on fast-medium bowling as research can be completed on the field or in-match so presenting ecologically valid data set for exercise scientists and coaches.

2.5. Reliability and Validity of Mobile Measuring Technology

Sport and exercise science research is ultimately completed to provide a performance increment or change to the participant though there seems to be limited dissemination of research findings to wider sports professionals which has created a “gap” in understanding between research and actual coaching practice (Bishop, 2008). A reason for this disjointed model is linked to the lack of valid, reliable and applied research tools with a significant amount (e.g. nearly two thirds) of physiological research completed within laboratory setting, restricting the ecological validity and possible translation of findings to the coach in the applied setting (Williams and Kendall, 2007).

As with any advancement in technology, systems in the market place must maintain data precision standards and be empirically evaluated which means more robust trials beyond small scale in-house white papers (Goodwin et al., 2008). For example, it was claimed that the Lifeshirt™ has progressed through rigorous public testing over a number of years with > 90 studies involving 1700 participants which, due to pressure of business, cannot be said for many other multivariable systems (Grossman, 2004, Heilman and Porges, 2007). Attempting to capture data from new technology which has had inadequate pilot testing can lead to data error occurring. Movement artefacts are a hazard of the field based testing environment but awareness of the issues associated with the cause of the error is important so improvements can be made. For example, capturing HR data with dry sensors, which in a clinical environment would use electrode gel, can lead to high impedance affecting the quality of the signal being processed (Karlsson et al., 2008). New technology entering the market place should progress through independent and ideally peer reviewed assessment so allowing the exercise professional to judge the quality and value of the data the device may capture.

2.6 Reproducibility and Precision of Measurement

With the need to use more ecologically valid data it is important that any new applied monitoring technology meets the rigours of scientific investigation. It is crucial that measurements made within sports science research are precise and adequately reliable and valid (Atkinson and Nevill, 1998, Hopkins, 2000a). The ability of new applied monitoring systems to measure the intended variable and reproduce that measurement accurately is vital for the widespread use of “monitoring tools” within research projects (Currell and Jeukendrup, 2008, Thomas et al., 2010). It is important to research and understand what variability exists between devices. When assessing data reported from

new technology it must be accurate enough to follow trends. In some situations absolute precision is not necessary or indeed possible. Consistency in the variation that may exist can be accepted (Erickson, 1999, Brunton et al., 2000, Welk et al., 2004).

2.6.1 Reliability and Validity

Agreement between true value and measured value is the underlying principle of validity. Variations of validity have been noted by a number of authors (Currell and Jeukendrup, 2008, Hopkins, 2000a); Logical validity referring to the whether a test measures what it intends to, Criterion validity which includes concurrent and predictive. The former comparing a method against another new or alternative method at the same time, the latter is concerned with validating a process to predict a performance. Finally, construct validity links to measuring a hypothetical construct that is not observable yet can be assessed, such as being able to differentiate between two different groups of performers on a specific task. Validity of new technology is linked to a criterion objective measure (i.e. concurrent validity) such as a heart rate monitor being validated against an Electrocardiogram (Hopkins, 2000a, Thomas et al., 2010).

This research seeks to improve ecological validity of data capture through the capturing of data in-competition. Ecological validity was described as *“the evidence that the results of study...can be applied, and allow inferences to real-world conditions”* (Field, 2009. p785). It is clear that ecological validity has 3 dimensions all of which influence this theme (i) nature of research setting, (ii) nature of stimuli, and (iii) nature of the task (Schumckler, 2001). It is clear that understanding the research context will help clarify how ecological valid an outcome is. External validity is another theme that is being investigated within this research and is concerned with how applicable the findings from research are in relation to other populations (Steckler and McLeroy, 2007). The latter will depend on the homogeneity of the participants/sample and also uniqueness of the activity.

Brunton et al. (2000. p94) describes reliability as *“the consistency or repeatability”* of measurements with the greater the variance in measurements (i.e. test retest) meaning the less reliable the device is. Reliability investigations, be they within-subject, change in the mean, or retest correlation, allow for the development and understanding of the repeatability of a measure linked to a specific performance monitoring tool (Hopkins, 2000a). Atkinson and Nevill (1998) continue on this point by suggesting it is important within reliability research to extrapolate the measurement error to assess if the measurement tool would identify or detect changes or effects on sporting performance. Additionally when the reliability investigations have been completed on new technology the sample size can be calculated therefore reducing the risk of Type II errors occurring (Currell and Jeukendrup,

2008). Not all clinical or laboratory based measures will be perfectly reliable as the actual value will have an error component which could be systematic or random. Relative reliability is linked to the ranking position that subjects hold over a repeated tests design while absolute reliability is the change in measurement data for individuals across a test-rest scenario. The latter is commonly expressed in actual units through the use of standard error of measurement, coefficient of variation or limits of agreement, the former is linked to correlation coefficients (i.e. Pearson's) (Brunton et al., 2000). It is a recognized view of science that reliability is a necessary condition for validity though measurements can be reliable and not valid. The two concepts are interlinked and should be considered together (Welk et al., 2004).

2.6.2 Methods to Assess Reliability and Validity

It is clear that the advantages of monitoring players within their playing environment allows for greater ecological validity of the data to be collected. It is crucial that any new applied technology which monitor variables and produce performance data must be rigorously assessed (Thomas et al., 2010). Literature identifies reliability and validity studies that have ratified other new technology which has then been used to monitor performance within field based applied setting (Atkinson and Nevill, 1998, Schneider et al., 2003). Therefore the reliability and validity process is a crucial progression for research projects which allow for further research phases to progress with confidence in the data being collected.

Varying methodologies can be adopted to assess reliability and validity of monitoring equipment. Designing the correct rigorous protocol to allow for relevant statistical analysis to be completed is a key element in the process (Welk, 2005). For example, new GPS performance monitoring equipment has been validated using a within-subject/single subject repeated trials design (Petersen et al., 2009b). This process has been mirrored within accelerometry research to reduce the influence of inter-subject anthropometrical variation (Powell and Rowlands, 2004). The majority of accelerometry reliability and validity investigations have been completed within the area of physical activity where a number of new unproven triaxial accelerometers have been ratified by using different methodology (Welk, 2005). Apart from the aforementioned designs, a between-subject design which combines treadmill and free movement protocols have been completed and also intra and inter accelerometer unit variability has been assessed through a test-retest procedure on a mechanical vibration table (Powell et al., 2003, Rowlands et al., 2004). Within some experimental research where participants are completing a relatively unfamiliar activity such as treadmill walking or running whilst wearing measuring equipment, a familiarisation or habituation process would normally occur in the research design. This is designed to allow the participant to experience the activity prior to data being collected (Thomas et al., 2010). The researcher would hope that this process of experiencing the test

protocol would avoid a learning effect occurring and/or reduce the occurrences of spurious data which may be due to anxiety in the participant.

2.6.3 Laboratory versus Field Setting

It is common practice for new physiological monitoring technology to be assessed for precision initially in a controlled laboratory based environment, for example using an incremental treadmill based activity (Grossman et al., 2006, Leger and Thivierge, 1988, Rowlands et al., 2004). If acceptable levels of precision are identified in that controlled environment further field or free movement activities could then be completed in which there have been relatively few studies (Troost et al., 2005). There are gaps in the literature with regards to field based testing and many prediction equations are based from data collected from laboratory studies (Welk et al., 2000). Mixing laboratory and free living activities is noted (Eston et al., 1998) but the relationship between measurements in a controlled environment when compared to more free movement based trials commonly identifies lower precision in the latter condition with the external environment adding a further dimension to movement patterns in participants (Charmari et al., 2004, Welk et al., 2004, Vanhelst et al., 2009). Success in elite sporting environments requires the capturing of applied data (Carling et al., 2009), moreover sports coaches want more ecologically valid data on their athletes (Foster et al., 2006, Williams and Kendall, 2007). Understanding the possible changes in precision of measurement from the laboratory to the field is an important step within the research process.

2.6.4 Statistics used to Assess Reliability and Validity

2.6.4.1 Statistical Analysis to Assess Precision of Measurement

When assessing precision of measurement a range of statistics, in combination with descriptive data (mean \pm SD), are available for researchers. For example correlation coefficients, tests assessing mean differences (i.e. T Test) and limits of agreement are all procedures seen within the wider reliability and validity literature (Hopkins et al., 2009, Field and Miles, 2010).

There is no consensus on the choice of appropriate agreement statistics though it has been recommended that assessment of the distribution of errors, whether there is a relation between error and the magnitude of measured value, should be considered (Atkinson and Nevill, 1998, Brunton et al., 2000). The characteristics of the data set will assist the researcher in deciding on the analysis to be complete. Apart from the parametric normal distribution type assessment, the

magnitude of measured variance is something that should be noted in the data set. Atkinson and Neville (1998, p220) note that “When the amount of random error increases as the measured values increase the data are said to be heteroscedastic”. Data falling within this remit should be transformed logarithmically or analysed based on ranks. When assessing the relationship between data, the difference between an observed and a predicted value is termed a residual. By plotting the residual value against the predicted value it is possible to assess the uniformity of the data. If data is non-uniform it is termed heteroscedastic (Hopkins, 2000a) (Figure 7). Heteroscedastic data needs assessing as in the current format it could affect the accuracy of further analysis (e.g. Confidence intervals which assume variance to be equal). Also data with heteroscedastic errors can have practical implications as athletes who score the highest values have the greatest variance in data which could mask the detection of performance changes. If there is no relation between the error and size of measured value data is homoscedastic (Atkinson and Nevill, 1998, Hopkins, 2000a, Field and Miles, 2010).

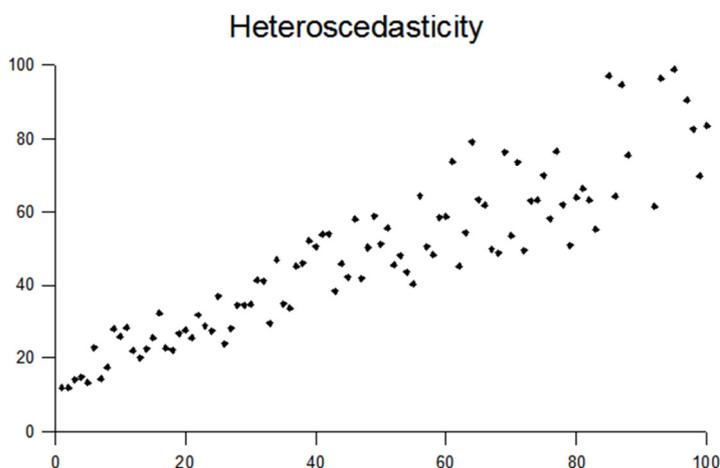


Figure 7. Example of heteroscedastic data with increasing variance as values increase (Engineering Statistics Handbook, 2012).

The statistical analysis used will also relate to the research design and associated hypotheses or outcome analysis that is required. If hypothesis testing is chosen, determining whether to accept or reject the experimental (H_1) and null (H_0) hypotheses will shape the statistical approach taken. Precision of measurement studies adopting this philosophy can be seen, for example a Paired samples T-test (two tailed) were used in research assessing validity of thermometer equipment (Gant

et al., 2006) and Analysis of Variance (ANOVA) used when assessing mean differences in accelerometer counts (Rowlands et al., 2004). The value of completing hypothesis testing within these types of studies is questioned as they may provide information on group means and systematic bias only, which could be considered a somewhat limited view of the results or data. Alternative statistical procedures are required when more insight in to individual differences or a level of agreement between measures is necessary rather than an arbitrary cut-off point. Use of alternative analysis techniques to allow for estimation of agreement should be considered including the use of either standard error of measurement or limits of agreement in precision of measurement studies (Atkinson and Nevill, 2001). Ultimately it appears that the only agreement on the statistical processes to employ within precision of measurement studies is that there is disagreement on the approach. Some checklists are published and it seems most authors suggest using a variety of justified measures in order to fully understand the data generated (Brunton et al., 2000, Hopkins et al., 2009, Harper-Smith et al., 2010).

2.6.4.2 Relative Precision of Measurement

Correlation Coefficient

Correlation coefficient is a common method used for assessing precision of measurement (Atkinson and Nevill, 1998). A correlation is associated with the degree of relationship that exists between two variables (x and y). Correlation can be seen on a scatter plot presenting either positive or negative outcomes, with the former relationship demonstrating an incremental association (i.e. as x increases so does y) and the latter having the opposite occurring (i.e. as x increases y decreases). Data can be uncorrelated with no clear relationship being apparent (Brunton et al., 2000, Winter et al., 2001).

A numerical statistic is obtained from correlation coefficient tests. Pearson's Product Moment Correlation Coefficient, cited within reliability and validity studies, is frequently used for normally distributed numerical interval or ratio data while Spearman's rank correlation coefficient is used for non-parametric categorical data (i.e. rankings). Both correlations provide an *r* statistic which can be positive and negative, ranging between 0, representing no correlation, to 1 representing a strong relationship exists (Currell and Jeukendrup, 2008). Intra class correlations (ICC) are popular in reliability statistics as it is linked to an advantage it has over Pearson's correlation in that it is univariate (i.e. measuring same variable) rather than bivariate and can be used for multiple retests. It is also claimed that ICC is more sensitive to systematic bias though with 6 different ways to calculate

the correlation comparing results across research could be restricted (Atkinson and Nevill, 1998, Hopkins, 2000b, Field and Miles, 2010). Similar to Pearson’s coefficient, the ICC r statistic noted suggest closer to a score of 1 indicates high strength/level of relationship. Added credibility to correlation statistics are gained if results are reported with confidence intervals (discussed on following page). An associated statistic used within this type of analysis is coefficient of determination (r^2) which expresses the variance in one variable that can be attributed to the second variable (Atkinson and Nevill, 1998, Winter et al., 2001).

Correlation coefficients have a number of limitations when used to report on precision of measurement studies. Correlation statistics only determine the relationship between two variables and no prediction is made from the relationship between the independent and dependent variable (Brunton et al., 2000, Winter et al., 2001). Correlations only assess for association not agreement in data, should not be reported in isolation, are “blind to possibility of bias” (Bland and Altman, 2003) and there are examples noted of high correlation coefficients being reported which has hidden disagreement between the data set. This concept was highlighted in Bland and Altman’s 2003 paper, when citing data from Borg et al. (1995). In the example it was noted that there is often misinterpretation of the regression line when applied to correlations. The regression line, which is often used on correlation plots, and line of equality are not necessarily similar. In some cases using the line of equality provides immediate graphical view of any systematic bias in the data set. The data was presented with the regression line, then the same data with the line of equality was added (Figure 8). It became apparent that data was positioned to the left of the line of equality suggesting bias which was not immediately clear when the regression line was only included.

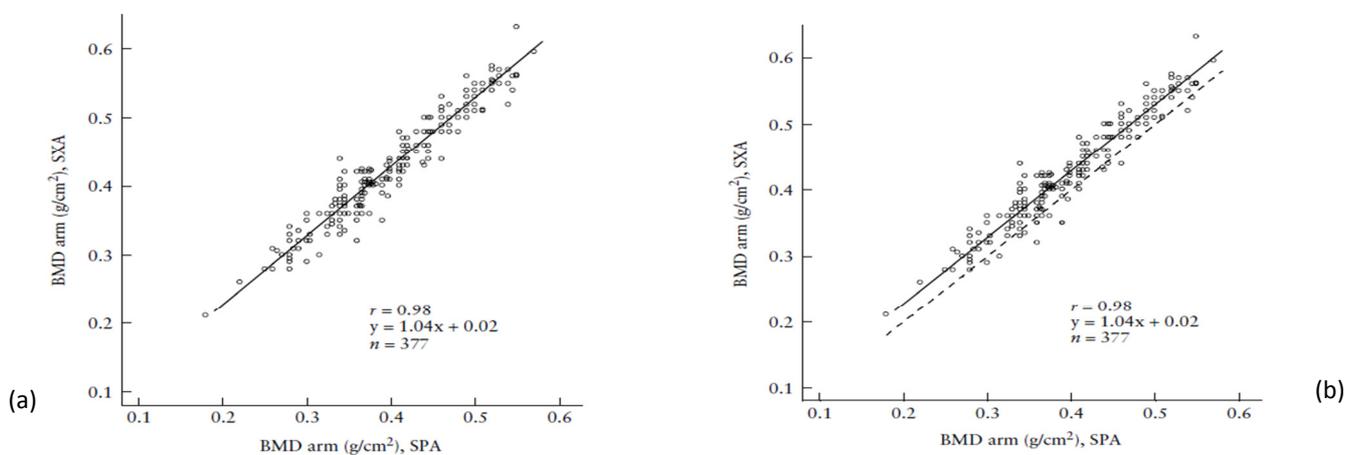


Figure 8. Scatter plot (a) Data from Borg et al. (1993) with regression line (—), Scatter plot (b) with line of equality (----) added (cited Bland and Altman 2003, p86).

Correlations are also affected by the population range selected. Some population samples contain extreme values, more so than would be seen within a truly representative sample, this can also produce a higher correlation coefficient. Correlation should only be used if a true sample of the population has been selected. ICC has similar constraints as Pearson's in the sense that it is affected by sample heterogeneity which could mean that measurement error is still present even with a high correlation statistic (i.e. $r > .9$) (Atkinson and Nevill, 1998, Bland and Altman, 2003). There is a danger that studies only using correlation coefficients will have concluded that methods are comparable or measurement tools are reliable but actually systematic bias may exist. Although relative reliability is useful it is agreed that correlations are not sensitive enough and using a variety of statistical approaches including absolute measure of reliability (i.e. Limits of Agreement) may improve the understanding of the precision of a device (Atkinson and Nevill, 1998, Atkinson and Nevill, 2001, Winter et al., 2001).

Standard Error of Measurement (SEM)

SEM is the within-subject standard deviation, or sometimes termed the typical error of measurement (Equation 1). While standard deviation (SD) provides variance from a group of subjects, SEM provides variance statistic from a single subject using the mean, standard deviation, and the reliability (ICC).

SEM is sometimes confused with the standard error of mean (Equation 2) which is sampling variation in group mean. Confidence Limits/Intervals present boundaries linked to the uncertainty in the mean so, even though there are some positives with the statistic, standard error of the mean becomes redundant (Hopkins et al., 2008). A benefit of the SEM is that it is reported in actual units, limitations include that data cannot be heteroscedastic, and with the variations in ICC calculations which are utilised in the equation, this can produce different results (Atkinson and Nevill, 1998).

$$SEM = SD\sqrt{1-r}$$

Equation 1: Standard Error of Measurement

$$SE_{\bar{x}} = \frac{s}{\sqrt{n}}$$

Equation 2: Standard Error of Mean

Coefficient of Variation

Coefficient of variation is an estimate of measurement error calculated using the SD of data divided by the mean (SD/mean x 100). CV expresses the SD as a proportion (i.e. percentage) of the mean and is considered a “dimensionless statistic” which is easier to compare the amount of variation between protocols (Atkinson and Nevill, 1998, Currell and Jeukendrup, 2008). CV assumes data is normally distributed (as does SEM) though CV “assumes that the largest test-retest variation occurs in the individuals scoring the highest values on the test” (Atkinson and Nevill 1998. p230). The latter would link to the data set being heteroscedastic in nature which influences other possible statistical procedures. The use of CV has been criticised by Bland and Altman (1987) who claim the problem “with expressing the error as a percentage is that x% of smallest observation will differ markedly from x% of largest observation” (cited Brunton et al., 2000. P98). Also an arbitrary < 10% figure has been suggested which could be interpreted, if data is normally distributed, that 68% of differences between test and retest are within 10% of the mean of the data therefore not including 32% of the differences (Atkinson and Nevill, 1998).

Confidence Intervals

Accuracy of a sample mean can be further clarified by calculating boundaries, or confidence intervals, where the actual mean value may fall. 95% CI will provide statistical confirmation that the mean value calculated should be considered within boundaries calculated though is only used within parametric data sets (Field and Miles, 2010).

2.6.4.3 Absolute Precision of Measurement

Limits of Agreement

Limits of Agreement (LOA) were developed to assist and provide further analysis on precision of measurement studies (Hopkins, 2000a, Bland and Altman, 2003). It is seen as an alternative to other possibly misleading approaches of comparing methods of measurements or within reliability studies. Summarising the absolute differences between the two methods is a corner stone of the process by calculating the mean and Standard Deviation (SD) of these (Bland and Altman, 1986, Bland and Altman, 2003).

The background to the LOA is interlinked to the concept of reference intervals which have been used routinely in clinical environment. LOA are used to make statements about probability for expected

values within a data set which meets the normal distribution criteria (Atkinson and Nevill, 2001). Reference intervals have been used to ascertain the spread of population with regard to a certain variable (i.e. elite athletes in top 2.5%). In normally distributed data approximately 68% of observations (i.e. data) will be within ± 1 SD of the mean, while 95% of population will be within ± 2 SD and 99% will be within ± 3 SD. Expanding on this, 95% is a reference interval which excludes the upper and lower 2.5% of observations from the normal distribution curve, and this concept has been used when assessing precision of measurement. The 95% reference interval concept within the LOA model links to the expectancy that most differences would be positioned ± 2 SD (or specifically 1.96 SD) from the mean difference if the differences data is normally distributed (Bland and Altman, 1986, Bland and Altman, 2003). Neville et al. (2009) further clarify this relationship within a reliability context by stating, *“If the SD is multiplied by 1.96 and added to and subtracted from the mean difference between test and retest it would be expected that the majority (95%) of individuals would show test-retest differences, purely due to measurement error of no greater than this calculated reference range”* (p258).

The LOA range has an upper (Mean difference + (1.96 x SD)) and lower value (Mean difference – (1.96 x SD)). It is suggested that if differences lie within 2 SD of the mean difference they are not “clinically important” and within a precision of measurement (i.e. validity) context, methods are interchangeable (Bland and Altman, 1986, Hopkins, 2000a, Bland and Altman, 2003). Atkinson and Nevill (1998) continue to clarify the LOA theorem if used within reliability study, *“It would be expected that the test-retest differences purely due to measurement error would be no greater than the limits of agreement for 95% of individuals in a population”* (p822).

As mentioned the 95% LOA is linked to assumptions about the data, one being that the differences in the data are normally distributed. It is suggested that a scatter diagram, plotting difference against the average of the two measures, is completed (Bland and Altman, 1986, Bland and Altman, 2003, Field and Miles, 2010). A plot of the difference between the methods against their mean allows for a visual interpretation of the measurement error against the true value. The latter true value not being known, so the mean of the two measures is used. With reference to plotting the data, Bland and Altman state (1986) *“It is a mistake to plot the difference against either value separately because the difference will be related to each, a well-known statistical artefact”* (p308). Within the LOA model approximately 95% of the data points should be within the limits (± 1.96 SD). An example of a scatter diagram with 95% of data within the 2 SD using artificial data can be seen in Figure 9 (Bland and Altman 2003).

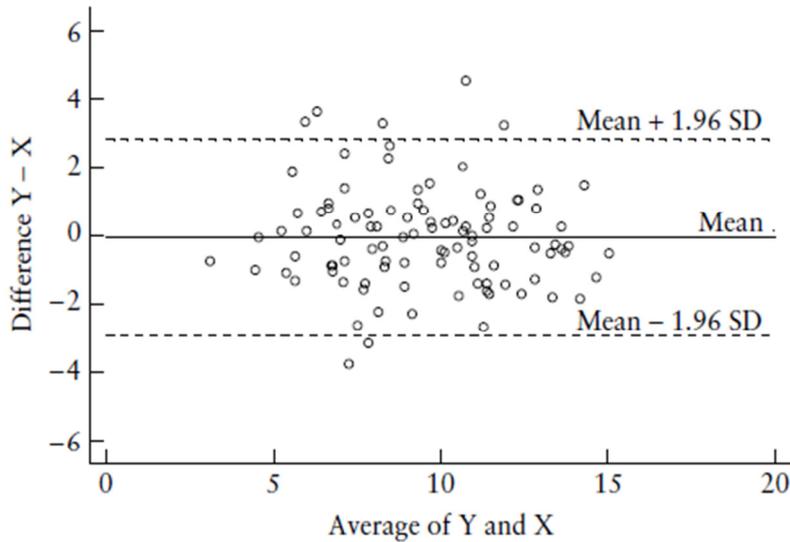


Figure 9. Plot of difference against mean for the artificial data X and Y with mean difference and 95% limits of agreement indicated (Bland and Altman, 2003, p90).

Some researchers see the scatter plot as the analysis, this is not the case and it should only be used as a graphical check of the data spread before further analysis occurs. For example if a scatter plot shows divergence as magnitude of values increase (i.e. heteroscedasticity), which can often occur, log transformation of data can be completed which allows the LOA analysis to continue (Atkinson and Nevill, 1998, Bland and Altman, 2003).

To further exemplify the concept, a worked example and scatter plot (Figure 10) was provided by Bland and Altman (1986) whereby data demonstrating different blood pressure methods, finger and arm pressure, were assessed for differences. Mean difference was calculated by subtracting the mean of the finger pressure from the mean of the arm pressure. This resulted in 4.3 mm Hg and the SD 14.6 mm Hg. Therefore the lower 95% limit was calculated as $4.3 - (1.96 \times 14.6) = -24$ mm Hg and the upper 95% limit is $4.3 + (1.96 \times 14.6) = 33$ mm Hg. It was therefore estimated that 95% LOA for subjects using the finger measurement will be between 24 and 33 mm Hg when compared to the reference method (i.e. arm pressure).

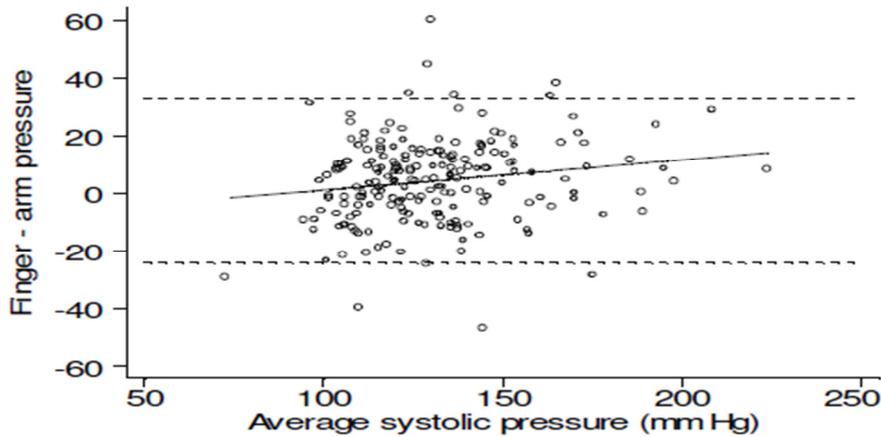


Figure 10. A typical data set, the measurement of systolic blood pressure by a test method, finger pressure and a standard method, arm blood pressure (Bland and Altman, 1986, p1085).

Results from LOA can be interpreted as there is a 95% chance that a subject's data is within the range noted or, if sufficient number of subjects were tested it could be stated that 95% of subjects would have a their data within the range identified. Any data within that range, reference range, is deemed normal while outside of that range is suggestive of a real change or difference in the data set (Hopkins, 2000a).

LOA have been used for validity of methods studies though reproducibility of data can also be analysed comparably using the previously cited 95% LOA. If one method has poor repeatability than agreement between two methods is likely to be poor. Within reliability studies the mean difference should be zero though if this is not the case then they are not true replicates of the same measurement. The British Standards Institution state, that 95% of differences should be within 2SD of the mean. Using the same procedure of calculating the SD of the differences between the pairs of repeated measures ($SD \times 1.96$) it is stated, this provides a *“repeatability coefficient, which is the difference that will be exceeded by only 5% of pairs of measurements on the same subject”* (Bland and Altman 2003, p92).

It is unlikely that different methods will agree exactly so knowing the range of differences allows an interpretation on precision to be made. There is misinterpretation of the LOA analysis with some papers not analysing or discussing the LOA rather relying scatter plots or on numerical figures generated from correlations (Bland and Altman, 2003). LOA within validity research has some limitations claiming the LOA statistic is harder to interpret and make decisions on than the typical

error due to large reference ranges that can occur. Without additional evidence it is difficult to assess practical significance of the measure with regards to individual practice (Hopkins, 2008). Also specifically within reproducibility studies it is noted that caution should be applied with acceptance of data as being reliable or not as the LOA is only related to the participants involved as the first test is used within the LOA calculation (Atkinson and Nevill, 1998). Hopkins et al. (2009) does query the value of LOA suggesting regression analysis as an alternative though admits it could be beneficial in comparison of methods analysis (i.e. validity) where data units being measured are the same.

The LOA process is an analysis of estimation not hypothesis testing so should consider some sampling error. Confidence intervals or limits should be incorporated along with mean bias in to LOA analysis to fully address the data set (Bland and Altman, 1986, Bland and Altman, 2003). Confidence limits (CL) are not to be confused with LOA. CL are the boundaries, upper and lower, within which a population may lie and aid in the interpretation of analysis (Atkinson and Nevill, 2001). The size of LOA and the relation to whether the methods agree sufficiently well is a clinical rather than a statistical decision (i.e. there is no “cut off point”). Professional judgement and experience will influence whether a difference is acceptable or not (Atkinson and Nevill, 1998, Bland and Altman, 1986, Bland and Altman, 2003).

2.6.4.4 Summary on Measurement of Reliability and Validity

In summary, it is clear that there are a range of statistical analysis which can be completed when measuring reliability and validity. It is important to use an array of appropriate analysis techniques in order to achieve a comprehensive picture of the reproducibility and precision of the monitoring device being assessed.

2.7 Multi-Variable Monitoring Devices

Technological progress has assisted in the improvement of sporting performance (Jobson et al., 2009) and advances in monitoring technology now permit high-quality data to be recorded during physical activity (Achten and Jeukendrup, 2003). It is clear that there is scope for more applied research to be completed within different sporting activity settings so a clearer understanding of the key physiological responses can be gained (Bartlett, 2006). Elite coaches want real life applied research that can be utilised for performance (Gore et al., 1993, Achten and Jeukendrup, 2003) however, to date it seems the use of new technology by these professionals appears limited in some sports (Buchanan, 2008). This section will aim to provide a short review of the development of multivariable mobile monitoring devices.

2.7.1 Technological Development of Multivariable Devices

Lymbers and Dittman (2007) stated that measuring a single physiological variable provides an incomplete picture of the participant during activity. In order to gain fuller understanding of physical performance there have been recent attempts by various manufacturers to amalgamate multiple well established individual physiological monitoring devices in to one multivariable applied monitoring tool. The intention of this development is to create one user friendly unobtrusive multivariable system allowing for a more comprehensive analysis of physical activity (Lymberis and Dittmar, 2007, Grossman, 2004, Goodwin et al., 2008). With synchronised multivariable data capture now possible, relationships between key performance indicators could be investigated which may highlight new opportunities for the athlete, exercise specialist and coach to progress performance (Goodwin et al., 2008, Karlsson et al., 2008).

Technology has advanced from the static PC/laptop arena and wearable monitoring devices reporting real time data has become a reality (Healey, 2000). Goodwin et al. (2008, p326) cites Moore's Law (1965) which indicates the speed of advancing technology. The law suggests that there is a doubling of computational power and speed every 24 months leading to smaller, more effective and less expensive devices being developed. Previous technical limitations, meaning only intermittent pictures of activity were being captured, has now been resolved allowing for an "on-going movie" of physiological related data to be presented (Cárdenas et al., 2003). This advancing of technology allows further strides in the development of multivariable monitoring devices. Firstly, miniaturisation of physiological monitoring devices has assisted in the integration of once quite bulky single variable systems in to smaller multivariable systems. The first multivariable devices were

reportedly light weight at 1 – 2 kg (Healey, 2000), while now more advanced systems (e.g. Lifeshirt™, Vivometrics, CA, USA) are half that original mass so improving the participant experience and therefore possible engagement in the data collection process (Grossman, 2004).

Moreover, a potential paradox exists as more powerful computing technology increases the quantity of data collected allowing for evermore detailed analysis. This is countered against the potential paralysis by analysis as vast volumes of potentially meaningless data are downloaded without time synchronisation or location markers relative to the activity that has occurred (Healey, 2000, Cárdenas et al., 2003). Careful consideration of which data to focus on and a clear synchronised timeline relative to the activity being assessed is crucial if the monitoring data is to be useful for improvements in performance.

2.7.2 Classification of Mobile Monitoring Devices

Goodwin et al. (2008) categorises the area of mobile monitoring technology, using the term “Telemetrics”, and identifying active and passive systems. Active systems see users engage with mobile phone devices to report personal data in to a system for analysis. Passive systems include “ubiquitous computing” where technology is interlinked invisibly in the physical surroundings and “wearable computing” whereby monitoring systems are as mobile as the user. The latter of the passive systems is of more interest within monitoring sporting performance. Along with the aforementioned technological advances, a crucial step forward within the wearable mobile multivariable monitoring technology is the development of textile based systems and the integration of sensors within clothing or as part of more wearable garment. With up to 90% of the skin surface in possible contact with a textile surface it appears a logical move to develop this area if sensors can extract meaningful and accurate information (Dittmar et al., 2005). As with any new innovation, differing options are marketed; Smart Wearable Health Systems and Applications or Intelligent Biomedical Clothing (Lymberis and Dittmar, 2007), Smart Fabric (Zephyr Technology, 2013), Lifemonitor sensor (Equival, 2013) have, amongst others, been terms used by manufacturers to describe how textile fibres with mechanical, optical or electrical properties can now be woven in to a garment with the role of sensing, communicating or creating a network for the exercise professional or participants to monitor or respond to (Dittmar et al., 2005).

New technology can monitor a number of physiological and activity variables which can be assessed and reported in real-time or post-performance. Variables such as heart rate and function, breathing rate, skin temperature and activity (i.e. accelerometry) can now be simultaneously assessed by devices worn by the performer (Zephyr Technology, 2013). Integration of physiological and activity

variables to assess performance could provide more accurate information about activity and performance (Brage et al., 2005). Examples of multivariable monitoring systems include the Lifeshirt™, which suggests that their system “is the first non-invasive, continuous ambulatory monitoring system that can collect data on pulmonary, cardiac, and other physiologic data, and correlate them over time” (Vivometrics, 2009). An alternative system is the Bioharness™ (Zephyr Technology, MD, USA) which has similar synchronised variables integrated within a smaller and lighter chest strap (Figure 11).

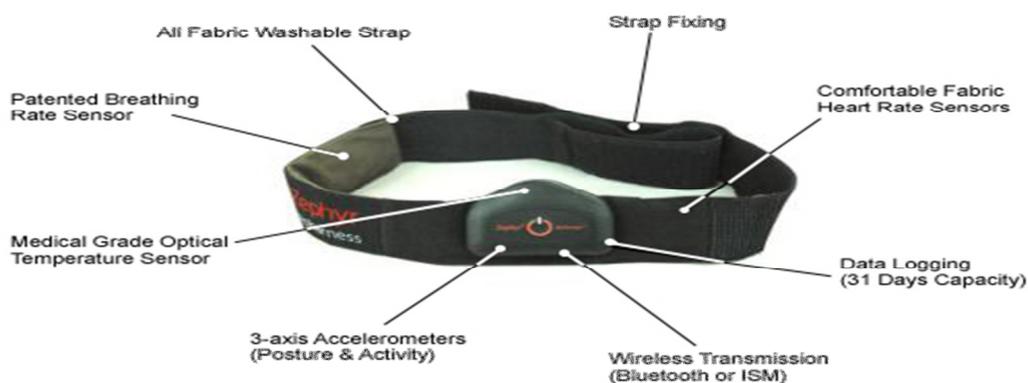


Figure 11. Diagram of the Bioharness™ and associated parts (Zephyr Technology, 2010, <http://www.zephyranywhere.com/products/>).

With the reduction in equipment size and improvements in wear-ability devices become unobtrusive, data collection is non-invasive and pain free for the participant in the day-to-day natural environment (Healey, 2000, Lymberis and Dittmar, 2007). Capturing participants’ ecological behaviour without artificial reactivity to the measurement processes is the intended consequence of the new mobile monitoring systems (Goodwin et al., 2008). Multivariable, multi-participant, ecologically valid monitoring may improve the exercise professionals understanding of performance if data management and statistical approaches adopted are clearly thought through (Goodwin et al., 2008).

2.8 Technology used within multivariable devices

The more popular measurements integrated in to multi-variable monitoring systems include; Heart rate, Breathing frequency, Accelerometry (including Posture) and Skin temperature. These 5 individual systems will be reviewed to ascertain their technological development and precision of measurement.

2.8.1 Heart Rate Monitors

With the increase drive for healthier populations and better sporting performance the use of portable telemetric Heart Rate Monitors (HRM) to provide feedback on physical performance is now common place (Laukkanen and Virtanen, 1998, Terbizan et al., 2002, Vuori, 1998). Current HRM devices allow for the assessment of cardio vascular status in free living, physical training and sporting environments. As there is a strong relationship between heart rate (HR) and oxygen consumption, HRM are seen as a sound method to analyse training sessions or sporting performance (Astrand et al., 2003, McArdle et al., 2009). Associated technology integrated within devices has progressed rapidly in recent decades and the 3rd generation devices allows for more specific data collection, interpretation and analysis such as HR training zones and heart rate variability (HRV) (Noakes et al., 1998, Boudet and Chamoux, 2000, Achten and Jeukendrup, 2003).

2.8.1.1 Technology Associated with Assessing Heart Rate

In the early part of the 20th Century a physiologist, Willem Einthoven, was a pioneer in the development of the graphical representation of electrical events within the heart (i.e. the Electrocardiogram ECG) which were linked to mechanical myocardial contraction. Three sections of the ECG being, the P wave (depolarisation of atria), QRS wave (depolarisation of ventricles) and T wave (repolarisation of ventricles) were derived from this landmark research (Achten and Jeukendrup, 2003, Powers and Howley, 2007). Currently the 12 lead ECG is considered the definitive clinical tool for assessing the electrical events within the cardiac muscle tissue (Cho et al., 2009, McArdle et al., 2009). A clinical ECG trace (Figure 12) will provide basic “heart rate” information though is more attuned to providing in-depth assessment of the health and functionality of the cardiac muscle (Tortora and Grabowski, 2003). The associated equipment size, expense and operator expertise linked to an ECG makes it inappropriate for everyday use when measuring cardio-vascular

stress in physical activity or sporting performance. For these latter reasons, coupled with ever improving technology, the development of portable, light weight, user friendly HRM devices were developed for use in training and sporting environments (Laukkanen and Virtanen, 1998, Achten and Jeukendrup, 2003, Powers and Howley, 2007).

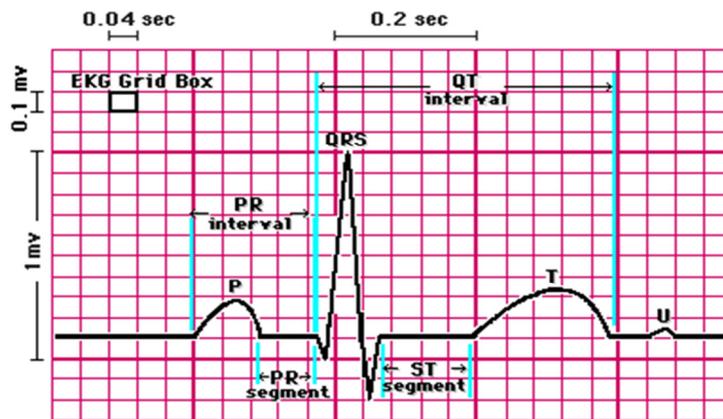


Figure 12. A typical ECG trace demonstrating the electrical activity HRM interpret (Tortora and Grabowski, 2003, p677).

The majority of HRM produce HR data by mirroring the monitoring principles seen within an ECG. HRM detect electrical activity of the heart during a cardiac cycle using small electrodes which are in contact with the skin normally positioned over the chest (Boudet and Chamoux, 2000). Some HRM may be positioned at the wrist, finger or ear lobe and detect blood pressure pulsating changes, or work from photo electric cells monitoring light changes in blood vessels or process the electrical activity of the heart as it dissipates through the body (Laukkanen and Virtanen, 1998, McArdle et al., 2009). Chest HRM commonly use a thin lightweight elasticated chest strap worn by the performer which has contact electrodes embedded within a plastic or fabric protective casing. Chest HRM is determined by sampling the ECG signal produced, normally focussing on the R wave of the QRS complex, and through the device specific algorithms HR data is transmitted telemetrically to a receiver which is frequently a watch-like device worn by the performer (Laukkanen and Virtanen, 1998, Boudet and Chamoux, 2000, Cho et al., 2009).

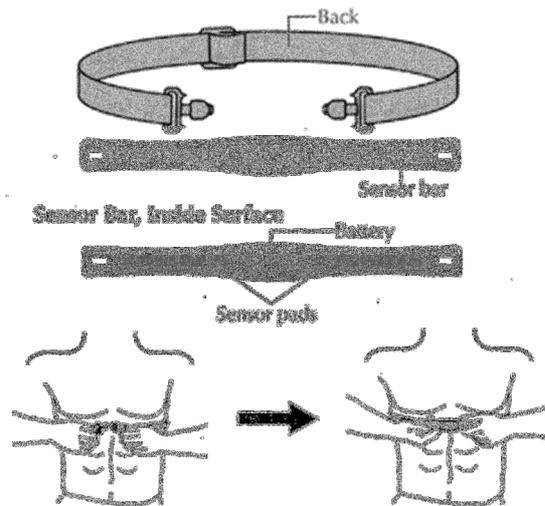


Figure 13. Example schematic of typical HRM set up (Healthgoods.com, 2013, http://www.healthgoods.com/Acumen_Heart_Rate_Monitor_Strap_p/an-strap.htm).

It is documented that there is a reduction in data accuracy of HRM at higher intensities (i.e. > 9 km.h⁻¹) and this is noted as a possible limiting factor in their use (Terbizan et al., 2002, Kingsley et al., 2004). Research in to the design of the chest strap and contact electrodes has led to different chest HRM to utilise various garments or straps to hold the respective electrodes in place. The majority of devices are non-textile in nature (e.g. Polar HRM) though newer devices are utilising textile electrodes (e.g. Bioharness™) to offer alternative options for comfort though a common issue for chest HRM is maintaining the connection with the electrical activity signals during activity (Cho et al., 2009). If HRM electrodes miss data at high exercise intensities due to losing connection momentarily, this may affect HR data being transmitted. Reasons for loss of data from HRM have been reportedly linked to electrode movement, Electro-myogram (i.e. EMG) noise and also differing data processing technology embedded within the HRM (Leger and Thivierge, 1988, Boudet and Chamoux, 2000, Cho et al., 2009).

Chest HRM use straps with electrodes integrated within them (Figure 13), are designed to sit flat on the skin which is an advantage over other devices though this means they are susceptible to movement during activity (Seaward et al., 1990). This latter point was noted that the in some athletes the muscular V-shape body may mean chest straps slip down during sporting performance(Leger and Thivierge, 1988). Minimal research has occurred in to investigating movement of electrodes and quality of HR signals. Cho et al. (2009) assessed different chest strap support systems identified that, rather than a single horizontal chest strap, a cross-shape holding formation embroidered within a moulded sports top was more effective in reducing the

displacement of HRM electrodes and maintaining data signals. Though initially interesting results for the stability of chest HRM the research included only basic dynamic movement patterns (i.e. static arm moves) using just two participants (i.e. one classed as normal and one as athletic shape), so this area requires further sports specific scientific investigation.

Other inaccuracies in data within chest HRM are derived from movement artefacts linked to EMG noise. Chest electrodes detect ECG electrical signals which ranges between 1 – 2 mV though in dry skin this could be as low as 200 μ M (Astrand et al., 2003, Boudet and Chamoux, 2000). Active musculature can produce EMG activity up to 90mV depending on the size of the muscle group contracting so could conceivably overlap and interrupt the detection of ECG signals. This error could be intensified if the chest electrodes are positioned incorrectly. Many manufacturers will attempt to filter out extremes of electrical signals generated, for example Polar Electro (1996) note peak QRS wave frequency could be 10-15 Hz while associated ECG formations, P and T waves, are at 1-5 Hz so the latter electrical activity is filtered out by the manufacturer. The same principle would apply for EMG and other electrical noise (e.g. electrical cables) but careful positioning away from large musculature is still important (Polar Electro, 1996, Boudet and Chamoux, 2000, McArdle et al., 2005).

Rapid changes in HR can cause differences in HRM output due to the technical data sampling and processing model that is utilised by each HRM provider. Early work on accuracy of HRM noted that arrhythmias or rapid increase/decrease could lead to errors in data output (Godsen et al., 1991). Boudet and Chamoux (2000) assessed three Polar chest HRM reactions to abnormal acceleration and deceleration of HR using an ECG simulator. Results noted that the HRM tested had a 35-40 sec^{-1} delay and 10-15 sec^{-1} delay respectively in response to a simulated sudden decelerating (i.e. 120 to 30 $\text{beat}\cdot\text{min}^{-1}$) and an accelerating (i.e. 30 – 120 $\text{beat}\cdot\text{min}^{-1}$) HR change. The extended lag time between extreme changes in HR is due to the signal processing and data manipulation systems and is likely to be specific to the manufacturer (Boudet and Chamoux, 2000). The technological model adopted within HRM is designed for stable HR data during rest and activity. Polar Electro (1996), HRM utilise a model of ECG activity to check with the electrical data detected from the performer. The comparative model checks the data correlates, within a specified range, to the ECG model which will continually adapt as exercise progresses. If a detected ECG signal does not meet a threshold (i.e. meet the model) an integrated averaged output is generated.

There is a high element of secrecy between manufacturers with regards to signal processing and data smoothing. From their research Boudet and Chamoux (2000. p378) stated that “*HRM tested cannot follow, measure and record sudden short changes in HR*”. There is seems to be a compromise between various aspects such as data accuracy, stability, consumer friendliness of the devices and

advances in credible technology must be ahead of advances in marketing strategies (Leger and Thivierge, 1988, Boudet and Chamoux, 2000).

2.8.1.2 Research on the Precision of HRM

The accuracy and precision of the data produced by HRM is an ever present research area since the first device was launched in 1978. As more HRM arrive on the market with additional advanced technology and data output options the technology must still be ratified in controlled scientific protocols (Laukkanen and Virtanen, 1998, Achten and Jeukendrup, 2003, Gamelin et al., 2006).

Research on the assessment of the HRM precision of measurement was influenced by the technology available. Karvonen et al. (1984) noted that the HRM was valid though differences (5 beat.min⁻¹) in HR between an ECG and the HRM (Sports Tester PE 2000) could have been due to calculation methods between the ECG ruler and HRM “microcomputer”. It is observed that in a number of the early studies (i.e. 1980’s), unlike in recent years, wireless transmission to a watch/receiver was not the norm (Ledger et al., 1988, Macfarlane et al., 1989). There is though some common methodology developing across this research area with HRM devices assessed over a set period of time to elicit different HR through steady state exercise intensity or artificial electrical stimulation. With human HRM testing, a single or multi ergometer (i.e. cycle, treadmill, step test) mode of activity is used with HR assessed simultaneously with ECG data (Macfarlane et al., 1989, Seaward et al., 1990, Gamelin et al., 2006).

Laukkanen and Virtanen (1998) cited initial work by Karvonen et al. (1984) and Vogelaere et al. (1986) on the accuracy of HRM was linked to Sports Tester range of HRM and early results identified that the system was valid for assessing HR in a laboratory setting. Following this work there was more of a focus on analysing a broad range of HRM technology (i.e. chest, ear lobe, finger) to assess which was more effective when compared against a standard ECG. Leger and Thivierge (1988) completed an assessment on 13 and Macfarlane et al. (1989) analysed 7 HRM, though Seaward et al. (1990) chose a different focus with one brand of chest HRM tested (i.e. Polar model 8799) but with 4 different activity protocols, using 23 participants. Further investigation notes that Leger and Thivierge (1988) asked participants (n=10) to work at varying intensities (i.e. rest, 65-75%, 85-95%) related to the theoretical maximum HR (i.e. 220-age) with 10 sec⁻¹ of simultaneous data collected from ECG and the respective HRM. HR values from all devices tested were averaged over 10 secs⁻¹ for comparison. Slight variations on the previous protocols are seen in other research, as Macfarlane et al. (1989) first assessed the HRM through an ECG simulator for 5 minute periods between ranges

of 25-240 beat.min⁻¹ and then completed human testing (n=16) using a number of procedures which elicit HR of 100-125 and 130-160 beat.min⁻¹, collecting simultaneous data for over 150 sec⁻¹.

As noted in an earlier section, statistically defining the precision of equipment has varied in some papers due to the analysis adopted. Somewhat arbitrary classifications of performance have been suggested in relation to the results of a Pearson's Product Moment Correlation (*r* value) and Standard Error Estimate (SEE), these were; Excellent (*r* = .93 - 0.98, SEE 3.7% - 6.8%), Good (*r* = .84, SEE 11.7%), Inadequate (*r* < .65, SEE>15%) (Leger and Thivierge, 1988). Bland-Altman LOA principles have been noted in other papers assessing the agreement between true and observed values, noting bias or accuracy and error (variability) (Macfarlane et al., 1989). Minor differences may exist in how HR data collected is processed to be analysed. Many research papers collect the supposed "raw HR data" from the HRM and then average it over the set time period for their respective analysis. The internal data sampling and processing mechanisms within HRM already average the original HR data before it appears on the receiver/wrist watch. It has been claimed this could produce a small systematic bias in estimation in HR (Laukkanen and Virtanen, 1998). The preparation of data before analysis can also differ between papers, Leger and Thivierge (1988) completed data smoothing process where artefacts were removed and HR values were considered to be unrealistic if they were 20 beat.min⁻¹ either side of the central tendency. The number of data omissions was noted as an indication of HRM stability though the lack of a rationale for this data cleaning method could restrict the analysis. In contrast, other studies state that no editing of HR values from the testing occurred so the HRM capacities can be fully appreciated (Macfarlane et al., 1989). Both scenarios have some credibility as noting the percentage of erroneous data to be removed will relate to the accuracy of the device but in reality the HRM will be used independently in the applied sporting setting so data should be presented and analysed in a raw manner.

Results on the precision of measurement identified that chest HRM were deemed more credible when compared to non-chest HRM, as they maintained the accuracy of performance across different modes of exercise (Leger and Thivierge, 1988, Macfarlane et al., 1989, Seaward et al., 1990). Validity reduced as exercise intensity increased for all HRM, though the devices classed by Leger and Thivierge (1988) as "excellent" (e.g. Exersentry, Sports Tester PE3000 etc.) saw the least decrement in performance. These latter "excellent" devices also had the least number of doubtful data points and those which accumulated more than 2 % of erroneous data were classed as not reliable. Macfarlane et al. (1989) also noted the very same HRM devices as being the most credible, producing a mean bias of less than 1.0 beat.min⁻¹ in comparison to some of the photo-cell (i.e. ear lobe) monitors which noted a 16.88 beat.min⁻¹ bias. From this early group of work a brand of HRM received particular attention, Polar Electro, and from testing was noted as being as accurate as

intermittent ECG sampling at a range of exercise intensities. Results noted that the Polar HRM was in excellent agreement with criterion with HR data producing very good correlations (e.g. $r = .99$) and 95% Confidence Intervals ranging between $\pm 2 \text{ beat}\cdot\text{min}^{-1}$ (Seaward et al., 1990). Similarly to the previous, Godsen et al. (1991) completed assessment of the HRM (Polar Vantage XL) over a number of activities (i.e. treadmill running, weight training, rowing, arm leg ergometry) and results noted HR values were $\pm 6 \text{ beat}\cdot\text{min}^{-1}$ 95 % of the time.

Technological developments saw the validity of the HRM available on the commercial market ($n=7$) a decade later being investigated (Terbizan et al., 2002). An incremental treadmill based protocol (i.e. 0, 5.2, 6.4, 9.6 $\text{km}\cdot\text{h}^{-1}$) was used and, though no rationale is provided in the original paper, a validity performance criteria of $r > .9$ was adopted from the work of Leger and Thivierge (1988). Results showed that 5 HRM were deemed as credible with some devices maintaining r values $>.9$ over the first 3 intensities. Surprisingly one non-chest HRM (i.e. Cateye PL6000) performed as well as a leading chest HRM (e.g. Polar Vantage XL). Two HRM, one handheld and one chest, failed to meet the set criteria at any of the intensities (e.g. $r < .82$ during first activity stage). Within a wider research project Kingsley et al. (2005) identifies credible HR precision for the Polar S810 with LOA, in an averaged sample, were less than $2 \text{ beat}\cdot\text{min}^{-1}$ across all intensities of a cycle ergometer test. This tight agreement was linked to the use of a cycle ergometry, reducing upper body movement, possibly reducing artefacts occurring meaning closer synchronisation of data. Though some specific data in saw wider LOA at higher intensities. Terbizan et al. (2002) also highlights none of the HRM tested were valid at the highest intensity (i.e. $9.6 \text{ km}\cdot\text{h}^{-1}$) which is a theme consistently reported across earlier research. Reasons for the reduction in accuracy, as noted earlier, does cast some doubt over the usefulness of HRM in some sports as many performers will be moving at velocities in excess of $10 \text{ km}\cdot\text{h}^{-1}$ during play.

There is a recent significant rise in volume of research in the area of HRM specifically linked to assessing the precision of HRV. HRV is associated with the regularity of inter-heart beat differences (i.e. R-R intervals) which is associated with vagal control/autonomic responsiveness. Low HRV appears to be linked to deleterious health and other CV related conditions (Achten and Jeukendrup, 2003, Nunan et al., 2008). More advanced HRM which provide information on HRV are proving to be credible alternatives for the ECG which used to be the only method to access data on HRV. The Polar S810 has been noted by many researchers as being credible in assessing HRV by providing narrow LOA, good correlations and small effect when tested (Kingsley et al., 2004, Gamelin et al., 2006, Nunan et al., 2008). Even though the majority of specific HRV data is collected at rest and not HR *per se*, it is still derived from the same ECG stimulus so still demonstrates how functional and credible the HRM is.

To summarise, it is clear that even with some improvements in modern non-chest HRM (Terbizan et al., 2002) research has shown that the most accurate HR information is obtained from chest electrodes though there is a decrement in precision as exercise intensity increases (Achten and Jeukendrup, 2003, Vuori, 1998). Chest electrodes have been developed in to the most successful device as the QRS complex contains most “energy” (i.e. mV) from the cardiac cycle, its frequency spectrum (i.e. Hz) is sufficiently different to allow some filtering from other possible electrical artefacts and the QRS formation remains relatively constant during exercise allowing on-going signal detection to occur (Polar Electro, 1996, Boudet and Chamoux, 2000, McArdle et al., 2005). There is a range of chest HRM manufactured in the market place which are deemed to be valid though across the research published, multiple papers noted Polar Electro as being a consistent high performer in testing (Seaward et al., 1990, Godsen et al., 1991, Terbizan et al., 2002, Gamelin et al., 2006). It has been argued that through the 20 years of the research process Polar Electro has now been recognised as the one of the market leaders in HRM technology (Laukkanen and Virtanen, 1998).

2.8.2 Breathing Frequency

Human respiration or ventilation responses have often been measured within a laboratory environment with minimal naturalistic investigation reported. There is a dearth of information on respiratory responses in an applied or natural setting which if investigated could provide a further insight in to CV health and sporting performance (Grossman et al., 2006).

The majority of respiratory research has been collected in the laboratory or clinical environment with measures gained through the use of spirometry and/or pneumo-tachographs which are expertise and equipment laden. Also data captured from both the latter measures are derived from the subject accepting, what has been termed, an invasive procedure such as the wearing of a face mask or placing a tube in to their mouth in a sealed coupling arrangement (Witt et al., 2006). It is not surprising that that invasive methods can produce unnatural breathing responses in “experimental conditions”. Research (Askanzi et al., 1980) identifies that assessment of subjects when wearing a mouth piece there were increases in tidal volume (32 %) and minute ventilation (31 %) though frequency of breathing was not significantly altered. It was hypothesised that the changes in respiratory values could be due to alterations in sensory stimuli or psychological anxiety. Assessing respiratory related variables in a less invasive and applied manner may lessen the unnatural responses identified.

2.8.2.1 Technology Associated with Assessing Breathing Frequency

A non-invasive respiratory assessment has been available for a number of years in the clinical environment though the wider accessibility to this technology has not been forthcoming. A well-documented non-invasive approach revolves around the measurement and interpretation of the chest wall motion and mechanics of breathing (Witt et al., 2006). In 1967 Mead et al. presented a paper on assessing pulmonary ventilation measured from body surface measurements from which a 2-degree-of-freedom model of chest wall movements was developed. The model proposes that the breathing cycle is composed of movement in a chest and abdominal portion so measures or monitoring at both these points are required if correct interpretation of breathing is required. There is a paradoxical motion of the ribs and abdomen which non-invasive devices can monitor and interpret into valuable natural respiratory information (Powers and Howley, 2007, DePaulo and McCool, 2002). More recently a 3-degree-of-freedom model has been noted to include a measure of axial chest wall motion which reflect the change in chest wall shape with alterations in posture (McCool et al., 2002). The non-invasive respiratory research originates from clinical situations. In critically ill patients this method of breathing assessment was successfully used to monitor breathing patterns (i.e. tidal volume, avoidance of hyperinflation etc.) due to its non-invasiveness which created a less stressful environment and could be used with unconscious patients and/or patients with limited movement (Leino et al., 2001, Wolf and Arnold, 2005).

The technology associated with non-invasive respiratory assessment notes Magnetometry (Mag), Electrical Impedance Tomography (EIT) and Plethysmography all have the respiratory analysis origins in the thoracic movement associated with breathing. Specific differences between the methods are that a Mag measures changes in anterior-posterior displacement of the rib cage and abdomen using pairs of electromagnetic coils. In the Mag modified version, one set of coils ($n=2$) are secured at the chest and abdomen which are then both attached through wires to the Mag. These coils then transmit and receive an electromagnetic signal based on chest and abdomen movements (McCool et al., 2002). EIT utilises small amounts of electrical current released sequentially via multiple electrodes ($n=16$) which are applied around the circumference of the chest. The voltage differential between the receiving and transmitting electrodes creates a tomogram of the electrical properties of the tissue allowing for a graphical insight in to the internal contents of the lung at the regional level (Wolf and Arnold, 2005, Cheny et al., 1999). Respiratory Inductive Plethysmography (RIP) assesses changes in cross-sectional areas by measuring changes in the electrical impedance. This is completed by using two elasticated belts that contain Teflon-coated wires, arranged in a zigzag formation, which are placed around the rib cage and abdomen. When the chest or abdomen moves the bands produce an independent signal which is included in an algorithm calibrated against a known gas volume to

produce information on breathing cycles (Witt et al., 2006, Wolf and Arnold, 2005). Devices working using similar principles to RIP such as thoracic impedance, piezo-electric or other strain gauges are available though not as well validated (Grossman et al., 2010). RIP seems to be the more popular method within the non-invasive respiratory research area, probably due to the ease of equipment application, though all technologies have been progressed in recent years becoming smaller, light weight and transportable for ambulatory applied research (Leino et al., 2001, McCool et al., 2002, Clarenbach et al., 2005).

All the methods mentioned can identify breathing patterns and timings based on the thoracic movements noted previously. EIT provides regional and global quantification in lung volume though has specific clinical output for detecting make-up of internal tissue in the lung (i.e. gas, blood clots etc.). The information from which may then need immediate action from medical professionals (Chen et al., 1999, Wolf and Arnold, 2005). Mag and RIP also originate in the clinical setting and are more aligned to monitoring respiratory cycles and volumes of gas breathed by subjects/patients. Rhythmical in and ex-halation can easily be converted in to respiration rate but both devices produce specific data on lung volumes by a calibration process via spirometers, pneumo-tachographs or equivalent devices (i.e. Metabolic carts such as Cosmed or Metamax system) before data collected is initiated (Grossman et al., 2006, Kent et al., 2009). A RIP calibration process within a research project is described where-by subjects repeatedly inflate and deflate a fixed volume bag (i.e. 800ml) while wearing a nose clip (Kent et al., 2009).

2.8.2.2 Research on the Precision of Breathing Frequency Measurement

McCool et al. (2002) researching accuracy of a Mag when compared to a spirometer during rest and exercise state (i.e. 3.5 mph @ 3%) presented a strong coefficient of determination (CoD) for tidal volume (V_T) ($r^2 = .90$) at rest and during exercise ($r^2 = .79$). Breathing timing (sec^{-1}), inspiration and expiration, were similar with r^2 values ranging between .95 -.97. Actual differences in V_T identified were $10.1 \pm 6.6 \%$ and $13.5 \pm 8.6 \%$ while inspiration and expiration times showed a $6.9 \pm 6.8\%$ and $9.2 \pm 9.9 \%$ for rest and exercise respectively. Results were deemed as positive and providing useful measures for practitioners.

In a series of clinically based studies, it has been claimed that RIP was not precise enough for use in a medical critical care environment with a deviation $< 10\%$ for quantitative measurements of V_T in some patients who were all anaesthetised. A baseline drift of $25.4 \pm 29.1 \text{ mL}\cdot\text{min}^{-1}$ was identified in the data being recorded by the RIP (Respirtrace Plus). It was suggested that imprecision of some data could be attributed to changes in subjects skin temperature affecting the RIP or insufficient

acclimatisation of the device prior to commencing measurement (Neumann et al., 1998). In another study setting a mixed group of healthy, CV unhealthy anaesthetised and acute lung injury participants were fitted with RIP devices (Respirtrace plus and Respirgraph the former the newer model) as part of their normal treatment. In healthy subjects the Respirtrace plus also was found to produce a “drift” over time though produced less errors in the assessment of V_T (1.7 ± 1.1 % versus 9.3 ± 2.1 %) (Leino et al 2001). Within the clinical setting RIP is applicable if semi-quantitative data or basic bedside monitoring of respiratory cycles are required in static patients (Valta et al., 1992, Neumann et al., 1998).

As the technology has become more commercially viable further research using RIP has been completed outside of the clinical setting (Clarenbach et al., 2005). In this applied setting the confidence intervals within the data generated by the equipment can be wider so valuable respiratory responses have been noted, for example, the technology has been used to ascertain respiratory related data assessing effectiveness of breathing training devices (Tomich et al., 2007).

The exercise related research is continuing to develop and the precision of measurement using healthy populations during different exercise modes is being published. A series of publications have focussed on one monitoring device using RIP technology (Lifeshirt™). An indication of the precision between the criterion and portable RIP (Lifeshirt™) reports a range of outcomes with a high degree of accuracy reported by Clarenbach et al. (2005), while Kent et al. (2009) note that differences between systems remained within clinically acceptable limits and Witt et al. (2006) were more pragmatic in suggesting the device provides reasonable estimates of ambulatory field based respiratory measures only and is not a replacement for more invasive pneumo-tachograph (i.e. criterion).

The methodologies from the studies note the simultaneous synchronised assessment of the RIP against the criterion which has been a spirometer or pneumo-tachograph. The vast majority of exercise studies have been laboratory based using standard exercise modes (i.e. treadmill) though some have also investigated equipment’s precision within applied settings (Grossman et al., 2006, Witt et al., 2006). Exercise intensities have been created via heart rate responses to work classified as either low, intermediate, submaximal and maximal (Clarenbach et al., 2005). Intensities of work have also been assessed through sub-maximal increments in treadmill velocity (i.e. 3.7, 6.1 and 8.9 $\text{km}\cdot\text{h}^{-1}$), or attainment of a percentage of peak oxygen uptake and also assessed to maximal intensities (Witt et al., 2006, Kent et al., 2009). When attention is given to data processing, a series of RIP papers state breath-by-breath analysis is too variable with CV of 17.5% being identified (Kent

et al., 2009). To control variance and potentially identify a more stable trend, data has been averaged over a specific number of breaths completed (e.g. n=20) or more commonly within a time phase 30-60 sec⁻¹. (Clarenbach et al., 2005). This processing of respiratory data is recommended by professional organisations (American Thoracic Society 2003). In some papers, respiratory data was specifically found to be heteroscedastic and therefore was log transformed in agreement with Atkinson and Nevill (1998). Relative and absolute results have been presented within results sections, though some differing statistical analysis and use of terminology has varied between research limiting the cross comparison at times (Kent et al., 2009, Witt et al., 2006).

Detail from particular studies identifies Clarenbach et al. (2005), stating that a high degree of accuracy was identified with specific reference to respiratory cycle time (TT), minute ventilation (V_I) and V_T. Healthy and CV unhealthy participants (n=31) completed a treadmill protocol working at age-related heart rates. Breath-by-breath analysis identified no significant bias between devices with 95% CI ≤ 2% for V_T, V_I and ≤ 1% for TT which suggests “equivalent agreement”. Presence or absence of CV disease did not affect the precision of the data though the RIP analysis identified differing breathing patterns between healthy and CV unhealthy (i.e. CPOD) subjects. When 20 breaths were averaged, comparison of mean values identified through LOA that 95% of differences would be expected to fall within ±1% for TT and ±8% V_T and V_I. Additionally correlation coefficients saw r^2 exceeding .97 ($P < .001$). It is suggested there is a ±5% inaccuracy of respiratory flow meters repeatability and CoV of 25-28% for V_I meaning the results within this study were “excellent” (American Thoracic Society, 2003, Clarenbach et al., 2005).

Witt et al. (2006) identified no significant differences between the RIP and pneumo-tachograph when subjects (n=10) completed a sub-maximal and maximal treadmill based protocol. Strong CoD were reported for f_R ($r^2 = .92$), V_T (.87) and for V_I (.96). LOA mean bias for f_R did not increase proportionally with increments in intensity with the smallest bias at slow walk (3.7 km.h⁻¹; 0.95 ± 1.70 br.min⁻¹) and highest at slow jog (8.9 km.h⁻¹; 3.21 ± 7.06 br.min⁻¹). The Bland-Altman plot for f_R can be seen in Figure 14.

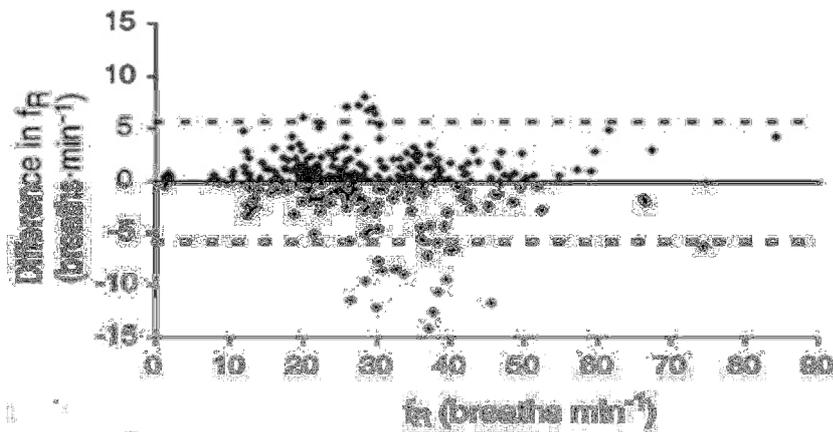


Figure 14. Bland–Altman analysis of the pooled minute average data for breathing frequency (f_R) X-axes represent mean of respiratory inductive plethysmograph (RIP) and pneumotachograph (PT) values. Y axes represent the difference between the RIP and PT. Dotted lines represent 95% confidence intervals and solid line represents the mean bias (cited in Witt et al., 2006, p392).

There was a tendency for increases in absolute bias as exercise intensity increases though this was linked to heteroscedasticity of data. Overall averaging across all respiratory measures saw there was a relative bias of less than 18% and from these results it was stated that the device can track respiratory values through sub-maximal to maximal workloads (Witt et al., 2006). Comparing with other research, Witt et al. suggested their results demonstrated less precision within the device than previously presented work (i.e. Clarenbach et al., 2005) though this could be attributed to data processing (i.e. averaging) methods used. Additionally, Witt et al. (2006) cite other researchers (i.e. Caretti et al. 1994) who identified lower correlations ($r^2 = .60$) when examining RIP on a treadmill. It was postulated that movement associated artefacts could affect data collection while using RIP.

In a more applied investigation, 14 everyday activities were completed by subjects ($n=9$) over a 90 minute period while wearing RIP (Lifeshirt™) and a portable spirometry system (Oxycom mobile). Grossman et al. (2010) identified mean correlations between criterion and RIP were good for V_I ($r = .95 \pm 0.03$), f_R ($r = .92 \pm 0.05$) and positive for V_T ($r = .89 \pm 0.11$). LOA analysis noted no bias in V_T but 0.4 br.min^{-1} under estimation for f_R and 0.4 L.min^{-1} for V_I . Even with strong correlations the 95% CI shown by Bland-Altman plot shows minute by minute data is quite divergent from criterion. CI were wider than expected therefore meaning that RIP device is not always precise in free moving conditions though is suitable for research purposes in which average trends are noted. Strong individual correlations support the use of RIP to evaluate respiratory function in everyday activities in healthy population. Further analysis via t-tests noted differences between the two data set though

the strongest similarity was for f_R . Apart from failing to include comparative analysis from a specific relevant paper by Witt et al. (2006), who was testing the same RIP device, the sample size was also quite small, all of which limits the analysis somewhat.

In an earlier applied piece of research, Grossman et al. (2006), investigated the reliability RIP (Lifeshirt™) with participants ($n=16$) completing a series of yoga classes. Pearson's product moment correlation coefficients for the base line measure, which was taken seated at the start of each Yoga sessions, were positive for f_R ($r = .83$) and V_T ($r = .82$) though lower for V_I ($r = .76$). Correlation coefficients lowered at second baseline measure and during actual physical activity completed later in the yoga session. Other studies (McCool et al., 2002) have noted that there are position specific calculations of respiratory volumes so data could have been influenced by the yoga activities within this research. It was noted by Grossman et al. (2006) that f_R could be the strongest performing variable as it is one of the easiest measures to monitor using the RIP technology as there is no need for calibration as it detects the cyclical motion of the chest wall and abdominal movements. Limitations to the research include the lack of rationale for use of Pearson's Product Moment correlation to analyse between session reliability as ICC could be used (Hopkins, 2000b, Hopkins et al., 2009). Also they acknowledge the lack of a respiratory criterion for comparison restricts the value of the data. Associated with this issue it was noted the loss of data relationship between RIP and criterion when measures are not performed simultaneously (Fiamma et al., 2006). This supports the notion, mentioned earlier, of altered breathing patterns when executed through invasive respiratory equipment. Consideration of this issue is needed when comparing data from synchronised RIP-Criterion studies to independent RIP studies without a reference measure.

Kent et al. (2009) assessed the validity, versus criterion (pneumo-tachograph) and reproducibility of cardio-respiratory variables, over 4 testing occasions. Participants ($n=16$) completed an incremental exercise and constant workload test. Agreement between two systems was within acceptable ranges and bias over the days was also within acceptable limits (approximately 10%), which was mirrored by the calibrated laboratory system used. The incremental workload test saw an acceptable bias (3.5 %) in ventilation between the two systems but this increased, suggesting a decrease in accuracy, as intensity of activity increased. The CV of 9.5 % ($4.61 \text{ L}\cdot\text{min}^{-1}$) was noted though this decreased accuracy trend was reversed with the expiratory time measure, as differences in this variable reduced between systems with an average difference 2.2 %. There was no significant bias noted in respiratory rate ($P = .895$) and CV 1.4 %. The constant steady state work protocol identified that ventilation under estimated volumes (5.8 %, $1.81 \text{ L}\cdot\text{min}^{-1}$) though CV was at an acceptable threshold at 9.7%. Negligible mean difference in f_R (0.2 %, $0.06 \text{ br}\cdot\text{min}^{-1}$) were seen with reliability CV at 0.4 %. Significant expiratory time bias between systems was identified ($P = .008$) though mean difference

was small (1.2 %, 0.015 sec⁻¹). Reliability CV over 4 tests, both the incremental and constant work test, produced CV of approximately 10% for both RIP and criterion. Present research noted differences between systems remained within clinically acceptable limits.

In summary, RIP has been shown to have credible precision across different environmental conditions. Stemming from the clinical setting early research was completed in mainly sedentary subjects. More extensive investigation is required in the exercise domain especially as different systems using the RIP technological principles offer more basic data (e.g. just breathing frequency).

2.8.3 Accelerometry

Accelerometers (ACC) are widely accepted as an unobtrusive and discrete method to assess and interpret the frequency and intensity of physical activity in a range of populations (Welk et al., 2004). ACC devices work on the principle of quantifying accelerations and decelerations of movement that generate activity counts which could provide information on patterns of activity over a set time period (King et al., 2004, Powell and Rowlands, 2004). These activity counts can be objectively interpreted as a quantification of physical activity completed in the set epoch by the performer (Powell et al., 2003). They have predominately been used within the general population aiming to assess levels of physical activity and relating findings to energy expenditure, health status and obesity research (Powell and Rowlands, 2004, Chen and Bassett, 2005).

2.8.3.1 Technology Associated with Assessing Accelerometry

Technical improvements with ACC devices have led to a reduction in the size and mass of hardware, extended data collection time, wireless connectivity and real time reporting of information (Chen and Bassett, 2005). ACC can be classed as uni-axial, measuring movement in one direction, through to tri-axial which measure accelerations in three orthogonal planes (e.g. Vertical, antero-posterior, medio-lateral). Uni-axial devices measure in the vertical plane only while tri axial devices have a potentially wider range of movement capture and with the technical improvements of devices noted, means physical activity can be assessed effectively (Chen and Bassett, 2005, Eston et al., 1998).

ACC assess movement via a piezoelectric sensor(s) with a cantilever beam or integrated chip configuration (Figure 15). The ACC contain a piezoelectric element and a seismic mass with the latter aspect reacting to movements/accelerations. The seismic mass causes changes in tension or deformation within the piezoelectric sensors which subsequently generates a proportional voltage

output within the device. This output is linked to a direction/axis which then is related to an intensity of activity (i.e. a count) (Chen and Bassett, 2005). ACC will generate data or activity counts which could be presented individually, based on specific axis/planes of movement, or cumulatively via a calculation including all planes/axes. The latter integrated activity measure is sometimes referred to as Vector Magnitude Units (VMU)(Powell and Rowlands, 2004). Output from ACC is not standardised between different commercial devices. For example, different ACC devices may sample data at different rates (i.e. 1-64 Hz) with the higher frequencies being needed to provide data for high intensity movements. Additionally the epoch for data collection can be varied (i.e. 1 sec⁻¹ to 1 day⁻¹) depending on the monitoring aim (Chen and Bassett, 2005). A comparative evaluation of three ACC found, even with different technology amongst them, strong correlations in data produced between monitors (Welk et al., 2000). Even with the latter finding the arbitrary technical filtering and interpretation of activity counts across commercially available ACC in the market, means direct analysis between ACC brands is a complex issue.

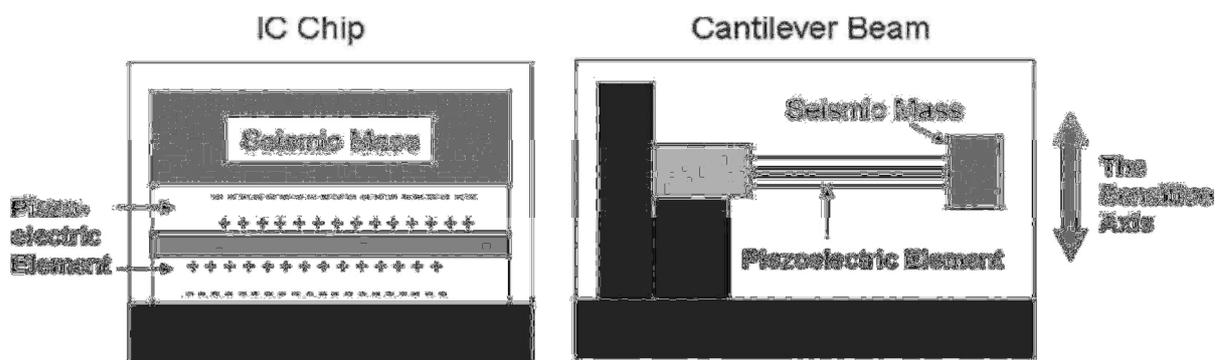


Figure 15. Two piezo-electric configurations (Chen and Bassett, 2005, p491)

Within the majority of physical activity ACC research completed, the norm is for the performer/participant to attach and wear the device around the waist with specific alignment to the hip. It is suggested that there is no difference in activity counts identified between left and right hip positioning (Trost et al., 1998) though Welk et al. (2000) did identify statistical differences in activity counts in one of three ACC devices when 3 positions were tested for the ACC which were situated around the hip/axillary line. Welk et al. (2004) does question if reproducibility of data becomes more susceptible in uni-axial monitors as it is theorised that with three measuring planes, tri-axial devices' magnitude of output remains more robust regardless of positioning. Recent developments of some

multi-function monitoring systems have seen ACC positioned over the chest (i.e. longitudinal axis) as they are now integrated with other measuring components such as heart rate (Brage et al., 2005, Zephyr Technology, 2013). With either positioning of the ACC on the waist or chest, limitations of current models include the lack of data on upper body limb activity and the terrain activity is being completed on, none of which can be accounted for within an activity profile generated (Powell and Rowlands, 2004).

2.8.3.2 Research on the Precision of Accelerometry

Research investigating the precision of measurement in relation to ACC and activity data have utilised similar laboratory based protocols. A treadmill based protocol has been adapted by a number of authors (Brage et al., 2003, King et al., 2004, Vanhelst et al., 2009) to validate and check reproducibility of ACC data. Incremental walking ($2 - 6 \text{ km}^{-1}$) and running ($> 8 \text{ km.h}^{-1}$) stages of 5 to 10 min^{-1} in duration are utilised to achieve a controlled steady state activity status and then data collection would occur in this period. Oxygen consumption is then used as an indirect criterion measure for ACC due to the link between increased activity and increased metabolic cost (i.e. VO_2) (Rowlands et al., 2004). The use of oxygen consumption as a criterion measure for ACC is common as other gold standard methods (i.e. Double Labelled Water, indirect calorimetry) are more costly, require high level of expertise and time intense, so prohibitive (Fruin and Walberg Rankin, 2004). Some authors have compared credible ACC devices against one another though, as mentioned, the non-standard activity count production between devices limits the analysis (Rowlands et al., 2004).

A number of ACC devices have been leaders in the area and presented in over 20 academic papers. Computer Science Applications (CSA) ACC and Tritrac (or RT3) ACC both have been shown to have a sound relationship with oxygen consumption during increased activity and are considered a reliable and valid tool in assessing activity in specific populations (King et al., 2004, Powell and Rowlands, 2004, Rowlands et al., 2004). Further analysis though has identified that ACC have been shown to weaker credibility at the extremes of activity (i.e. static/resting and high intensity work).

Trost et al. (1998) investigated ambulatory treadmill activity (e.g. $4.8, 6.4, 9.6 \text{ km}^{-1}$) state CSA is a valid tool for quantifying activity with strong correlations between activity counts and energy expenditure ($r = .87, P < .001$), Oxygen consumption ($r = .87, P < .001$) and treadmill speed ($r = .90, P < .001$) reported. These findings have subsequently been (Welk et al., 2000) and more recent research (Brage et al., 2003) on CSA seems to identify a lower precision of measurement at higher intensities of movement. The latter work noted the CSA produced linear relationship in output versus speed with significantly different ($P < .05$) activity counts at lower intensities between $3 - 8 \text{ km}^{-1}$. At

intensities 9 - 18 km⁻¹ the device reported no differences between counts produced, when increments would be expected, and a levelling off at 10,000 cts.min⁻¹ occurred. This phenomenon could restrict the effective precision of data and use of these single axis devices in some circumstances.

As noted earlier, tri axial ACC assess movement in multiple planes allowing for more data on movement to be collected and therefore they have been claimed to be more effective at reporting activity levels (Chen and Bassett, 2005). In a field based trial (Hendelman et al., 2000) walking activities of a tri axial (Tritrac) ACC have higher correlations ($r = .89$) with energy expenditure when compared with CSA uni-axial ($r = .77$) device. Further support for tri axial ACC was presented by Welk et al. (2000) who completed a lab (e.g. 4.8, 6.4, 9.6 km⁻¹) and field analysis on three ACC. The findings presented $r = .85 - .92$ for validity with the tri axial (Tritrac) device being deemed superior to the uni axial (CSA) comparator. There were also strong correlations between activity counts and oxygen consumption ($r = .88$ boys, $r = .79$ men) for a tri axial (RT3) ACC which was being validated using an incremental treadmill based task (Rowlands et al., 2004). Results identify that the tri axial device differentiated between low intensity activity (> 6 km.h⁻¹) but ability to discriminate between running speeds of 8-10 km.h⁻¹ decreased with further increments in ACC count outputs not occurring (Rowlands et al., 2004). This decrement in precision of measurement as intensity increases seems to mirror the issues identified in uni-axial (CSA) devices and questions whether the tri axial devices are more comprehensive in data capture.

Reproducibility of data is important to give credibility to data generated. Good test-retest reliability was noted by Welk et al. (2000) when 3 ACC (i.e. Tritrac, CSA Biotrainer) and produced r values of .85 - .95 with the tri axial device being the most effective. It could be hypothesised that the tri axial ACC three orthogonal planes could potentially increase the possibility of variance in activity data if not checked individually. Rowlands et al. (2004) investigating tri axial (RT3) ACC did not find significant differences between vertical axis and VMU with the latter integrated value being a better predictor of oxygen consumption. Further research into this area identified that inter and intra instrument variability exists within the RT3 ACC as Powell et al. (2003), using a mechanical jig to vibrate devices along single planes, presented results that noted antero-posterior axis counts.min⁻¹ were significantly ($P < .001$) higher than two other axis at 5.1 Hz (0.219g) and 10.2 Hz (0.414g). Inter instrument ICC were strong ($r = .99$; $P < .001$) for activity counts across all axes. The inter and intra instrument CV for mean activity counts at each axis was higher at 2.1 Hz (0.135 g) compared to other frequencies. Inter instrument CV ranged from 21.9 - 26.7 % at 2.1 Hz, 6.3 - 9.0 % at 5.1 Hz, 4.2 - 7.2 % at 10.2 Hz while intra instrument CV were ranged 7.3 - 12.4 % at 2.1 Hz, 0.9 - 1.7 % at 5.1 Hz and 1.0 - 1.1 % at 10.2 Hz (Powell et al., 2003). Powell and Rowlands (2004) completed participant based

inter monitor variability assessment of the RT3 tri axial ACC and noted inter monitor CV by activity were between 1.5 – 6 % though the lowest intensity activity, a sit-to-stand task, produced higher CV (8.7 – 25.6 %). Overall though, as running treadmill speed increased, the variability between devices increased with some axes being more variable than others.

From the evidence it seems that single or multi plane ACC have some limitations with precision of measurement linked to very low or high intensity activity. Reasons for this limitation in ACC data output have been linked to running mechanics and technical limitations of devices and has implications for the use of single or tri axial ACC (King et al., 2004). Differences exist in the biomechanics of walking and running which will possibly elicit a different output within the ACC. Brage et al. (2003) describe walking ($< 8 \text{ km.h}^{-1}$) as an inverted pendulum with potential energy constantly interchanging while running ($> 8 \text{ km.h}^{-1}$) should be thought of as more of a bouncing model which then alters at approximately 11 km.h^{-1} . At these higher intensities “*duration of the contact phase of the stride decreases and the rebound becomes asymmetric...To restore vertical momentum, average contact phase acceleration must increase with shorter contact duration*” (Brage et al. 2003, p1452). The vertical mechanical power component is highest during walking activities then remains constant through incremental running intensities while accelerations in other directions increases significantly in the same period (Brage et al., 2003, Vanhelst et al., 2009). The change in running mechanics as intensity increases could lead to the associated levelling off of activity counts seen, especially in single plane devices (Brage et al., 2003).

It has been posited that rather than relying on VMU or vertical axis, other individual axes (i.e. anterior posterior) may be better predictors of activity at higher intensities (Chen and Bassett, 2005) though this was not supported unanimously (Powell and Rowlands, 2004).

With various devices being configured differently, the technical set up of ACC may influence the data output. The technical elements of ACC (i.e. Piezoelectric element) are not effective at measuring static component and are only effective for dynamic events (Chen and Bassett, 2005). This may well explain the lack of precision in some ACC at rest/low intensity activity. It has been suggested that the CSA may be near or on the technical measurement limit ($\pm 2.13 \text{ g}$) at higher running intensities which could explain the plateau in output in this device (Brage et al., 2003).

Comparing ACC data between participants is problematic as differences in ACC count-oxygen consumption has been postulated and linked to differences in anthropometrics, body composition, gender, pre-test aerobic fitness levels and individual running mechanics (Rowlands et al., 2004, Brooks et al., 2005, Vanhelst et al., 2009).

In summary, ACC have now become a recognised device to provide an objective quantitative measure of activity across a variety of populations. A lack of uniformity with regards to the counts accelerometers provide means cross comparison of devices is limited. They are now unobtrusive technologically advanced units though limitations on capturing all types of activity at different intensities completed by an individual still exist.

2.8.4 Posture

Posture, or inclinometry, has previously been assessed within workforce and occupational health with the aim to achieve a profile of day-to-day activities and working patterns. The data collected has assessed repetitive movement patterns of multiple limbs or body parts with the intention of investigating how alterations of body positions over time may link with ergonomic interventions and injury occurrence (Hansson et al., 2006, Attwells et al., 2006). There are small groups of movement based studies utilising the technology to assess dynamic recovery from injury or movement analysis (Crosbie et al., 1997, Stanton et al., 2004). For the purposes of this review, posture is primarily concerned with trunk angle of the participant during physical activity.

2.8.4.1 Technology associated with Assessing Posture

In comparison to more expensive, subjective (i.e. observation) and time costly methods, quantifying posture (i.e. inclinometry) through accelerometry based technology is now more common (Foerster et al., 1999). Less technically based devices such as the Leighton Flexometer have been validated and used within research (Daneshmandi et al., 2010) but are potentially more susceptible to human methodological error during data collection. Accelerometry devices have the advantage of being direct, objective, relatively low-cost with data logged for long periods therefore allowing for a comprehensive view to be attained (Amasay et al., 2009). Despite the latter, depending on the technical specification (i.e. sampling frequency, uni, bi, or tri-axial) some accelerometry based inclinometers have limitations with the quality of data recorded (Amasay et al., 2009, Bernmark and Wiktorin, 2002, Hansson et al., 2006). Sampling frequency can limit the devices ability to capture all movement occurring. For example, Bernmark and Wiktorin (2002) noted differing sampling rates of three inclinometers; Physiometer (10 Hz), Abduflex (1 Hz) and Intometer (4 Hz), which influences the potential precision of data and comparison of data between studies. Some 3D video based systems may have higher sampling rates (50-500 Hz) but can be costly and require a long set-up pre-data collection (Bernmark and Wiktorin, 2002, Wong and Wong, 2008).

Data associated with current accelerometry inclinometry devices can be attained from the use of piezoelectric elements (as described and reviewed in earlier Accelerometry section) reporting a gravitational force which is processed as vertical posture data (Mathie et al., 2001). Data from these inclinometers is relative to the gravitational vertical line and is position specific on the participant with limb, head, body being monitored for various work place research (Bernmark and Wiktorin, 2002, Hansson et al., 2006, Hansson et al., 2001). As Nevins et al. (2002. p1087) states, *“The assumption is made that accelerations on the body (other than gravity) are in general much smaller than gravity. Hence the signal and resulting vector is only dependent on the orientation of the sensor with respect to gravity. The accelerometer then becomes an inclinometer”*. With miniaturisation of devices, remotely assessing posture of participants within a natural environment is possible allowing for insights in to movement patterns and how this may relate to motor performance (Veltink et al., 1996). Moreover, to avoid artificial participant awareness of posture influencing results it is important to get observations from participants during longer periods of time in a natural setting and current accelerometry technology appears to permit this type of data to be collected (Nevins et al., 2002).

2.8.4.2 Research on Precision of Posture Measurement

Piezoelectric accelerometry technology within uni-, bi- and triaxial devices has been noted as being adequately precise for monitoring physical activity (Chen and Bassett, 2005). When considering the measuring of posture, using uni-directional accelerometers can lead to greater measurement error if postures of $\pm 60^\circ$ are being measured due to the single plane movement being assessed (Hansson et al., 2001). Tri-axial accelerometry has allowed for more precise posture related data to be captured for longer periods (Hansson et al., 2006). Though rather than 3 distinct signals being reported from triaxial devices, a combined posture figure is often reported, with no rotational element included suggesting summing and processing of data has occurred which, due to manufacturers proprietary concerns, is rarely open to scrutiny (Foerster et al., 1999, Hansson et al., 2001).

Early understanding of the use of accelerometers to measure inclinometry was provided by Hansson et al. (2001). They combined 3 uniaxial accelerometers (NAC 103, California), mounted mutually orthogonally, reporting good absolute precision of 1.3° and reproducibility 0.2° . This early work was developed when Bernmark and Wiktorin (2002) compared a similar accelerometry inclinometer (20 Hz) system versus a high precision video analysis (50 Hz) system (Optoelectronic measuring system, Qualisys, Sweden). Various static to more physically active arm specific movement patterns were

focussed on and good precision (mean difference -1° ; 95% CI -2.8° to 0.1° ; $r = 1.00$) was reported though increased errors were noted at higher intensity movements.

A specific triaxial accelerometry inclinometer device, the Virtual Corsett (Micro Strain Inc, VT, USA) is a health related data logger used to remind patients about trunk position during a physical (physiotherapy) recovery programme (Amasay et al., 2009). The device (7.6 Hz), compared statically with potentiometer (1000 Hz), presented mean errors of $< 1^{\circ}$ though larger differences were recorded at more extreme angles. Dynamic testing followed similar results with error noted at $\sim 3^{\circ}$, with larger differences (12°) at the more extremes ranges. Though positive results, the device would not be suitable for faster movements or sporting activity but an increased sampling frequency may improve data recording capacities.

In field based environment it is difficult to get the reproducibility of data for various reasons; participants may not replicate the precise same movement pattern or position test-to-test, also the inter-user placement of inclinometry devices by may lead to variability in data occurring (Foerster et al., 1999, Hansson et al., 2006). Therefore data collectors should repeat data capture and attention to equipment placement is needed to minimise variability. A baseline measure may be appropriate for each instance of data analysis, though in field based settings this may not always be possible (Hansson et al., 2006, Venturni et al., 2006).

The majority of relevant research in the area has focussed on physical workload in occupational settings, an example being the work of Hansson and colleagues using a previously validated 20 Hz tri-axial accelerometry (Logger Teknologi HB, Akarp, Sweden) (Hansson et al., 2001) to evaluate the usability of inclinometry technology in an industrial setting. Although only 6 participants were used, they completed pre-set "light to heavy" tasks for 20 minutes while movements of the head, arms and upper back were recorded. After a 0° reference point for data analysis was secured, mean values for each posture and also time held within a specific posture zones were assessed. They noted systematic variability for all tasks between-day (3.4°) and between-participant (4.0°) with future recommendations on the importance of accessing homogenous groups for future research. Using validated devices, focussing on participants included within the study and understanding the variation associated with the data collected are key issues similar research should consider.

There is a limited amount of literature from the sport performance area using accelerometry to assess posture, more commonly trunk angle has been assessed by video analysis systems as part of a wider study on movement (Paradisis and Cooke, 2001). Assessing trunk posture during physical activity can provide the exercise professional with valuable information on movement efficiency

between different groups. Depending on the specificity of analysis and equipment available to researchers, the “trunk” has been reported as a single entity and also been separated into different sections aligned with the spinal column (Crosbie et al., 1997). Using video analysis procedure, the trunk was separated into thoracic, lumbar and pelvic areas. Values were consistent (i.e. 2-3°) when subjects walked 10 m at a self-chosen pace (Crosbie et al., 1997). Some wider variation in trunk posture movement patterns were reported with trunk angle (i.e. forward-backward lean) varying between participants (3-10°) and increasing with higher running speed, a 5° increase at highest speeds (Krebs et al., 1992, Thorstensson et al., 1984). Moreover, when velocity is constant ($0.38 \pm 0.27 \text{ m}\cdot\text{sec}^{-1}$) and ground gradient increases from 0% through to 10% a corresponding increased trunk gradient from 6° to 12° (standing static values 2.6° at 0°, 3.1° at 10°) at highest gradient has been reported suggesting the terrain where activity is performed will effect movement patterns (Leroux et al., 2002). Within a training based study where core stability was conditioned and subsequently was improved, the study failed to report a significant change in trunk position during treadmill running. Trunk flexion angles were reported between 9.1° and 10.4° during a run to volitional exhaustion (Stanton et al., 2004). Finally, trunk angle has also been one of the variables reported in running economy research with more economical runners having 5.9° trunk flexion angles and this figure was reduced ($> 3.3^\circ$) in runners in the less economical group (Williams and Cavanagh, 1987). It appears that trunk position may vary, be individualised and change when movement intensity increases which, in sporting context, may have implications on the execution of a sporting skill. These studies provide an indication of normal ranges of trunk position during different activity intensities, though due to logistics of measuring posture, were completed on a treadmill therefore may have limited ecological validity for wider competitive sporting performance.

2.8.5 Skin Temperature

Historically, assessing skin temperature is one of the first clinical procedures completed when addressing patients' health status in relation to fevers and recently it has assisted with diagnosis of critical care conditions (i.e. hypovolemic shock). This multifaceted relationship between temperature and health status has been the primary reason to research the methods by which a patient's temperature can be accurately measured (Burnham et al., 2006, Ring, 2006).

Core body temperature and its relationship to peripheral temperature are of great interest within the medical fraternity with variations from the norm being linked to poor health status in sedentary state. This area is also of great interest to athletes and exercise scientists who need to understand how the thermoregulatory physiological responses may vary when performing in a broad continuum

of environmental conditions (Kistemaker et al., 2006, Powers and Howley, 2007). Temperature of the skin may be useful for local tissue analysis or provide an indication of temperature gradient from the periphery to the core. The core temperature has commonly been measured from the mouth, axilla, oesophagus (T_o), rectum (T_R) and pulmonary artery (T_p) (Kocoglu et al., 2002). None of these measuring sites actually reflect true core temperature as true core temperature is that of the hypothalamus in its thermostat controlling role, though the pulmonary artery is claimed to be closest and cited as the best clinical option. A number of papers have used alternative sites as a standard “core measure” with the T_R and T_o being noted as the non-clinical criterion.

Despite wide possible fluctuations in environmental conditions, core temperature is relatively constant while the skin and superficial tissues are perpetually influenced by the external environment and often this temperature fluctuates. When temperature is measured from any of the sites previously mentioned it is generally the information of core tissues that is the intended measure (Kistemaker et al., 2006). There is a balance between accessing direct precise information which may have limitations and indirect but more available measures. The key issue is how to assess and interpret temperature, core and skin, in a non-laboratory or clinical environment (Kistemaker et al., 2006).

2.8.5.1 Technology Associated with Assessing Thermometry

Heat can be emitted from the body in a variety of ways with radiation, conduction, convection being three modes all of which utilise a temperature gradient to exist between the environment and skin (Powers and Howley, 2007). A fourth method, evaporation, facilitates heat loss through a vapour pressure gradient between the skin and environment. This latter method of heat loss observes water on the skins surface being energised in to gas which therefore removes heat from the body (McArdle et al., 2009). To assess the temperature, peripherally or centrally, in the body requires the harnessing of one of these heat emitting processes to occur.

Historical developments of technology in this area have allowed the progress of contact and non-contact thermometry. Contact thermometers were the first to be developed using the principle of conduction and early devices reacted to heat by causing substances (i.e. beads or mercury) to rise and fall in warmer and cooler conditions. Eventually the clinical thermometer was developed, by Wunderlich in 1868, in a sealed glass tube with a limited temperature scale linked to the human body parameters. Recently the once ubiquitous mercury glass thermometer has made way for other devices which contain less hazardous material, quicker and easier to utilise, and more technologically advanced (Kocoglu et al., 2002, Ring, 2006, Simpson et al., 2006). Thermo-electrical technology has

permitted the development of contact skin thermistors or thermocouples which have also been extensively used within laboratory assessments to assess local skin temperature (Burnham et al., 2006). This technology has been extended in to thermal sensitive probes which can assess temperature internally (i.e. T_O and T_R). Due to the practical and social issues of assessing temperature via T_R and T_O , a telemetric pill has been developed to assess core temperature which reports data to the experimenter via radio wave signal (Easton et al., 2007). Currently this technology is very expensive, is still being investigated for accuracy and obviously has an element of invasiveness for the subject which limits its use in some studies.

A variety of alternative non-contact temperature assessments have been developed which may be more hygienic, quicker to use and acceptable to a wider population. An example being the Schlieren photography which is based on the principles associated with heat convection. This process provides a picture of “heat loss” in the human body by illuminating the change in refractive index in relation to air density around the body. This has been deemed useful for clothing manufacturers in development of insulating clothing though the process currently had limited wider value (Ring, 2006).

One of the major non-contact technologies used to assess temperature is based on the principles of heat radiation. Radiation is the transfer of heat from one surface to another without actual contact which is accomplished through infrared red (IFR) rays (McArdle et al., 2009, Powers and Howley, 2007). The skin surface, regardless of colour, is a very efficient radiator so has been researched in order to achieve accurate indications of local body and core temperature (Ring, 2006). It is claimed that at rest, due to a temperature gradient between the skin and environment, approximately 60% of heat loss occurs through radiation in a thermo neutral environment (Powers and Howley, 2007). Within clinical practice IFR thermometry has become the norm with ear or tympanic devices measuring radiation from auditory canal and tympanic membrane. The latter location has been validated with core (T_O) temperature and in medical environments is the chosen method within medical situations due to its quick, contactless and hygienic process (Simpson et al., 2006, Stavem et al., 1997). Interestingly there has been confusion over the definition of this measurement process with Erickson (1999) stating that tympanic temperature requiring actual contact with the surface of the inner ear via a contact thermistor while IFR (non-contact) method is actually only ear-based temperature (i.e. air in ear canal + tympanic IFR). The use of the term “IFR tympanic” has been adopted through errors in communication in the literature. IFR thermometry has also been developed to assess external skin temperature, again primarily for medical reasons and assessment of shock, though may also assist in further enhancing the understanding of the physiological thermal response of the athlete (Buono et al., 2007, Erickson, 1999, Ring, 2006).

Even though the technology is now widely available and used, IFR thermometry is consistently progressing and some populations are yet to be tested. Also the effectiveness in certain environments (i.e. exercise) have yet to be fully explored and the wider role of IFR use in temperature assessment is still being examined, all of which mean further research on precision of measurement is required (Stavem et al., 1997, Burnham et al., 2006, Buono et al., 2007).

A clear advantage of IFR skin thermometry is that temperature may be measured at any site of the surface skin of the body without the need for wires or a requirement to insert devices in to any orifice (e.g. ear canal). The IFR sensor detects IFR radiation, within its field of view, which is naturally emitted from the specific target location (Erickson, 1999). Technologically IFR thermometers contain thermopiles, which are made up of thermocouples and all of which are classed as a thermo-electrical devices. A series of thermocouples, containing two strips of welded metal, each having a hot and cold end, generate a voltage in relation to the differential in heat they monitor. The cold junction on the thermocouple has a temperature corresponding to temperature of the ambient air while the hot junction receives the target radiation. The heat differential is interpreted through a thermistor and reported as temperature data ($^{\circ}\text{C}$) (Yu-chiao, 2005). Depending on the IFR device the temperature value may then be used for a calculation to predict core or an alternative reference temperature (Erickson, 1999, Yu-chiao, 2005). The latter would not occur if local skin temperature is the intended aim of the device. It is clear some IFR thermometers (i.e. tympanic/ear) which present information are predictive of core temperature and use a physiological site "offset", i.e. the difference between the temperature measured at the second body site to the common reference body temperature at the first body site. This offset is achieved through the use of norm data measured/collected in a clinical setting (Erickson 1999).

2.8.5.2 Research on Precision of Thermometry (Infra-Red Devices)

When investigating early research in the area, clinical based research is concerned with assessing precision of IFR tympanic and IFR skin based devices. Investigating research on both these areas provides a fuller understanding of the IFR technology. Hershler et al. (1992) and Matsukawa et al. (2000) completed similar studies comparing small contactless IFR temperature sensor to a standard contact skin temperature measure. In both papers the contact thermistor used was a clinical level device though not noted as a standard reference temperature measure which could limit the findings. Hershler et al. (1992) tested each device (Thermistor, Thermalert TH5, IFR First Temp) against inanimate objects and human subjects within an environmentally controlled room and identified a very strong correlation between measures ($r = .99$) and mean differences reported at $< 0.1^{\circ}\text{C}$. Matsukawa et al. (2000) collected thermal data at different locations on the body from

subjects (n=10) using thermocouples (Mon-a-therm) comparing it to IFR skin thermometer (Genius). IFR device provided comparable data with correlation coefficients ranging between .78 (Forearm), .97 (fingertip) and .97 (skin temp gradients – arm to finger and calf to toe). Both papers did not fully investigate the data and present somewhat basic analysis. Matsukawa et al. (2000) used Bland-Altman LoA analysis but this failed to be interpret or discuss the outcome though reported a mean difference of $0.5 \pm 0.5^{\circ}\text{C}$ for forearm and fingertip measures. A more recent investigation by Burnham et al. (2006) assessed three devices, IFR skin thermometer (Derma Temp), IFR tympanic thermometer (Genius 3000, IMS) and a skin thermistor (Rochester) which was compared to intramuscular temperature at a depth of 1 cm. Six locations on the body of subjects (n=17) were assessed by both IFR thermometers and contact thermistor. Results noted IFR devices were cooler (0.2°C) in comparison to the contact thermistor though demonstrated high reliability (test-rest) with r values ranging between .96 – .97. Further strong correlations ($r = .86 - .97$) were seen between intramuscular and skin temperatures though skin temperature is systematically lower. Despite the lack of a criterion, comparison data adds to knowledge base in the area. Interestingly within Hershler et al. (1992) research, the change in angle of the IFR device ($< 90^{\circ}$) and increasing distance from in relation to the target area (i.e. skin surface) reduced the precision in comparison to the contact thermistor measure. Uniformity of the surface that device was measuring upon affected accuracy with uneven surfaces producing increases in error, though good test-retest reliability was reported (Hershler et al., 1992). It is noted elsewhere that IFR device should be at 90° to the measured surface, at the appropriate distance and that clear training for research operatives is needed to produce accurate data from the IFR technology (Erickson, 1999, Buono et al., 2007). Despite the issue associated with the lack of a reference temperature and weak overall analysis used, these papers provide data demonstrating initial evidence that IFR skin temperature data is comparable to contact thermistors, but it is clear the positioning IFR device is important to the accuracy of data.

Another clinically based study using recognised criterion comparisons and fuller statistical analysis saw Stavem et al. (1997) assessing (intensive care n=16; Internal medicine n=103) IFR tympanic thermometry (First Temp, IMS) in right and left ears, against thermistor type devices (Ohmeda Criticath) measuring T_p , T_o and T_R (using Portex probe). Within the ICU patients there was better agreement between T_p and T_o data in comparison with the tympanic (right ear) and pulmonary artery (Figure 16) suggesting reduced precision of the IFR tympanic thermometer.

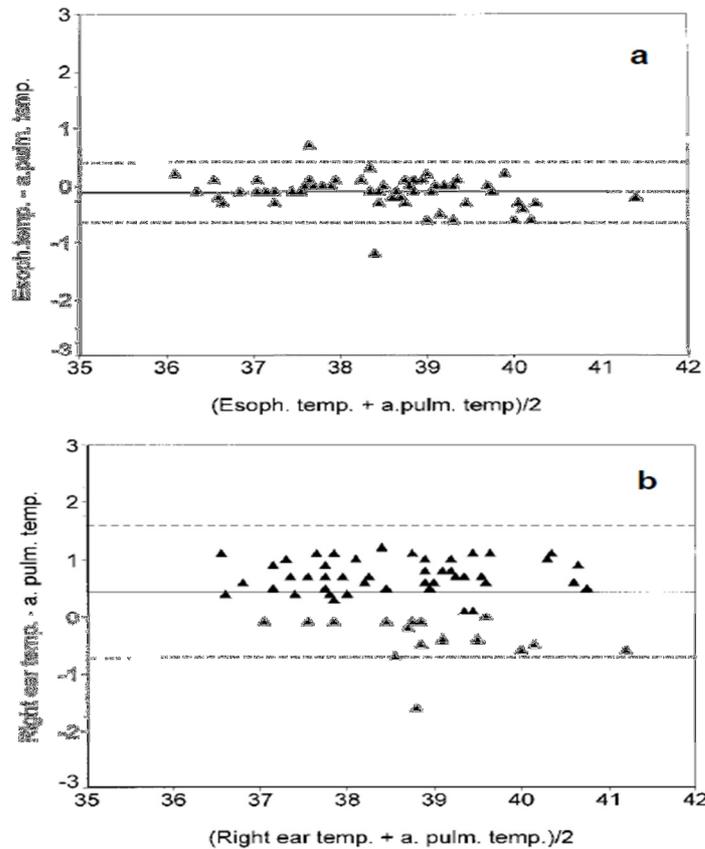


Figure 16. Differences between method pairs versus mean of the pairs in intensive care patients. *Solid line* represents mean. *Broken lines* represent mean ± 2 SD. Ear temperatures are measured in core mode: a esophageal *Esoph.* and pulmonary artery *A. pulm.* temperatures, b right ear and pulmonary artery temperatures *A. pulm.* Temperatures (cited from Stavem et al., 1997, p102)

Mean bias between the criterion, T_p , and IFR tympanic measures was higher, $+0.45^\circ\text{C}$, when compared to T_R and T_O which had a mean bias of -0.16°C and -0.11°C respectively. The results from the internal medicine patients demonstrated a consistent bias between T_R and IFR tympanic measurements of 0.07°C . Results from this paper provide a stronger insight in to the precision of measurement due to the use of recognised reference measures and more extensive analysis methods completed (Stavem et al., 1997).

Another population group (Kocoglu et al., 2002), paediatric patients ($n=110$), were assessed within a medical environment, where IFR tympanic thermometry (Braun Thermoscan) was compared to T_R and axillary temperature using a mercury glass thermometer. Accepting the T_R as the reference value, results suggest more accurate data is provided by the IFR tympanic device in comparison to the measurement taken at the axillary. There was no significant difference in the measurements

taken by all three devices. Specifically though, in comparison to the T_R measures, mean IFR tympanic temperature differed by $-0.17 \pm 0.37^\circ\text{C}$ while axillary was less accurate differing by $0.72 \pm 0.36^\circ\text{C}$, adding to credibility of the IFR devices in providing measurements within acceptable limits (Kocoglu et al., 2002). Research within an exercise context has queried the precision of the same IFR device.

Douglas et al. (2007) assessed a number of temperature devices commonly used by sports professionals, the one of interest for this review being IFR technology. Participants ($n=25$) temperature was assessed pre, during ($t=180\text{mins}$), and post exercise ($t=60\text{mins}$). Comparing to T_R the IFR device (Braun Thermoscan) presented an adequate correlation ($r = .70$) though a mean bias of -1.0°C and LOA $\pm 1.14^\circ\text{C}$ was noted. Additionally significant differences between IFR data and T_R were seen during exercise ($P < .001$) and post exercise ($P \leq .001$) (Douglas et al., 2007). Validity threshold for a device was set at $\pm 0.27^\circ\text{C}$ from T_R (Gant et al., 2006) and none of the temperature devices tested were classed as valid. The IFR temperature device was one which was not suitable based on the mean bias parameters. In the context of the paper it was suggested T_R was deemed the most appropriate method and sports medicine personnel should be trained and prepared to use this device to assess athletes who are suffering from heat stress.

The relationship between the skin and core temperature under differing environmental conditions was investigated by Kistemaker et al. (2006). Two IFR skin thermometer (Sensor Touch professional and Sensor Touch Consumer) working on the principle of measuring IFR radiation through the skin from the superficial temporal artery were compared against a reference temperature. Subjects ($n=22$) had temperature data monitored continuously via T_R , T_O thermistor and every 5 minutes via IFR skin thermometer. Protocol required subjects to experience a cool room (10°C) and then progress on to a warm chamber (30°C) where they rested on a chair before exercising on a cycle ergometer ($1 \text{ W}\cdot\text{kg}^{-1}$) for 30 minutes. T_R was noted as the reference temperature. Results (Figure 17) note that IFR Sensor Touch temperature readings were significantly below the reference value ($P < .01$) during the first 5 minutes of the protocol. The differences then became non-significant in the latter minutes of the rest phase.

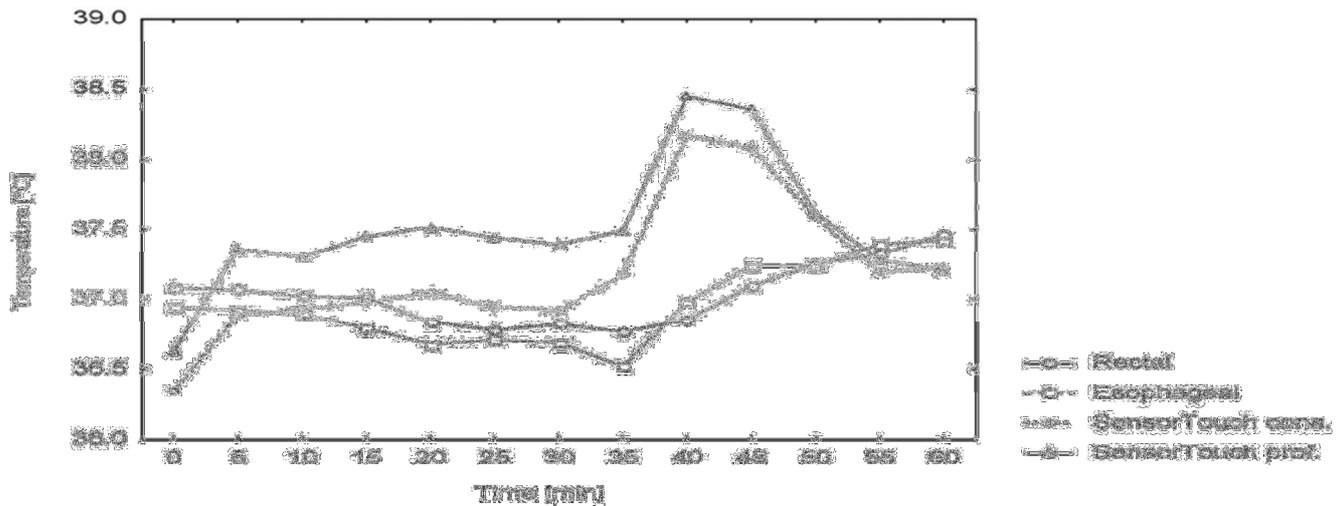


Figure 17. Average temperature response of the 12 subjects. At $t = 0$ min, the subjects entered the warm chamber (30°C), coming from the cold chamber (10°C). At $t = 30$ min, the subjects started to exercise on a bicycle, at an external load of $1 \text{ W}\cdot\text{kg}^{-1}$ (cited Kitesmaker et al., 2006, p255.)

These results, which saw subjects moving from cool to a warm environment, provides evidence of skin temperatures apparent lag time when compared to core temperature within these conditions. Soon after the start of exercise differences between devices again become significant ($P < .001$), with reference temperature rising to 37.3°C and IFR skin thermometers noting values up to 40.5°C (Figure 17). When subjects reported onset of sweating (time = 45 minutes) IFR skin temperatures decreased towards the reference values and differences disappeared. The decreasing trend in skin temperature, related to the evaporation effect of sweating, was opposite to the trend seen in the reference core values which were increasing (Kistemaker et al., 2006). The precision of data produced from the IFR skin thermometer is questioned within this research due to the significant differences seen, especially during the exercise component, which appear to be related to thermoregulatory responses to exercise. T_R has been reported as changing more slowly in comparison to IFR (ear) temperature so could add further explanation with regards to the precision of data when the former is used as a reference temperature (Stavem et al 1997).

A follow up experiment by Kistemaker et al. (2006) was completed on how different pre-exercise cooling methods related to temperature responses from different temperature devices. T_R , T_O , skin thermistors (forehead, chest, upper leg) were assessed along with IFR skin thermometer (Sensor

Touch) and IFR tympanic thermometer (Braun AG). Different pre exercise climatic related protocols were implemented being, light exercise in cold chamber (10°C), wearing a polyethylene full body suit cooled with water, or a non-cooling process was completed via subjects resting in a room (30°C). An overview of the results notes the IFR skin thermometer was accurate when compared to the reference (core) temperature under stable conditions (i.e. before exercise) though similar differences noted earlier between skin and rectal temperature were then seen when exercise commenced (time = +15 minutes) (Figure 18).

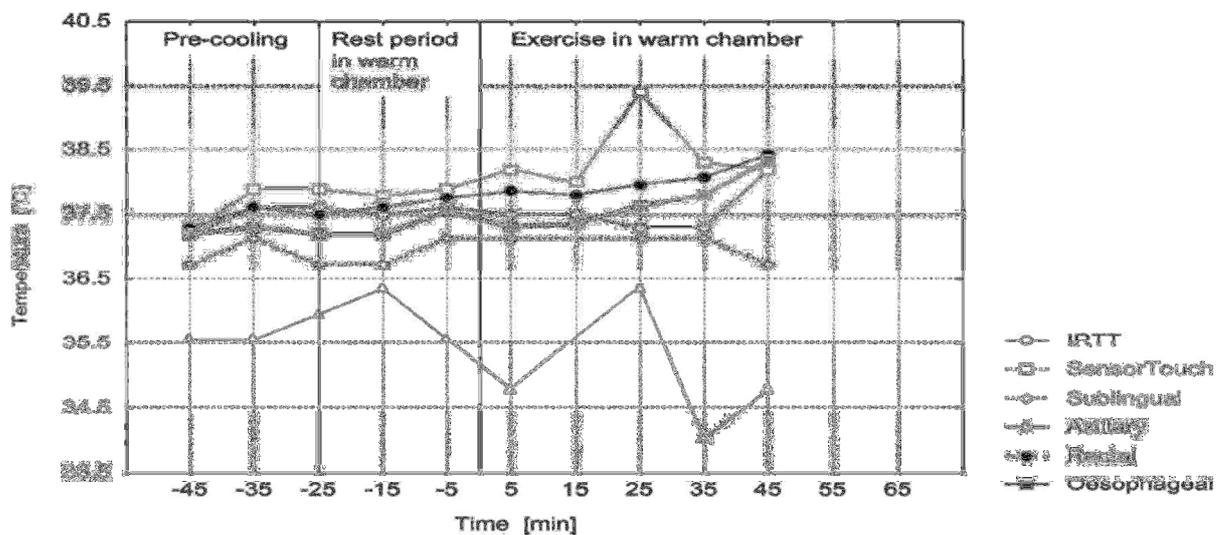


Figure 18. Rectal temperature, IRTT and Sensor Touch data at all-time points during the experiment. The points indicate the median values, the boxes indicate the 25% to 75% range and the whiskers indicate the whole range, excluding outliers (individual circles) (Cited in Kistemaker et al., 2006, p259).

Buono et al. (2007) completed accuracy assessment of skin temperature assessed at 3 sites using contact thermistors (YSI series 400) against an IFR (Extech Instruments). Using an environmental chamber three different air temperatures (15, 25 and 35°C) were created and subjects (n=6) completed a resting task (t=10mins), then walked on a treadmill at 3mph (t=15mins) and finally exited the chamber and sat in a thermo-neutral environments (25°C). In both conditions (i.e. rest and exercise) no significant differences were seen between technologies and a strong correlation was noted ($r = .95 - .98$) between resting mean skin temperature and IFR devices. Results suggest that IFR technology can accurately measure skin temperature in hot and cold environmental conditions (Buono et al., 2007).

The physiological thermoregulatory response may add to the understanding of skin thermometry and data that has been reported. Physiologically the temperature related response to exercise sees an initial vasoconstriction response in peripheral areas (i.e. skin) as working muscles demand increased blood flow. This response will reduce the skin temperature temporarily. Moving of peripheral blood, which is marginally cooler due to the environment, to central areas realises a slight decrease in core temperature before an increase occurs linked to metabolic reactions required to sustain exercise. Exercise will elicit a higher core temperature than the thermoregulatory set point so triggering a homeostatic response. As body temperature increases, blood vessels vasodilate therefore skin temperature increases and sweating will occur (Kistemaker et al., 2006, McArdle et al., 2009, Powers and Howley, 2007).

Some disadvantages have been noted linked to IFR thermometry one being the effect of the external environment. It was reported that increasing room temperature from 20 to 35°C raises ear temperature significantly (Zehner and Terndrop, 1991 cited by Stavem et al., 1997). Also, skin temperature may be susceptible to environmental changes (i.e. transition from hot to cold) which adds doubt to the devices reliability. Additionally the sweat response to exercise which also influences the stability of skin based measures (Kistemaker et al., 2006). Gant et al. (2006) presented validity criteria with regards to the systematic bias identified in thermometry data. Citing the British Standard for Clinical Thermometers, a bias of more than $\pm 0.1^{\circ}\text{C}$ between methods could be practically significant and would affect decisions made on a subject's thermal status. Incorporating this limit within the LOA model, Gant et al. (2006) go on to suggest that the "*largest difference between methods that can be expected for any individual and that biological variation is inherent in our measurements, we deemed that this statistic should not be larger than $\pm 0.3^{\circ}\text{C}$* " (p1928). With this in mind many of the IFR thermometers tested were outside of this precision parameter which adds to the caution that data from IFR thermometers should be interpreted.

2.8.6 Summary

By providing data to a body of research where it is lacking could ultimately lead to the further understanding of new technology. Multi variable monitoring devices are now becoming available for performers which allow for an in-match real time assessment to occur. The precision of each individual monitoring variable needs to be understood for informed commentary can be made on the data collected. The research reviewed identifies varying limits agreement and reproducibility of the variables when tested for precision. Evidencing other research will allow for raised awareness of the

possible sources of inaccuracy and that will assist interpreting the data collected. Extrapolating results gained from the laboratory in to the field (i.e. real life) also needs to be communicated with caution. As noted, a significant amount of reliability and validity testing has occurred within a controlled laboratory environment. Treadmill running has been identified as producing a biomechanically different style of running in comparison to running in normal “free” external conditions. The moving belt on a treadmill decreases energy required within the running stride and Nelson, Dilman, Lagasse and Bickett (1972) identified that treadmill running has lower vertical velocity and less variable vertical and horizontal velocity than overland running (cited Vanhelst et al. 2009). This has implications for extrapolation of laboratory based results to the real world and investigations into treadmill set up and further uncontrolled trials should be considered. Coaches require real life credible applied research that can be utilised for performance (Gore et al., 1993, Achten and Jeukendrup, 2003, Williams and Kendall, 2007). By completing a series of assessments on mobile monitoring technology, in controlled settings, it will be possible to assess the validity and reliability of data collected. By assessing an applied monitoring system this research project may also facilitate the link between sports science research and coaching practice and therefore the enhancement of sporting performance.

Chapter 3 - Physiological Profile of Professional Cricketers

3.0 Abstract

This study aims to provide a physiologic profile of professional cricketers and note positional differences at the start of the competitive season. Fifteen participants (9 bowlers, 6 batsmen) aged 25.0 ± 5.0 years (mean \pm SD) took part in this study. Participants (bowlers and batsmen) completed a series of field-based fitness assessments: body composition (sum of 7 skinfolds, 72.5 ± 16.5 and 65.5 ± 19.3 mm, respectively), flexibility (sit and reach 8.1 ± 10.3 and 6.0 ± 6.2 cm, respectively), predicted maximal oxygen uptake (multistage shuttle run, 54.1 ± 2.8 and 56.1 ± 4.5 mL.kg.min⁻¹, respectively), upper- (medicine ball throw, 7.7 ± 0.6 and 7.0 ± 0.1 m, respectively) and lower-body strength (countermovement jump, 45.7 ± 5.8 and 43.9 ± 4.1 cm, respectively), speed (sprint 17.7 m, 2.76 ± 0.6 and 2.77 ± 0.1 sec⁻¹, respectively), and explosive power (repeated jump, 31.0 ± 2.0 and 34.1 ± 4.8 cm, respectively). The data provided the physical fitness profile for each player, which, compared with normative data, identified that this cohort of professional cricketers had some superior fitness parameters compared with the general population, and where applicable, were comparable with other professional athletes. In addition, after effect size calculations, the results showed that some physical fitness differences existed between playing positions. Cricket professionals possess a superior level of physical fitness and strength but the lack of literature restricts exercise professionals ability to enhance these qualities. Moreover, research should move to use more ecologically valid measurements in order to identify position-specific physical requirements of the modern game.

Key words: Fitness assessment, Field based testing, Elite sports performance

3.1 Introduction

In recent years cricket has become a professional multi-million dollar sport with more than 100 countries recognised by the International Cricket Council. High profile international competitions have seen a corresponding increase in interest in the game (International Cricket Council, 2009). Varied match formats of cricket, differing specialist positions, and the eclectic environment it is often played in require players to be able to cope with a broad continuum of physiological playing intensities (Noakes and Durandt, 2000, Smith et al., 2007). With the advent of the shorter more intense formats of the game (i.e. T20 and one day cricket) the idea of cricket as a leisurely activity is perhaps disingenuous (Woolmer et al., 2008).

Cricket lacks the depth of peer reviewed literature in comparison to other sports. Though there are biomechanical (Bartlett et al., 1996, Elliott et al., 2002, Portus et al., 2000, Ranson et al., 2007) and anthropometrically (Stuelcken et al., 2007) based studies linked to bowling, there seems to be few articles reporting whole team physiological profiles. Literature has focused predominately on prevalence and avoidance of injury in cricket (Dennis et al., 2008, Pyne et al., 2006). It has been reported there is an indifferent culture towards planned physical preparation at all levels of cricket with many players inadequately physically conditioned, which has been linked to injury occurrence (Elliott, 2000, Finch et al., 1999).

A collation of research provides an embryonic view of the professional cricketer's physiological needs. Fast bowlers delivering balls $\sim 44.4 \text{ m}\cdot\text{sec}^{-1}$, requires all players to have high speed and agility facets, as well as fast reactions in the modern game (Pearson, 2004). A fast bowler could bowl 10 x 6 ball overs in a 'spell'; covering approximately 1.9 Km in 5.3 discontinuous minutes with running speeds at $\sim 1.3 \text{ m}\cdot\text{sec}^{-1}$ (Noakes and Durandt, 2000, Stretch et al., 2000). The bowler enters 60 episodes of upper and lower body actions (i.e. acceleration and deceleration) requiring a significant ability to work at high anaerobic intensities repetitively. Blood lactate concentrations in fast bowlers have been reported at a moderate $5 \text{ mmol}\cdot\text{L}^{-1}$ with heart rate peaks of fast and slow bowlers measured at between 159 and 190 $\text{beats}\cdot\text{min}^{-1}$, respectively (Duffield et al., 2009, Johnstone et al., 2008). Fast bowlers can achieve high ground reaction forces (e.g. 5 to 9 times body mass) requiring strong eccentric strength in the quadriceps and a strong core (e.g. lumbo-pelvic area) to withstand this repetitive action (Elliott, 2000, Noakes et al., 1998). Lower body strength has been suggested as a significant factor when determining delivery velocity between groups of performers (Pyne et al., 2006). Alternatively, a batsman scoring 100 runs could possibly cover approximately 3.2 Km in 8 discontinuous "active" minutes, running at $\sim 24 \text{ Km}\cdot\text{h}^{-1}$ (Bartlett, 2003, Noakes and Durandt, 2000). Multiple acceleration/deceleration episodes throughout the innings (Bartlett, 2003, Stretch et al.,

2000) lead to potential dissimilar energy system requirements to the bowler (i.e. intermittent repetitive high intensity anaerobic) with recovery time between bouts of activity being erratic due to the demands of the match. Nevertheless, withstanding these different positional requirements it appears that there is a need for trained athletes who can play cricket (Woolmer et al., 2008). Moreover, the intermittent repetitive acceleration/deceleration episodes continue when fielding where a player could cover 15 km in a day. This aspect of the game requires intermittent upper body explosive action (i.e. throwing ball over various distances) for 2–3 hour periods alongside some prolonged low-intensity activity periods (Rudkin and O'Donoghue, 2008).

For all on-field positions, especially fast bowlers, the repetitive high intensity acceleration-deceleration (i.e. eccentric muscle action) element can lead to cricket specific fatigue due to altered muscle action in players linked to the loss of elastic energy element within muscle (Morgan and Allen, 2000). From the limited data at the professional level it has been suggested that elite cricket players have recorded similar aerobic and anaerobic “fitness” levels as professional international rugby union players (Bartlett, 2003, Noakes and Durandt, 2000). In addition, like other team sports (Gabbett, 2002) literature suggests that there are different requirements between the playing positions.

Based on the previous literature review (section 2.1), it appears that extensive information is currently unavailable in professional cricket (Noakes and Durandt, 2000, Vanderford et al., 2004) and conducting sport-specific investigations that focus on clearly defining the anthropometrical and physiological fitness variables would seem novel and valuable to conditioning practitioners.

The aim of this study is to assess the anthropometrical and physiological profile of a professional cricket team and identify differences between on-field playing positions, prior to the commencement of a competitive first-class season. The hypothesis states there will be significant differences in the physiological profile of batsmen and bowlers.

3.2 Methods

3.2.1 General Design

A cross section experimental design was used to establish a fitness profile for a team of professional cricketers. A variety of physical assessment test items were selected to provide a broad ranging profile of fitness whilst in the applied setting with many tests specific to the sport, which acted as dependent variables against the playing positions that were the independent variable. Some of the assessments utilised are commonly performed and provide valid and reliable data which can be compared to normative data, see specific commentary below for further details.

3.2.2 Participants

Fifteen professional male cricketers, aged 25.0 ± 5.0 years (mean \pm SD), provided written consent to participate in the present study. All participants were members of an England and Wales Cricket Board (ECB) First Class (professional) County Cricket team. The team members have first class competition experience of 2-17 years, with 5 players in the cohort having participated at full international level. Of the fifteen participants, nine were classified as being predominately bowlers, where two were classed as slow bowlers and seven as medium/fast bowlers. Six remaining participants were classified as being predominately batsmen, including the wicketkeeper. Classifications were noted from players' statistics (Engel, 2012). For 5 months preceding the assessment (i.e. close season) 6 participants had been engaged in a periodised strength development programme, training 3 sessions per week. The remainder of the team were involved in competitive cricket overseas and were not involved in a periodised training plan. Local institutional ethical agreement was gained (Ethics No LS3/2/09) (Appendix 1) for the study and participants were informed of the experiment risks and signed informed consent documents prior to the investigation.

3.2.3 Procedures

In the 24 hours prior to physical fitness assessment participants were instructed to keep hydrated, avoid strenuous exercise and excessive caffeine ingestion. Participants were fully briefed on each assessment they were participating in and progressed through a series of anthropometrical and physiological tests as part of a pre-season assessment day (Figure 19). Once anthropometrical and body composition was complete, participants completed a 10 minute standardised warm-up which included approximately 5-7 minute light aerobic multi-directional movement and 3-5 minute controlled dynamic stretching, delivered by the team's strength and conditioning coach. To avoid the accumulation of fatigue as the testing continued there was a minimum of 10 minutes between the

end of one test and commencement of another. Additionally participants were encouraged to consume water and/or carbohydrate drinks during breaks in proceedings and tests did not commence until participants heart rate had returned to pre-test baseline values (± 10 beats.min⁻¹).

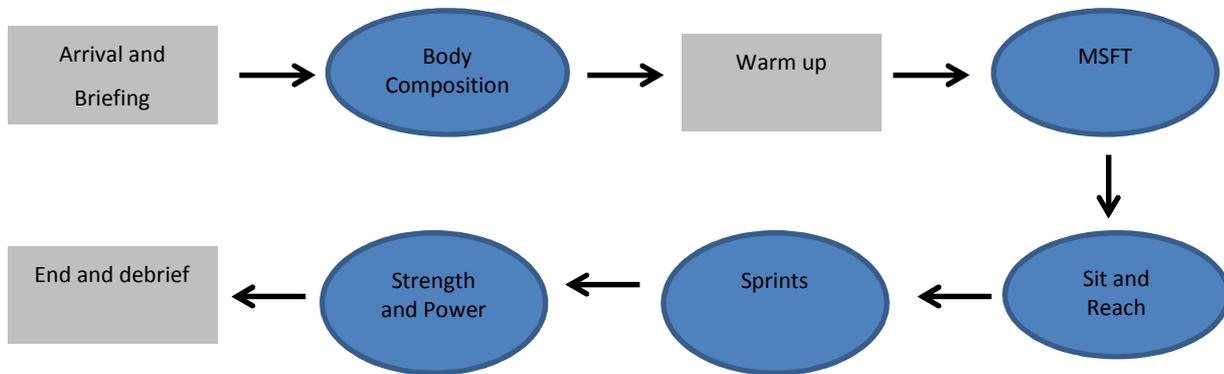


Figure 19: Schematic of testing protocol which participants progressed through

Stature was recorded during inspiration using a stadiometer (Model Seca 214, Birmingham, UK), and was measured to the nearest 0.1 cm. Body mass was determined using standard walk-on scales (Model Seca 761, Birmingham, UK) and recorded to the nearest 0.1 kg. Skinfold thickness was measured at seven sites to the nearest 0.1 mm on the participants using Harpenden callipers (British Indicators Ltd., West Sussex, UK); biceps, triceps, subscapular, supraspinale, abdominal, front of thigh and medial calf. One experienced investigator collected all anthropometrical and body composition data following recommended set protocols as documented elsewhere (Norton et al., 1996). This seven site protocol was adopted due to national governing body restrictions which standardise body composition procedures across all clubs to enhance the comparison of data (Smith et al., 2007).

A multi-stage fitness test (MSFT; CD version, Coachwise UK) was completed to gain a predictive assessment for maximal aerobic capacity ($\dot{V}O_2$ max). This field based predictor of $\dot{V}O_2$ max is a valid procedure permitting multiple participants to be tested at the same time and also replicates movement patterns within a field based sport (Ramsbottom et al., 1988). Other field based tests considered were 5 km run and the Cooper 12-minute run tests (Powers and Howley, 2007) but players were familiar with the MSFT and therefore data comparisons could be made. Moreover, it would have been unrealistic to complete individual treadmill based tests due to time and financial constraints. Therefore, following a standard protocol (Ledger et al., 1988), participants were required to make each 20 m shuttle in time with the audible “beep”. Two warnings were given to participants if they failed to make the 20 m shuttle in time, with the 3rd failure seeing the participant removed

from the test. The last successfully completed shuttle was noted. Predicted $\dot{V}O_2$ max was calculated from the shuttles completed (Ramsbottom et al., 1988). Participants' end heart rate was collected (RS100, Polar, Finland) by researchers immediately on individual withdrawal from the test, in $\text{beats}\cdot\text{min}^{-1}$.

Flexibility measures were taken by a trained assessor. Lower back and hamstring assessment was assessed using a 'Sit and Reach' box (Cranlea, Birmingham, UK) following a recommended set protocol (Phillips, 2007). Participants removed shoes, reached forward on expiration, pushed the measuring device to its furthest point, while keeping knees extended in this process. Each participant was allowed 3 attempts with the highest score past the toe line recorded, to the nearest 0.1 cm.

Speed was assessed using adapted sprint tests protocols (Smith et al., 2007); the 'Sprint 1' and 'Sprint 3' tests. 'Sprint 1' requires participants to maximally sprint a 17.68 m distance, which is equivalent to running between batting creases at opposing ends of the full cricket wicket (22.56 m). Alternatively, 'Sprint 3' requires participants to perform three repeated maximal sprint trials between the same markers. Both tests were completed whilst the participant was carrying a standard size willow cricket bat (0.97 m x 0.11 m), weighing ~1.3 kg (Engel, 2007). Participants were required to ensure a section of the bat crossed the batting crease at each end of the sprint and used cricket specific turning techniques to minimise turning time. Time was recorded to the nearest 0.01 sec^{-1} using the Smart Speed Timing Gate System (SSTGS; Fusion Sport, Australia). McDougal et al. (1991) identified that this is a cricket specific sprint test reported CVs of 1.2% for single sprint and 0.8% for Sprint 3 (Cited in Smith et al. 2007). This process was chosen under national governing body guidance over other standard speed tests to provide an output which provides the coach with sport-specific data to analyse.

Upper body strength and power was obtained using a medicine ball throw and timed press-up tests. The medicine ball test involved participants performing a reverse over-head throw of a 5 kg ball. A tape measure was placed at the heel of the participant's feet (0 m), and the participant was instructed to perform a maximal reverse over-head throw without moving the feet (no jumping/foot shuffle). After a single habituation trial, each participant had three attempts with the best score recorded to the nearest 0.1 m. The press-up test was completed by all participants, using a standardised protocol, where participants were instructed to perform the maximum total number of press-ups they can do in a 1 minute period, without any breaks. A press-up was only counted if the participant's elbows broke movement through a 90° angle, subjectively assessed by an investigator. Both protocols were based upon previously recommended techniques (American College of Sports Medicine, 2000, Powers and Howley, 2007). Conversely, lower body strength and power was

obtained using vertical jump testing, utilising the SSTGS. Participants performed two forms of assessment; counter-movement jump and repeated jumps. From these tests measures of jump height (m), contact time (m.sec⁻¹), and subsequent reactive strength index (RSI) were obtained, as documented previously (Lloyd et al., 2008), following recommended protocols (Oliver et al., 2008). RSI gives an indication of jump height obtained relative to ground contact time, as a lower body power measure.

3.2.4 Data Analysis

A cross sectional design was employed to assess the anthropometrical and physiological characteristics of professional male cricket players. All the descriptive results for this study are presented as mean \pm one standard deviation (mean \pm SD) and 95 % confidence intervals (95 % C.I). Magnitude of differences between the batsmen and bowlers were interpreted using Cohen's Effect Size (ES), as described in previous literature (Hopkins, 2008, Pyne et al., 2006). Qualitative terms were assigned to ES thresholds: .2 – .6 Small; .6 – 1.2 Moderate; 1.2 – 2.0 Large; > 2.0 Very Large (Field and Miles, 2010, Hopkins et al., 2009).

3.3 Results

From the data (Table 2) it seems that the variance of stature, body mass, body mass index, and sum of skinfolds is small. The bowlers appear taller and have a greater body mass than the batsman, indicated by the moderate ES in both cases, but there is only a small difference in actual body composition, inferred from the skinfold data.

The physiological testing data (Table 3) highlights some variances between physical fitness attributes for the professional bowlers and batsmen. There is a low variance in the results for the field-based aerobic fitness assessment throughout the team, though batsmen do have a moderately greater (3.7 %) predicted $\dot{V}O_2$ max value than the bowlers. The sit and reach test indicates that there is a variance in lower lumbar and hamstring flexibility throughout the team, with the bowlers having a greater indicated capacity than the batsman, although this was only a small difference. Running speed in the team for both the 'Sprint 1' and 'Sprint 3' tests is similar; however the bowlers achieved moderately better results than the batsmen whilst performing the maximal repeated sprints (1.5 %). There are large differences in the upper body strength and power tests, with the batsman completing the 'press-up' test better than the bowlers (47 %), whereas conversely the bowlers produced greater reverse throws compared to their respective team-mates (10 %). In relation to lower body strength and power, though similar results in the counter-movement jump was observed, the batsman showed greater reactive strength index (RSI) during the repeated jumps compared to the bowlers as an indication of lower body power (10 % and 19 %, respectively).

Table 2. Anthropometrical and body composition measures for professional cricketers.

	Team		Bowlers		Batsmen		Effect Size	
	M ± SD	95% CI	M ± SD	95% C.I	M ± SD	95% CI	ES	
Age (yrs)	25.0 ± 5.0	22.5-27.5	24.3 ± 4.7	21.2-27.5	26.0 ± 5.6	21.5-30.5	0.3	Small
Stature (m)	1.83 ± 0.06	1.80-1.87	1.85 ± 0.07	1.81-1.90	1.81 ± 0.05	1.77-1.84	0.7	Moderate
Body mass (kg)	81.1 ± 9.1	76.5-85.7	83.5 ± 10.1	76.9-90.1	77.5 ± 6.3	72.5-82.5	0.6	Moderate
Body mass index (kg.m ⁻²)	24.1 ± 0.9	23.1-25.1	24.2 ± 1.9	23.0-25.6	23.8 ± 2.0	22.0-25.6	0.2	Small
Sum 7 skinfold (mm)	69.7 ± 17.4	60.9-78.5	72.5 ± 16.5	61.7-83.3	65.5 ± 19.3	50.0-80.9	0.4	Small

Tabular report: M ± SD = mean and standard deviation, 95% CI = 95 % Confidence interval, ES = Effect Size

Table 3. Aerobic fitness, flexibility and speed measures for professional cricketers.

	Team		Bowlers		Batsmen		Effect Size	
	M ± SD	95% CI	M ± SD	95% C.I	M ± SD	95% CI	ES	
Aerobic fitness - Multi-stage fitness test								
Completed shuttles	12.4 ± 0.9	11.9-12.8	12.2 ± 0.8	11.6-12.8	12.6 ± 0.9	11.8-13.3	-	-
End heart rate (beats.min ⁻¹)	190.4 ± 11.2	1.85-1.96	192 ± 8.7	1.86-1.98	187.8 ± 15.1	1.76-2.00	-	-
Predicted $\dot{V}O_2$ max (mL.kg ⁻¹ .min ⁻¹)	54.9 ± 3.7	53.1-56.8	54.1 ± 2.8 ^a	52.0-56.0	56.1 ± 4.5	52.5-59.7	0.5	Moderate
Flexibility - Sit and Reach								
Post-toe line (cm)	7.0 ± 8.7	2.9-11.7	8.1 ± 10.3	1.4-14.9	6.0 ± 6.2	1.0-11.0	0.1	Small
Speed								
Sprint 1 (sec ⁻¹)	2.77 ± 0.1	2.73-2.81	2.76 ± 0.6	2.72-2.81	2.77 ± 0.1	2.69-2.85	0.1	Small
Sprint 3 (sec ⁻¹)	9.68 ± 0.2	9.55-9.80	9.62 ± 0.2	9.50-9.76	9.76 ± 0.3	9.51-10.0	0.5	Moderate

Strength and power

Medicine ball throw (m)	7.5 ± 0.6	7.14-7.79	7.7 ± 0.6	7.3-8.2	7.0 ± 0.1	6.9-7.1	1.3	Large
Press-up test (reps.min ⁻¹)	63.9 ± 15.8	55.9-71.9	54.7 ± 8.9	49.0-60.6	80.4 ± 11.2 ^b	70.6-90.2	2.4	Large
CMJ - best jump height (cm)	45 ± 5.1	42.4-47.6	45.7 ± 5.8	41.9-49.5	43.9 ± 4.1	40.7-47.2	0.2	Small
RJ - best jump height (cm)	32.2 ± 3.6	30.4-34.1	31 ± 2.0	29.7-32.4	34.1 ± 4.8	30.2-37.9	0.8	Moderate
RJ - best RSI	1.7 ± 0.4	1.6-1.9	1.6 ± 0.2	1.5-1.8	1.9 ± 0.5	1.5-2.3	0.9	Moderate

Tabular report: Mean ± SD = mean and standard deviation, 95% CI = 95 % Confidence interval; CMJ = Counter movement jump; RJ = Repeated jump; RSI = Reactive strength index, ES = Effect Size ^a Only 8 bowlers completed test due to injury; ^b Only 5 batsmen completed test due to injury

3.4 Discussion

There is a lack of peer-reviewed information linked to the physiological profile of professional cricket players and possible differences that may exist between on-field playing positions. This study is unique in highlighting the physiological characteristics in the modern era of the game. Moreover, it identified that there were differences in the physiological profile of batsmen and bowlers, accepting the experimental hypothesis. Providing reliable data to a body of research where it is lacking could ultimately lead to the examination and development of optimum conditioning and training regimes to enhance athletic prediction and performance, in line with other sports or position-specific demands, and may help minimise predisposition to injury.

It is evident from match analysis literature that there are physiological similarities between cricket and other sports as mentioned previously but there are specific demands for this actual sport, and associated playing positions, that must be considered by conditioning practitioners in order to optimise performance (Vanderford et al., 2004). In agreement with previous literature, bowlers assessed in this cohort were heavier and taller than the batsmen (Stuelcken et al., 2007). While it is suggested that size is not necessarily advantageous for batting it has been noted that a tall stature could be perceived as a positive variable for bowlers, in terms of delivery release angle and force production (Glazier et al., 2000, Norton et al., 1996, Pyne et al., 2006, Stuelcken et al., 2007). Similarly, like other recent studies (Pyne et al., 2006, Stuelcken et al., 2007) it seems that the seven fast bowlers within the present sample support anecdotal evidence of the modern game (i.e. last 15 years) linked with the possible benefit of increased stature for bowlers, as 80 % of leading elite test match bowlers, as categorised by number of wickets taken, are over 1.83 m in stature (Cricinfo, 2008, Engel, 2007). Such information is not applicable to conditioning coaches, but certainly supports talent identification criteria.

Previous research has identified a range of total skinfolds in elite male cricketers as 32.1–85.8 mm (Smith et al., 2007), and all the participants within this study fall within this range. Mean skinfolds are 10 mm less within a previous article (Stuelcken et al., 2007) though perhaps this can be associated to the participants being players from Australia rather than England as in the present study. Previously it has been suggested that cultural activities associated with elite sport, and its wider association with training and conditioning, are different depending on the country, and this finding could reaffirm this concept (Oakley and Green, 2001). Though there were small differences in absolute figures of total skinfold count and BMI values between the batsmen and bowling group demonstrated, it is partly evident that slow bowlers possess different body composition characteristics, linked with less athletic demands to perform at the professional level due to the

increased reliance on skill or technique rather than physical conditioning, which warrants further investigation to confirm.

A further basic characteristic observation from the present study to previous literature is the similar mean ages of the participants. It could be hypothesised that the physical stresses and associated injuries linked to the demands of professional bowling require a younger physique or that the fast bowling position has a limited career span due to injury in later years. Fast bowlers suffer the highest rate of injury in comparison to other playing positions (Elliott, 2000, Finch et al., 1999). Historical analysis of playing statistics possibly supports the notion of a limited or intermittent career span for fast bowlers. Within a compiled list of 10 performers who are ranked on the most consecutive appearances made, only one fast bowler is noted within OD Internationals and none at the 5-day/MD Test match level, both of which is dominated by batsman (Engel, 2007). Fast bowlers are seen as a key match winning position in cricket and further research in to the specific attributes and longevity of this bowler should be investigated (Woolmer et al., 2008). Similarly, through further investigation of the age of the players identifies a range of 19 years (17 – 36 years) across the team with the eldest player being a batsman. This is a unique element within this particular sport at the professional level, few other sports which require significant intermittent physical effort would have such a broad range of ages. Specialist batsman can continue to perform at the elite level in to their mid-thirties which is perhaps due to less physically intense elements of their respective position.

When focusing upon physiological conditioning, the mean results (Table 3) for predicted maximal oxygen uptake for the present sample of professional crickets indicates that these individuals have a “superior” level of aerobic fitness in comparison to the wider general population (McArdle et al., 2009). Such findings are similar to Smith et al. (2007), and since end-heart rate acted as proxy demonstration of players working at or near maximal, these findings can be seen to be valid. Cricket has a “moderate aerobic endurance” component in relation to these results, which may relate to the movement patterns of the game, as match analysis indicates that fielders move ~15.5 km in a day, though over 77 % of this distance is at walking pace (Rudkin and O'Donoghue, 2008). To provide perspective with other elite level sports it can be seen that elite professionals possess $\dot{V}O_2$ max levels ranging between 50.8-62.5 mL.kg.min⁻¹ in rugby union (Duthie et al., 2003), 36.0–64.6 mL.kg⁻¹.min⁻¹ in basketball (Harley and Doust, 1997) and 48-56 mL.kg.min⁻¹ in baseball and softball (Astrand et al., 2003, Wilmore and Costill, 2005). With the specific physiological and positional requirements of other sports comparisons between studies are sometimes not beneficial due to the specific requisites. In addition, intra-analysis identified that predicted aerobic endurance between the playing positions highlighted a moderate ES between bowlers and batsmen, with bowlers being

aerobically 'fitter', with possible causality being associated with the increase repetitive nature of bowling deliveries in comparison to batting.

As highlighted, cricket has episodes of high intensity sprint activity and this is a key characteristic of the game (Noakes and Durandt, 2000, Rudkin and O'Donoghue, 2008). Sprint distances between 20-70 m have been suggested, with the lesser distance being the most common (Pearson, 2004, Stretch et al., 2000, Woolmer et al., 2008). But, more recently, movement analysis while fielding suggests that high intensity activity occurs in less than 2 % of the total game time and each episode may last under 2 s (Rudkin and O'Donoghue, 2008). Analysis of batting activity identifies repetitive high and low intensity activity at ratios of 1:47 and 1:67, in shorter (i.e. one day) and longer (i.e. 5 day test matches), respectively. During this study, participants 'Sprint 1' mean times closely correspond to figures highlighted by Smith et al. (2007). Intra-analysis identified differences in absolute times between the specific positions, with the bowlers faster on 'Sprint 1' and 'Sprint 3', though ES magnitude between batsmen and bowlers was considered small. It could have been hypothesised that batsmen should have had a faster 'Sprint 3' time than bowlers due their positional specialism and the batting specific technical agility turning component of the test. Inconclusive results of the sprint times could be related to all players having batted throughout their respective careers, and so the turning component may be a well learned technical component. Additionally, commonality of short distance sprinting is probably linked to the ubiquitous fielding role players have, and with bowlers frequently having to complete repeated sprints during delivery spells. Direct comparison of sprint results to other sports is difficult due to the unique distances used in the cricket fitness assessment, but basketball and rugby league players mean times to cover 20 m were noted at 3.12 sec⁻¹ (Harley and Doust, 1997), 3.1 and 2.9 sec⁻¹ for a forward and back, respectively (Gabbett, 2002) suggesting similar performance levels.

Strength and power tests provided somewhat ambiguous results between the two playing positions. Research has demonstrated that upper body strength correlates to higher bowling velocity (Portus et al., 2000, Pyne et al., 2006). Bowlers demonstrated higher performance in the maximal medicine ball throw whereas the batsmen had higher mean totals in the muscular endurance press up task. Both these results were supported by strong ES. One repetition maximal medicine ball throw may be more aligned to the bowler's physiological requirements, due to the playing conditions in which bowlers would bowl one delivery (i.e. upper body maximal contraction) with approximately 30 second intervals (Christie et al., 2007) which mirrors this test. The immediate repetitive endurance movement pattern of the press up, rather than it being more aligned to physiological status of the batsmen, may actually be more foreign to the bowling participants. Both batsmen and bowlers were

rated as “excellent” in this assessment though comparison to other sports are limited due to varying protocols and availability of data on this activity (McArdle et al., 2005, Wilmore and Costill, 2005).

A variety of jumps were performed by the participants. It is suggested that tests such a counter movement jump (CMJ) will give an indication of slow ($> 0.025 \text{ sec}^{-1}$) stretch shortening cycle performance (Cronin and Hansen, 2005). The mean team CMJ height (Table 3) was comparable to figures seen within rugby players and basketball, 45-55 cm and 47 cm, respectively (Duthie et al., 2003, Harley and Doust, 1997). Although negligible differences in lower body power were recorded between the two playing groups, the bowlers jumped higher in absolute terms in the CMJ (small ES), which supports the findings of Pyne et al. (2006), who identified that best predictors of fast bowling velocity in juniors and seniors were seen by CMJ performance. However, batsmen performed better during the 5 repeated jumps (moderate ES), which again correlates with the better performance of repeated strength/power endurance related activities within the upper body. Nevertheless, with small sample numbers further large group analysis is required for any conclusions to be inferred.

Additionally, the sit and reach test indicates that there is a high variance in lower lumbar and hamstring flexibility throughout the team, with the bowlers having a greater indicated capacity than the batsman, although this was only a small difference. Greater flexibility in this specific area could be needed within the bowling group due to the technical movements that occur during the bowling delivery process. Cross sport comparison is affected by methodological issues associated with the test and so results may only be useful for intra-group comparison (Phillips, 2007). Apart from injury related papers (Dennis et al., 2008) there seems to be limited information linked to flexibility in cricket players and performance.

As with any applied investigation there are some clear inherent limitations of the present study, fundamentally related to the field nature of the tests and restricted sample in the respective cohort, which restricts further analysis and inference. For example, Duthie et al. (2003) reports that field tests, such as repetitive press ups, can lack reliability and validity unless strict adherence to protocols is ensured. Similar, perhaps development of the testing protocols is needed in relation to recent research on movement patterns in the game, with more measures of first step quickness ($>5 \text{ m}$) through to maximum speed as these high intensity movements could be related to crucial episodes in the match (Cronin and Hansen, 2005). For example, future assessment cricket specific speed should consider assessing the shorter distances (i.e. 5 m, 10 m, 15 m) as this may be the match specific distances associated with higher levels of and match winning fielding performance. Nonetheless, the present study does provide novel information linked to the physiological profile of professional cricket players, using relatively accurate and reproducible methods, which was the

objective. Likewise, previous authors have reported relatively accurate and reproducible data produced from all of the methods elsewhere within specific studies and supportive literature review text (Ledger et al., 1988, Wells and Dillon, 1952).

3.5 Conclusions

There is limited and incomplete peer reviewed information on the anthropometrical and physiological profile of professional cricketers. As the different formats of the game develop more position specific specialist players will be required. The selection of specialist performers could partly be based on their physiological attributes. Strength and conditioning specialists will require clear applied, reliable and valid data on players to develop enhanced bespoke programmes which will allow for improvements in performance. This embryonic profile data suggests that strength and conditioning coaches should, after completion of general training program, focus on developing lower body speed (explosive and repetitive) and anaerobic upper body power within players. These initial findings could be utilised within junior or developing players training to allow for a smooth physiological transition in to the professional arena. Significant differences between playing positions may develop further as cricket further engages within strength and conditioning practices, and therefore with the identification of specific positional requirements provides practitioners with increased customised training programme designs. Robust profiles of players will also assist in talent identification of emerging players.

The current data collected, although informative for the coach, does not provide an applied view of performance. Fitness screenings of players may not always provide links to actual performance during competition. It is clear that long term research should look to engage and use mobile monitoring technology as this may provide a better understanding of the physiological responses of players' in a match situation. This in-match assessment could, in turn, present new performance indicators on players and allow technical coaches to potentially make tactical decisions based on real match data being streamed from a wireless monitoring device. Also strength and conditioning specialists could access previously unseen in-match data which could help to optimise 'cricket-specific' conditioning programmes which may ultimately raise playing standards to even higher levels.

If new mobile monitoring technology is adopted by the coach and sports science support staff it is essential that the methods used to obtain such physiological data are as accurate, reproducible, and as ecologically valid as possible. Having a comprehensive understanding of a mobile physiological

monitoring device is vital if data is then to be utilised to improve players' performance. Therefore the next phase in the process is to identify a potential unobtrusive mobile monitoring device and assess its precision and reproducibility of data within controlled laboratory conditions. This reliability and validity research phase will allow the exercise specialist to fully understand and assess the data which is produced and therefore make sound judgements about its applicability to sporting performance.

Chapter 4 - Validity of the Bioharness™ Monitoring System

4.0 Abstract

The Bioharness™ monitoring system may provide physiological information on human performance but there is limited information on its validity. The objective of this study was to assess the validity of all 5 Bioharness™ variables using a laboratory based treadmill protocol. 22 healthy males participated. Heart rate (HR), Breathing Frequency (BF) and Accelerometry (ACC) precision were assessed during a discontinuous incremental (0 -12 km.h⁻¹) treadmill protocol. Infra-red skin temperature (ST) was assessed during a 45 min⁻¹ sub-maximal cycle ergometer test, completed twice, with environmental temperature controlled at 20 ± 0.1 °C and 30 ± 0.1 °C. Posture (P) was assessed using a tilt table moved through 160°. Adopted precision of measurement devices were; HR:Polar T31 (Polar Electro), BF:Spirometer (Cortex Metalyser), ACC:Oxygen expenditure (Cortex Metalyser), ST:Skin thermistors (Grant Instruments), P:Goniometer (Leighton Flexometer). Strong relationships ($r = .89$ to $.99$, $P < .01$) were reported for HR, BF, ACC and P. Limits of agreement identified differences in HR (-3.05 ± 32.20 beat.min⁻¹), BF (-3.46 ± 43.70 br.min⁻¹) and P ($0.20 \pm 2.62^\circ$). ST established a moderate relationship (-0.61 ± 1.98 °C; $r = .76$, $P < .01$). Higher velocities on the treadmill decreased the precision of measurement, especially HR and BF. Global results suggest that the Bioharness™ is a valid multivariable monitoring device within the laboratory environment.

Key words: Physiological technology, Precision of measurement, Exercise

4.1 Introduction

After completing a physiological profile of professional cricketers it is clear, through the use of mobile monitoring technology, there is potentially scope to present more applied data for the coach in order to enhance players' performance. Accessing performance data from players during competitive matches would require a robust monitoring device which would not compromise players' performance. Wider research highlights progress with mobile monitoring technology has assisted with the improvement of the collection of physiologically related data across a wide variety of free living situations. From everyday physical activity scenarios through to sporting performance, mobile monitoring technology now allows high-quality data to be recorded in increasingly ecologically valid situations (Achten and Jeukendrup, 2003, Brage et al., 2005, Grossman et al., 2010, Jobson et al., 2009).

Technology such as the Bioharness™ (Zephyr Technology Ltd, MD, USA) can simultaneously measure 5 physiological and activity related variables which can be monitored in real time, wirelessly, or downloaded from the device after the activity. Previous research supports the validity of each individual variable which is integrated in to the latter device; Heart rate (HR) through chest mounted electrodes (Leger and Thivierge, 1988, Macfarlane et al., 1989, Terbizan et al., 2002), Breathing Frequency (BF) through respiratory inductive plethysmography (Grossman et al., 2010, McCool et al., 2002, Witt et al., 2006), Skin Temperature (ST) using infra-red technology (Burnham et al., 2006, Hershler et al., 1992, Matsukawa et al., 2000), Tri axial Accelerometry (ACC) (Powell and Rowlands, 2004, Rowlands et al., 2004) and Posture (P) (i.e. inclinometry) (Hansson et al., 2006, Hansson et al., 2001) using a piezoelectric element. However, there is limited evidence linked to the precision of measurement for multi-variable monitoring devices. Devices such as the Bioharness™, are being used within a variety of applied situations including physical activity monitoring and also within the emergency professions. Measurements made by mobile monitoring technology in any environment must have known precision and clarity as to what variability may exist (Atkinson and Nevill, 1998, Welk et al., 2004). The consistent agreement between the true (i.e. Criterion) and measured (i.e. Predictor) variable is the underlying principle of validity (Brunton et al., 2000, Currell and Jeukendrup, 2008). Any mobile monitoring technology which allows for data to be collected in free living situations must be rigorously assessed using controlled methodologies in order for precision of measurement to be known (Thomas et al., 2005, Welk, 2005). Therefore, the aim of this study is to assess the validity of each variable measured by the Bioharness™ in relation to credible criterion measures within a physically active laboratory situation. It is hypothesised that each variable within

the Bioharness™ device will meet appropriate levels of agreement after validity statistics have been applied to the data set.

4.2 Methods

4.2.1 General design

To assess the Bioharness™, appropriate respective criterion measures and protocols were identified. In all testing scenarios data from the adopted criterion and the Bioharness™ used one synchronized timeline linked to a laptop computer. A treadmill protocol assessed ACC, HR and BF with the latter two variables being analysed at specific velocities. ST, assessed during a cycle ergometry test, carried out in both hot and thermo-neutral conditions. P was validated using a tilt table protocol. Due to the experimental design it was only possible to analyse ACC and P as whole data sets.

4.2.2 Apparatus

Overview of the Bioharness™ monitoring device. The Bioharness™ is worn against the skin by the participant via an elasticated strap attached around the chest (50 g, 50 mm width). The monitoring device (weight 35 g, 80x40x15 mm), which attaches to the front of the chest strap, acts a data logger or transmitter, and has a memory of up to 480 hours and battery life of up to 10 hours in logging mode. Five variables are measured simultaneously, time stamped and exportable to Excel. HR data is captured through electrode sensors housed within the chest strap (i.e. detecting R wave forms) sampled at 250 Hz and reported as beats per minute (beat.min⁻¹). BF is provided using a capacitive pressure sensor (18 Hz) that detects circumference expansion and contraction of the torso producing an output as breaths per minute (br.min⁻¹). Tri axial ACC, using piezoelectric technology (i.e. cantilever beam set up) samples at 18 Hz and reports in counts per second (ct.sec⁻¹; 1 Hz). It is a micro electro-mechanical sensor accelerometer with a capacitive measurement scheme and is sensitive along 3 orthogonal axes (vertical (x), sagittal (z) and lateral (y)) (Figure 20). Acceleration data is measured in gravitational force (g) in a range of -3 to +3 g on each single axis or as Vector Magnitude Units (VMU) which is an integrated value over the previous 1 second epoch, calculated using the following equation:

$$VMU = \sqrt{A_x^2 + A_y^2 + A_z^2}$$

Equation 3. Calculation used for producing Bioharness™ VMU data (Zephyr Technology, 2012).

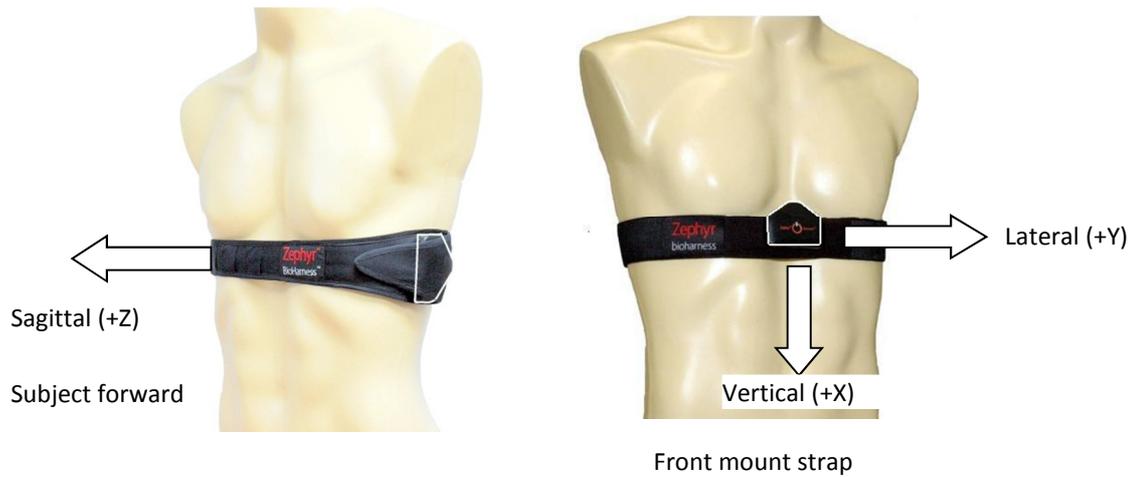


Figure 20. Individual axes of accelerometer within the Bioharness™ (Zephyr Technology, 2012).

The P variable uses similar piezoelectric technology as described. Acting as an inclinometer, data is reported in angular degrees ($^{\circ}$), ranges between -90° and $+90^{\circ}$, monitoring how far the device is “off the vertical”. ST data is collected through an infrared sensitive sensor behind a clear window on the apex of the monitoring device. It records peripheral skin temperature at the inferior sternum. This sensor reports data in degrees Celsius ($^{\circ}\text{C}$).

4.2.3 Participants

After securing local institutional ethical agreement (Ethics No LS3/11/09) (Appendix 1) 22 male volunteers (Mean \pm SD; age 21.5 ± 2.8 yrs, body mass 71.4 ± 7.9 kg, body stature 1.79 ± 0.1 m) who were physically active, injury free and familiar with using a treadmill and/or cycle ergometer consented to participate. Participants were asked to refrain from consuming alcohol and caffeine, keep hydrated and rested 24 hours prior to testing. On arrival to the laboratory anthropometrical measures (Stewart and Eston, 2007) were taken with stature (Seca 214, Birmingham, UK) and body mass (Seca 761, Birmingham, UK) measured.

4.2.4 Procedures

Precision of Bioharness™; Heart rate (HR), Breathing Frequency (BF) and Accelerometry (ACC)

Using one standard Bioharness™ device, which was concurrently compared with adopted criterion measures, precision of the HR, BF and ACC were assessed by participants (n=12) completing an adapted discontinuous incremental treadmill protocol (Rowlands et al., 2004). Adopted criterion measures within this procedure were the Polar T31 (Polar Electro, Kempele, Finland) for HR. This was chosen after use of a wired 5 lead ECG led to signal interference occurring during running on the treadmill. The Polar HRM has been noted as the world leader in its class and has been repeatedly validated in peer reviewed papers (Goodie et al., 2000, Laukkanen and Virtanen, 1998). Moreover, the Polar T31 presented excellent correlations ($r = .98, P < .01$) with a 3-lead ECG (Biopac student lab) when tested during a cycle ergometer task within our laboratories. For BF, a face mask (Hans Rudolf Inc, USA) was worn by participants in order to connect a Tripple-V spirometer which was attached to a metalyser (version 3B; Cortex Medical, Germany). Oxygen (O₂) expenditure was assessed for ACC also using the aforementioned metalyser, which have been reported as valid and reliable (de Groot et al., MedbÃ, et al., 2002). Moreover, metalysers were calibrated prior to each testing occurrence according to the manufacturers specifications. The criterion, O₂ expenditure, is considered an indirect measure of ACC so additionally a count of steps taken during each active stage was made for each participant which acts as a raw assessment of activity. The right foot, observed by two data collectors, was counted each time it was placed on to the treadmill during a walking/running stride and the mean of the counts was used to relate to ACC. In a thermo-neutral environment (24.1 ± 1.9 °C) the protocol consisted of 6 discontinuous incremental stages (adapted from Rowlands et al. 2004): rest (0 km.h⁻¹), walking (4 and 6 km.h⁻¹); and running (8, 10 and 12 km.h⁻¹) performed on an electronically driven treadmill (HP Cosmos Mercury, Germany). Stages lasted a total of 8 minutes; 2 minutes rest, 4 minutes being active (i.e. walking or running) followed by 2 minutes recovery. The active stages allowed sufficient time for the participants to achieve steady-state activity therefore assessing the Bioharness™ device ability to collect data at different constant velocities. Data was collected every 5 seconds for the last 90 seconds of each of the respective active stages. Participants were fitted with all the respective equipment (Figure 21) 15 minutes prior to the test commencing and remained on the treadmill throughout.

4.2.5 Infra-red skin temperature (ST)

Infra-red ST variable was assessed during an adapted version of a continuous submaximal cycle ergometer trial. Participants (n=10) cycled (Monarch Ergomedic, Model 824E, Varberg, Sweden) at 60 rpm⁻¹ in a University environmental chamber for 45 minutes against a resistance equivalent to 4% of body mass on two separate occasions, one week apart, in a randomised cross-over design. On one occasion the ambient temperature was set to 20 ± 0.1 °C, on the other occasion set at 30 ± 0.1 °C. The use of skin thermistors is well established in the literature therefore was adopted as the criterion measure (Garrett and Griffiths, 2001, Schlader et al., 2011). A Bioharness™ device and the criterion measure, a separate skin thermistor (Type EUS-U-V5-V2; Grant Instruments, Cambridge, England), was secured on lower pectoral using medical grade tape (Hypafix, BSN Medical GmbH, Hamburg, Germany). Ambient temperature, thermistor temperature and Bioharness™ infra-red temperature were recorded at 1 minute intervals throughout the procedure (Figure 21).

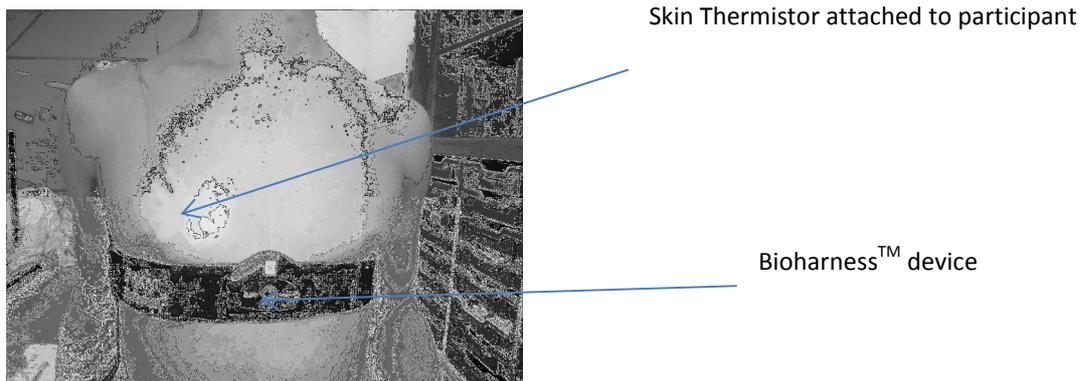


Figure 21. Picture of the Bioharness™ as worn by a subject participating in the testing process with skin thermistor attached.

4.2.6 Posture (P) (Inclinometer)

This variable was assessed using reference data derived from a credible goniometry device (Daneshmandi et al., 2010), the Leighton Flexometer (Spokane, WA, USA). In a controlled procedure, both devices were secured to an inversion (i.e. tilt) table (F500III, STL International) which was moved through 160° as noted elsewhere (Bernmark and Wiktorin, 2002). The flexometer was calibrated (to 0°) using a spirit level and then moved through 160° (+80 to -80) at 10° intervals, pausing for 10 seconds, at each interval allowing data to be recorded.

4.2.7 Data Analysis

Data was exported to statistical software packages (Excel Microsoft Windows, USA; SPSS v17, SPSS Inc, Chicago, USA) for analysis. Concurrent validity for all variables were analysed against their respective criterion measures, identifying means and standard deviations ($M \pm SD$) for the data. To fully understand the data generated a range of precision of measurement statistics in combination with descriptive data has been previously reported (Bland and Altman, 1986, Brunton et al., 2000, Hopkins, 2000a, Hopkins et al., 2009).

Characteristics of the data set were considered and appropriate statistical procedures were followed thereafter. After plotting the predicted against the residuals for HR, BF, ST and P (Figure 22), data was considered to be non-uniform (i.e. heteroscedastic) so was transformed logarithmically (log) in order to provide a true interpretation (Atkinson and Nevill, 1998, Hopkins, 2000a, Hopkins et al., 2009). It was decided that descriptive data for these variables would be reported in absolute values and validity statistics presented log transformed. The combined data presentation approach was determined in order for comparison with other studies to occur, the majority of which report absolute data.

Adopting a composite of validity statistics may provide a more informed view to assess agreement between methods (Harper-Smith et al., 2010). The following statistical analysis was calculated for each variable; Descriptive statistics including absolute mean bias and 95% Confidence Intervals (CI), Validity statistics (log transformed) including mean bias, 95% Limits of Agreement (LoA), Pearson's Product Moment Correlation Coefficient (PCC), Coefficient of Determination (CoD) as described in previous literature (Hopkins, 2000a).

Within the descriptive statistics, the mean bias and associated 95% CI provides an indication of raw difference between the data sets. Correlation coefficients, such as PCC (r), provide a good indication of the relationship between data sets. CoD (r^2), linked to the correlation analysis, express the variance in one variable that can be attributed to the second variable (Atkinson and Nevill, 1998, Bland and Altman, 2003, Brunton et al., 2000, Winter et al., 2001). Correlation statistics should not be reported in isolation as they can be blind to bias (Bland and Altman 2003). As noted elsewhere (Finni et al., 2007), the LoA method (Bland and Altman, 1986) is used to compare the agreement between methods. Summarising the differences between the two methods is a corner stone of the process. It is expected that the differences outside of ± 2 SD from the mean difference are not practically important. If 95% of data are within 2 SD it is considered an acceptable 'limit of agreement' and methods or equipment is thought to be interchangeable (Bland and Altman, 2003).

LoA cannot be used when units between two methods are not comparable hence ACC data is not analysed in this way.

Previously precision of HR measurement research has removed data sets when data is clearly erroneous in the belief that a technical breakdown has occurred with the system (Leger and Thivierge, 1988). Analysis completed which includes erroneous data sets would possibly reduce the practical usefulness of the results especially if the erroneous data was linked to only two or three participants. The reporting of data removal (i.e. cleaning) has been used as an additional validity statistic with high volumes of data being removed reducing the credibility of the device. Therefore reporting of raw and clean data sets was completed on HR and BF data where some highly erroneous data was noted. Based on estimated maximal values of each physiological variable (McArdle et al., 2009) considering other research, (Leger and Thivierge, 1988) the following data set removal criteria was established; If absolute mean of a data set difference was $\pm 20 \text{ beat}\cdot\text{min}^{-1}$ for HR, $\pm 7 \text{ br}\cdot\text{min}^{-1}$ for BF from the criterion the data set from the specific stage was removed.

4.3 Results

4.3.1 Overview of the Validity of the Bioharness™

The results for whole data set (Table 4) note strong relationships for HR, BF and P ($P < .01$) with relatively small mean bias for each variable. In comparison ST presented less precise results. Scatter plot of data (Figure 3) presents a non-linear relationship for BF and HR. Non-linearity for BF starts from ~ 45 br.min⁻¹ and for HR starts from ~ 175 beat.min⁻¹, respectively (Figure 23). A strong relationship for ACC was reported ($P < .01$) (Table 5) and trend lines for VMU and participants mean step counts matched increments in intensity (Figure 24).

Table 4. Bioharness™ data in comparison to the respective criterion measure.

Variable	Descriptive Data			Validity Data (Log)		
	Predicted	Criterion	Mean Bias	Mean Bias	PCC	CoD
	M ± SD	M ± SD	± 95% CI	± 95% LoA	<i>r</i>	<i>r</i> ²
HR(beat.min ⁻¹)	122.6 ± 38.7	126.4 ± 39.0	-3.80 ± 0.93	-3.05 ± 32.20	.89*	79%
BF (br.min ⁻¹)	24.5 ± 8.3	26.5 ± 11.9	-2.01 ± 0.32	-3.46 ± 43.70	.91*	83%
ST (°C)	34.7 ± 1.4	34.9 ± 1.5	-0.22 ± 0.10	-0.61 ± 1.98	.76*	58%
P (°)	42.4 ± 24.7	42.4 ± 24.8	0.06 ± 0.32	0.20 ± 2.62	.99*	96%

Tabular report of validity statistics: Descriptive statistics, Standard Deviation (SD), Mean Bias, 95% Confidence Intervals (CI), Log transformed mean bias, 95% Limits of Agreement (LoA), Pearson's Product Correlation Coefficient (PCC) and Coefficient of Determination (CoD) across whole data set. * $P < .01$

Table 5. Relationship of ACC data to the respective criterion measure (oxygen uptake, mL.kg⁻¹.min⁻¹) and mean step counts per stage.

	PCC
	<i>r</i>
Activity (VMU/ct.sec ⁻¹)	.97*
Vertical peak (g.sec ⁻¹)	.95*
Mean Step Counts (min ⁻¹)	.99*

A tabular report of validity statistics: Pearson’s Product Correlation Coefficient (PCC) for ACC Vector Magnitude Units (VMU) and Vertical peak output versus oxygen uptake, mL.kg⁻¹.min⁻¹. * *P* < .01

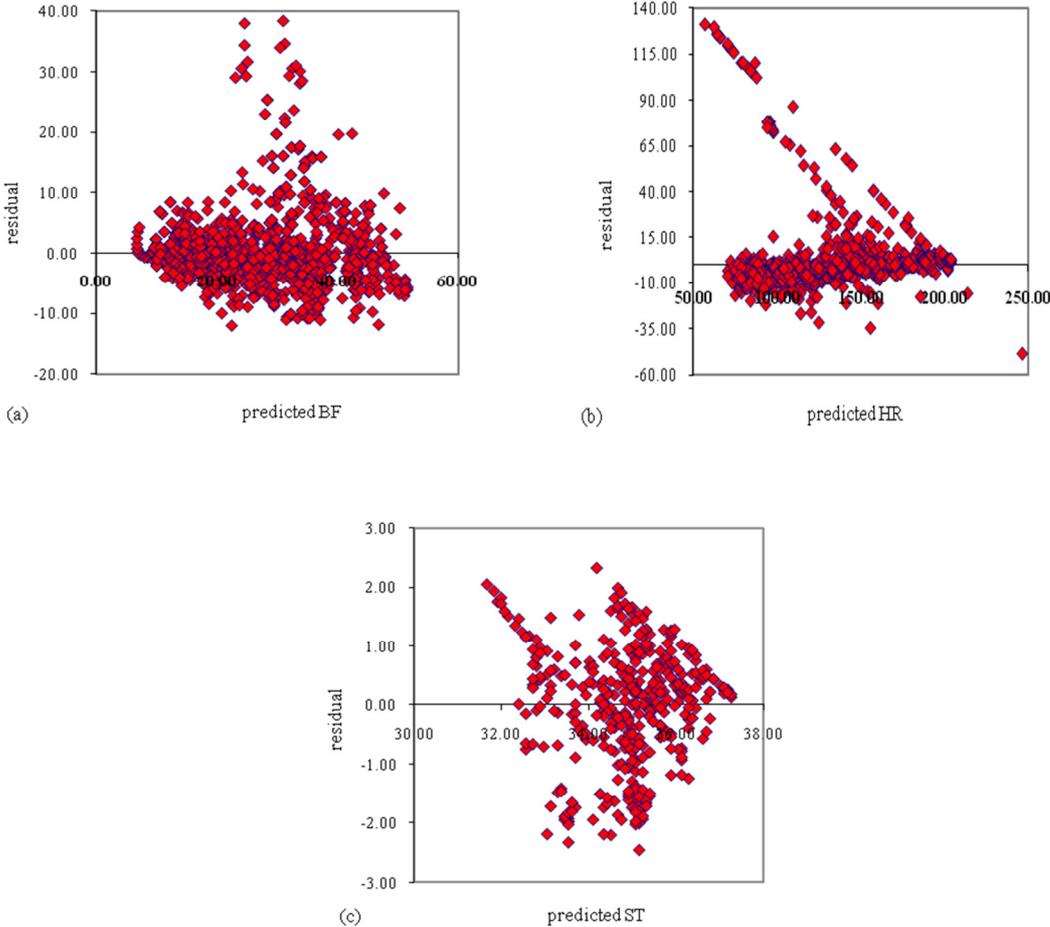


Figure 22. Residual versus predicted plot demonstrating the relationship for (a) BF, (b) HR, and (c) ST.

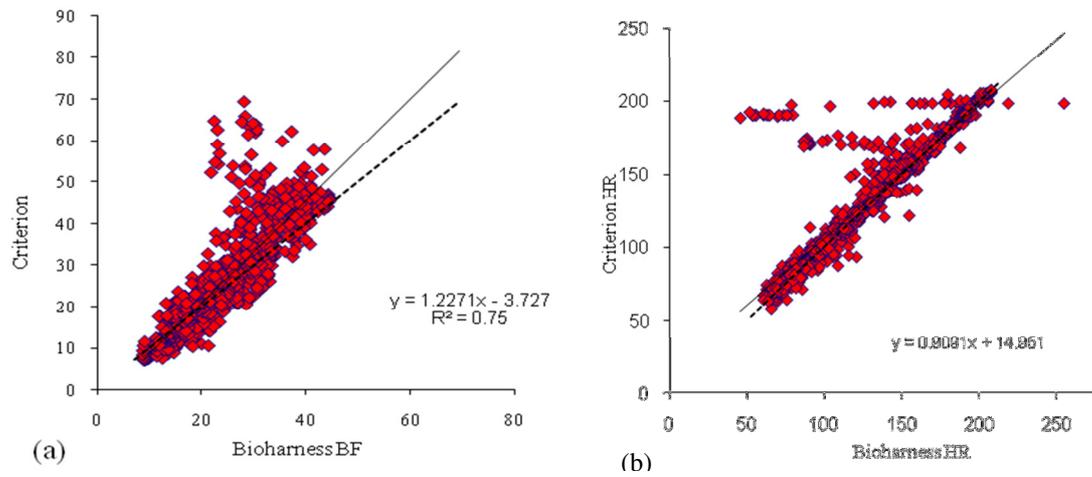


Figure 23. Scatter plot demonstrating the relationship between (a) BioharnessTM BF and Criterion and (b) BioharnessTM HR and Criterion across all velocities on treadmill.

Nb. line of identity (- - -), regression line (—).

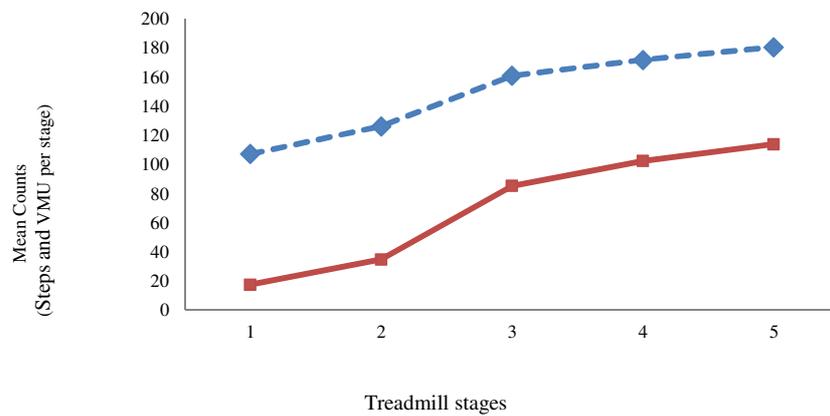


Figure 24. Trend in data between mean footsteps (- -◇- -) and mean VMU (-□-) per active stages of treadmill protocol (Nb. Treadmill stages 1 to 5 refers to 4 km.h⁻¹ to 12 km.h⁻¹ respectively).

4.3.2 Velocity specific validity results for HR

Strong consistent positive relationships ($r > .94$, $P < .01$) were noted until 10 – 12 km.h⁻¹ (Table 6). Improving precision of measurement for HR data is seen from 0 km⁻¹, with absolute HR mean bias $< \pm 1$ beat.min⁻¹ and 95 % LoA values reducing, until the higher velocities where accuracy of the device reduces.

Table 6. Heart rate (beat.min⁻¹) data at varying intensities.

Velocity	Descriptive Data			Validity Data (Log)		
	Predicted	Criterion	Mean Bias	Mean Bias	PCC	CoD
	M \pm SD	M \pm SD	\pm 95% CI	\pm 95% LoA	r	r^2
0km.h⁻¹	81.6 \pm 14.2	82.6 \pm 14.3	-0.98 \pm 0.58	-1.21 \pm 11.30	.94*	88%
4km.h⁻¹	90.9 \pm 14.1	91.8 \pm 13.8	-0.83 \pm 0.52	-0.97 \pm 9.00	.95*	90%
6km.h⁻¹	105.3 \pm 14.0	105.0 \pm 13.8	0.32 \pm 0.57	0.28 \pm 8.80	.94*	88%
8km.h⁻¹	142.2 \pm 20.1	142.8 \pm 19.6	-0.60 \pm 0.61	-0.48 \pm 7.20	.97*	94%
10km.h⁻¹	156.6 \pm 24.9	161.0 \pm 20.1	-4.44 \pm 2.23	-3.32 \pm 28.10	.63*	40%
12km.h⁻¹	160.4 \pm 37.6	176.8 \pm 18.4	-16.37 \pm 4.66	-12.30 \pm 72.90	.11	1%

Tabular report of validity statistics: Descriptive statistics, Standard Deviation (SD), Mean Bias, 95% Confidence Intervals (CI), Log transformed mean bias, 95% Limits of Agreement (LoA), Pearson's Product Correlation Coefficient (PCC) and Coefficient of Determination (CoD) across whole data set. * $P < .01$

Velocity specific validity results for BF

Between rest and 8 km.h⁻¹ consistent moderate positive correlations are noted ($r > .81$, $P < .01$) with absolute mean bias remaining < 1.6 br.min⁻¹ (Table 7). Decreased precision is seen at the highest velocities with greater mean bias, weak correlations and high LoA noted.

Table 7. Breathing frequency (br.min⁻¹) data at varying intensities.

Velocity	Descriptive Data			Validity Data (Log)		
	Predicted	Criterion	Mean Bias	Mean Bias	PCC	CoD
	M ± SD	M ± SD	± 95% CI	± 95% LoA	<i>r</i>	<i>r</i> ²
0km.h⁻¹	15.9 ± 3.9	15.0 ± 4.5	0.81 ± 0.35	7.31 ± 40.30	.81*	66%
4km.h⁻¹	18.9 ± 4.7	19.1 ± 5.8	0.18 ± 0.39	0.57 ± 35.20	.84*	71%
6km.h⁻¹	20.9 ± 5.9	21.0 ± 6.7	-0.14 ± 0.48	0.51 ± 42.40	.81*	66%
8km.h⁻¹	26.6 ± 5.8	28.1 ± 7.7	-1.57 ± 0.53	-4.13 ± 33.80	.83*	69%
10km.h⁻¹	29.5 ± 6.0	34.1 ± 8.3	-4.61 ± 0.99	-12.82 ± 55.80	.44*	19%
12km.h⁻¹	33.4 ± 5.9	40.8 ± 10.0	-7.41 ± 1.25	-16.96 ± 56.96	.35*	12%

Tabular report of validity statistics: Descriptive statistics, Standard Deviation (SD), Mean Bias, 95% Confidence Intervals (CI), Log transformed mean bias, 95% Limits of Agreement (LoA), Pearson's Product Correlation Coefficient (PCC) and Coefficient of Determination (CoD) across whole data set. * $P < .01$

Velocity specific results for HR and BF after erroneous data removed

Erroneous data sets at the highest velocity were removed following a cleaning process described previously. Validity data was recalculated and improvement in accuracy of data is seen (Table 8). HR data for 10 km.h⁻¹ (n=12) and 12 km.h⁻¹ (n=10) presented strong correlations, consistent LoA and continued to underestimate HR which mirrors the data trends captured between 4 – 8 km.h⁻¹ in the raw data set. BF data for 10 and 12 km.h⁻¹ (n=10) continued with similar trends seen from 4 km.h⁻¹ with moderate correlations, increasing underestimation of BF (i.e. mean bias) and large but stabilising LoA values

Table 8. Clean heart rate (beat.min⁻¹) and breathing frequency (br.min⁻¹) data at 10 and 12 km.h⁻¹.

Velocity	Descriptive Data			Validity Data (Log)		
	Predicted	Criterion	Mean Bias ±95%	Mean Bias	PCC	CoD
	M ± SD	M ± SD	CI	± 95% LoA	<i>r</i>	<i>r</i> ²
Heart rate						
10km.h⁻¹	159.6 ± 21.4	160.0 ± 20.6	-0.45 ± 0.75	0.40 ± 7.70	.96*	92%
12km.h⁻¹	174.3 ± 20.4	176.0 ± 19.1	-1.64 ± 0.89	-1.00 ± 7.40	.95*	90%
All data	122.2 ± 38.1	122.8 ± 38.2	-0.65 ± 0.26	-0.60 ± 8.88	.99*	96%
Breathing						
10km.h⁻¹	30.4 ± 5.3	31.6 ± 7.0	-1.27 ± 0.51	-3.20 ± 23.90	.86*	75%
12km.h⁻¹	34.6 ± 5.4	37.8 ± 5.4	-3.14 ± 0.61	-7.40 ± 23.50	.86*	75%
All data	24.4 ± 8.4	25.3 ± 10.4	-0.84 ± 0.22	-0.60 ± 33.99	.94*	88%

Tabular report of validity statistics: Descriptive statistics, Standard Deviation (SD), Mean Bias, 95% Confidence Intervals (CI), Log transformed mean bias, 95% Limits of Agreement (LoA), Pearson's Product Correlation Coefficient (PCC) and Coefficient of Determination (CoD) across whole data set. * *P* < .01

4.3.3 Temperature specific validity results for ST data

Results from the hot and thermo-neutral environments produced moderate (*r* = .75, *P* < .01) and weak (*r* = .42, *P* < .01) relationships respectively (Table 9). Mean bias was greater in hot conditions though data spread (LoA) was wider in thermo neutral conditions.

Table 9. Skin temperature (°C) data in hot, thermo-neutral conditions and combined data overview.

Temperature Condition	Descriptive Data			Validity Data (Log)		
	Predicted	Criterion	Mean Bias	Mean Bias	PCC	CoD
	M ± SD	M ± SD	± 95% CI	± 95% LoA	<i>r</i>	<i>r</i> ²
Hot 30°C	35.4 ± 1.0	35.9 ± 1.1	-0.49 ± 0.10	-1.36 ± 4.14	.75*	56%
Neutral 20°C	33.8 ± 1.5	33.8 ± 1.2	0.03 ± 0.19	0.06 ± 9.12	.42*	18%
Combined	34.7 ± 1.4	34.9 ± 1.5	-0.22 ± 0.10	-0.60 ± 5.92	.75*	56%

Tabular report of validity statistics: Descriptive statistics, Standard Deviation (SD), Mean Bias, 95% Confidence Intervals (CI), Log transformed mean bias, 95% Limits of Agreement (LoA), Pearson's Product Correlation Coefficient (PCC) and Coefficient of Determination (CoD) across whole data set. * *P* < .01

4.3.4 Validity of the ACC variable

Analysis was completed on the whole data set and shows a strong relationship between VMU and relative oxygen uptake ($r = .97, P < .01$) (Table 10). Further relationships between relative oxygen uptake and the individual axis of the ACC are also presented with peak acceleration, vertical and lateral axis presenting strong correlations ($r > .84, P < .01$) and sagittal axis with no relationship.

Table 10. Relationship of ACC data to the respective criterion measure (oxygen uptake $\text{mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$).

Accelerometer axis	PCC <i>r</i>
Activity ($\text{VMU}/\text{ct}\cdot\text{sec}^{-1}$)	.97*
Vertical peak ($\text{g}\cdot\text{sec}^{-1}$)	.95*
Lateral peak ($\text{g}\cdot\text{sec}^{-1}$)	.84*
Sagittal peak ($\text{g}\cdot\text{sec}^{-1}$)	.07

Tabular report of validity statistics: Pearson's Product Correlation Coefficient (PCC). * $P < .01$

4.3.5 Validity of the P variable

The P variable was tested using a tilt table protocol and data analysed as a whole (Table 4) with strong relationship ($r = .99, P < .01$) and very small bias between measures identified.

4.4 Discussion

4.4.1 Main findings – Validity of the Bioharness™

Mobile multivariable physiological monitoring devices used within free living or sporting scenarios can now provide time synchronised data which may enable further insights in to day-to-day activity levels and athletic performance. Comprehensive assessment of the precision of monitoring technology will allow for better understanding of its variability which exists and therefore allows for better interpretation of data collected (Welk et al., 2004).

Global results (Table 4 and 5) from this laboratory based study suggest that the Bioharness™ monitoring system is valid and demonstrates relatively accurate data in relation to the analysis completed. Collectively, with all data considered, the validity statistics for HR, BF, P and ACC suggest credible precision of measurement is attained and limits for each variable have been established. When data is analysed at each velocity, even with a moderate/strong correlation and relatively small mean bias, HR and BF LoA suggests some divergence of data at higher velocities in both absolute and log transformed values.

4.4.2 Velocity specific findings for heart rate (HR) and breathing frequency (BF) raw data

Velocity specific analysis for HR and BF identified differences in the precision of data. Relative to the respective criterions, there was a general trend of decreased accuracy as velocity increased $\geq 10 \text{ km.h}^{-1}$ which has been reported elsewhere for HR (Kingsley et al., 2004, Leger and Thivierge, 1988, Terbizan et al., 2002) and for BF (Grossman et al., 2010, Witt et al., 2006).

Analysis of global HR results finds similar LoA ($\pm 6 \text{ beat.min}^{-1}$) as reported for the Polar heart rate monitor (Godsen et al., 1991) and Acti-heart device (Brage et al., 2005). HR validity data, specifically relationships, remained consistently strong ($r > .94$) $\leq 8 \text{ km.h}^{-1}$ which would align it to the “excellent” category (Leger and Thivierge, 1988) and matches data noted in other research (Seaward et al., 1990, Wajciechowski et al., 1991). Improved accuracy of HR data from rest to 8 km.h^{-1} could be attributed to accumulated physiological responses of exercise (i.e. perspiration/moisture) which may improve connectivity between the skin and the HR electrodes (Lopes and White, 2006, Powers and Howley, 2007). Evidence of decreasing precision of the Bioharness™, specifically underestimation, with increasing velocity is further supported as the relationship of HR data becomes non-linear (Figure 23) at $\sim 175 \text{ beat.min}^{-1}$, which corresponds to mean HR attained within the 12 km.h^{-1} stage.

Interestingly BF precision of measurement also improves from rest to 6 km.h⁻¹, with moderate relationships and decreasing mean bias, but then the accuracy decreases rapidly through to the highest velocity. Moreover, scatter plot analysis (Figure 23) suggests that the BF variable may have a threshold of accuracy at ~45 br.min⁻¹ which is the point where non-linear relationship in data becomes visible. A general trend of decreasing precision of measurement using similar respiratory inductive plethysmography (RIP) technology has been noted elsewhere within another multivariable device (Grossman et al., 2010, Witt et al., 2006). A comparable system, the LifeshirtTM, presented stronger BF results from similarly active protocols but this device uses 2 measuring bands (i.e. 2 degree model) in comparison to the BioharnessTM which uses one measuring band to assess this respiratory function (Witt et al., 2006). Two measuring bands will be able to capture both abdominal and thoracic respiratory related movements and McCool (2002) has considered 3 bands to incorporate changes in sterno-umbilical distance. Further clarification of which thoracic landmarks influence the precision of RIP data may improve the accuracy of this variable, without losing the multi-functionality and portable nature of the device.

It is worth noting that the HR and BF non-linear scatter plot data (Figure 23) is attributed to specific participants at the highest velocities rather than a cross participant general data trend. One participant had erroneous data in both variables but otherwise there was no consistency in this issue. A number of other participants presented BF > 40 br.min⁻¹ and HR > 190 beat.min⁻¹ without consistent erroneous data being captured. Therefore threshold values intimated from the scatter plot should be used with caution and requires further investigation.

4.4.3 Velocity specific findings for heart rate (HR) and breathing frequency (BF) for cleaned data

A data cleaning process (Leger and Thivierge, 1988) led to a decrease in data sets as velocity increased and can be used as evidence for credibility of a monitoring system. A total of 3 data sets (i.e. 3 participants) were removed from each variable at the higher velocities suggesting increasingly erroneous data is being captured at ≥ 10 km.h⁻¹, a trend previously noted (Leger and Thivierge, 1988, Terbizan et al., 2002).

Increasing errors with higher velocities in these variables can occur partly due to the data signal that the monitoring device requires becoming corrupted by movement artefacts (Cho et al., 2009, Witt et al., 2006) such as; EMG activity (Boudet and Chamoux, 2000, McArdle et al., 2009), movement of the monitoring device (Clarenbach et al., 2005, Leger and Thivierge, 1988), and specific to BF, changes in the mechanics of breathing (McArdle et al., 2009, McCool et al., 2002). Additional cross technology

(i.e. criterion versus predicted) data processing issues and discipline specific data handling methods could also influence the data output (Boudet and Chamoux, 2000, Kent et al., 2009).

4.4.4 Validity of accelerometry (ACC) variable

The validation of the ACC variable against VO_2 ($\text{mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$), which is considered an indirect criterion measure, and mean stride (step) counts per stage during the treadmill protocol, both have been noted elsewhere (McArdle et al., 2009, Rowlands et al., 2004). VMU was chosen as the main ACC unit since this is an integrated activity count providing an overall picture of activity commonly used in other research (Powell and Rowlands, 2004). Strong relationships ($r > .95$) were noted for VMU suggesting the ACC demonstrates validity especially when compared against other devices which were deemed credible despite reporting weaker correlations ($r > \sim .80$) (Rowlands et al., 2004, Welk et al., 2004). Strong relationships and corresponding matching trend lines (Figure 24) for mean stride counts provide further confirmation for the direct validity of this variable against movement data. The Bioharness™ ACC could have been compared against another peer reviewed ACC (e.g. RT3) providing an indication of data trends, however completing this analysis may have had limited results due to the lack of consensus as to how ACC counts are produced by individual devices. Assessment at different velocities in relation to VO_2 was not possible as subjects were not standardised for cardio-vascular fitness before the protocol. It is suggested that ACC could become less accurate at higher intensities due to technical limitations and as running mechanics alter (Brage et al., 2003, Powell and Rowlands, 2004), all of which should be investigated further for this device.

4.4.5 Validity of posture (P) variable

Due to difficulties assessing validity of the P variable against a criterion within the treadmill protocol, data was assessed in a controlled procedure using a tilt table. Results present credible data with narrow LoA (0.20 ± 2.62) and strong relationship ($r > .99$) versus the criterion which mirrors other research using similar technology in the area (Bernmark and Wiktorin, 2002). The frequency of inclinometer devices using similar ACC technology is increasing with research from occupational studies being more common (Hansson et al., 2006, Hansson et al., 2001). Data from the Bioharness™ P variable is generated from similar piezoelectric technology as seen within the ACC which has produced valid data within this research. The combined results associated with the ACC and P variable adds evidence to the credibility of the piezoelectric technical set up within the Bioharness™.

4.4.6 Validity of skin temperature (ST) variable

Infra-red ST global data set, validated against skin thermistors, initially suggests the Bioharness™ has less precision when compared to other infra-red ST research (Hershler et al., 1992). Moreover, LoA have not been extensively reported for infra-red temperature validity studies though the combined data note a tighter agreement when compared to previous research (Matsukawa et al., 2000). A consideration in this analysis of the Bioharness™ is that the latter two research papers were completed in a non-exercise environment which is arguably more controlled so it is expected that there is less variance in their data. Exercise adds another dimension to the validation of ST and there are few comparable data sets available in the literature. Other somewhat limited analysis reported no significant differences in infra-red temperature devices tested and strong correlations ($r > .95$) from a low intensity treadmill protocol incorporating an environmental chamber (Buono et al., 2007). Stronger correlations reported could be linked different methodological procedures and data analysis. For methods involving temperature measurement, a threshold of accuracy of $0.1\text{ }^{\circ}\text{C}$ has been proposed for systematic bias and $\pm 0.3\text{ }^{\circ}\text{C}$ for 95% LoA (Gant et al., 2006). These thresholds are not met by the Bioharness™ in any of the data sets collected. The weak relationships in data could possibly be explained by low number of data sets and LoA analysis suggests relatively large discrepancies between the criterion and Bioharness™, especially when considering the narrow temperature data range. The equivocal results for the infra-red ST could be explained by the onset of sweating during exercise (Kistemaker et al., 2006), technical issues with the skin thermistors (Buono et al., 2007), changes in infra-red device angle to the body (Hershler et al., 1992) and distance from the skin surface (Matsukawa et al., 2000). Further examination of the ST precision of measurement should be considered.

4.4.7 Limitations

Reporting of absolute and/or logarithmically transformed HR and BF data relating to heteroscedasticity is highlighted within the paper. Even though absolute data is interpreted more easily by the reader, log transformed data should be reported, if data fails to meet necessary criteria, in order for a full comprehension of the data. There is a lack of clarity as to the objective model to decide if data is heteroscedastic or not, also there are different log transformation models so further clarification on best practice should be investigated. Moreover, the sample size could be considered

a limitation of the study though numbers of participants in this research matches or even exceed other peer reviewed papers dealing with similar themes.

4.5 Conclusion

The results suggest that, with prior understanding of data limitations, the Bioharness™ has proved to be a valid multivariable monitoring device within ambulatory laboratory testing. ACC and P variables presented strong data which relates to the advanced piezoelectric technology used. Using the device to capture HR and BF data during high intensity activities should be completed with the understanding that the validity of this data could be influenced by artefacts at treadmill velocities of $\geq 10 \text{ km.h}^{-1}$. Research on similar HR and BF devices report decreasing accuracy at higher activity levels therefore establishing a transparent data cleaning procedure should be considered. Further development of infra-red ST technology within the device should be considered.

The Bioharness™ device is designed to enable naturalistic physiologically based monitoring to occur across differing free movement scenarios without the need for obtrusive invasive equipment. The design limitations associated with incorporating multi-variable monitoring within a device which must be unobtrusive to the wearer may place some limitations on the effectiveness of the functioning of individual elements. Free movement physiological data, which the Bioharness™ aims to capture, is inherently variable (Welk et al., 2004), so the next progression for the device is assessment of its reliability and if that latter process produces appropriate data, further testing in a less controlled field based setting should occur, allowing for a more comprehensive appreciation of its capacities in the mode of use it was intended to be used.

Chapter 5 - Reliability of the Bioharness™ Monitoring System

5.0 Abstract

The Bioharness™ monitoring system may provide physiological information on human performance but the reliability of this data is fundamental for confidence in the equipment being used. The objective of this study was to assess the reliability of each of the 5 Bioharness™ variables using a treadmill based protocol. 10 healthy males participated. A between and within subject design to assess the reliability of Heart rate (HR), Breathing Frequency (BF), Accelerometry (ACC) and Infra-red skin temperature (ST) was completed via a repeated, discontinuous, incremental treadmill protocol. Posture (P) was assessed by a tilt table, moved through 160°. Between subject data reported low Coefficient of Variation (CV) and strong correlations(r) for ACC and P (CV < 7.6%; $r = .99$, $P < .01$). In contrast, HR and BF (CV ~ 19.4%; $r \sim .70$, $P < .01$) and ST (CV 3.7%; $r = .61$, $P < .01$), present more variable data. Intra and inter device data presented strong relationships ($r > .89$, $P < .01$) and low CV (< 10.1%) for HR, ACC, P and ST. BF produced weaker relationships ($r < .72$) and higher CV (< 17.4%). In comparison to the other variables BF variable consistently presents less reliability. Global results suggest that the Bioharness™ is a reliable multivariable monitoring device during laboratory testing within the limits presented.

Key words: Physiological technology, Reproducibility of measurement, Exercise

5.1 Introduction

The development of mobile monitoring technology has assisted in allowing high-quality data to be recorded in a variety of free living active situations (Achten and Jeukendrup, 2003, Jobson et al., 2009). Mobile monitoring technology can collate information on multiple integrated physiological and activity variables which can be assessed in real-time or downloaded post-performance. The previous section (Chapter 4) presented the case that the Bioharness™ device is a valid monitoring tool within a laboratory environment. Understanding the reproducibility, or repeatability, of data is crucial if advancement of ecologically valid assessment of activity is to continue. Mobile monitoring device such as the Bioharness™ (Zephyr Technology Ltd, MD, USA), can collate information on multiple integrated physiological and activity variables which can be assessed in real-time or post-performance (See Chapter 4.1 for device details). Measurements made by mobile monitoring technology in any environment must have known clarity as to what variability may exist (Atkinson and Nevill, 1998, Welk et al., 2004) therefore this chapter will describe the reliability of this device.

The aim of this study is to assess the reliability of each variable measured by the Bioharness™ device within a physically active laboratory situation. It is hypothesised that each variable within the Bioharness™ device will meet appropriate levels of reproducibility after a series of reliability statistics have been applied to the data set.

5.2 Methods

5.2.1 General design

To assess the reproducibility of the Bioharness™ variables appropriate assessment protocols were identified. A between (n = 10, using 1 Bioharness™ device) and within subject (n = 1, testing 4 different Bioharness™ devices) design, using a repeated treadmill protocol, allowed the assessment of ST, HR, BF and ACC with the latter 3 variables being assessed at different velocities. P variable was assessed as a whole data set through a separate mechanical protocol. All data collection was synchronized to one timeline linked to a laptop computer.

5.2.2 The Bioharness™ monitoring device

The Bioharness™ device is described previously in 4.2.2.

5.2.3 Participants

After securing local institutional ethical agreement (Ethics No LS3/11/09P) (Appendix 1) 10 male volunteers (age 20.5 ± 2.1 yrs, body mass 70.4 ± 9.4 kg, body stature 1.77 ± 0.1 m) who were physically active, injury free and familiar with using a treadmill consented to participate. Participants were asked to refrain from consuming alcohol and caffeine, keep hydrated and rested 24 hours before testing. On arrival to the laboratory anthropometrical measures (Stewart and Eston, 2007) were taken with stature (Seca 214, Birmingham, UK) and body mass (Seca 761, Birmingham, UK) measured.

5.2.4 Procedures

Reproducibility of HR, BF, ACC and ST

Reproducibility of these variables were assessed by participants completing an adapted discontinuous incremental treadmill protocol (Rowlands et al., 2004). For details of protocol see section 4.2.4. The retest was completed 5-7 days from the date of first test.

5.2.5 Reproducibility of P

For details of the protocol see section 4.2.6. This protocol was then repeated.

5.2.6 Data Analysis

Data was exported to statistical software packages (Excel Microsoft Windows, USA; SPSS v17, SPSS Inc, Chicago, USA) for analysis. When assessing reproducibility a range of statistical procedures have been cited in combination with descriptive data are available for researchers providing a comprehensive summary (Atkinson and Nevill, 1998, Hopkins et al., 2009, Kent et al., 2009, Nunan et al., 2008, Sandercock et al., 2005). Reliability of the data was assessed through the use of descriptive statistics (mean (M) \pm standard deviation (SD)), Change in mean, 95% Confidence Limits (CL) and reliability statistics, Coefficient of Variation (CV), Inter Class Correlations (ICC).

The change in mean and associated 95% CL will provide an indication of absolute variation between the data sets. CV expresses the SD as a proportion of the mean, is considered a dimensionless statistic and therefore easier to compare variation between protocols (Atkinson and Nevill, 1998, Currell and Jeukendrup, 2008, Hopkins, 2000b). Information on the relationship between sets of data is provided by correlation coefficients. ICC is more sensitive to systematic bias and also can be used for multiple retests so have been preferred within reliability studies (Atkinson and Nevill, 1998, Hopkins, 2000b). These statistics analysed collectively provide a clear overview on the reproducibility of data.

Characteristics of the data set were considered and appropriate statistical procedures followed thereafter. After plotting the between subject predicted against the residuals for HR and BF (Figure 25), data were considered to be non-uniform (i.e. heteroscedastic or not normally distributed) so were logarithmically (log) transformed in order to provide a true interpretation (Atkinson and Nevill, 1998, Hopkins et al., 2009, Hopkins et al., 2001). Descriptive data for these variables were reported in absolute values and reliability statistics presented log transformed which was determined in order for comparison with other studies to occur, the majority of which report absolute data.

Previously research assessing reliability of a monitoring device has removed data sets when data is clearly erroneous in the belief that a technical breakdown has occurred with the system (Leger and Thivierge, 1988). Analysis completed which includes highly erroneous data sets would possibly reduce the practical usefulness of the results especially if this data was linked to a small clearly identifiable number of participants. The reporting of data removal (i.e. cleaning) has been used as additional evidence for reproducibility with high volumes of data being removed possibly reducing the reliability of the device. Therefore reporting of raw and clean data sets was completed on HR and BF data where some highly erroneous data was noted. Based on estimated maximal values of each physiological variable (McArdle et al., 2009), day-to-day biological variation (Achten and Jeukendrup, 2003) and considering other research (Leger and Thivierge, 1988), the following data set

removal criteria was established; If absolute mean of a data set presented a difference of ± 20 $\text{beat}\cdot\text{min}^{-1}$ for HR, ± 7 $\text{br}\cdot\text{min}^{-1}$ for BF in comparison to equivalent data from the specific stage, the data was removed.

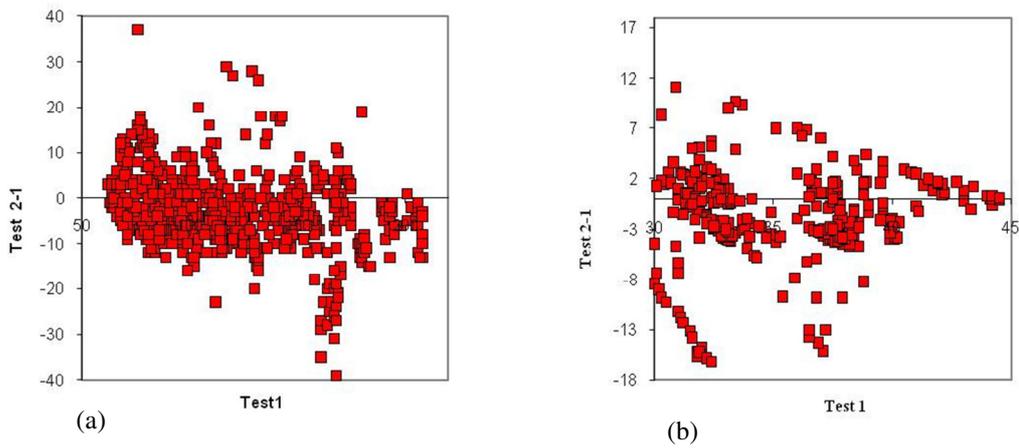


Figure 25. Residual versus predicted plot demonstrating the data spread for (a) HR and (b) BF.

5.3 Results

5.3.1 Overview of the Reliability of the Bioharness™ (Between subjects)

Between subject results (Table 11) for the whole data set note low CV and strong relationships for ACC and P ($P < .01$). Less reliable variables are, ST, HR and BF, with the former variable having low CV and weak relationships. HR and BF present moderate relationships and a large CV.

Table 11. Bioharness™ reproducibility across whole data set.

Variables	Descriptive Data			Reliability Data		
	Test 1	Test 2	Change in	95% CL	CV%	ICC
	M ± SD	M ± SD	mean			
HR beat.min ⁻¹	120.6 ± 38.0	113.5 ± 35.1	-7.31	-9.07 to -5.54	19.4	.67*
BF br.min ⁻¹	25.5 ± 8.1	26.0 ± 8.1	0.51	0.16 to 0.86	19.4	.71*
ACC ct.sec ⁻¹	0.71 ± 0.39	0.71 ± 0.39	0.002	-0.001 to 0.006	6.5	.99*
ST degrees °C	32.5 ± 1.7	32.0 ± 2.0	-0.5	-0.61 to -0.42	3.7	.61*
P degrees	45.1 ± 22.9	44.8 ± 23.9	-0.34	-0.31 to -1.00	7.6	.99*

Tabular report of reliability statistics: Descriptive statistics, Standard Deviation (SD), 95% Confidence Limits (95% CL), Change in Mean, Coefficient of Variation (CV) and Intra Class Correlations (ICC). * $P < .01$

5.3.2 Between subjects velocity specific HR reliability

HR results (Table 12) noted moderate to strong relationship ($r > .84$, $P < .01$), a lowering CV ($< 6.2\%$) and change in mean < 3.16 beat.min⁻¹ with velocity ≤ 8 km.h⁻¹. Reproducibility of data decreased at velocities at ≥ 10 km.h⁻¹ with increases in change of mean (> 14.01 beat.min⁻¹), CV $> 24.7\%$ and no relationships in data.

Table 12. Velocity specific reproducibility of HR (beat.min⁻¹) data.

Velocity	Descriptive Data			Reliability Data		
	Test 1	Test 2	Change in	95% CL	CV%	ICC
	M ± SD	M ± SD	mean			
0 km.h⁻¹	80.2 ± 12.0	81.1 ± 11.7	0.90	-0.09 to 1.89	5.9	.84*
4km.h⁻¹	89.5 ± 11.1	86.6 ± 11.4	-2.96	-3.72 to -2.71	4.5	.88*
6km.h⁻¹	103.6 ± 11.6	100.9 ± 12.2	-2.66	-3.55 to -1.76	4.3	.87*
8km.h⁻¹	135.7 ± 19.2	132.5 ± 18.5	-3.16	-4.05 to -2.27	3.4	.94*
10km.h⁻¹	153.9 ± 23.7	138.3±33.9	-14.01	-19.73 to -8.28	24.7	.08
12km.h⁻¹	160.4 ± 38.3	141.1 ± 42.6	-19.30	-28.43 to -10.16	30.5	.04

Tabular report of reliability statistics: Descriptive statistics, Standard Deviation (SD), 95% Confidence Limits (95% CL), Change in Mean, Coefficient of Variation (CV) and Intra Class Correlations (ICC). * $P < .01$

5.3.3 Between subjects velocity specific BF reliability

BF data (Table 13) presents a weak relationship ($r < .51$), with elevated CV values (ranging 16.8 – 21.9%). The change in mean remains $<1 \text{ br.m}^{-1}$ and this value reduces from rest to the active stages.

Table 13. Velocity specific reproducibility of BF (br.min⁻¹) data.

Velocity	Descriptive Data			Reliability Data		
	Test 1	Test 2	Change in	95% CL	CV%	ICC
	M ± SD	M ± SD	mean			
0 km.h⁻¹	16.8 ± 4.2	17.7 ± 1.9	0.89	0.24 to 1.53	21.9	.06
4km.h⁻¹	19.4 ± 4.5	20.3 ± 3.3	0.87	0.31 to 1.43	16.8	.51*
6km.h⁻¹	22.3 ± 4.0	22.5 ± 5.4	0.17	-0.57 to 0.90	19.8	.49*
8km.h⁻¹	27.5 ± 4.0	27.4 ± 4.2	-0.16	-1.13 to 0.81	19.4	-.21
10km.h⁻¹	31.7 ± 4.5	32.3 ± 5.4	0.58	-0.46 to 1.62	19.7	-.03
12km.h⁻¹	35.5 ± 5.7	36.1 ± 6.5	0.61	-0.47 to 1.69	17.9	.23

Tabular report of reliability statistics: Descriptive statistics, Standard Deviation (SD), 95% Confidence Limits (95% CL), Change in Mean, Coefficient of Variation (CV) and Intra Class Correlations (ICC) * $P < .01$

5.3.4 Velocity specific results for HR and BF after erroneous data removed

Data considered to be highly erroneous was removed following the procedure described earlier. HR (n = 6) and BF data (n = 8) produced data (Table 14) mirroring trends from statistics seen at lower velocities. Considering this clean data set with the other velocities, HR change in mean remained < 3.16 br.min⁻¹, CV < 6% and moderate to strong relationship ($r > .84$) were noted. BF data continued with < 1 br.min⁻¹ for change in mean, CV presented its lowest values at 10 and 12 km⁻¹ and a low to moderate relationship were identified.

Table 14. Clean HR (beat.min⁻¹) and BF (br.min⁻¹) data at 10 and 12 km.h⁻¹.

Velocity	Descriptive Data			Reliability Data		
	Test 1 M ± SD	Test 2 M ± SD	Change in mean	95% CL	CV%	ICC
Heart rate						
10km.h⁻¹	155.4 ± 21.0	153.4 ± 23.3	-1.98	-3.30 to -0.66	3.5	.95*
12km.h⁻¹	168.9 ± 21.5	168.1 ± 20.7	-0.77	-2.47 to 0.93	3.7	.91*
All data	116.2 ± 35.7	113.5 ± 34.6	-2.68	-3.15 to -2.22	4.8	.98*
Breathing Fr						
10km.h⁻¹	32.7 ± 3.8	33.2 ± 3.3	0.51	-0.21 to 1.22	10.4	.22
12km.h⁻¹	35.9 ± 5.8	36.7 ± 5.9	0.77	-0.11 to 1.65	12.7	.54*
All data	25.1 ± 8.1	25.6 ± 7.9	0.52	0.21 to 0.82	17.7	.75*

Tabular report of reliability statistics: Descriptive statistics, Standard Deviation (SD), 95% Confidence Limits (95% CL), Change in Mean, Coefficient of Variation (CV) and Intra Class Correlations (ICC) * $P < .01$

5.3.5 Between subjects velocity specific ACC reliability results

At rest, ACC data (Table 15) presented the least reliable data with largest change in mean, largest CV and weakest relationship. As velocity increased, the change in mean reduced and became consistent, CV decreased (< 9.3%) and moderate to strong ($r > .66$) relationship are reported.

Table 15. Reproducibility of Bioharness™ ACC data (Vector Magnitude Units, $\text{ct}\cdot\text{sec}^{-1}$).

Velocity	Descriptive Data			Reliability Data		
	Test 1	Test 2	Change in	95% CL	CV%	ICC
	M \pm SD	M \pm SD	mean			
0 km.h⁻¹	0.04 \pm 0.10	0.02 \pm 0.02	-0.026	-0.041 to -0.011	131.1	-.03
4km.h⁻¹	0.17 \pm 0.03	0.18 \pm 0.03	0.007	0.003 to 0.010	9.3	.66*
6km.h⁻¹	0.41 \pm 0.22	0.42 \pm 0.23	0.007	0.002 to 0.012	5.9	.99*
8km.h⁻¹	0.86 \pm 0.15	0.86 \pm 0.13	0.002	-0.009 to 0.13	6.5	.85*
10km.h⁻¹	1.04 \pm 0.09	1.03 \pm 0.09	-0.010	-0.020 to 0.001	5.0	.68*
12km.h⁻¹	1.12 \pm 0.10	1.13 \pm 0.09	0.006	-0.004 to 0.016	4.3	.75*

Tabular report of reliability statistics: Descriptive statistics, Standard Deviation (SD), 95% Confidence Limits (95% CL), Change in Mean, Coefficient of Variation (CV) and Intra Class Correlations (ICC). * $P < .01$

5.3.6 Overview of within subject (intra device) and between subject (inter) reliability of the Bioharness™

General findings for intra (Table 16) and inter (Table 17) device reliability presented mainly strong statistics for HR, ACC, ST and P ($r > .89$, $P < .01$; $\text{CV} \leq 10.1\%$). BF variable performed less effectively in comparison ($r < .72$; $\text{CV} 11.4 - 17.4\%$). No data was considered highly erroneous so analysis includes all data.

Table 16. Overview of intra device reproducibility of Bioharness™ device.

Variable	Device No	Descriptive Data			Reliability Data		
		Test 1 M ± SD	Test 2 M ± SD	Change in mean	95% CL	CV%	ICC
HR (beat.min ⁻¹)	Device 4	104.5 ± 28.4	98.1 ± 27.9	-6.4	-6.99 to -5.73	2.5	.99*
	Device 5	104.4 ± 30.7	106.0 ± 29.7	1.6	0.54 to 2.58	4.7	.98*
	Device 6	100.7 ± 24.1	111.0 ± 29.2	10.3	8.73 to 11.86	5.4	.97*
	Device 8	103.1 ± 28.3	102.2 ± 24.2	-0.9	-2.15 to 0.41	5.9	.97*
BF (br.min ⁻¹)	Device 4	24.6 ± 2.8	28.1 ± 8.1	3.4	2.39 to 4.47	13.7	.57
	Device 5	29.6 ± 8.3	24.6 ± 3.7	-4.7	-6.05 to -3.88	13.2	.59
	Device 6	25.1 ± 3.9	26.1 ± 4.0	1.0	0.20 to 1.81	11.4	.41
	Device 8	29.7 ± 7.4	32.5 ± 9.4	2.9	1.64 to 4.09	13.2	.72*
ACC (ct.sec ⁻¹)	Device 4	0.77 ± 0.42	0.80 ± 0.42	0.03	0.01 to 0.04	7.0	.99*
	Device 5	0.81 ± 0.42	0.81 ± 0.43	0.01	-0.01 to 0.02	5.4	.99*
	Device 6	0.80 ± 0.42	0.77 ± 0.41	0.02	-0.04 to -0.01	5.6	.99*
	Device 8	0.81 ± 0.43	0.81 ± 0.43	0.01	-0.01 to 0.02	5.7	.99*
ST (°C)	Device 4	30.8 ± 1.51	30.1 ± 0.66	-0.69	-0.81 to -0.56	1.5	.90*
	Device 5	30.1 ± 1.76	30.5 ± 1.24	0.36	0.25 to 0.48	1.5	.92*
	Device 6	29.3 ± 1.24	30.2 ± 1.33	0.89	0.79 to 0.98	1.2	.92*
	Device 8	31.2 ± 1.51	29.2 ± 0.66	-1.94	-2.17 to -1.71	2.7	.48
P (°)	Device 4	46.9 ± 25.0	45.1 ± 25.7	-1.8	-0.51 to -2.91	10.1	.99*
	Device 5	44.0 ± 24.4	45.4 ± 24.8	1.4	0.61 to 2.14	1.6	.99*
	Device 6	44.8 ± 23.5	44.4 ± 24.9	-0.4	-1.55 to 0.80	5.5	.99*
	Device 8	44.8 ± 23.3	44.1 ± 25.2	-0.6	-2.29 to 1.04	8.8	.99*

Tabular report of reliability statistics: Descriptive statistics, Standard Deviation (SD), 95% Confidence Limits (95% CL), Change in Mean, Coefficient of Variation (CV) and Intra Class Correlations (ICC). * $P < .01$

Table 17. Overview of inter device reproducibility of Bioharness™ device.

Variable	Device No	Descriptive Data		Reliability Data		
		M ± SD	Change in mean	95% CL	CV%	ICC
HR (beat.min ⁻¹)	Device 4	104.5 ± 28.4	-	-	-	-
	Device 5	103.4 ± 30.6	-1.04	-1.85 to -0.24	3.9	.99*
	Device 6	100.3 ± 24.1	-3.02	-4.61 to -1.43	6.8	.95*
	Device 8	103.6 ± 28.2	3.68	2.27 to 5.09	6.5	.96*
BF (br.min ⁻¹)	Device 4	24.6 ± 2.8	-	-	-	-
	Device 5	29.3 ± 8.2	4.7	3.67 to 5.74	12.3	.59
	Device 6	25.0 ± 3.9	-4.4	-5.59 to -3.14	15.8	.48
	Device 8	29.7 ± 7.3	4.6	3.34 to 5.95	17.4	.33
ACC (ct.sec ⁻¹)	Device 4	0.77 ± 0.42	-	-	-	-
	Device 5	0.79 ± 0.42	0.02	0.01 to 0.04	6.2	.99*
	Device 6	0.79 ± 0.42	-0.01	-0.02 to 0.01	5.3	.99*
	Device 8	0.80 ± 0.42	0.02	0.01 to 0.04	5.9	.99*
ST (°C)	Device 4	30.8 ± 1.7	-	-	-	-
	Device 5	30.2 ± 1.7	-0.62	0.72 to 0.52	1.2	.95*
	Device 6	29.4 ± 1.2	-0.81	0.94 to 0.68	1.7	.89*
	Device 8	31.2 ± 1.5	1.76	1.64 to 1.89	1.5	.89*
P (°)	Device 4	46.9 ± 25.0	-	-	-	-
	Device 5	44.0 ± 24.4	-2.9	-4.25 to -1.50	9.3	.99*
	Device 6	44.8 ± 23.5	0.8	-0.22 to 1.72	8.0	.99*
	Device 7	44.8 ± 23.3	0.0	-0.45 to 0.45	0.9	.99*

Tabular report of reliability statistics: Descriptive statistics, Standard Deviation (SD), 95% Confidence Limits (95% CL), Change in Mean, Coefficient of Variation (CV) and Intra Class Correlations (ICC). * $P < .01$

5.3.7 Velocity specific intra and inter device reliability of the HR, BF and ACC variable of the Bioharness™

Further velocity specific intra and inter device results note low CV for HR (< 7.3%) and ACC (< 10%) with a general trend of decreasing variance with increasing treadmill velocity. At 0 km.h⁻¹, ACC presented high inter and intra device variance (CV range ~50 – 130%) which reduced at the onset of activity. BF presented CV values < 11.4% with one exception during the inter device analysis (CV = 17.8%). ICC values for all variables were predominately low ($r < .70$; $P < .05$) with exception of one HR result (10 km.h⁻¹, $r = .86$).

5.4 Discussion

Multivariable monitoring devices within sport and exercise can now provide time synchronised data which possibly could allow for further insights in to performance. Ensuring that a comprehensive precision of measurement assessment has occurred will allow for an understanding of the variability which exists and is a crucial step in achieving credibility in the market place (Welk et al., 2004). The aims of the study were to assess the reliability of the Bioharness™ monitoring device due to limited information being available on this issue.

5.4.1 Reliability of the Bioharness™

Overall results suggest that, the Bioharness™ produces adequately reliable data for HR, ST, ACC and P, with the latter two variables presenting the most accurate data. The erroneous data at higher velocities for HR and BF variables sets suggests caution should be applied to data collected during activities involving movement above 10 km.h⁻¹. BF variable presented more data variance though when data cleaning occurred between subject reliability improved, as it did for HR. ST achieved the least test-retest reliability between participants, though produced stronger results within subject.

5.4.2 Reliability of heart rate (HR)

HR data suggests adequate reproducibility across both testing designs at moderate velocity (≥ 8 km.h⁻¹) (Table 13). Considering the between-subject design, before data cleaning, there is weaker reproducibility in the data at higher velocities (≥ 10 km.h⁻¹) which is linked to an increase in highly

erroneous data being produced. This latter phenomena was not apparent in the within subject data with reliability statistics being strong ($r > .99$; $CV < 6.8\%$) throughout all velocities. After erroneous data had been removed at $\geq 10\text{km.h}^{-1}$, the between subject data presents equivalently strong results with slight trend of decreasing CV with increases in velocity, as previously reported elsewhere (Achten and Jeukendrup, 2003). In an arguably less intense yoga environment the results improve on correlations ($r \sim .60$) and match CV data (1.9 – 5.7%) found for the Lifeshirt™, a multi variable assessment device (Grossman et al., 2006, Kent et al., 2009) and also is similar to unpublished data (CV 1.7 – 6.7%) from our laboratory on the Polar HR monitor (T31, Polar Electro, Kempele, Finland). There is an expectation that this data should be within credible limits as monitoring HR telemetrically through electrodes housed within a chest strap has had over 20 years of development (Achten and Jeukendrup, 2003, Laukkanen and Virtanen, 1998).

5.4.3 Reliability of accelerometer (ACC)

Strong reproducibility data for ACC variable was noted in all testing scenarios and supports the notion that piezoelectric technology within the device can be deemed reliable (Table 15, 16 and 17). A low change in mean, low CV ($< 8\%$) and very strong relationships ($r > .99$) match or exceed previous research suggesting the ACC provides reliable data within the testing environment (Brage et al., 2003, Powell et al., 2003, Welk et al., 2000). ACC data at rest (i.e. 0 km.h^{-1}) was not included in the overall analysis as during pilot testing this data was inconsistent. During the rest stage inevitable slight irregular motion of the subject was registered as an activity count. This erratic non-rhythmical data production led to spurious variance in comparison to the remainder of the ACC data set. Piezoelectric elements are more effective in dynamic rather than a static mode (Chen and Bassett, 2005) and the data notes a lowering of CV as treadmill velocity increases ($4 - 12 \text{ km.h}^{-1}$) which also corresponds to findings for other reliable ACC such as the RT3 (Powell et al., 2003) and Actiheart device (Brage et al., 2005). Additional evidence from a study incorporating a free movement trial (e.g. sit-to-stand task) produced a wide range CV (8.7 – 25.6%) between subjects which further corroborate this technical finding within the Bioharness™ (Powell and Rowlands, 2004, Brage et al., 2005).

5.4.4 Reliability of posture (P)

P variable, as assessed by a tilt table, produced good reliability statistics ($r > .99$; $CV < \sim 10\%$). Additional analysis was completed during the treadmill activity comparing posture during the within subject protocol which produced additional evidence that this variable is reliable (Table 11, 16 and 17). There are other tools to measure angular degrees in humans and even though it has been reported digital inclinometers are more reliable than goniometers they are not extensively used due to the expense (Venturni et al., 2006). Other research on this variable using similar technology has also demonstrated good precision of measurement (Hansson et al., 2006). The same piezoelectric technology is used within P and ACC variable and both have demonstrated good reproducibility data.

5.4.5 Reliability of breathing frequency (BF)

Across both experimental designs wider statistical analysis suggests the BF variable produced less reliable data in comparison to the other Bioharness™ variables (Table 11, 13, 14, 16 and 17). As with the HR variable, higher running velocities ($\geq 10 \text{ km}\cdot\text{h}^{-1}$) lead to an increase in erroneous data occurring. After data cleaning, variance during the active stages ($> 4 \text{ km}\cdot\text{h}^{-1}$) seems to remain constant with slight decreases in CV at the higher velocities. Weak relationships were identified and CV values ranged from 21.9% at rest to a low of 10.4% at $10 \text{ km}\cdot\text{h}^{-1}$. Comparing data to corresponding respiratory inductive plethysmography (RIP) technology, a non-active environment presented stronger test-retest relationships (r value) of $\sim .8$ (Grossman et al., 2006) and a repeated within subject treadmill test for the Lifeshirt™ device reported CV $\sim 10\%$ (Kent et al., 2009). Weaker data from the Bioharness™ could be linked to the RIP technical set up of Bioharness™ device. The Lifeshirt™ adopts a 2 degree (i.e. 2 measuring band) model allowing thoracic and abdominal movements to be considered in producing respiratory data (McCool et al., 2002) in comparison to the one thoracic measuring band used within the Bioharness™. The BF CV results suggest quite high variance especially when considering respiratory values during calibration should be within $\pm 3\%$ (Zeballos et al., 2003) and evidence has presented lower CV (9.1%) within maximal testing (Garrard and Emmons, 1986). Though Kent et al. (2009) reported high CV ($\sim 17\%$) for breath-by-breath data gained from a Cosmed metalyser which also corresponds to unpublished CV data from our laboratory using a Cortex 3B metalyser (Cortex Medical, Germany). It seems that BF may be a physiological variable with higher variance, especially if analysed breath-by-breath and discipline specific data processing methods with regards to data averaging protocols are seemingly not standardised, and so could influence outcomes presented (Kent et al., 2009).

5.4.6 Reliability of skin temperature (ST)

Repeatability of ST in a thermo-neutral environment during the treadmill activity produced somewhat equivocal results (Table 11, 16 and 17). ST noted lower relationships in data for between subject design ($r = .61$) than reported in other research (Burnham et al., 2006, Gant et al., 2006) though a low CV (3.7%) was maintained. For the within subject design, except for one device, relationships were strong ($r > .89$) which coupled with a low CV ($< 1.7\%$) suggest the device attains good reliability. The difference in reliability between the two testing designs could be related to the positioning of the infra-red device relative to the subject. In the single subject (intra device) design, when the subject somatotype was standardised, data were more consistent. Previously the infra-red device placement, including lens angle and distance from skin, have been identified as important in attaining credible data and could have influenced the inter subject data collection (Hershler et al., 1992, Matsukawa et al., 2000).

5.4.7 Limitations

It is important to identify if technical breakdown of equipment occurs as this is noted as an additional indication of reliability (Leger and Thivierge, 1988, Terbizan et al., 2002). Failure to clean data with a transparent system may present skewed data. Between subject numbers reduced from $n = 10$ to $n = 6$ for HR and $n = 8$ for BF at the highest velocities (i.e. $\geq 10 \text{ km}\cdot\text{h}^{-1}$) while in contrast no data was removed in the within subject testing. Though not formally assessed, the disparity between the two testing designs and number of useable data sets warrants further discussion. Increased number of errors for HR and BF variables between subject could have occurred due to the data signal that the monitoring device requires becoming corrupted by varying cross subject movement artefacts (Cho et al., 2009, Witt et al., 2006) such as; EMG activity (Boudet and Chamoux, 2000, McArdle et al., 2009), changes in the mechanics of breathing (McArdle et al., 2009, McCool et al., 2002) or movement of the monitoring device (Clarenbach et al., 2005, Leger and Thivierge, 1988). The full data set and stronger reliability results from the single subject design attained suggests that inter subject differences may influence the device's ability to collect precise information. Body type was not formally assessed though anecdotally the within subject participant, from which the full data set was attained, possessed ectomorph characteristics. Although firm conclusions cannot be drawn from this issue, further work should be completed on the effects of body shape, generic user set-up information and data credibility.

Velocity specific analysis allows for identification of micro level limits in the equipment though at times data sets begin to reduce in number and this can affect the statistical analysis. For example low ICC values within inter and intra reliability velocity specific analysis if reported out of context could be misinterpreted, though could attributed to low number of data points, especially as when data was amalgamated r values were deemed strong.

Some of the variation in the data collected can be attributed to a number of sources and needs to be factored in to any analysis of new monitoring technology. Inter and intra subject biological variation (i.e. circadian rhythm, fatigue or subject motivation) and general “noise” from the testing environment (i.e. EMG) can influence reproducibility of data. Additionally some technical error will exist which is outside the control of the researcher, all of which influence statistics outcomes and conclusions drawn (Achten and Jeukendrup, 2003, Hopkins et al., 2001, Massin et al., 2000).

5.5 Conclusion

When considering all data the Bioharness™ can be considered a reliable device within the limitations presented within this study. Within subject reliability data is very strong suggesting the fit of the device on different individuals could be an important factor in attaining consistent data especially for HR and BF. Being able to access a reliable and valid monitor which measures a range of physiological variables simultaneously in free living conditions will allow for further invaluable understanding of human performance in a variety of environments. Having established the reliability and validity of the Bioharness™ system within a laboratory setting, it seems a logical next stage in the progression of the research project is to assess the validity and reliability of the Bioharness™ in a less controlled field based environment which better reflects the environment in which the device has been designed to operate within.

Chapter 6 - Field Based Reliability and Validity of the Bioharness™ Monitoring System

6.0 Abstract

The Bioharness™ device is designed for monitoring physiological variables in free-living situations but has only been proven to be reliable and valid in a laboratory environment. Therefore, this study aimed to determine the reliability and validity of the Bioharness™ using a field based protocol. Twenty healthy males participated. Heart rate (HR), breathing frequency (BF) and accelerometry (ACC) were assessed by simultaneous measurement of two Bioharness™ devices and a test-retest of a discontinuous incremental walk-jog-run protocol (4 – 11 km.h⁻¹) completed in a sports hall. Adopted precision of measurement devices were; HR: Polar T31 (Polar Electro), BF: Spirometer (Cortex Metalyser), ACC: Oxygen expenditure (Cortex Metalyser). For all data, precision of measurement reported good relationships ($r = .61$ to $.67$, $P < .01$) and large Limits of Agreement for HR (> 79.2 beat.min⁻¹) and BF (> 54.7 br.min⁻¹). ACC presented excellent precision ($r = .94$, $P < .01$). Results for HR ($r = \sim .91$, $P < .01$; CV $< 7.6\%$) and ACC ($r > .97$, $P < .01$; CV $< 14.7\%$) suggested these variables are reliable. BF presented more variable data ($r = .46 - .61$, $P < .01$; CV $< 23.7\%$). As velocity of movement increased (> 8 km.h⁻¹) data became more erroneous. A data cleaning protocol removed gross errors in the data analysis and subsequent reliability and validity statistics improved across all variables. In conclusion, the Bioharness™ HR and ACC variables have demonstrated reliability and validity in a field setting, though data collected at higher velocities should be treated with caution. Measuring human physiological responses in a field based environment allows for more ecologically valid data to be collected and devices such as the Bioharness™ could be used by exercise professionals to begin to further investigate this area.

Key Words: Multi-variable, Physiological monitoring, Ecological validity, New technology

6.1 Introduction

Exercise Science research is ultimately completed to provide an improvement for the coach and performer to implement. Advances in human monitoring technology now permit multi-variable data to be recorded unobtrusively and analysed during or post sporting performance (Achten and Jeukendrup, 2003, Jobson et al., 2009). The integration of multiple “physiologically” related variables could provide more ecologically valid and accurate information on athletes and consequently improvements in performance, all of which coaches have requested (Brage et al., 2005, Carling et al., 2009, Foster et al., 2006, Williams and Kendall, 2007). Paradoxically though, the use of new technology by some exercise and coaching professionals is limited in some sports (Buchanan, 2008). Moreover, it has been reported that at times, inadequate dissemination or application of research to wider sport professionals creates a “gap” in understanding between exercise science research and actual coaching practice (Bishop, 2008, Bishop et al., 2006, Williams and Kendall, 2007). The limited and disjointed dissemination of information could be linked to the lack of valid and reliable field based research tools.

As noted earlier (Chapters 4 and 5), the Bioharness™ is promoted as a field based physiological measuring system. Earlier investigations (Chapter 4 and 5) noted that the Bioharness™ was shown to be reliable and valid in a laboratory environment with Hailstone and Kilding (2011) supporting this view with regards to breathing frequency. It is common practice for new applied physiological monitoring technology to be initially assessed in a controlled laboratory based environment and if acceptable levels of precision are identified, it is logical to go on to complete field/free movement activities (Grossman et al., 2006, Leger and Thivierge, 1988, Rowlands et al., 2004, Trost et al., 2005). There is a plethora of sport specific field based testing protocols though many lack wider ecological validity with regards to movement patterns and velocities included within them (Carling et al., 2009). To capture a broad activity spectrum, combining and adapting recognised field based walking (Brown and Wise, 2007) and progressive running tests (Ledger et al., 1988, Ramsbottom et al., 1988) may be the better option, especially if assessing the capacity of a new physiological measuring device for a wide sporting audience.

In summary, there are gaps in the literature with regards to field based testing of applied technology and many prediction equations within field based devices are based from data collected from laboratory studies (Welk et al., 2000). Having already determined the validity and reliability of the Bioharness™ under laboratory conditions, understanding the possible changes in precision of measurement from the laboratory to the field is an important step within the research process. The

aim of this study is to assess the reliability and validity of each variable measured in the Bioharness™ in relation to criterion measures within a physically active field based setting.

6.2 Methods

6.2.1 General design

To assess the Bioharness™ in a field based environment, appropriate respective criterion measures and protocols were identified. Data collected used one synchronized timeline linked to a laptop computer. A discontinuous incremental walk-jog-run (WJR) protocol, over 20 m, was developed after considering intermittent activity patterns witnessed in athletic performance (Carling et al., 2009) and adapting other recognised field based protocols (Brown and Wise, 2007, Ledger et al., 1988, Ramsbottom et al., 1988). Reliability and validity of accelerometry (ACC), heart rate (HR) and breathing frequency (BF) were assessed. The validity experimental design only permitted analysis of ACC as one data set, though velocity specific analysis was permitted within the reliability testing. Due to technical limitations the other two Bioharness™ variables, skin temperature and posture were not assessed in this study.

6.2.2 Apparatus

Overview of the Bioharness™ monitoring device

The Bioharness™ device is described previously in 4.2.2.

6.2.3 Participants

After securing local institutional ethical agreement (Ethics No LS1/10/10P) (Appendix 1), 20 male volunteers (Mean \pm SD; age 21.5 ± 2.8 years, body mass 71.4 ± 7.9 kg, body stature 1.79 ± 0.1 m) who were physical active and injury free consented to participate. Participants refrained from consuming alcohol and caffeine, kept hydrated and rested 24 hours prior to testing. On arrival to the testing area stature (Seca 214, Birmingham, UK) and body mass (Seca 761, Birmingham, UK) were measured (Stewart and Eston, 2007).

6.2.4 Procedures

Precision of Bioharness™; Validity of Heart rate (HR), Breathing Frequency (BF) and Accelerometry (ACC)

One standard Bioharness™ device was concurrently compared with adopted criterion measures. Precision of the HR, BF and ACC were assessed by participants (n=10) completing the WJR shuttle protocol. Adopted criterion measures were discussed in Chapter 4 (section 4.2.4) and within this procedure were, for HR, the Polar T31 (Polar Electro™, Kempele, Finland). For BF, a face mask (Hans Rudolf Inc, USA) was worn by participants in order to connect a Tripple-V spirometer which was attached to a portable metalyser (Metamax 3B™; Cortex Medical, Germany; weight 650g). Oxygen (O₂) expenditure was assessed for ACC also using the aforementioned portable metalyser which was calibrated prior to testing according to the manufacturers specifications. The latter criterion (O₂ expenditure) is considered an indirect measure of ACC (Rowlands et al., 2004). All equipment was fitted on to participants by one experienced researcher throughout all phases of data collection.

6.2.5 Reliability of HR, BF, ACC

Test-retest design

Using one standard Bioharness™ device, participants (n=10) completed the same WJR shuttle protocol using a test-retest design. Re-tests were completed at the same time of day, between 48 and 72 hours apart, with participants instructed to follow same pre-test protocol before testing.

Simultaneous wearing of two Bioharness™ devices

Using two standard Bioharness™ devices, of similar age and usage, participants (n=10) completed the WJR protocol. One device (B) was positioned in the normal position around the chest as described by manufacturer. The second device (A) was positioned directly above the first without being in contact with the former.

6.2.6 WJR Test protocol

Test protocol - General information

In a purpose built indoor sports hall (20.1 ± 2.5 °C) the protocol consisted of participants completing a discontinuous WJR 20 meter shuttle activity starting at 4 km.h⁻¹ and increasing to 11 km.h⁻¹

mirroring a wide range of physical activity/exercise tasks in the wider sporting world. Two days before data collection commenced participants received a full briefing of the protocol at the location of test, including a familiarisation period with equipment to be worn and a partial dry-run practice of each stage without equipment.

Walking stage

With monitoring equipment fitted and data being collected, a 10 minute familiarisation period occurred. When the participant was ready, on the lead experimenters command, participants received a 10 second count down before completing a 6 minute walking stage (Brown and Wise, 2007). Initially walking was at a velocity of 4 km.h⁻¹ for 3 minutes after which this increased to a velocity of 6 km.h⁻¹ for a further 2 minutes. Maintaining the correct velocity for these walking stages was assured by the use of research team acting as pace makers. At the end of the walking stage participants had 1 minute of unrecorded active rest before the jog-run shuttle activity was started. Within this walking test phase, data were collected for the last 60 seconds of each of the respective active 4 km.h⁻¹ and 6 km.h⁻¹ stages.

Jog-Run stage

Utilising the Multi Stage Shuttle Run (MSSR) (Ledger et al., 1988, Ramsbottom et al., 1988) participants completed 6 min 20 seconds of 20 metre shuttles, which equated to Level 1 to the end of Level 6 of the MSSR. Jog-run shuttles were completed in time with an audible beep (MSSR CD version; Coachwise Ltd, UK) relayed to participants via a laptop computer and speaker system. Participants increased velocity by 0.5 km.h⁻¹ at ~1 minute intervals starting at 8 km.h⁻¹ increasing through to 11 km.h⁻¹ and data were collected for the duration of stage.

6.2.7 Data Analysis

Data were exported to statistical software packages (Excel Microsoft Windows, USA; SPSS v17, SPSS Inc, Chicago, USA) for analysis. Concurrent validity for all variables were analysed against their respective criterion measures, identifying means and standard deviations ($M \pm SD$) for the data. To fully understand the data generated, a range of reliability and validity statistics in combination with descriptive data has been previously been reported (Bland and Altman, 1986, Brunton et al., 2000, Hopkins, 2000a, Hopkins et al., 2009).

Characteristics of the data set were considered and appropriate statistical procedures were followed thereafter. After plotting the predicted against the residuals for HR and BF, data were considered to

be non-uniform (i.e. heteroscedastic) so were transformed logarithmically (log) in order to provide a true interpretation (Atkinson and Nevill, 1998, Hopkins, 2000a, Hopkins et al., 2009). It was decided that descriptive data for these variables would be reported in absolute values while reliability and validity statistics are presented log transformed. The combined data presentation approach was determined in order for comparison with other studies to occur, the majority of which have reported absolute data.

Adopting a composite of reliability and validity statistics may provide a more informed view to assess agreement between methods (Harper-Smith et al., 2010). The following statistical analysis was calculated for each variable; Descriptive statistics including absolute mean bias and 95% Confidence Intervals/limits (CI/CL). Validity statistics (log transformed) included; Mean bias, 95% Limits of Agreement (LoA), Pearson's Product Moment Correlation Coefficient (PCC), Coefficient of Determination (CoD). Reliability statistics included; Mean difference, Coefficient of Variation (CV), Intra Class Correlation Coefficients (ICC). Within the descriptive statistics, the mean bias and associated 95% CI/CL provides an indication of raw difference between the data sets. Correlation coefficients, such as PCC/ICC (r), provide a good indication of the relationship between data sets. Boundaries for the correlation statistics are not confirmed, though amalgamated thoughts of Leger and Thivierge (1988) and Hopkins (2000b) suggest; $r > .9$ Excellent or very strong, $r = .7 - .9$ Very large, $r = .5 - .7$ Good to moderate, $r < .5$ Moderate to minor. CoD (r^2), linked to the correlation analysis, express the variance in one variable that can be attributed to the second variable (Atkinson and Nevill, 1998, Bland and Altman, 2003, Brunton et al., 2000, Winter et al., 2001). Correlation statistics should not be reported in isolation as they can be blind to bias (Bland and Altman 2003). As noted elsewhere (Finni et al., 2007), the LoA method (Bland and Altman, 1986) is used to compare the agreement between methods. Summarising the differences between the two methods is a corner stone of the process. It is expected that the differences outside of ± 2 SD from the mean difference are not practically important. If 95% of data are within 2 SD it is considered an acceptable 'limit of agreement' and methods or equipment is thought to be interchangeable (Bland and Altman, 2003). LoA cannot be used when units between two methods are not comparable hence ACC data is not analysed in this way. An acceptable reliability boundary for CV ($< 10\%$) has been cited in some papers though this is not accepted unanimously in the literature (Atkinson and Nevill, 1998, Currell and Jeukendrup, 2008, Hopkins, 2000b).

Previously reliability and validity research has removed data sets when data is clearly erroneous in the belief that a technical breakdown has occurred with the system (Leger and Thivierge, 1988). Analysis completed which includes erroneous data sets would possibly reduce the practical usefulness of the results especially if the erroneous data was linked to only two or three participants.

The reporting of data removal (i.e. cleaning) has been used as an additional validity statistic with high volumes of data being removed reducing the credibility of the device. Based on estimated maximal values of each physiological variable (McArdle et al., 2009) and considering other literature (Field and Miles, 2010, Leger and Thivierge, 1988) the following data set removal criteria was established; If absolute mean of a data set difference was ± 20 beat.min⁻¹ for HR, or ± 7 br.min⁻¹ for BF, from the criterion the participants data from the specific velocity stage was removed.

6.3 Results

6.3.1 Validity of the BioharnessTM; Precision of measurement results for HR

When considering all data (n=10 participants) collected HR data (Table 18) produced good to moderate relationships ($r = .61$; $P < .01$) with a relatively low mean bias though LoA were large. When data with clear technical error was removed (HR n=9 participants remain) the relationship became stronger, mean bias and LoA reduced. At 4 – 6 km.h⁻¹ relationships in HR data are very strong with a small mean bias and LoA. Above 8km.h⁻¹ precision reduced with relationships becoming moderate to minor, and LoA became large ($> \pm 97$ beat.min⁻¹). After data cleaning at 8 – 10.5 km.h⁻¹ (n=9) and 11 km.h⁻¹ (n=8) results improved with very large to moderate relationships seen, smaller mean bias and LoA.

6.3.2 Precision of measurement results for BF

When all BF data (n=10) are considered (Table 18) good to moderate relationships ($r = .67$; $P < .01$) are noted though LoA were large. Velocity specific precision at 4 – 6 km.h⁻¹ presented moderate relationships but large LoA remained ($> \pm 43.4$ br.min⁻¹). At higher velocities (> 8 km.h⁻¹), statistics presented reduced precision. Cleaned data (n=9) improves results with good relationship ($r > .60$; $P < .01$), reduced mean bias (< -1.43 br.min⁻¹) though LoA remains high ($> \pm 36.7$ br.min⁻¹).

6.3.3 Precision of measurement results for ACC

ACC data (Table 19) produced excellent data relationships between oxygen uptake (mL.kg⁻¹.min⁻¹) and VMU counts ($r > .90$; $P < .01$) at both second-to-second and over a mean 10 second assessment.

Table 18. Precision of HR (beat.min⁻¹) and BF (br.min⁻¹) data in comparison to respective criterion measure.

Variable	Velocity	Data	Predicted M ± SD	Criterion M ± SD	Mean bias ±95%CI	Mean bias ±95%LoA	PCC <i>r</i>	CoD <i>r</i> ²	
<i>HR (beat.min⁻¹)</i>	All velocities	All	123.3 ± 38.4	125.9 ± 34.4	-2.56 ± 1.4	-2.56 ± 79.2	.61*	37%	
		Clean	122.6 ± 34.0	122.6 ± 34.6	-0.02 ± 0.5	-0.02 ± 11.5	.98*	96%	
	4-6 km.h ⁻¹	All	92.6 ± 11.9	91.3 ± 10.9	1.26 ± 0.4	1.26 ± 9.6	.92*	85%	
		Clean	-	-	-	-	-	-	
	8—10.5 km.h ⁻¹	All	143.7 ± 30.4	142.3 ± 21.6	1.45 ± 1.6	1.45 ± 97.4	.58*	34%	
		Clean	141.8 ± 22.0	142.5 ± 21.2	-0.64 ± 0.7	-0.64 ± 12.2	.93*	87%	
	11 km.h ⁻¹	All	146.3 ± 18.3	170.4 ± 11.5	-24.08 ± 6.4	-24.1 ± 120.4	.57*	33%	
		Clean	173.2 ± 14.2	175.3 ± 9.6	-2.08 ± 1.9	-2.08 ± 12.7	.67*	45%	
	<i>BF (br.min⁻¹)</i>	All velocities	All	29.1 ± 7.2	32.7 ± 11.5	-3.57 ± 0.4	-3.57 ± 54.7	.67*	45%
			Clean	29.0 ± 7.4	30.2 ± 8.2	-1.19 ± 0.3	-1.19 ± 34.4	.82*	67%
4-6 km.h ⁻¹		All	23.9 ± 4.1	24.9 ± 6.6	-0.96 ± 0.5	-0.96 ± 43.4	.59*	35%	
		Clean	23.4 ± 3.7	24.0 ± 5.0	-0.60 ± 0.4	-0.60 ± 36.7	.60*	36%	
8—10.5 km.h ⁻¹		All	30.5 ± 5.8	35.3 ± 10.7	-4.79 ± 0.87	-4.79 ± 57.3	.48*	23%	
		Clean	30.6 ± 5.9	32.4 ± 6.2	-1.81 ± 0.42	-1.81 ± 33.5	.70*	49%	
11 km.h ⁻¹		All data	37.0 ± 6.1	43.5 ± 11.4	-6.53 ± 1.81	-6.53 ± 73.7	-.21	44%	
		Clean data	38.6 ± 4.9	40.1 ± 5.9	-1.43 ± 0.45	-1.43 ± 17.1	.83*	69%	

Tabular report of validity statistics: Descriptive statistics, Standard Deviation (SD), Mean Bias, 95% Confidence Intervals (CI), Log transformed mean bias, 95% Limits of Agreement (LoA), Pearson's Product Correlation Coefficient (PCC) and Coefficient of Determination (CoD) across whole data set. * *P* < .01

Table 19. Relationship of ACC data to respective criterion measure (oxygen uptake, mL.kg⁻¹.min⁻¹).

	PCC
	<i>r</i>
Activity (VMU/ct.sec ⁻¹)	.91*
Activity (VMU/ct.mean 10 sec ⁻¹)	.94*

A tabular report of validity statistics: Pearson's Product Correlation Coefficient (PCC) for ACC Vector Magnitude Units (VMU) versus oxygen uptake, mL.min⁻¹.kg⁻¹. * *P* < .01

6.3.4 Reliability of the Bioharness™ during simultaneous wearing of two devices.

Reliability of HR during simultaneous protocol

When all data (n=10) were considered (Table 20) low CV (7.6%) and excellent relationship (*r* = .91; *P* < .01) are noted. At 4 - 6 km.h⁻¹ excellent relationship (*r* = .99; *P* < .01) and low CV (< 2%) are seen though as velocity increased, the strength of the data relationships decrease and CV increases. Data cleaning at 8 km.h⁻¹ and 11km.h⁻¹ (n=9) improves reliability statistics, mirroring the raw values noted at 4 km.h⁻¹.

6.3.5 Reliability of BF during simultaneous protocol

In comparison to HR, the BF results (Table 21) for all data (n=10) were weaker though after data was cleaned, CV decreased and *r* values improved, as they did for HR data (n=8). Even with relatively small change in mean, at lower intensity BF data presents indifferent reliability statistics with moderate-to-high CV (> 14%) and weak relationships in data (*r* < .38). Data cleaning (8 km.h⁻¹ n=7; 11 km.h⁻¹ n=9) improves these statistics with CV < 10%, and *r* values between .52 and .89.

6.3.6 Velocity specific reliability of ACC data during simultaneous protocol

ACC data (Table 22) presents consistent reliability statistics with small change in means and narrow 95% CL. The relationship in data remains significant though reduces from excellent (*r* =.93) to good/moderate (*r* =.66) as velocities increase, while CV is relatively constant through this same period.

Table 20. Reproducibility of the HR (beat.min⁻¹) variable during simultaneous wearing of two devices.

Variable	Velocity	Data	Device A M ± SD	Device B M ± SD	Change in Mean	95% CL	CV%	ICC
<i>HR (beat.min⁻¹)</i>	All velocities	All	140.4 ± 33.3	143.7 ± 34.0	3.32	2.94 to 3.71	7.6	.91*
		Clean	140.7 ± 33.4	141.0 ± 33.4	0.39	0.22 to 0.56	2.9	.98*
	4-6 km.h ⁻¹	All	97.9 ± 15.4	97.7 ± 15.5	-0.29	-0.40 to -0.18	1.6	.99*
		Clean	-	-	-	-	-	-
	8—10.5 km.h ⁻¹	All	150.7 ± 22.7	155.2 ± 23.0	4.54	4.06 to 5.01	6.8	.82*
		Clean	151.7 ± 22.4	152.8 ± 22.2	1.14	0.88 to 1.39	3.4	.95*
	11 km.h ⁻¹	All	172.1 ± 22.9	174.8 ± 14.4	2.63	1.20 to 4.05	14.4	.51*
		Clean	174.6 ± 13.2	173.4 ± 12.9	-1.29	-1.74 to -0.84	2.6	.99*

Tabular report of reliability statistics: Descriptive statistics, Standard Deviation (SD), Change in mean, 95% Confidence Limits (CL), Coefficient of Variation (CV) and Intra Class Coefficient (ICC)

* $P < .01$

Table 21. Reproducibility of the BF ($\text{br}\cdot\text{min}^{-1}$) variable during simultaneous wearing of two devices.

Variable	Velocity	Data	Device A M \pm SD	Device B M \pm SD	Change in Mean	95% CL	CV%	ICC
<i>BF (br.min⁻¹)</i>	All velocities	All	32.2 \pm 12.4	29.6 \pm 7.3	-2.57	-2.88 to -2.55	23.7	.46*
		Clean	30.1 \pm 6.8	29.8 \pm 6.8	-0.38	-0.50 to -0.27	9.0	.86*
	4-6 km.h ⁻¹	All	26.8 \pm 3.3	25.5 \pm 4.5	-1.32	-1.57 to -1.07	14.0	.38*
		Clean	27.0 \pm 2.7	26.0 \pm 3.9	-0.98	-1.19 to -0.77	9.8	.52*
	8—10.5 km.h ⁻¹	All	30.2 \pm 7.9	29.6 \pm 7.3	-0.54	-0.84 to -0.24	22.8	.39*
		Clean	30.5 \pm 7.0	30.4 \pm 6.8	-0.17	-0.31 to -0.03	8.4	.89*
	11 km.h ⁻¹	All	48.1 \pm 20.1	35.9 \pm 6.9	-12.21	-13.59 to 10.82	33.6	.22*
		Clean	36.6 \pm 8.2	36.7 \pm 6.7	0.07	-0.35 to 0.49	8.4	.87*

Tabular report of reliability statistics: Descriptive statistics, Standard Deviation (SD), Change in mean, 95% Confidence Limits (CL), Coefficient of Variation (CV) and Intra Class Coefficient (ICC)

* $P < .01$

Table 22. Reproducibility of the ACC (VMU/ct.sec⁻¹) variable during simultaneous wearing of two devices.

Variable	Velocity	Data	Device A M ± SD	Device B M ± SD	Change in Mean	95% CL	CV%	ICC
<i>ACC (VMUct.sec⁻¹)</i>	All velocities	All	0.91 ± 0.39	0.86 ± 0.36	-0.05	-0.05 to -0.04	12.4	.97*
	4-6 km.h ⁻¹	All	0.29 ± 0.11	0.29 ± 0.10	-0.003	0.01 to 0.00	10.3	.93*
	8—10.5 km.h ⁻¹	All	1.09 ± 0.20	1.03 ± 0.19	-0.05	-0.06 to -0.05	12.6	.80*
	11 km.h ⁻¹	All	1.16 ± 0.18	1.11 ± 0.17	-0.04	-0.06 to -0.03	11.8	.66*

Tabular report of reliability statistics: Descriptive statistics, Standard Deviation (SD), Change in mean, 95% Confidence Limits (CL), Coefficient of Variation (CV) and Intra Class Coefficient (ICC)

* $P < .01$

6.3.7 Reliability of Bioharness™ during the test-retest protocol

Reliability results for test-retest for all HR

For all HR data (n=10) very strong reliability statistics are noted with excellent relationships in data and low CV (Table 23). At 4 - 6 km.h⁻¹, HR data (Table 23) notes small change in mean, low CV (5.9%) and very strong relationships in data ($r = .97, P < .01$). At higher velocities, change in mean and CV increase slightly and relationships decrease from good to moderate. Data cleaning (n=8) improves reliability statistics though change in mean remains approximately -5 beat.min⁻¹.

6.3.8 Velocity specific test-retest reproducibility of BF data

When considering all data (n=10) BF variable presents an indifferent set of statistics. A low change in mean (< 1 br.min⁻¹), high CV and erratic relationships in data are seen (Table 24). Cleaned data (n=8) at 8 – 10.5 km.h⁻¹ presented the strongest relationships ($r = .91, P < .01$) and lowest CV (6.6%) within the data set.

6.3.9 Velocity specific test-retest reproducibility of ACC data

ACC results (Table 25) notes consistent data at all velocities. Very strong relationships in data at 4 – 6 km.h⁻¹ ($r = .84, P < .01$) then diminish as velocity increases though CV remains stable.

Table 23. Reproducibility of the HR (beat.min⁻¹) variable during a test-retest protocol.

Variable	Velocity	Data	Device A M ± SD	Device B M ± SD	Change in Mean	95% CL	CV%	ICC
<i>HR (beat.min⁻¹)</i>	All velocities	All	146.1 ± 35.4	141.1 ± 33.4	-4.26	-4.82 to -3.69	8.0	.92*
		Clean	143.1 ± 34.4	138.8 ± 32.7	-4.30	-4.56 to -3.92	4.6	.97*
	4-6 km.h ⁻¹	All	99.5 ± 16.8	99.7 ± 16.8	-1.82	-2.41 to -1.23	5.9	.89*
		Clean	-	-	-	-	-	-
	8—10.5 km.h ⁻¹	All	157.0 ± 25.0	151.9 ± 22.5	-5.09	-5.89 to -4.28	8.7	.73*
		Clean	156.5 ± 22.7	151.4 ± 21.5	-5.13	-5.55 to -4.71	4.1	.93*
	11 km.h ⁻¹	All	179.9 ± 17.7	175.1 ± 18.5	-4.80	-6.44 to -3.16	7.4	.54*
		Clean	177.6 ± 12.0	172.0 ± 13.3	-5.58	-6.34 to -4.82	2.8	.85*

Tabular report of reliability statistics: Descriptive statistics, Standard Deviation (SD), Change in mean, 95% Confidence Limits (CL), Coefficient of Variation (CV) and Intra Class Coefficient (ICC)

* $P < .01$

Table 24. Reproducibility of the BF ($\text{br}\cdot\text{min}^{-1}$) variable during a test-retest protocol.

Variable	Velocity	Data	Device A	Device B	Change in Mean	95% CL	CV%	ICC
			M \pm SD	M \pm SD				
<i>BF (br.min⁻¹)</i>	All velocities	All	30.6 \pm 7.2	30.4 \pm 7.5	-0.11	-0.33 to 0.11	18.1	.61*
		Clean	31.0 \pm 6.9	31.5 \pm 6.5	0.51	0.39 to 0.64	7.7	.90*
	4-6 km.h ⁻¹	All	24.4 \pm 4.1	23.4 \pm 5.0	-0.99	-1.50 to -0.48	25.1	-.18
		Clean	23.4 \pm 3.0	24.5 \pm 3.9	1.09	0.81 to 1.37	10.1	.65*
	8—10.5 km.h ⁻¹	All	31.4 \pm 6.6	31.6 \pm 6.6	0.22	-0.03 to 0.48	15.9	.63*
		Clean	32.2 \pm 6.0	32.7 \pm 5.7	0.55	0.41 to 0.69	6.6	.91*
	11 km.h ⁻¹	All	37.9 \pm 4.2	37.8 \pm 3.8	-0.11	-0.71 to 0.49	12.0	-.12
		Clean	38.3 \pm 3.2	37.6 \pm 3.2	-0.67	-1.11 to -0.23	7.3	.30*

Tabular report of reliability statistics: Descriptive statistics, Standard Deviation (SD), Change in mean, 95% Confidence Limits (CL), Coefficient of Variation (CV) and Intra Class Coefficient (ICC)

* $P < .01$

Table 25. Reproducibility of the ACC (VMU/ct.sec⁻¹) variable during a test-retest protocol.

Variable	Velocity	Data	Device A M ± SD	Device B M ± SD	Change in Mean	95% CL	CV%	ICC
	All velocities	All	0.85 ± 0.36	0.87 ± 0.36	0.02	0.02 to 0.03	14.7	.92*
ACC (VMUct.sec ⁻¹)	4-6 km.h ⁻¹	All	0.29 ± 0.10	0.31 ± 0.11	0.02	0.01 to 0.02	15.8	.84*
	8—10.5 km.h ⁻¹	All	1.02 ± 0.17	1.05 ± 0.18	0.02	0.01 to 0.03	14.5	.53*
	11 km.h ⁻¹	All	1.10 ± 0.16	1.12 ± 0.16	0.02	0.00 to 0.04	13.2	.39*

Tabular report of reliability statistics: Descriptive statistics, Standard Deviation (SD), Change in mean, 95% Confidence Limits (CL), Coefficient of Variation (CV) and Intra Class Coefficient (ICC)

* $P < .01$

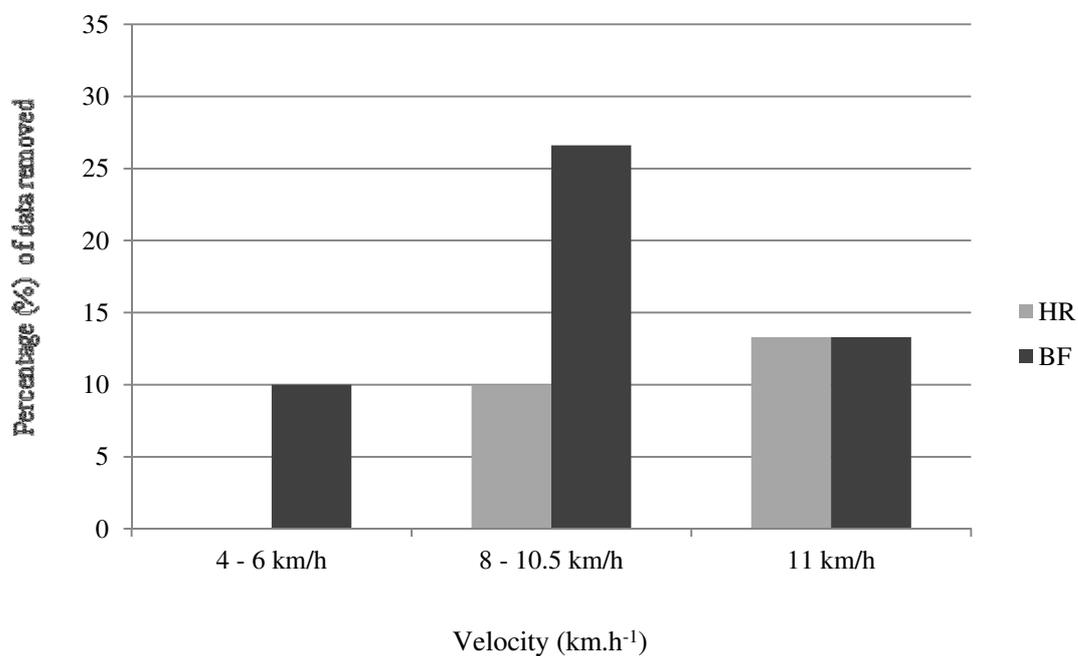


Figure 26. Profile of HR and BF data removal (%) at different velocities during data cleaning process.

6.3.10 Data removal

The trend for the volume of data removal through the cleaning process as velocity increased can be seen in Figure 26. The figure demonstrates more data is removed at higher exercise intensities. No data was removed from the ACC data set.

6.4 Discussion

6.4.1 General findings

This is the first investigation reporting the reliability and validity of the Bioharness™ device in an applied field based scenario. This multi-variable technology is designed to allow physiological monitoring during free movement, therefore understanding precision and variance of data in this environment is important, especially for the exercise scientists seeking to monitor performers in more ecologically valid scenarios. Overall results suggest that HR and ACC variable are reliable and valid but with the BF variable presenting indifferent data which has also been noted previously in a laboratory environment (Chapter 4 and 5). Further specific variable and velocity specific analysis identifies differences in the data sets which are discussed in the following sections.

6.4.2 Accelerometry

When data for each specific variable was considered, the ACC variable presents the strongest reliability and validity, with good data relationships and relatively low variance reported, concurring with previous laboratory based testing (Chapter 4 and 5). Assessment of the validity of the ACC used indirect methods, therefore it was not possible to ascertain how precision of measurement varied with increasing velocities. Reproducibility at different velocities (Table 22 and 25) identified that CV was relatively consistent with a tendency for the variability of ACC data to increase at higher velocities, which is consistent with previous accelerometry research (Troost et al., 2005). Use of piezoelectric technology within accelerometers is now well established (Chen and Bassett, 2005) and the non-reliance of this variable on a skin-based contact for data production may explain the positive reliability and validity results in this field environment.

6.4.3 Heart rate and Breathing frequency

In comparison to ACC and considering all data, HR and BF variables presented less precision and more variance. When HR is investigated specifically (Table 18, 20, 23), it appears this variable produced a good level of precision and reproducible data at walking pace (i.e. 4-6 km.h⁻¹) though was less conclusive as velocities increased. Larger LoA are noted at velocities > 8 km.h⁻¹ though reliability statistics remained relatively strong until the highest velocity, all of which mirrors the laboratory based results on this device (Chapter 5). For similar HR technology tested within a laboratory

environment, a slightly lower CV is reported (Kent et al., 2009) but it is documented that there is a decrease in precision at velocities $> 9 \text{ km}\cdot\text{h}^{-1}$ (Kingsley et al., 2004, Terbizan et al., 2002), which is constant with these research findings.

BF data were the weakest of all variables assessed (Table 18, 21 and 24). Relatively large LoA, moderate-to-low relationships and high CVs were seen in data throughout all velocities which reflect previous laboratory based data reported in Chapter 4 and 5. In comparison, the Lifeshirt™ monitoring device, which uses similar BF technology, reported CV of ~10% though this was after averaging data in the last 30 seconds of a treadmill based protocol (Kent et al., 2009). Physiologically, when measured directly, BF has been noted as having a relatively high test-retest variance (Kent et al., 2009), therefore the indirect assessment method of respiratory inductive plethysmography technology may add another layer of variance on to an already inconsistent variable.

Interestingly, the Bioharness™ BF variable has been tested previously (Hailstone and Kilding, 2011) and contrary to this research the variable was reported to be valid and reliable within a treadmill based protocol. Without identifying the version of the Bioharness™ device and using different statistical techniques, the authors reported no significant differences at different physical intensities, identifying $\sim 2 \text{ br}\cdot\text{min}^{-1}$ as an acceptable difference. Critically, Hailstone and Kilding (2011) specific data capture and analysis procedure seemingly only took a short (15 second) sample of respiratory data. The 15 seconds of data was then cleaned, though no overview of the cleaning process was provided, and then averaged before statistical procedures were applied. It is hypothesised that the current research presents a more comprehensive view of the BF variable with data sampled for 2 minutes at $4 - 6 \text{ km}\cdot\text{h}^{-1}$, 5 minutes at $8 - 10.5 \text{ km}\cdot\text{h}^{-1}$, 1 minute at $11 \text{ km}\cdot\text{h}^{-1}$ all of which is presented in raw and clean data, without averaging. Different data handling methods can influence results, a standard data processing method should be considered in future research in order to clearly compare devices and research (Boudet and Chamoux, 2000, Kent et al., 2009). Exercise professionals and coaches using the Bioharness™ would want to know the data precision as it is reported from the device, so it is felt this current research may be providing a more realistic view of precision and reproducibility.

6.4.4 Data cleaning and variance

The cleaning protocol on HR and BF data was completed in an attempt to present a comprehensive picture of the device, highlighting and removing gross technical error from the data through the employment of recognised procedures (Field and Miles, 2010, Leger and Thivierge, 1988). With both raw and clean data sets presented, the exercise professional can ascertain further information on

stability of each variable in the device. With regards to the latter point, the majority of data sets were removed errors at velocities $> 8 \text{ km.h}^{-1}$ (Figure 26) and primarily from specific individuals, rather than across all participants. In comparison to the HR variable, the BF variable had more data sets removed with a peak occurring at $8 - 10.5 \text{ km.h}^{-1}$. When cleaned data is assessed, both HR and BF variable improved the reliability and validity, though the latter variable still presented weaker results confirming previous comments about respiratory measurement within this device.

There are possible reasons for increased data variance from the Bioharness™, especially at higher velocities, for HR and BF. Data production for HR and BF, using chest mounted electrodes and respiratory inductive plethysmography respectively, are reliant on a constant close connection with the performer's body. It is posited that physical activity at higher velocities are associated with possible breaks in connection with the performers body, increasing movement artefacts linked to chest strap instability or electromyogram noise, all of which may intermittently corrupt data (Astrand et al., 2003, Boudet and Chamoux, 2000, Cho et al., 2009, Witt et al., 2006).

The total variability of a device is the combination of biological variation and technical variation (Hailstone and Kilding, 2011) and an outcome of the research design (i.e. test-retest and simultaneous wearing) provided an opportunity to consider these two sources of variation. The simultaneous data collection for each variable may logically mean that biological variance is removed. A limitation for the latter was it meant that one of the two Bioharness™ devices were not in the manufacturers recommended optimal position possibly allowing for possible increased artefacts to influence data collection (Cho et al., 2009, McArdle et al., 2005, Welk, 2005, Witt et al., 2006).

Reliability statistics for ACC and HR were stronger (i.e. less variance) from the simultaneous wearing of two Bioharness™ devices in comparison to the test-retest protocol (Tables 20, 22, 23 and 25). With relatively free movement permitted, it is more likely differences in ACC data will occur between trials. Other accelerometry research where simultaneous data collection has occurred concurs with this research, noting correlation coefficients between $.72 - .92$, when devices are positioned on contra-lateral hips (Troost et al., 2005). Variation in data from simultaneous wearing of the ACC could be attributed to the positioning of the device on the chest as the ACC is calibrated to a specific anatomical location (Welk, 2005).

Day-to-day variation of heart rate can vary, in absolute terms, between $3 - 8 \text{ beat.min}^{-1}$ with higher variance reported for sub-maximal activity in comparison to maximal activity (CV $\sim 4.1\%$ sub-max;

~1.6% max) (Achten and Jeukendrup, 2003, Astrand et al., 2003, Lamberts et al., 2004, Michaels and Cadoret, 1967). CV results for the simultaneous HR data collection (Table 20) fall within this range during walking and also at the other higher velocities when technical error is removed and, this may provide further indirect evidence that the HR variable is reliable. These positive results from the simultaneous wearing of the device also suggest there is some flexibility, as seen with other established chest mounted HRM, with the anatomical location and fitting of the Bioharness™ around the chest and subsequent capturing HR data.

Moreover, it does not seem that the same flexibility of placement may exist for BF variable as data comparisons between simultaneous and test-retest were inconclusive (Table 21 and 24). Though it is clear that each data set continued to produce comparatively weak reliability statistics which could be linked to the positioning and technical set up of the device (McCool et al., 2002), changes in breathing mechanics as velocity of movement increases (McArdle et al., 2005, Powers and Howley, 2007) and/or, as mentioned, that the notion that respiratory rate is normally variable (Kent et al., 2009).

6.4.5 Laboratory testing versus Field testing

The relationship between measurements in a controlled environment when compared to more free movement based trials commonly identifies lower precision in the latter condition with the external environment adding a further dimension to movement patterns in participants (Charmari et al., 2004, Vanhelst et al., 2009, Welk et al., 2004). Comparing equivalent data collected on the Bioharness™ (Chapter 4 and 5), a trend of less precision and more variable data within a field based environment is seen in comparison to laboratory testing. Considering the most consistent variable during testing, ACC demonstrated a trend of greater variance in the field environment in comparison to a laboratory treadmill based event, a trend of which has been noted elsewhere (Bartlett et al., 2007, Hendelman et al., 2000, Welk, 2005, Welk et al., 2000). The WJR protocol allowed relatively free movement with non-specified turning episodes every 20 metres, involving acceleration and deceleration, therefore different running mechanics and physiological effort may well occur (Vanhelst et al., 2009), all of which can add to variability of data collected. Knowing how performers' data sets may change from a controlled to a field environment is a useful process for the exercise scientist who works in both scenarios.

6.5 Conclusions

The Bioharness™ ACC and HR variables demonstrate relative reliability and validity in the field based environment. Although at higher velocities the precision and reproducibility was less effective, within the scope of this thesis the lower velocity (i.e. $<10 \text{ km}\cdot\text{h}^{-1}$) activity occurs more frequently between deliveries/overs within the bowling activity. BF variable appears to present more variable data and may need further development to be effective in the wider active or sporting environment. Any improvements to the device should be balanced with the maintenance of its unobtrusive and light-weight structure. It is clear that there is scope for more applied research to be completed, using up-to-date technology within a variety of sports or activities, which will allow a clearer understanding of the key performance variables to be gained (Bartlett, 2006). Previous literature has highlighted that elite coaches want real life ecologically valid, applied research that can be utilised for performance enhancement (Achten and Jeukendrup, 2003, Gore et al., 1993) and this research provides a useful insight in to the Bioharness™ monitoring device for coaches and exercise scientists alike. The research in the previous chapters (Chapters 4, 5, 6) assessing the reliability and validity of the Bioharness™ has now provided an indication of which variables are suitable to use for analysis of sporting performance in fast-medium bowlers. The next phase of the research is to use the system during competitive sporting performance and assess if data collected from the device can assist coaches and players with their performance.

**Chapter 7 - Professional sporting performance and the use of the
Bioharness™ monitoring device**

7.0 Abstract

Coaches require more applied data accessed from competitive in-match environments to provide a unique insight into players' performance. Therefore, the objectives of this study were to (1) assess the effectiveness of the Bioharness™ mobile physiological monitoring system to develop a physiological profile of fast-medium bowlers across One Day (OD) and Multi Day (MD) formats of professional cricket; and (2) using this device to investigate the relationship between in-match data and bowling performance. Ten professional cricket bowlers used the Bioharness™ during competitive matches, over three seasons, collecting >80 hours of data in-match. Data was organised into match states using the accelerometry data which corresponded to bowling activity. Heart rate (HR) data had polynomial smoothing applied. Results for performance profile reported that OD cricket stimulated higher mean heart rate (HR) (OD, 142 vs MD, 137 beats.min⁻¹, $P < .05$; Effect Size (ES) ≥ -0.13) when compared to MD matches, except for age related HR max, HR 10 seconds, pre and 60 seconds post bowling ($P > .05$). Higher mean HR was reported during bowling (OD, 142 vs MD, 137 beats.min⁻¹; ES ≥ -0.12), between over (129 vs 120 beats.min⁻¹, $P < .01$; ES ≥ -0.27) and fielding (115 vs 106 beats.min⁻¹, $P < .01$; ES ≥ -0.20) activity. Accelerometry (ACC) data presented a trend of higher values in OD cricket with peak acceleration significantly higher when all data was reported (OD, 227.6 vs MD 214.9 ct.episode⁻¹, $P < .01$; ES -0.14) and during bowling activity (234.1 vs 226.6 ct.episode⁻¹, $P < .05$; ES -0.12). Higher OD lateral right axis values were reported in combined data (-89.5 vs -84.8 ct.episode⁻¹, $P < .01$; ES -0.11), and during bowling (-99.5 vs -93.5 ct.episode⁻¹, $P < .05$; ES -0.13). Left lateral axis was lower during OD bowling (115.4 vs 122.6 ct.episode⁻¹, $P < .05$; ES -0.17) and in between over activity (52.5 vs 66.4 ct.episode⁻¹, $P < .05$; ES -0.20). Except for a lower OD value in sagittal anterior axis (172.7 vs 222.5 ct.episode⁻¹, $P < .05$; ES -0.27). Data for ACC were higher during OD fielding activities ($P < .01$; ES ≥ -0.25). When data was applied to bowling performance (runs per over) no significant relationships were identified. The Bioharness™ successfully identified differences in HR and accelerometry between OD and MD cricket, with the OD format having greater cardio-vascular cost and higher activity counts. Specific ACC data requires further investigation to confirm the role of specific axes during different match states. The lack of association with the Bioharness™ and bowling performance maybe related to complexity of the interacting variables deciding the outcome during competitive cricket. This research successfully presents in-match data from professional sport which has provided a better understanding for coaches and exercise scientists of the requirements of fast-medium bowling in cricket. Furthermore, clear differentiation between the physical demands of professional OD and MD cricket has been established. Therefore, physiological preparation for each format should reflect this. Future research should utilise mobile monitoring technology, short and long term, to help optimise sporting performance and avoid injury occurrence.

Key words; Cricket, Fast-medium bowling, Physiological profiles, In-match, Heart rate, Accelerometry

7.1 Introduction

Previous chapters 3 to 6 in this research have presented a need for valid and reliable unobtrusive mobile monitoring technology which offers the coach and player information streams providing an insight in to competitive performance. This research has identified the Bioharness™ device as being a valid and reliable tool at appropriate velocities for cricket which, if used on players where the need exists, could be used to collect performance related data in a competitive match without compromising or affecting individual performances.

Within a cricket team, fast-medium bowling is recognised as the most physically demanding role with performers covering more absolute distance, the most distance per hour and completing a higher number sprints in comparison to other playing positions (Petersen et al., 2010, Petersen et al., 2011b). There is a growing indication that One Day (OD) cricket has a higher physical work load than Multi Day (MD) cricket with greater absolute distances, more sprints completed and less recovery time reported in this shorter format of the game (Petersen et al., 2010, Petersen et al., 2011b, Petersen et al., 2009c). Fast-medium bowlers also have the highest injury occurrence and shortest career spans relative to their peers (Elliott, 2000, Dennis et al., 2005, Dennis et al., 2008) which may be linked to the limited literature on the athletic profile of fast-medium bowlers (Pyne et al., 2006, Stuelcken et al., 2007). In contrast to other sports, such as football and rugby, team and position specific research on physiology and performance is well documented (Reilly et al., 2000, Duthie et al., 2003, Barbero-Alvarez et al., 2008).

Attempts have been made to report physiological responses during bowling (Table 1) though these have mainly been in simulated non-competitive bowling environments. The latter is surprising, as advances in physiological monitoring technology now permit the exercise scientist and coach to access more objective data from in-match competitive situations, potentially providing new insights in to performance, training and coaching (Petersen et al., 2010, Petersen et al., 2009b). Simulated bowling episodes have presented exercise professionals with initial physiological profiles of bowlers but, these studies leave a question surrounding the ecological validity of the data (Burnett et al., 1995, Duffield et al., 2009, Gore et al., 1993). When physiological data from simulated and competitive environments are compared, HR (the most widely reported variable) appears to differ (i.e. ~ 10 beats \cdot min $^{-1}$) between the two bowling events suggesting there is a need for more in-match monitoring of performers (Duffield et al., 2009, Johnstone et al., 2008).

Current fast-medium bowling research (Duffield et al., 2009, Johnstone et al., 2008, Petersen et al., 2009a, Petersen et al., 2011b) has seen a logical focus on the physical responses and movement

during the actual bowling episode, though this information is far from complete, has not fully addressed differences in match format and data are often presented from relatively short collection periods. Moreover, the between over bowling activity, where-by during competitive situations the fast-medium bowler has time to recover, is another key window of performance yet to be investigated. In previous research this between over non-bowling episode, is often not fully explained and mentioned as a side issue when it could be hypothesised that the activity or recovery completed within that period may affect performance in the subsequent bowling period.

A key performance objective for bowlers across all formats of cricket is maintenance of accuracy in order to reduce the runs scored over-to-over which in turn increase pressure on batters (Davies and Collins, 2012, Phillips et al., 2012, Woolmer et al., 2008). From the sparse data set, somewhat contradictory findings exist with regards to the causes of changes in bowling performance. For example, less accuracy is reported when technique alters within a bowling spell (Portus et al., 2000) and also hydration status may affect performance (Devlin et al., 2001). Contrary to the previous, Duffield et al (2009) did not find any significant change in ball-to-ball accuracy or speed of delivery during 2 x 6 over spells. Despite seemingly a vital theme for the coach and player, the area of cardiovascular stress, activity (i.e. physiological work), and bowling performance has yet to be considered within a competitive match situation.

Therefore, by using new unobtrusive monitoring technology (Bioharness™) already highlighted in earlier chapters (Chapters 4, 5, 6) further investigation may be possible to fully understand fast-medium bowlers' physiological responses and relative bowling performance during OD and MD competitive matches. This information could improve conditioning and recovery practices, optimising playing performance and therefore extend career longevity (Petersen et al., 2011a). Moreover, it is now possible for technical coaches to monitor players' physiological performance in real-time thus permitting the coach to make tactical decisions about players if a link between a physiological variable and performance could be identified.

The aim of this study were to; (1) develop a performance profile of professional fast-medium bowlers across different forms of competitive cricket through measuring in-match physiological responses using the Bioharness™ mobile monitoring device, and (2) investigate the relationship between bowling performance and physiological data captured by the Bioharness™ mobile monitoring device from professional cricket fast-medium bowlers during competition.

7.2 Methods

7.2.1 General Design

To assess the in-match physiological responses of fast-medium bowlers using the Bioharness™ device a longitudinal strategy was adopted where-by data was collected from performers over 3 seasons. Participants were requested to wear the monitoring device during the days play and data were analysed retrospectively using official match scorers' information and activity patterns during the match.

7.2.2 Apparatus

The Bioharness™ device is described previously in Chapter 4 (section 4.2.2).

7.2.3 Participants

After securing local institutional ethical agreement (Ethics No LS3/2/09P(R1) (Appendix 1) 10 professional first-class cricketers (mean \pm SD; age 24.8 ± 5.2 years) classified as right arm fast-medium paced bowlers (Cricinfo, 2012, Engel, 2007) consented to participate in the research project. Although it was not possible to assess bowlers' speed of delivery, all performers have been recorded bowling consistently between 128 – 136 km.h⁻¹ based on data collected from televised matches. Physiological and in-match data was collected during the first 3 months of competitive performance level matches (i.e. first-class and 2nd XI), over 3 consecutive seasons. An overview of the participant's physiological profiles is provided in Table 26.

Table 26. Physiological profile of 10 first-class fast/medium bowler participants (mean \pm SD).

Anthropometry	Mass (kg)	89.7 \pm 10.8	Strength	5RM Bench (Kg)	76.3 \pm 12.5
	Height (cm)	186.9 \pm 7.9		5RM Squat (Kg)	106.0 \pm 19.8
Body Composition	Sum of 8 skin fold (mm)	86.2 \pm 19.6	Power	CMJ (cm)	43.4 \pm 4.3
				Speed (linear)	5 metres (sec ⁻¹)
Speed (linear)	10 metres (sec ⁻¹)	1.8 \pm 0.1	Endurance	VO ₂ max (mL.kg ⁻¹ .min ⁻¹)	52.3 \pm 4.1
	20 metres (sec ⁻¹)	3.0 \pm 0.1		End HR (beats.min ⁻¹)	188.4 \pm 7.2

Tabular report: 5RM = 5 repetition maximum, CMJ = Counter Movement Jump, SJ – Static Jump, VO₂max is predicted from Multi Stage Shuttle Run, HR = Heart rate

7.2.4 Procedures; Data Collection

To control the data collection process a series of pre-match checks were completed before the Bioharness™ was fitted and data were included within the project. Participants followed an established prescribed pre-match routine avoiding consumption of alcohol, maintaining a hydrated and well rested state. Participants were requested to avoid caffeine 2 hours prior to the match commencing. An environmental measure was reported using a portable weather station (Oregon Scientific, Berkshire, UK) and online meteorological reports (The Met Office, UK) and if the environmental temperature reached $\geq 27^{\circ}\text{C}$ (80°F) during the match this data was retrospectively removed from the analysis (Sawaka and Young, 2006). If a match was affected by rain the data set was removed from the study. Pre-match urine sample determined hydration status of participants as measured by urine osmolality (Osmocheck, Vitech Scientific, UK) and by a urine colour chart (colour range 1–8; 1 = very pale yellow urine, 8 = very dark yellow/ brown). Some participants were taking nutritional supplements which influenced the colour of urine therefore urine osmolality was the main data used for hydration. If urine osmolality ≥ 800 mOsmols participants were deemed to be in a dehydrated state and data on that day were not used in the study (Armstrong et al., 1998, Harvey et al., 2008). Participants mean osmolality pre-match was 541.67 ± 227.07 mOsmols (Appendix 2). On 2 occasions players osmolality was ≥ 800 mOsmols and therefore the player did not participate in the study during that match.

The Bioharness™ device was fitted after the warm up, by the same researcher approximately 15 minutes prior to match performance commencing when pre-bowling baseline heart rate was captured. Participants, who were assigned one Bioharness™ device, were requested to keep the monitoring device on throughout all periods of play when on the cricket field. The Bioharness™ device was synchronised to a laptop computer (M750, Toshiba Portege) and official scorers at the match recorded times when overs were bowled and runs scored.

7.2.5 Match Classification

Matches were classified as either multiday (MD) lasting 3 or 4 days or one day (OD) in duration (Petersen et al., 2010, Petersen et al., 2011b). When the participants team are *in the field*, MD and OD cricket scenarios could require participants to bowl multiple 6-ball overs (i.e. 3 – 6 overs), termed bowling spells. When bowlers complete their 6-ball over they have a short period of time not bowling (i.e. between over) when another performer would bowl a 6-ball over and they would field. Participants typically bowl 3-4 spells in a day of MD cricket. Participants were not on the field of play when their team was batting and were resting and had limited physical work to complete in this time. Within OD cricket where there are a maximum of 40

– 50 overs bowled per team, 1-2 spells of bowling for each participant are common as in this form of cricket the bowler has restrictions on the total number of overs they can bowl (i.e. 8 or 10 overs maximum). MD has no such restrictions on overs bowled by an individual and a team could be bowling for a full day (~100 overs) (Engel, 2012, International Cricket Council, 2013).

7.2.6 Determining a Bowling Episode and Match States

Being able to identify different match states of (1) bowling, (2) between over and (3) fielding was of paramount importance for the overall analysis in the study. By outlining the parameters of an active bowling over, the definition of what constitutes “between-over” (i.e. non-bowling activity) data was also created. With an understanding of the reoccurrence of bowling overs, the match state of fielding could be defined by the absence of repeated overs being bowled.

After a controlled bowling episode (Appendix 3) ACC VMU activity was found to corroborate with when bowling activity occurred and therefore was deemed suitable to use as a marker for data selection. For this research it was not necessary to identify the point of ball release within an over, rather just when a bowling event (over) had occurred as the coach can only influence the macro level event (i.e. the next over) during the match. Also technically, the data capture rate of the BioHarness™ equipment was insufficient (e.g. ACC capture 18 Hz) to allow this ball-to-ball analysis to occur. Considering the latter and collecting velocity data of the run ups (Brower Timing TC system, Utah, USA) of participants (Table 27) allowed the defining of the start and end of an over of bowling. The start of an over was defined as 10 seconds prior to the peak VMU activity associated with bowling delivery 1, while the end of the over was defined as 10 seconds post peak VMU activity of the final delivery in the over.

Additionally, a bowling spell was defined as 2 or more consecutive overs bowled by the participant. This figure was developed from Duffield and colleagues (2009) who note that the CA-AIS fast bowling skills tests operates using a 4 over bowling spell and their own research operated on 6 over spells. Using a 2 over minimum ensures that the participant has been involved in the bowling process (i.e. 2 episodes of bowling data and 1 episode of between over data) for more than 10 minutes and within the context of OD games this time frame could still be a crucial period of play. For consistency, the 2 consecutive over minimum was also adopted for inclusion of data from MD matches.

Table 27. Run-up distance, time and velocity of 10 first class fast-medium bowler participants (mean \pm SD).

	Length (metres)	Time (sec ⁻¹)	Velocity (km.hr ⁻¹)
Run up	20.1 \pm 2.7	3.6 \pm 0.5	19.9 \pm 1.6

7.2.7 Bowling Data (Hours)

Table 28 reports the volume of data collected during competitive cricket matches with more time/overs being captured from MD cricket. These totals exceed data volumes reported by Petersen et al. (2010) who collected ~66 h of GPS competitive match data. In addition to the total volume of match data, there were 3 matches without corresponding scorers' information, 6 data collections were lost due to technical error which included 2 data collection episodes where environmental conditions exceeded the parameters set for the study (i.e. 1 temperature, 1 rain). Therefore 36 data files entered the analysis process from 7 participants, with each participant providing a minimum of 30 overs of bowling data.

Table 28. Total number of competitive in-match hours and overs of fast-medium bowling data collected.

	Total Hours	Total Overs
MD	52.2	181
OD	29.6	85
Totals	81.8	266

Where: MD = Multiday cricket and OD = One Day cricket

7.2.8 Rationale for variable selection to assess physiological profile of fast bowlers and the physiological parameters associated with performance in-match

The BioharnessTM variables used within the analysis were deduced from three sources of information; (i) previous precision of measurement research, (ii) physiological and exercise science evidence and (iii) sport specific technical coaching manuals.

(i) Previous precision of measurement research completed on the Bioharness™;

From the 5 variables which capture data within the Bioharness™ device, HR, ACC and P variables were selected as key variables. This was based on earlier studies, in both the laboratory and field based environment, where these variables were the most precise in this version of the Bioharness™ device (Chapters 4, 5, 6).

(ii) Physiological and exercise science evidence;

Heart rate (HR)

Exercise science literature supports the notion that during activity, HR is linked to the volume of oxygen consumed (VO_2) by the performer (Astrand et al., 2003, McArdle et al., 2005, Powers and Howley, 2007). VO_2 consumption reflects the use of O_2 during physical work, specifically, the interplay of arterial blood entering the working skeletal muscle and the subsequent extraction of O_2 by fibres (Hale 2003). The HR- VO_2 relationship has been correlated ($r = .70$) in field and laboratory settings and therefore the evidence suggests that HR seems to provide an adequate and more accessible indicator of cardio-vascular stress during physical activity/sport (Powers and Howley, 2007, Strath et al., 2000).

Specific use of HR data has been noted in the literature to indicate cardiovascular work and physical stress in sporting performance (Duthie et al., 2003). For example, the peak and mean HR has been used to assess intensity of cardiovascular work in the physiological assessment of team sports. Moreover, HR data has also been linked to identifying periods of play where performers are operating in prescribed zones of cardiovascular exercise intensity (e.g. HR > 160 beats.min⁻¹ corresponds to “very vigorous” exercise) (Barbero-Alvarez et al., 2008, Campbell et al., 2004, Duthie et al., 2003)

Using absolute HR provides a less accurate account of HR- VO_2 relationship as it will not take in to account individual differences (i.e. fitness, genetics) (Ekelund et al., 2001, Strath et al., 2000). Therefore an additional figure relative to the individual is required such as, a percentage (%) of theoretical maximum HR (Barbero-Alvarez et al., 2008, Tanaka et al., 2001), or HR changes during activity calculated from a pre-activity “baseline” level can be used for additional analysis which has similarities to heart rate reserve (Luke et al., 1997, Strath et al., 2000).

Other HR measures used to assess physical performance during exercise include HR recovery. A rapid recovery of HR back to baseline levels post-activity has been noted as an indicator of enhanced cardiovascular efficiency (Hale, 2003, McArdle et al., 2005). The ability of the HR to return to baseline levels after moderate-high intensity bouts of activity is affected by the hormonal release associated with the interplay of the sympathetic nervous system withdrawal and parasympathetic nervous system reactivation (McArdle et al., 2009, Pierpont and Voth, 2004). Acute heart rate recovery 1 or 2 minutes from cessation of

activity is an established method to assess this variable (Lambert and Borresen, 2006, Lamberts et al., 2009). If multiple bouts of intense physical activity occur (i.e. bowling a series of overs), HR recovery 60 seconds post-bowling activity may provide evidence of cumulative increase in baseline HR, which could be a easily accessible indicator of fatigue in the performer (Lambert and Borresen, 2006, Powers and Howley, 2007).

In summary, to provide a physiological profile of fast bowlers in-match for the HR variable, descriptive statistics will be collated including peak and mean HR from bowling episodes and between over episodes will be captured and assessed relative to the participant using theoretical maximum HR (220-age). Further relative HR analysis includes a recovery value, assessed relative to pre-exercise baseline data (i.e. pre over 1 HR), captured 60 seconds (HR_{60}) after the last delivery of each over bowled. Moreover, relative HR change from the end of one bowling episode/over to the start of the next will be assessed with difference between HR baseline and the HR 10 seconds prior at the first delivery of the next over being captured. Understanding these HR data will allow an insight in to the physiological parameters professional bowlers operate under during competitive performance and will enhance the understanding of exercise scientists and coaches to improve current conditioning practices.

Accelerometry (ACC)

ACC data has been linked to physical activity and Vector Magnitude Units (VMU), which are a combined tri-axial activity count, provides a quantifiable physical activity measure (Chen and Bassett, 2005) which could be linked to sporting performance over a period of play. Information on physical activity via data from VMUs such as, total amount, frequency, intensity and duration, can be gained by the use of accelerometers (Westerterp, 2009). In both laboratory and field based procedures, increases in total VMU counts have been linked to increases in participants VO_2 consumption (Rowlands et al., 2004). The assessment of VMU data in a sporting activity which is constant and rhythmical in both time and player movement patterns (e.g. bowling activity), could be used to identify and quantify information on physical performance (Mathie et al., 2003). For example, increases or decreases of VMU counts from bowling episode to episode, or a relative VMU activity which considers activity counts during bowling and VMU counts between overs can be calculated and linked to subsequent bowling performance. Moreover, assessing cumulative peak acceleration, individual x (vertical), y (lateral), and z (sagittal) axes of data may well allow for further specific insight in to performance relative to the specific planes of movement. Therefore, to provide a profile of fast-medium bowlers in-match, descriptive statistics will be collated on ACC from different match states. Cumulative ACC counts during and between overs will provide an indication of general physical activity which can be linked to bowling performance in the next subsequent over.

Posture (P)

Angle of the trunk during delivery may be of interest to coaches as the run-up when bowling is a consistent rhythmical activity and differences from the start of a bowling spell to the end could indicate a change in bowling action due to fatigue (Ferdinands, 2008, Woolmer et al., 2008). There is limited evidence to support this notion and trunk angle measured in running studies have noted an increase in angle between steady-state activity and running to volitional exhaustion (Stanton et al., 2004). Due to lack of objective evidence on the use of this variable within a sporting situation, posture data was not included within the analysis.

(iii) Sport specific technical coaching manuals:

Although there are varieties of bowling action, sport specific coaching manuals confirm that an aspect of effective bowling is consistency in technique (Ferdinands, 2008, Ferdinands et al., 2010, Woolmer et al., 2008). ACC will provide an insight in to this issue. Moreover, the physical nature of fast-medium bowling (Burnett et al., 1995, Duffield et al., 2009, Noakes and Durandt, 2000) therefore requires information on physical workload that the performer experiences during an over, between an over and how this affects subsequent performance. Therefore, HR and ACC data will provide an insight in to this aspect during competitive performance.

Bowling performance

Bowling performance will be assessed by match data captured by official scorers. The number of runs scored from each over was decided as the bowling performance indicator. Other performance measures such as wickets taken by the bowler, accuracy of delivery or a combination of the latter relative to the quality of the opponent was considered. Adopting wickets taken as a performance indicator was not adopted due to the various ways a bowler could achieve this outcome (i.e. taking a wicket from a bad ball) and also bowlers can perform well by purely maintaining a low run rate. Assessing the accuracy of the delivery using video technology to assess bowling performance has been noted elsewhere (More et al., 2010) but it was felt that the objective mapping of each delivery could vary with differing pitch and game conditions and with no standard system in place it would be difficult to implement. Therefore, the number of runs scored off the bowler is one of the primary methods to assess bowling performance over time within cricket and therefore adopted within this research (Engel, 2012, Woolmer et al., 2008).

7.2.9 Independent and Dependent variable confirmation

Physiological profile of fast-medium bowling

The dependent variable for this aspect of the study will be the physiological measures as assessed by the Bioharness™ device (i.e. Heart rate variables and Accelerometry variables). Independent variable will be the match type (i.e. OD or MD) and match state (i.e. bowling, between over or fielding).

Association between bowling performance and physiological data

The dependent variable for this aspect of the study will be bowling performance (i.e. runs per over). Independent variable will be the physiological measures as assessed by the Bioharness™ device.

7.2.10 Hypotheses

The hypotheses were split in to two groups based on the aims of the chapter.

7.2.10.1 Physiological profile of fast-medium bowling

Related to the first aim of this chapter, the physiological profile of fast-medium bowling, the following hypotheses were tested;

Heart rate

1. Relative HR during match activities – Mean, maximum and minimum values expressed as a percentage (%) relative to age (220-age) -
Hypothesis: There will be a significantly higher age related relative HR values (i.e. mean, min and max % of age) in OD cricket in comparison to MD cricket.
2. Absolute HR during match activities – Mean, maximum and minimum absolute values expressed $\text{beats}\cdot\text{min}^{-1}$ -
Hypothesis: There will be a significantly higher absolute HR values (i.e. mean, min and max) in OD cricket in comparison to MD cricket.
3. Relative HR change; HR at commencement of each over (10 secs before 1st delivery bowled) – Base line HR (pre-exercise pre-over 1) -
Hypothesis: There will be a significantly higher HR_{10r} in OD cricket in comparison to MD cricket.
4. HR recovery value 60 seconds post (HR_{60r}) bowling; HR 60 secs after last delivery – HR base line pre over 1 -
Hypothesis: There will be a significantly higher HR_{60r} in OD cricket in comparison to MD cricket.

Accelerometry

5. Cumulative VMU during match activities –
Hypothesis: There will be a significant difference in total activity (i.e. VMU) between OD and MD cricket.
6. Cumulative peak acceleration during match activities –
Hypothesis: There will be a significant difference in acceleration count between OD and MD cricket.
7. Cumulative vertical (x) axis during match activities –
Hypothesis: There will be a significant difference in vertical (x) axis count between OD and MD cricket.
8. Cumulative lateral (y) right axis during match activities -
Hypothesis: There will be a significant difference in lateral (y) right axis count between OD and MD cricket.
9. Cumulative sagittal (z) anterior axis during match activities –
Hypothesis: There will be a significant difference in sagittal (z) anterior axis count between OD and MD cricket.

7.2.10.1 Association between bowling performance and physiological data

Related to the second aim of this chapter, the relationship between cricket bowling performance criteria and physiological data captured by a mobile monitoring device, the following hypotheses were tested;

Heart rate

For the analysis assessing the association of HR with bowling performance, the following HR variables will be specifically assessed with the corresponding hypotheses noted (Figure 27);

10. Relative HR max during bowling; Mean HR from the over bowled expressed as a percentage of HR max (220 – age) -
Hypothesis: There will be a significant positive association between relative HR max during bowling activity and runs scored in the subsequent over.
11. Relative HR max between bowling overs; Mean HR between over expressed as a percentage of HR max (220 – age) -

Hypothesis: There will be a significant positive association between mean HR in-between overs and runs scored in the subsequent over.

12. HR recovery value 60 secs post (HR_{60}) bowling; HR 60 secs after last delivery – HR base line pre over 1 -

Hypothesis: There will be a significant positive association between HR recovery 60 seconds post bowling and runs scored in the subsequent over.

13. Relative HR change; HR at commencement of each over (10 secs before 1st delivery bowled) – Base line HR (pre-exercise pre-over 1) -

Hypothesis: There will be a significant positive association between relative HR change at the start of each over and runs scored in the subsequent over.

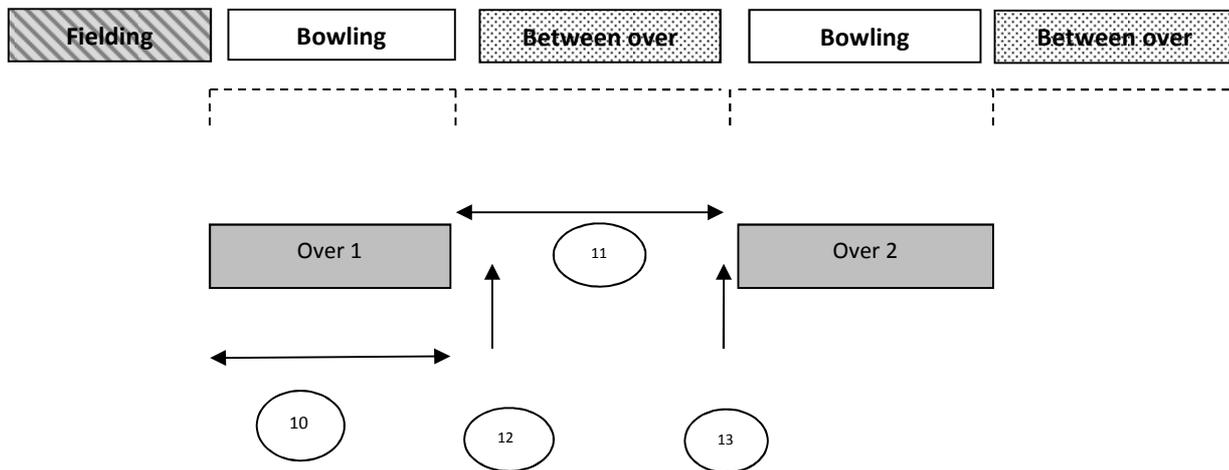


Figure 27. Schematic of HR data collection points linked to the associated hypotheses in Heart Rate 7.2.10. Each of numbers relates to a hypothesis and is representative to one data capture which is then reassessed repetitively through the bowling spell.

Accelerometry

For the analysis assessing the association of ACC with bowling performance the following variables will be specifically assessed with the corresponding hypotheses noted (Figure 28);

14. Total cumulative VMUs during bowling -

Hypothesis: There will be a significant positive association between total activity during the bowling episode and runs scored in the subsequent over.

15. Total cumulative VMUs between overs -

Hypothesis: There will be a significant positive association between total activity accumulated in a between over episode and runs scored in the subsequent over.

16. Total cumulative activity (bowling VMU + between over VMU) -

Hypothesis: There will be a significant positive association between relative activity and runs scored in the subsequent over.

17. Cumulative peak acceleration in previous over-

Hypothesis: There will be a significant positive association between cumulative peak acceleration and runs scored in the subsequent over.

18. Cumulative vertical axis (X) in previous over -

Hypothesis: There will be a significant positive association between accelerometry in the vertical direction (x axis) and runs scored in the subsequent over.

19. Cumulative lateral (Y) axis in previous over

Hypothesis: There will be a significant positive association between peak accelerometry in the left direction (y axis) and runs scored in the subsequent over.

20. Cumulative sagittal (Z) axis in previous over

Hypothesis: There will be a significant positive association between peak accelerometry in the anterior direction (z axis) and runs scored in the subsequent over.

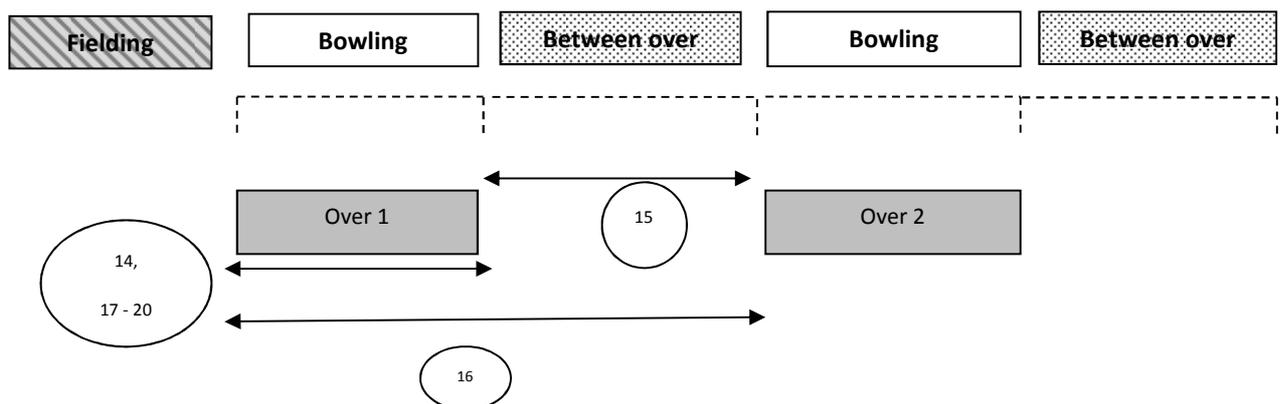


Figure 28. Schematic of ACC data collection points and associated hypotheses in Accelerometry 7.2.10. Each of numbers relates to a hypothesis and is representative to one data capture which is then reassessed repetitively through the bowling spell.

7.2.11 Data Analysis

Data were exported from the Bioharness™ device to statistical software packages (Excel Microsoft Windows, USA; SPSS v20, SPSS Inc, Chicago, USA) for analysis.

As previously reported in this thesis (Chapter 4-6), HR data from the Bioharness™ has been described as being erroneous during higher intensity activity and at times during the bowling episodes artefacts were identified which may well have been derived from movement of the Bioharness™ strap and/or EMG interference. Filtering and/or smoothing of erroneous data has occurred in other research where field based HR data has been collected (Zakeri et al., 2008). Two established options were considered to smooth/filter the data, (i) Butterworth smoothing technique (ii) Polynomial smoothing. The latter process was implemented to remove errors from the HR trace as the former is more aligned to mechanical data (Bernmark and Wiktorin, 2002, Bianchi and Sorrentino, 2007). Optimising the choice of the bandwidth, the periods over which the signal characteristics are taken, and the smoothing procedures were confirmed from previous literature (Ruppert et al., 1995, Wand, 2013). As discussed within chapters 4-6, due to more mechanical nature of ACC data this variable required no smoothing process to be applied. When reviewing the acceleration data from the vertical (x) axis, peak values for both upward (negative) and downward (positive) directions presented only upward (negative) values. Therefore values for the downward acceleration were removed from the analysis as they provided little useful information. With regards to the HR data, initial screening of the data set removed HR data if it was deemed too erroneous. This initial screening was based on a subjective comparison to the HR data trace captured during pilot bowling testing (Appendix 3). Based on the latter, HR data from 2 collections were removed from the research.

Using the principles described in 7.2.6, raw match data were managed using R version 3.0.0 automated batch processing method (R Core Team, 2013, Wand, 2013). Unique data processing programs (R Version 3.0.0, [http://www.R-project.org/.](http://www.R-project.org/)) were written and tested for a pilot analysis process using 5 match files which created a draft output from the automated analysis programme. This batch processed output (Figure 29) was cross-validated via visual inspection of HR and ACC charts and using official match score cards. Based on previous literature (Powers and Howley, 2007) an additional HR criteria was added based on unrealistic maximum and minimum values (i.e. data points < 50 or > 200 beats.min⁻¹ were excluded) to improve the smoothing of HR trace. Once this latter criteria was added all remaining data files (n=34) were then processed. Out of 266 overs (1596 deliveries) there were 48 errors (3% errors) identified which were then corrected manually via cross referencing with official scorers match cards to improve the final data output. Bowling data from participants were organised for analysis in to match states ((1) bowling, (2) between over and (3)

fielding)) (figure 27 and 28) and match format ((1) OD, (2) MD). Data was organised as episodes relative to the match states (Figure 29), with accelerometry data presented in a cumulative format, per episode (i.e. ct.episode⁻¹) and HR similarly organised though reported in standard units (beats.min⁻¹). A baseline HR value was also captured at the start of the Bioharness™ recording which was defined as mean HR over least active 1 min before the beginning of the first over. This baseline HR was utilised for relative HR data (i.e. HR_{10r}, HR_{60r}) and was specific for each match. The performance indicator, Runs per over (r.p.o), was positively skewed and was converted to a categorical variable for part of the analysis. Based on the median value (3.0) of the runs per over, coaching literature and runs per over values extracted from the data set, categories were created as follows; 0 runs per over = 1, 1-4 runs per over = 2, 5> runs per over = 3.

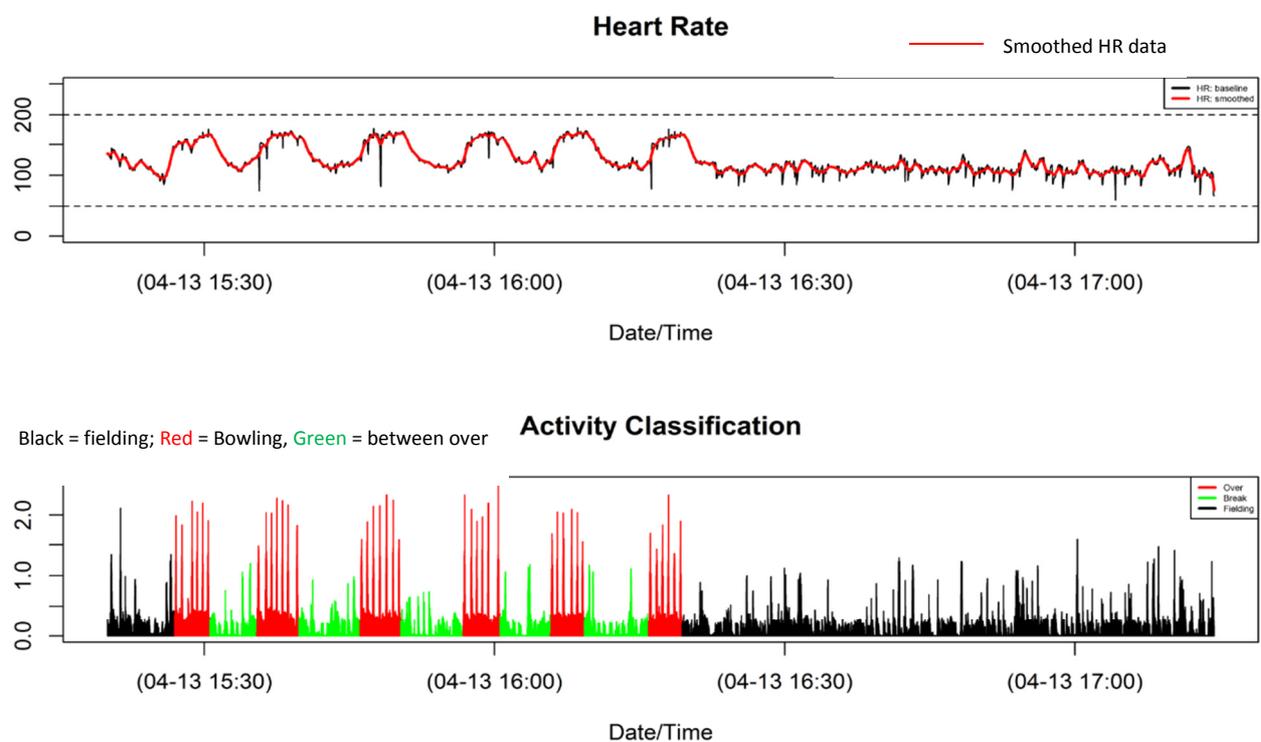


Figure 29. An example of screen shot of processed match data.

A variety of measures were used to assess the data set characteristics prior to deciding if parametric or non-parametric statistical analysis was appropriate. At a basic level, checks for normality of distribution were made by assessing histograms, Q-Q plots and the Central Tendency of the data (e.g. similarity of the mean and median). Using only these tests may not provide a comprehensive picture of data distribution (Newell et al., 2010). More complex objective measures of normality can be provided by Kolmogorov-Smirnov test and Shapiro-Wilk test, though the latter test is limited to smaller sample sizes (<50) and if large sample sizes are tested there is an increased likelihood of finding a significant result (i.e. not normal)

from minor deviations in the data (Field and Miles, 2010, Hopkins, 2008, O'Donoghue, 2012). Assessing Skewness and Kurtosis of the data set also conveys a statistic which provides an objective indication of distribution. The further each respective statistic is from zero, the increasing likelihood that data are not normally distributed. A process of converting Skewness and Kurtosis scores in to z-scores was completed to provide additional absolute assessment on distribution of a data set. If the resulting z-score absolute value is > 1.96 it is classed significantly different to a normal distribution at the 0.05 level. If the z-score value is > 2.58 significance is classed at 0.01, > 3.29 significance is classed at 0.001 (Field and Miles, 2010, Newell et al., 2010, O'Donoghue, 2012).

Table 29: Objective normality tests completed on key data sets.

	Kologorov- Smirnoff	Skewness	Kurtosis	Central Tendency	
				Mean	Median
Mean HR (beat.min ⁻¹)	D(208) = 0.06, <i>P</i> < .05	-0.44, z-score = 2.59 <i>P</i> < .01	-0.54, z-score = 1.59 <i>P</i> > .05	139.5	141.9
Mean HR %	D(208) = 0.07, <i>P</i> < .05	-0.43, z-score = 2.54 <i>P</i> < .05	-0.57, z-score = 1.70 <i>P</i> > .05	71.3	72.3
HR ₆₀ (beat.min ⁻¹)	D(208) = 0.06, <i>P</i> < .05	-0.46, z-score = 2.72 <i>P</i> < .01	-0.29, z-score = 0.85 <i>P</i> > .05	136.1	137.4
HR ₁₀ (beat.min ⁻¹)	D(208) = 0.04, <i>P</i> > .05	-0.09, z-score = 0.55 <i>P</i> > .05	-0.08, z-score = 0.23 <i>P</i> > .05	120.8	121.5
VMU (ct.episode ⁻¹)	D(192) = 0.11, <i>P</i> < .05	1.86, z-score = 10.63 <i>P</i> < .05	12.36, z-score = 35.4 <i>P</i> < .001	66.5	63.1
VMU b/over (ct.episode ⁻¹)	D(192) = 0.12, <i>P</i> < .05	-1.04, z-score = 5.94 <i>P</i> < .001	7.50, z-score = 21.49 <i>P</i> < .001	180.0	180.4
Acceleration (ct.episode ⁻¹)	D(192) = 0.51, <i>P</i> < .05	4.23, z-score = 24.0 <i>P</i> < .001	17.44, z-score = 49.9 <i>P</i> < .001	1139.1	127.6
Vertical (x) (ct.episode ⁻¹)	D(192) = 0.86, <i>P</i> < .05	0.16, z-score = 0.90 <i>P</i> > .05	1.85, z-score = 5.30 <i>P</i> < .001	-193.2	-190.8
Lateral (y) (ct.episode ⁻¹)	D(192) = 0.06, <i>P</i> > .05	0.86, z-score = 4.91 <i>P</i> < .001	4.64, z-score = 13.30 <i>P</i> < .001	57.4	61.2
Sagittal (z) (ct.episode ⁻¹)	D(192) = 0.09, <i>P</i> < .05	0.39, z-score = 2.29 <i>P</i> < .05	0.81, z-score = 2.32 <i>P</i> < .05	54.2	52.3

Distribution and normality checks were completed presenting the following outcomes in Table 29 and based on these results decisions on statistical analysis were made. Data for all key variables except HR₁₀ were classed as not normally distributed. Kolmogorov-Smirnov test, z-scores, histogram and Q-Q plot analysis all suggested HR₁₀ data being classed as normally distributed. Although Kolmogorov-Smirnov test was non-significant for Peak (y) lateral axis, z-scores and histogram analysis suggested data were not normally distributed. The latter outcomes meant that the statistical

analysis method would primarily utilise non-parametric tests, with HR₁₀ being analysed through parametric tests.

The selection of statistical tests within the non-parametric and parametric grouping was based the evidence reviewed and on inclusion of data. Even though some data within the analysis could be classed as related (e.g. participants' data was within both OD and MD scenarios) independent tests were chosen. This was decided as data sets are not directly paired and there are also unequal numbers of data sets from each bowler across the different scenarios being analysed. Importantly, if a related statistical design was selected there was a danger of large quantities of data being excluded from the analysis as if the data is not paired it is removed from the analysis (Field and Miles, 2010, Newell et al., 2010, O'Donoghue, 2012). When assessing the data over consecutive overs, 10 data files was deemed an appropriate minimum to consider any trends or relationships over to over. Therefore it was possible to assess 7 overs consecutively across all data collected.

The parametric tests used included the following; to test for differences between two groups Independent T-Test and for differences between 3 groups One-way ANOVA with Tukey Post-Hoc tests were used. For association between data sets a Pearson Product Moment Correlation was used. Non-parametric tests included; Testing for differences between 2 groups the Mann-Whitney (U) test; For 3 groups Kruskal-Wallis (H) test with post-hoc Mann-Whitney (U) test were completed. To control Type I error, Bonferroni adjustments were used if multiple comparisons were completed. For association between data Spearman Rank test was used and an Alpha level was set at $P < .05$. Where appropriate z-scores, and effect sizes (ES) using Pearsons r ($r = .10$ classed as small effect, $r = .30$ medium effect and $r = .50$ a large effect) were also reported to provide additional understanding of the significance of the outcome (Rosental, 1991 cited in Field, 2010).

7.3 Results

7.3.1 General Overview of Match Data

Across both formats of the game participants bowled more overs in the 1st spell in comparison to the 2nd (Mean \pm SD overs; Spell 1, 3.8 \pm 2.2; Spell 2, 2.6 \pm 1.8). The number of overs bowled was similar for both forms of the game (OD Spell 1, 3.9 \pm 2.2: Spell 2, 2.1 \pm 1.2; MD Spell 1, 3.7 \pm 2.2 : Spell 2, 3.0 \pm 2.2). The scoring rate per over across both match formats was 3.42 \pm 3.16 r.p.o. When assessing each format separately this figure was significantly higher in OD matches (4.00 \pm 3.04 r.p.o.) in comparison MD (3.1 \pm 3.2 r.p.o.) ($U = 4550.5$, $z = -2.49$, $P < .05$, $ES = -0.17$). In OD matches bowling episodes (208.2 \pm 25.6 sec⁻¹) and between over episodes (346.6 \pm 73.9 sec⁻¹) were completed in a faster time in comparison to MD matches bowling (235.2 \pm 38.2 sec⁻¹) and between over episodes (359.6 \pm 52.1 sec⁻¹).

7.3.2 Accelerometry Data

Descriptive Data for OD and MD formats across all Match States

Accelerometry data were analysed for statistical significant differences between OD and MD format (Table 30). Cumulative acceleration and Lateral right axis were found to have significant differences between OD and MD format though ES were small, with lower values noted in the MD format. Higher values were reported in the OD format for other variables but these were non-significant.

Table 30. Descriptive statistics (median \pm Inter quartile range) for bowlers' cumulative accelerometry data (ct.episode⁻¹) in OD and MD cricket.

	One Day	Multi Day				
	Mdn \pm IQR	Mdn \pm IQR	Change \pm	U	Z Score	ES
VMU	104.3 \pm 61.9	103.9 \pm 54.3	-0.4	25271.0	-1.27	-0.06
Peak acceleration	227.6 \pm 172.4	214.9 \pm 113.1	-12.7**	22570.0	-3.06	-0.14
Vertical x	-380.2 \pm 129.5	-378.0 \pm 92.3	-2.2	25805.5	-0.92	-0.04
Lateral y left	101.6 \pm 69.8	99.3 \pm 62.7	-2.3	26356.0	-0.55	-0.02
Lateral y right	-89.5 \pm 48.9	-84.8 \pm 44.1	-4.7**	23553.5	-2.41	-0.11
Sagittal z anterior	56.3 \pm 26.4	53.6 \pm 32.1	-2.7	25791.0	-0.93	-0.04
Sagittal z posterior	-136.6 \pm 94.4	-131.5 \pm 95.2	-5.1	25699.0	-0.99	-0.05

Tabular report: VMU = Vector Magnitude Units, the combined value of 3 axis, Acceleration = maximum 3-axis acceleration, Vertical (x) = Cumulative value on vertical axis, Lateral (y) left = Cumulative value on left direction, Lateral (y) right = Cumulative value on right direction, Sagittal (z) anterior = Cumulative value on the anterior direction, Sagittal (z) posterior = Cumulative value on the posterior direction, * Significant difference $P < .05$, ** Significance $P < .01$

Descriptive statistics for accelerometry during different match states across different match formats

Descriptive accelerometry data for OD and MD during bowling

During bowling activity (Table 31), accelerometry data presented some significant differences, with small ES, between OD and MD match formats. A significantly higher cumulative acceleration and Lateral right were recorded in OD compared to MD cricket, though ES was small. Lateral left recorded significantly higher values in MD cricket with small ES. There was a non-significant trend of higher values in OD match format for VMU, Sagittal anterior and sagittal posterior axis. Vertical axis data was $0.5 \text{ ct.episode}^{-1}$ higher in MD cricket. ES were small in all previous cases.

Descriptive accelerometry data for OD and MD between over

Between over accelerometry data (Table 32) presented one significant difference, with a small to medium ES, between match formats for Lateral left axis having higher values in MD cricket. Non-significant higher values were noted in OD format compared to MD for VMU, Acceleration, Vertical axis, Lateral right and Sagittal anterior. Non-significant higher values were noted in MD compared to OD for Sagittal posterior.

Descriptive accelerometry data for OD and MD during fielding

During fielding activities (Table 33) all accelerometry data presented significant differences between match formats with medium ES and higher accelerometry values noted during OD format compared to MD for VMU, Acceleration, Vertical axis, Lateral left, Lateral right and Sagittal posterior. Significantly higher values were noted during MD format compared to OD for Sagittal anterior.

Table 31. Descriptive statistics (median \pm Inter quartile range) for cumulative accelerometry data (ct.episode⁻¹) in OD and MD matches during bowling.

	One Day	Multi Day				
	Mdn \pm IQR	Mdn \pm IQR	Change \pm	U	Z Score	ES
VMU	115.4 \pm 143.4	113.7 \pm 16.5	-1.7	5860.0	-0.21	-0.01
Peak acceleration	234.1 \pm 57.9	226.6 \pm 32.9	-7.5*	5038.5	-1.91	-0.12
Vertical x	-374.5 \pm 71.3	-375.0 \pm 56.9	0.5	5691.5	-0.71	-0.05
Lateral y left	115.4 \pm 26.4	122.6 \pm 35.3	7.2*	4716.5	-2.58	-0.17
Lateral y right	-99.5 \pm 24.3	-93.5 \pm 20.4	-6.0*	5035.5	-1.92	-0.13
Sagittal z anterior	53.0 \pm 16.9	51.2 \pm 21.2	-1.8	5397.0	-1.17	-0.08
Sagittal z posterior	-154.1 \pm 31.1	-153.1 \pm 33.1	-1.0	5955.5	-0.01	0.01

Tabular report: VMU = Vector Magnitude Units, the combined value of 3 axis, Acceleration = maximum 3-axis acceleration, Vertical (x) = Cumulative value on vertical axis, Lateral (y) left = Cumulative value on left direction, Lateral (y) right = Cumulative value on right direction, Sagittal (z) anterior = Cumulative value on the anterior direction, Sagittal (z) posterior = Cumulative value on the posterior direction, * Significant difference $P < .05$, ** Significance $P < .01$

Table 32. Descriptive statistics (median \pm Inter quartile range) for cumulative accelerometry data (ct.episode⁻¹) in OD and MD matches between over.

	One Day	Multi Day				
	Mdn \pm IQR	Mdn \pm IQR	Change \pm	U	Z Score	ES
VMU	63.3 \pm 16.6	62.5 \pm 22.1	-0.8	3610.5	-0.11	-0.01
Peak acceleration	136.4 \pm 46.0	126.5 \pm 47.4	-9.9	3354.0	-0.87	-0.06
Vertical x	-365.3 \pm 104.7	-363.0 \pm 80.2	-2.3	3566.0	-0.24	-0.02
Lateral y left	52.5 \pm 24.3	66.4 \pm 32.7	13.8*	2664.0	-2.92	-0.20
Lateral y right	-57.6 \pm 20.8	-54.6 \pm 28.2	-3.0	3254.0	-1.17	-0.09
Sagittal z anterior	54.1 \pm 31.9	50.4 \pm 29.7	-3.7	3615.0	-0.10	-0.01
Sagittal z posterior	-59.4 \pm 44.9	-64.2 \pm 33.8	4.8	3552.5	-0.28	-0.02

Tabular report: VMU = Vector Magnitude Units, the combined value of 3 axis, Acceleration = maximum 3-axis acceleration, Vertical (x) = Cumulative value on vertical axis, Lateral (y) left = Cumulative value on left direction, Lateral (y) right = Cumulative value on right direction, Sagittal (z) anterior = Cumulative value on the anterior direction, Sagittal (z) posterior = Cumulative value on the posterior direction, * Significant difference $P < .05$, ** Significance $P < .01$

Table 33. Descriptive statistics (median \pm Inter quartile range) for cumulative accelerometry data (ct.episode⁻¹) in OD and MD matches while fielding.

	One Day	Multi Day	Change \pm	U	Z Score	ES
	Mdn \pm IQR	Mdn \pm IQR				
VMU	448.5 \pm 883.6	144.8 \pm 445.7	-303.7**	497.5	-2.42	-0.27
Peak acceleration	1349.9 \pm 2607.4	356.1 \pm 1097.5	-993.8**	448.5	-2.90	-0.32
Vertical x	-2634.4 \pm 4986.4	-770.8 \pm 2690.2	-1863.6**	493.5	-2.46	-0.27
Lateral y left	496.4 \pm 656.1	148.7 \pm 433.4	-347.7**	519.5	-2.20	-0.24
Lateral y right	-374.3 \pm 875.8	-141.9 \pm 442.6	-232.4**	466.5	-2.72	-0.30
Sagittal z anterior	172.7 \pm 768.3	222.5 \pm 431.9	49.8*	493.5	-2.46	-0.27
Sagittal z posterior	-473.0 \pm 919.4	-119.3 \pm 319.5	-353.7**	517.5	-2.22	-0.25

Tabular report: VMU = Vector Magnitude Units, the combined value of 3 axis, Acceleration = maximum 3-axis acceleration, Vertical (x) = Cumulative value on vertical axis, Lateral (y) left = Cumulative value on left direction, Lateral (y) right = Cumulative value on right direction, Sagittal (z) anterior = Cumulative value on the anterior direction, Sagittal (z) posterior = Cumulative value on the posterior direction, * Significant difference $P < .05$, ** Significance $P < .01$

7.3.3 Physiological Profile of Fast-Medium Bowlers in Cricket

Descriptive heart rate data for OD and MD for all Match States

Table 34 shows heart rate was higher across all variables within the OD. Significant differences in the data were identified between OD and MD cricket for HR, HR_{age}, HR_{max}, HR_{min} and HR_{minage}. Of the latter, the ES were within the small to medium size throughout the data set.

Descriptive heart rate data for OD and MD during Bowling

Except for HR_{60r}, in comparison to the MD format, heart rate values were higher during OD bowling and significant differences were noted for HR, HR_{age}, HR_{max}, HR_{min}, HR_{minage} (Table 35 and Figure 30). ES were small to medium apart from HR_{min} which was classified as medium to large. There was no significant difference between the two match formats reported for HR_{10r}. A non-significant higher trend in MD cricket was noted for HR_{60r} and HR_{maxage}.

Descriptive heart rate data for OD and MD Between overs

Between overs analysis (Table 36 and Figure 30) noted higher HR values occurring in the OD cricket format. These differences were significant for HR HR_{age}, HR_{min} and HR_{minage}. From the latter significant results, ES were deemed medium to large. A non-significant difference was noted for HR_{max} and HR_{maxage}.

Descriptive heart rate data for OD and MD during Fielding activities

For fielding activities, in comparison to MD cricket, all HR measures were significantly higher in the OD format with medium to large ES (Table 37 and Figure 30).

Table 34. Descriptive statistics (mean \pm SD; 95% Confidence Intervals) for bowlers absolute ($\text{beat}\cdot\text{min}^{-1}$) and relative (% of age) heart rate (HR) data across two match formats.

	One Day		Multi Day		Change e \pm	U	Z score	ES
	M \pm SD	95% CI	M \pm SD	95% CI				
HR	142.0 \pm 20.4	138.9 – 145.2	137.2 \pm 16.4	137.8 – 139.9	-4.8*	20148.5	-4.67	-0.21
HR _{age}	78.3 \pm 8.6	76.3 – 80.3	70.9 \pm 9.3	69.5 – 72.4	-7.4*	21610.5	-3.70	-0.17
HR _{max}	153.7 \pm 15.3	150.2 – 157.3	149.2 \pm 17.8	146.4 – 151.9	-4.5*	22836.0	-2.89	-0.13
HR _{maxage}	78.3 \pm 8.6	76.3 – 80.3	77.4 \pm 9.8	75.9 – 78.9	-0.9	25242.5	-1.29	-0.05
HR _{min}	119.0 \pm 15.2	117.0 – 121.8	107.7 \pm 15.6	106.1 – 109.4	-11.3*	15980.0	-7.43	-0.33
HR _{minage}	61.7 \pm 8.9	60.3 – 63.1	55.7 \pm 8.1	54.87– 56.60	-6.0*	17146.0	-6.66	-0.30

Tabular report; Absolute values: HR = Heart rate, HR_{max} = Heart rate maximum, HR_{min} = Heart rate minimum. Relative values: HR_{age} = Heart rate relative to age, HR_{maxage} = Heart rate maximum relative to age, HR_{minage} = Heart rate minimum relative to age, Change = difference from OD to MD, U = Mann-Whitney statistic, ES = Effect Size. * Significant difference $P < .05$

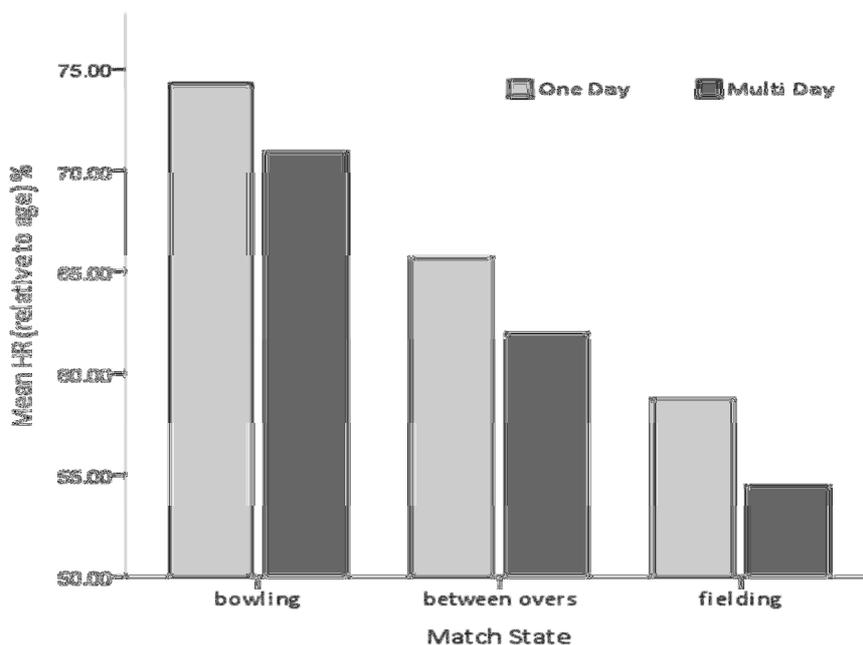


Figure 30: HR (relative to age) for OD and MD matches during different match state.

Table 35. Descriptive statistics (mean \pm SD; 95% Confidence Intervals) for absolute (beat.min⁻¹) and relative (% of age) heart rate (HR) data in OD and MD matches during bowling activity.

	One Day		Multi Day		Change \pm	U/t	Z	ES
	M \pm SD	95% CI	M \pm SD	95% CI				
HR	142.8 \pm 14.2	139.1 – 146.1	137.2 \pm 16.4	134.6 – 139.8	-5.6*	4380.5	-3.27	-0.21
HR _{age}	73.1 \pm 8.6	70.9 – 75.2	70.9 \pm 9.3	69.5 – 72.4	-2.2*	4734.0	-2.54	-0.17
HR _{max}	151.1 \pm 14.4	147.5 – 154.6	149.2 \pm 17.8	146.4 – 151.9	-1.9*	5074.0	-1.84	0.12
HR _{maxage}	77.1 \pm 8.5	74.9 – 79.2	77.4 \pm 9.81	75.8 – 78.9	+0.3	5661.5	-0.62	-0.04
HR _{min}	126.3 \pm 12.1	123.3 – 129.3	115.8 \pm 12.9	113.8 – 117.9	-10.5*	2944.5	-6.25	-0.41
HR _{minage}	65.6 \pm 8.6	63.5 – 67.8	59.9 \pm 6.8	58.8 – 60.9	-5.7*	3466.0	-5.17	-0.33
HR _{60r}	40.6 \pm 17.3	36.4 – 44.9	44.7 \pm 17.1	42.0 – 47.4	+4.1	4543.0	-1.42	-0.09
HR _{10r}	28.3 \pm 14.9	24.6 – 31.9	28.1 \pm 12.5	26.2 – 30.1	-0.2	-0.12	-	-0.03

Tabular report; Absolute values: HR_{10r} = heart rate 10 seconds before bowling relative to baseline heart rate, HR_{60r} = heart rate 60 seconds after bowling relative to base line heart, HR = Heart rate, HR_{max} = Heart rate maximum, HR_{min} = Heart rate minimum. Relative values: HR_{age} = Heart rate relative to age, HR_{maxage} = Heart rate maximum relative to age, HR_{minage} = Heart rate minimum relative to age, Change = difference from OD to MD, U/t= Mann-Whitney/T test statistic, ES = Effect Size * Significant difference $P < .05$

Table 36. Descriptive statistics (mean \pm SD; 95% Confidence Intervals) for absolute (beat.min⁻¹) and relative (% of age) heart rate (HR) data in OD and MD matches between overs.

	One Day		Multi Day		Change \pm	U	Z	ES
	M \pm SD	95% CI	M \pm SD	95% CI				
HR	128.8 \pm 9.3	126.4 – 131.3	119.9 \pm 12.6	117.7 – 122.1	-8.9**	2028.5	-4.81	-0.35
HR _{age}	65.7 \pm 5.2	64.3 – 67.1	62.0 \pm 7.1	60.8 – 63.3	-3.7**	2402.5	-3.70	-0.27
HR _{max}	150.6 \pm 16.4	146.3 – 154.9	145.8 \pm 19.5	142.4 – 149.3	-4.8	3204.5	-1.32	-0.10
HR _{maxage}	76.6 \pm 9.0	74.2 – 78.9	75.7 \pm 10.7	73.9 – 77.6	-0.9	3547.5	-0.30	-0.02
HR _{min}	117.7 \pm 9.1	115.5 – 120.4	104.4 \pm 11.6	104.4 – 108.5	-13.3**	1584.5	-6.14	-0.45
HR _{minage}	60.8 \pm 5.6	59.3 – 62.3	55.0 \pm 6.0	53.9 – 56.1	-5.8**	1757.0	-3.70	-0.27

Tabular report; Absolute values: HR = Heart rate, HR_{max} = Heart rate maximum, HR_{min} = Heart rate minimum. Relative values: HR_{age} = Heart rate relative to age, HR_{maxage} = Heart rate maximum relative to age, HR_{minage} = Heart rate minimum relative to age, Change = difference from OD to MD, U = Mann-Whitney statistic, ES = Effect Size. * Significant difference $P < .05$ ** Significance $P < .01$.

Table 37. Descriptive statistics (mean \pm SD; 95% Confidence Intervals) for absolute (beat.min⁻¹) and relative (% of age) heart rate (HR) data in OD and MD matches during fielding activities.

	One Day		Multi Day		Change \pm	U	Z Score	ES
	M \pm SD	95% CI	M \pm SD	95% CI				
HR	114.8 \pm 11.5	110.3 – 119.4	105.5 \pm 11.5	102.4 – 108.6	-9.3**	412.5	-3.26	-0.36
HR _{age}	58.8 \pm 6.4	56.2 – 61.3	54.5 \pm 6.1	52.8 – 56.1	-4.3**	456.5	-2.82	-0.31
HR _{max}	146.8 \pm 16.9	140.1 – 153.5	136.9 \pm 19.1	131.6 – 142.1	-9.9**	515.5	-2.24	-0.25
HR _{maxage}	74.9 \pm 9.4	71.2 – 78.6	70.8 \pm 10.2	68.1 – 73.6	-4.1**	560.5	-1.80	-0.20
HR _{min}	98.9 \pm 12.6	93.9 – 103.9	87.4 \pm 11.2	84.4 – 90.5	-11.5**	332.0	-4.05	-0.45
HR _{minage}	51.3 \pm 7.6	48.4 – 54.3	45.3 \pm 6.0	43.7 – 46.9	-6.0**	360.0	-3.77	-0.42

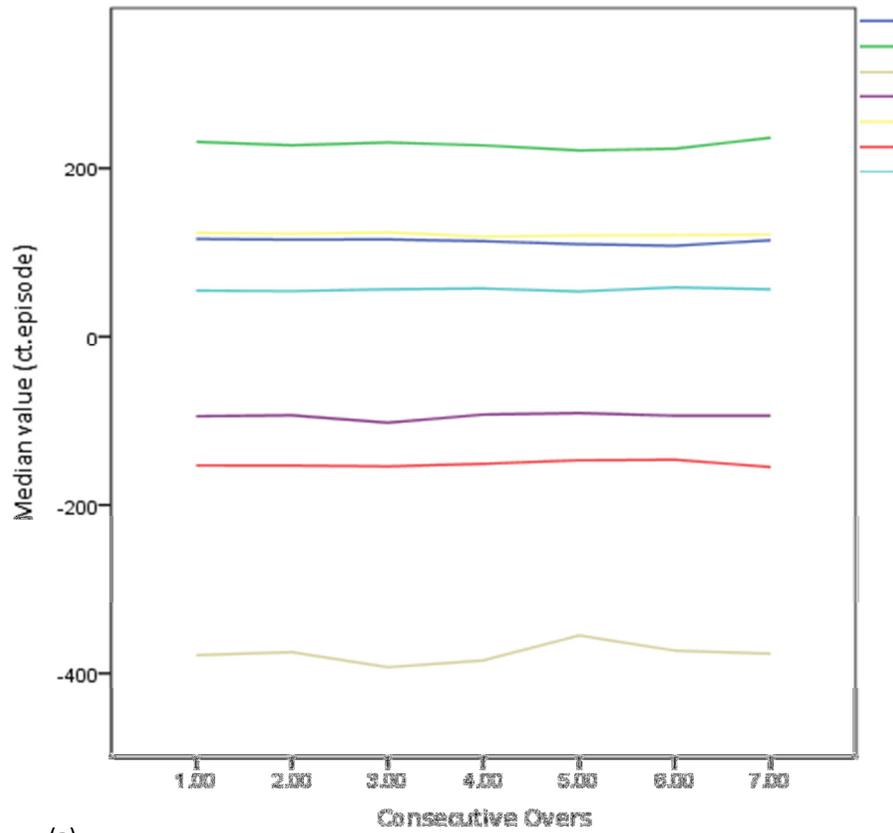
Tabular report; Absolute values: HR = Heart rate, HR_{max} = Heart rate maximum, HR_{min} = Heart rate minimum. Relative values: HR_{age} = Heart rate relative to age, HR_{maxage} = Heart rate maximum relative to age, HR_{minage} = Heart rate minimum relative to age, Change = difference from OD to MD, U = Mann-Whitney statistic, ES = Effect Size. * Significant difference $P < .05$ ** Significance $P < .01$.

7.3.4 Consecutive overs analysis

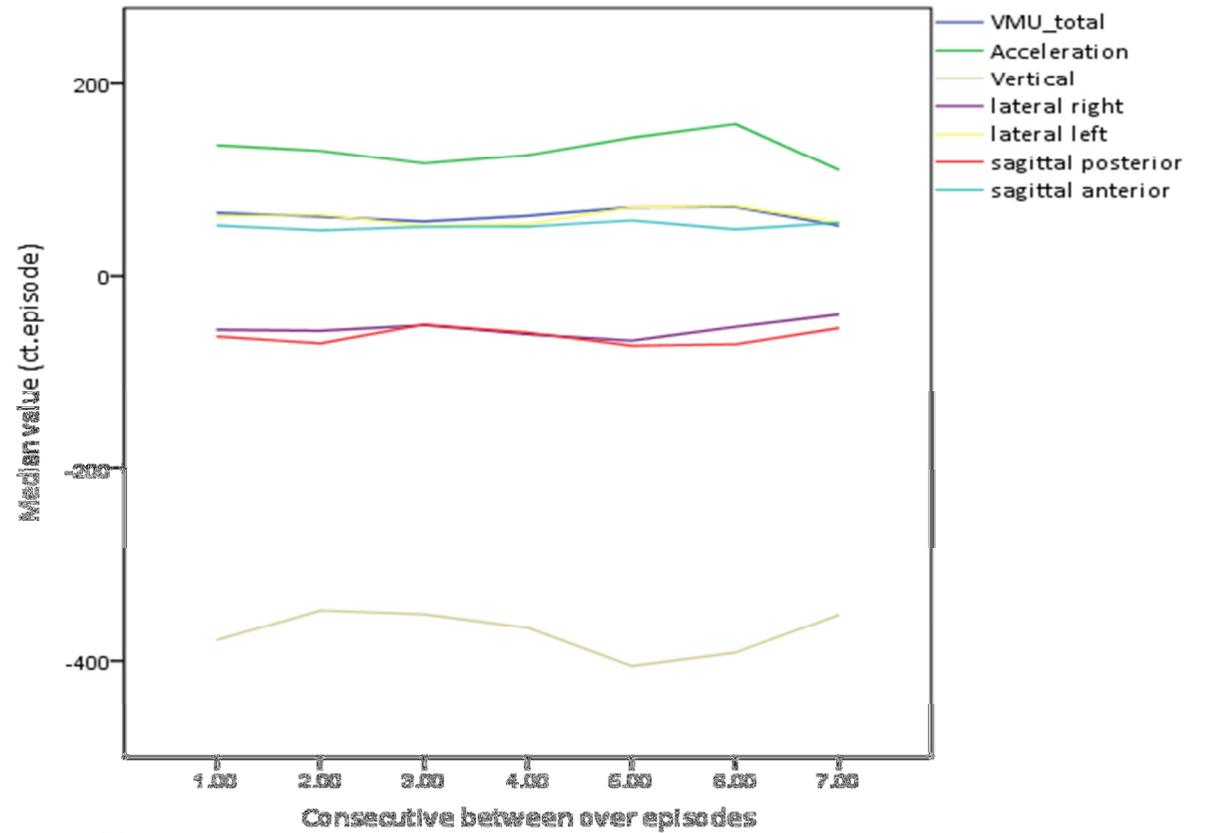
Accelerometry Data

When consecutive between over episodes ($n=7$) were assessed, initial observations appear to show VMU, vertical, lateral and sagittal peak values presented consistent data with small variations over to over (Figure 31). Further detailed observations (Figure 32) appear to show differences for VMU when presented between over and bowling match states. Statistical analysis identified a significant difference in data in the between over condition for VMU ($H(6) = 15.51, P < .05$) and also for Acceleration ($H(6) = 13.30, P < .05$). Follow up selected post-hoc (Mann-Whitney U) tests, with a Bonferroni adjustment ($P < .0167$), note a significant different lower VMU and Acceleration (medium ES) between over 1 and over 3 (VMU, $U(61) = 299.0, z = -2.40, P < .016, ES = -0.30$; Acceleration, $U(61) = 296.0, z = -2.43, P < .016, ES = -0.31$). Further post-hoc analysis identified non-significant differences, with small to medium ES, between over 2 and 4 (VMU, ($U(60) = 394.0, z = 0.77, P > .016, ES = -0.10$; Acceleration ($U(60) = 394.0, z = -0.77, P > .016, ES = -0.10$) and between over 4 and 6 (VMU, ($U(39) = 115.0, z = -1.43, P > .016, ES = -0.23$; Acceleration ($U(39) = 104.5, z = -1.75, P > .016, ES = -0.28$). Other ACC variables within this between over analysis presented non-significant differences over to over (Vertical axis, ($U(6) = 8.17, P > .05$); Lateral left, ($H(6) = 7.48, P > .05$); Lateral right ($H(6) = 8.92, P > .05$); Sagittal anterior, ($H(6) = 1.54, P > .05$); Sagittal posterior ($H(6) = 9.50, P > .05$)).

For consecutive bowling activity ACC variables presented no significant differences were observed for; VMU ($H(6) = 5.06, P > .05$), Acceleration ($H(6) = 6.63, P > .05$), Vertical axis ($H(6) = 11.09, P > .05$), Lateral left ($H(6) = 2.08, P > .05$), Lateral right ($H(6) = 2.99, P > .05$), Sagittal anterior ($H(6) = 3.43, P > .05$) and Sagittal posterior ($H(6) = 1.67, P > .05$) (See appendix 4 for descriptive data).



(a)



(b)

Figure 31. Trends for VMU and Vertical, Lateral and Sagittal values (a) during overs bowled and (b) during between over episodes

(Legend explanation; VMU_total= Vector Magnitude Units)

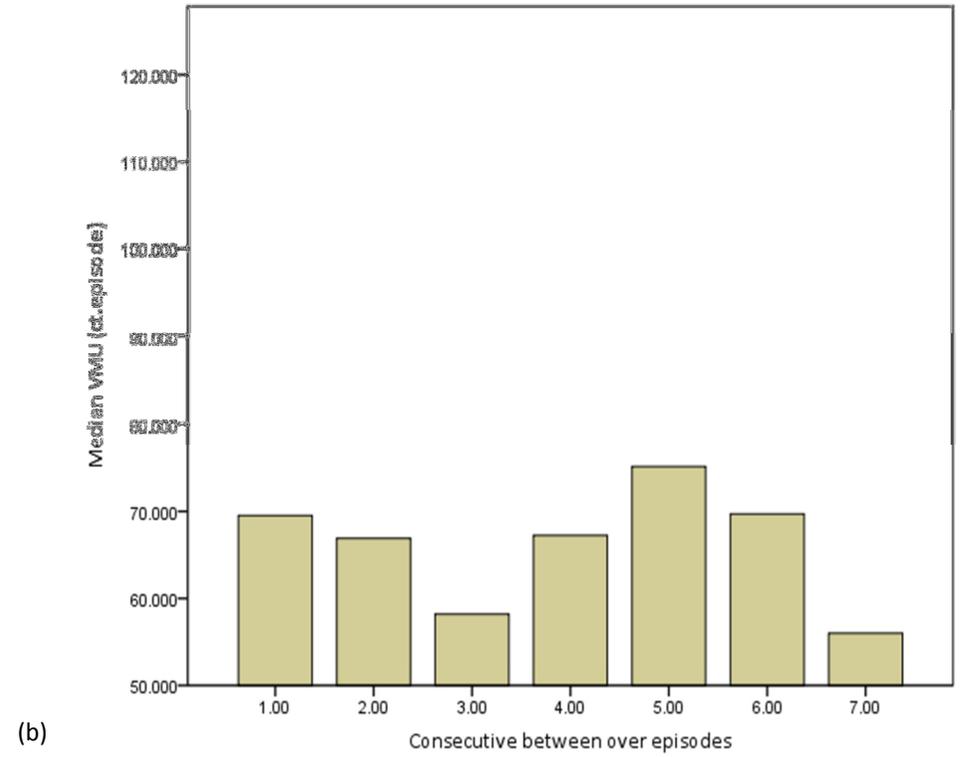
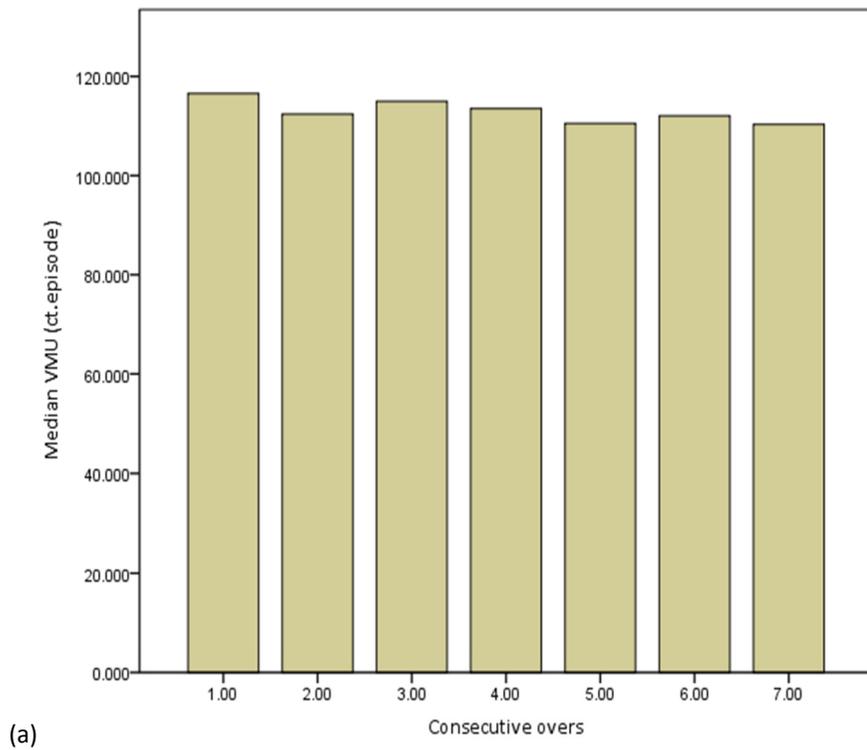


Figure 32. Median VMU over 7 consecutive (a) during bowling episodes and (b) between over episodes (■ Mdn Vector Magnitude Units)

Heart Rate Variables

Consecutive overs (n=7) from bowling spell 1 were identified across both match formats. During bowling (Figure 33 and 34) there appears to be a general trend of increasing HR values as bowling continues. Statistical analysis identified that there were no significant differences for any HR values between consecutive overs (One-way ANOVA, HR_{10r} $F(10,188) = 1.31, P > 0.05$); Kruskal-Wallis test, HR_{60r} ($H(6) = 7.57, P > 0.05$); HR ($H(6) = 5.17, P > 0.05$); HR_{age} ($H(6) = 4.02, P > 0.05$); HR_{max} ($H(6) = 3.52, P > 0.05$); HR_{maxage} ($H(6) = 3.31, P > 0.05$); HR_{min} ($H(6) = 4.86, P > 0.05$); HR_{minage} ($H(6) = 5.07, P > 0.05$) (see appendix 4 for descriptive data).

Between over HR trends appear to show an increase in values as the bowling spell continues (Figure 34). Further analysis noted there were no significant differences in the between over HR values (HR, ($H(6) = 5.17, P > 0.05$); HR_{age} , ($H(6) = 5.90, P > 0.05$); HR_{max} , ($H(6) = 6.0, P > 0.05$); HR_{maxage} , ($H(6) = 4.55, P > 0.05$); HR_{min} , ($H(6) = 4.60, P > 0.05$); HR_{minage} , ($H(6) = 6.47, P > 0.05$)).

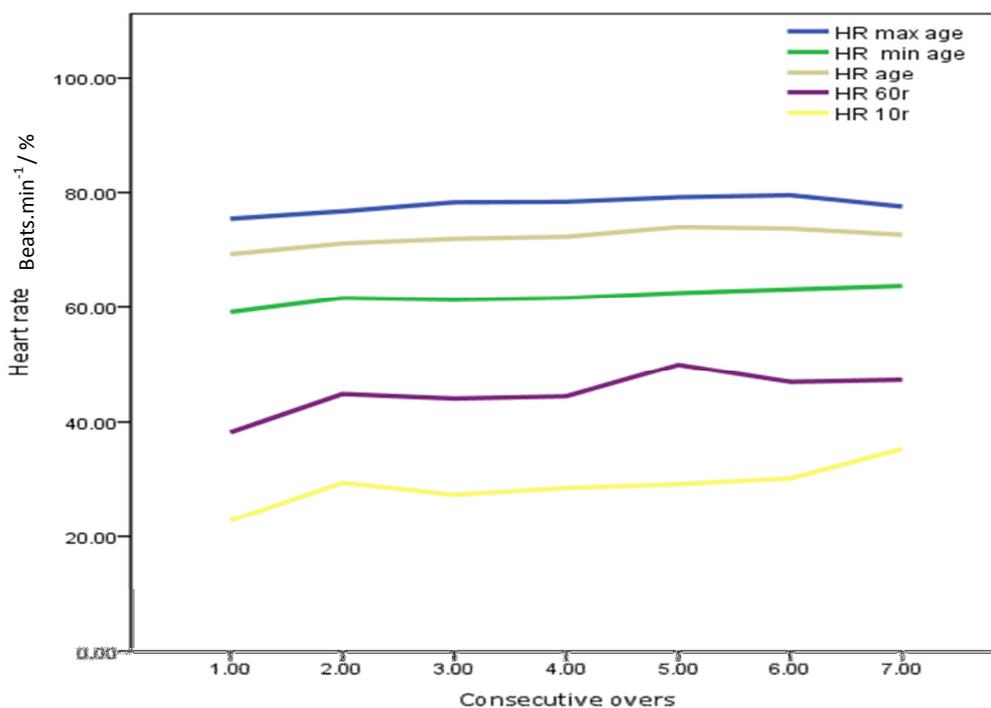


Figure 33. Trends for relative HR values (age related %), Pre (HR_{10r}) and Post (HR_{60r}) HR markers (beats.min⁻¹) during consecutive bowling of overs.

(Legend explanation; HR max age – maximum heart rate relative to age (%); HR min age – minimum heart rate relative to age (%); HR age – heart rate mean relative to age (%); - HR 60r – relative heart rate 60 seconds post bowling (beats.min⁻¹); HR 10r – relative heart rate 10 seconds prior to bowling (beats.min⁻¹))

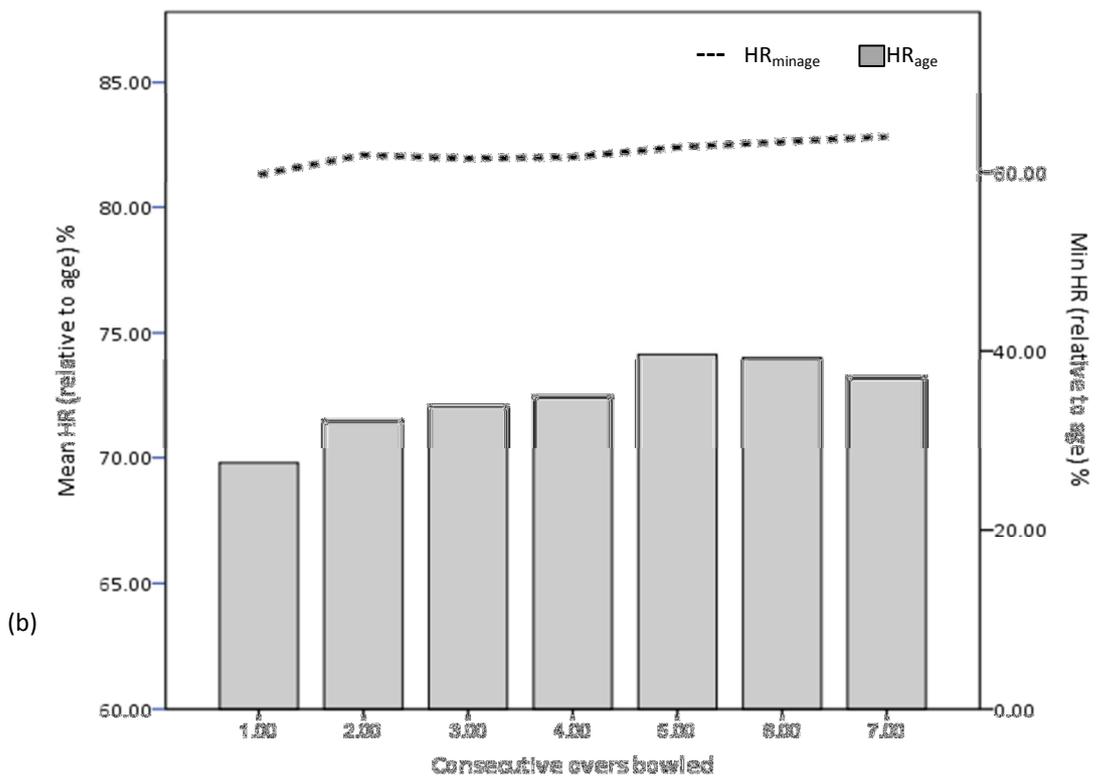
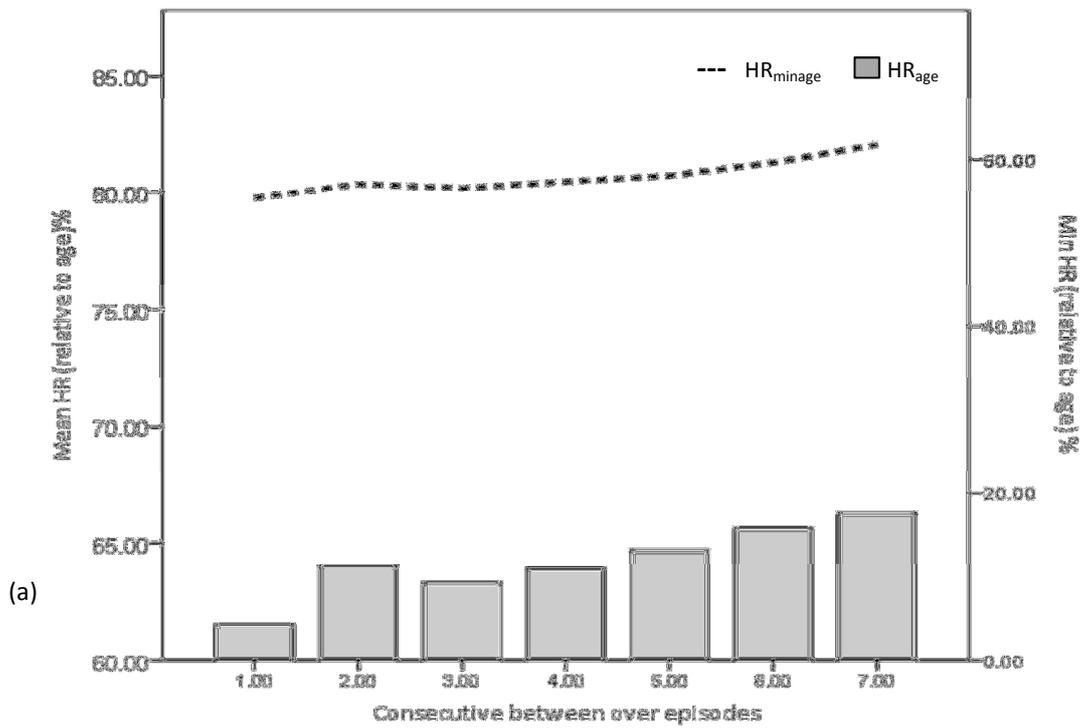


Figure 34. Mean HR (relative to age) and Min HR (relative to age) over 7 consecutive (a) between over episodes and (b) during bowling episodes.

Legend explanation; HR min age – minimum heart rate relative to age (%); HR age – heart rate mean relative to age (%)

7.3.5 Association between bowling performance and physiological data

Accelerometry and Bowling Performance

Spearman's Rank (ρ) was completed to find relationships in accelerometry data and runs scored in the subsequent over. Specific highlighted results report no significant relationships between runs scored in the subsequent over and VMU during bowling ($r = -.07, P > .05$) (Figure 35), VMU during between over episodes ($r = .03, P > .05$), cumulative activity (VMU bowling + VMU between over) ($r = .03, P > .05$) and acceleration ($r = -.07, P > .05$). No significant relationships in data were found for other accelerometry data during bowling activity ($r < .10, P > .05$) and between over episodes ($r < .07, P > .05$) relative to the runs scored in the subsequent over (See appendix 5 for other extended results).

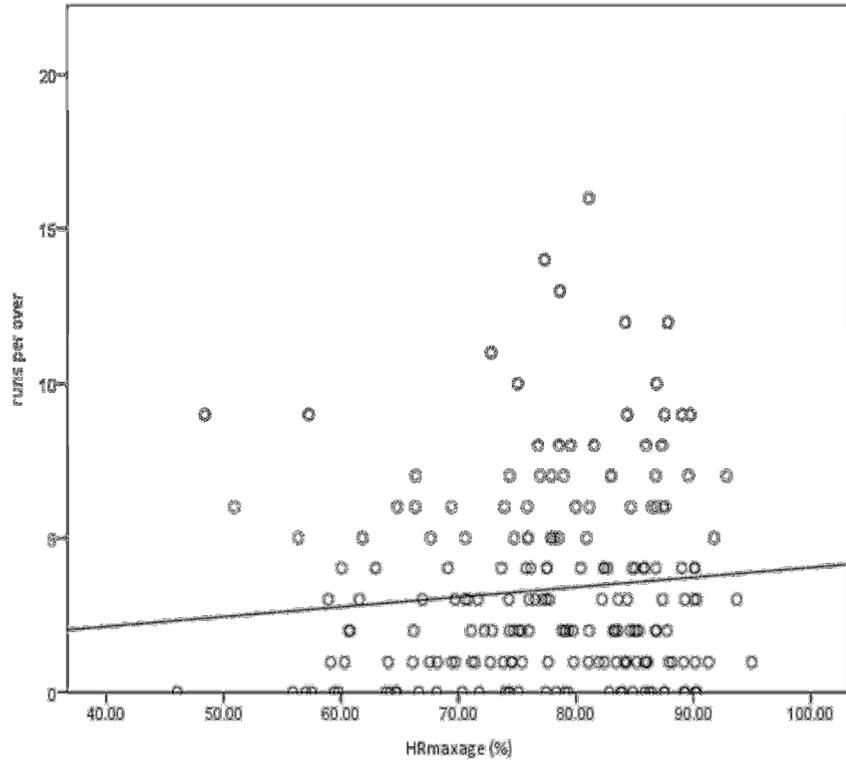
Further analysis of between over data reports that there was a significant difference between runs scored in subsequent over (in categorical form) and lateral left axis ($H(2) = 11.29, P < .05$). Post-hoc tests used a Bonferroni correction reducing the critical P value to .0167. For the between over lateral left axis there was a significant difference and medium ES noted between data when low (75.83 g.episode⁻¹) and medium (57.18 g.episode⁻¹) runs were scored in the subsequent over ($U = 542.0, z = -2.60, P < .001, ES = -0.28$). Also, a significant difference was reported for the between over peak lateral axis when low (75.83 g.episode⁻¹) and high (56.94 g.episode⁻¹) number of runs were scored in the subsequent over ($U = 835.5, z = -3.35, P < .001, ES = -0.30$). All other between over and during bowling ACC data reported no significant differences ($P > .05$) (see appendix 5 for extended results).

Heart rate and Bowling Performance

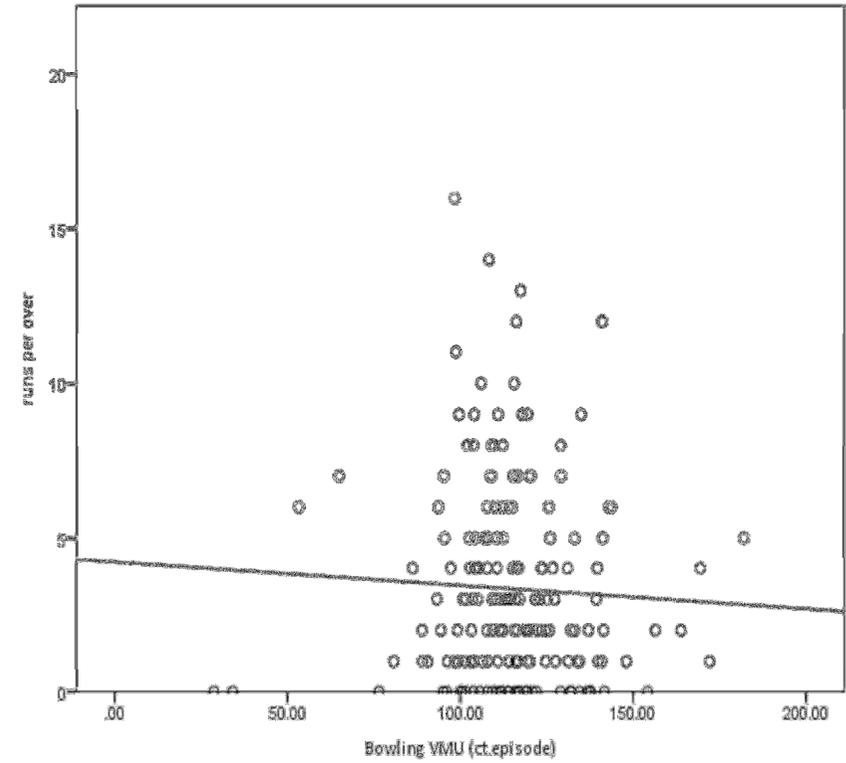
A Spearman's Rank (ρ) was completed to assess relationships in data and no significant relationships were noted. Selected results report weak relationships; $HR_{\max_{age}}$ ($r = .10, P > .05$) (Figure 35), HR_{60r} ($r = .09, P > .05$) and HR_{10r} ($r = -.06, P > .05$). HR_{10r} was completed via Pearson's Product Moment Correlation. No other significant relationships were found between the HR data during bowling activity ($r < .10, P > .05$) and between over episodes ($r < .01, P > .05$) and the runs scored in the subsequent over (see appendix 5 for other extended results).

Further analysis of between over heart rate data identified a significant difference between runs scored in subsequent over (in categorical form) and $HR_{\max_{age}}$ ($H(2) = 7.95, P < .05$), HR_{\max} ($H(2) = 6.96, P < .05$) and HR_{age} ($H(2) = 6.63, P < .05$). Follow up Mann-Whitney tests used a Bonferroni correction reducing the critical P value to .0167. A significant difference with medium ES was noted for $HR_{\max_{age}}$ between the low number of runs scored ($HR_{\max_{age}}$ 83.07%) and medium number of runs scored ($HR_{\max_{age}}$ 74.09%) ($U = 9.28, z = -2.81, P < .01, ES = -0.25$). There were no significant differences ($P > .0167$) between the other categories of runs and $HR_{\max_{age}}$. For HR_{\max} , follow up post-hoc tests revealed a significant difference and medium ES ($U = 941.5, z = -2.73, P < .01, ES = -0.25$) between low (159.0 $\text{beats}\cdot\text{min}^{-1}$) and medium (147.30 $\text{beats}\cdot\text{min}^{-1}$) categories of runs scored in the subsequent over. No other differences ($P > .0167$) were noted between other categories of runs within the HR_{\max} variable. Post-hoc tests note a significant difference and medium ES for between over HR_{age} during subsequent overs where low runs scored (HR_{age} 66.82%) and medium runs scored (HR_{age} 62.02%) ($U = 953.5, z = -2.66, P < .01, ES = -0.24$). All other between over heart rate data presented no significant differences ($P > .05$) between runs scored in subsequent over categories.

During bowling, a significant difference was identified for HR_{age} ($H(2) = 6.73, P < .05$) and HR ($H(2) = 6.74, P < .05$) between categories of runs scored in subsequent over. Post-hoc analysis, using a Bonferroni correction failed to reveal the specific differences ($P > .0167$) between categories of runs scored and heart rate variables. No other differences were noted in the data ($P > .05$).



(a)



(b)

Figure 35. Scatter plot showing no significant relationship between (a) HR_{maxage} (%) and runs scored in subsequent over ($r = .10, P > .05, r^2 = 1\%$) and (b) VMU ($r = -.07, P > .05, r^2 < 1\%$) during bowling episodes.

7.4 Discussion

The aims of this chapter were to use the Bioharness™ monitoring device to, (1) provide a performance profile of professional cricket fast-medium bowlers across different forms of cricket in-match and, (2) to investigate the relationship between cricket bowling performance and physiological data. Both aims were set within professional cricket capturing in-match data over three competitive seasons therefore enhancing the ecological validity of the current research base which have historically relied on simulated bowling events to develop the evidence base.

7.4.1 Performance profile of professional cricket fast-medium bowlers

To the author's knowledge, this research is the first to attempt to specifically identify an in-match physiological profile of professional fast-medium bowlers across two different formats of cricket. Using the Bioharness™, previously established as being valid and reliable in the laboratory and field setting (Chapter 4, 5, 6), this study has successfully differentiated physiological profiles for varying match states (i.e. bowling, between over, fielding) in performers and between two formats of cricket (One Day (OD) and Multi Day (MD)). Over 80 hours of match data were collected over three competitive seasons which is in excess of the 66 hours collected by Petersen et al. (2010) on time-motion based information using GPS technology.

When considering all data (Table 30 and 34), the results indicate that within OD cricket, accelerometry and Heart rate (HR) values were generally higher when compared to values in MD cricket. These headline findings suggest the nature of OD cricket could be more physiologically demanding for fast-medium bowlers and presents an exciting opportunity for coaches to use heart rate and accelerometry data to further improve conditioning, recovery, monitoring of workload and injury occurrence relative to OD and MD cricket. From these global results HR related hypotheses 1 and 2 and accelerometry related hypotheses 6 and 8 were supported (see 7.2.10.1).

7.4.2 Bowling

When considering the data during bowling Accelerometry data (Table 31) presented a somewhat complex picture with the majority of higher values being reported in OD cricket though statistically significantly higher values were only noted for peak acceleration and lateral right axis. With regards to HR (Table 35), with the exception of HR_{maxage} , HR_{60r} , and HR_{10r} , absolute and relative HR values were significantly higher in OD cricket in comparison to MD cricket.

The statistically higher peak acceleration and HR values for OD bowling provides clear evidence of increased physiological work for this match format in comparison to MD. Considering the match format organisation, OD cricket is played to a faster time line in comparison to MD cricket (see 7.3.1) and this notion is also supported by batting specific research (Duffield and Drinkwater, 2008). From match data, overs were bowled 27 seconds faster and between over episodes were 13 seconds shorter in OD cricket in comparison to MD cricket. The significantly higher peak acceleration values in OD bowling episodes may corroborate the faster pace of OD matches, with less time for recovery between balls and overs, which may all contribute to increased cardio-vascular workload (McArdle et al., 2009, Powers and Howley, 2007). Though Petersen et al. (2011a) does not differentiate specific in-match activity states, evidence on this theme identifies that there are differences in fast bowling activities between OD and MD matches with respect to the intensity of the distances covered. In OD matches fast bowlers complete $\sim 75 \text{ m}\cdot\text{h}^{-1}$ more distance at speeds aligned to running and sprinting ($> 3.5 \text{ m}\cdot\text{s}^{-1}$) in comparison to fast bowlers in MD matches (Petersen et al., 2011a). Therefore, it appears this information indicates that the different demands of OD versus MD cricket requires further investigation in the way players are selected and prepare for these different formats of the game.

Coaching literature (Davies and Collins, 2012, Pont, 2006, Woolmer et al., 2008) suggests good fast-medium bowling requires an element of consistency and rhythm during the bowling episode and there appears somewhat contradictory accelerometry data collected on this issue. As reported, peak acceleration is significantly higher in OD cricket and general activity, as measured through Vector Magnitude Units (VMU), has only marginally higher values for bowling across both formats of the game. Interestingly, fast bowlers were reported as covering similar hourly total distances in OD and MD cricket ($\sim 4 \text{ km}\cdot\text{h}^{-1}$) but there are emerging differences with regards to the intensities by which those distances were accumulated, with higher volume of distances per hour completed via sprinting and striding activities in OD cricket (Petersen et al., 2011b). Logically VMU, which is a composite accelerometry value, should be significantly higher in OD cricket if this format is more intense. When

the duration of bowling episodes are considered, the marginally (non-significant) higher VMU count reported is collected in a shorter time period therefore suggesting a greater intensity of activity occurs within OD cricket when bowling. When accelerometry data from consecutive overs is assessed (Appendix 4, Figure 31, 32), it presents a consistent stable over-to-over view, and seems to corroborate the consistency of bowling argument the coaching literature describes (Pont, 2006, Woolmer et al., 2008). Moreover, Duffield et al. (2009) provides additional evidence on this issue in that distance covered, as collected through GPS technology, did not differ between two bowling spells. Caution should be applied to the over-to-over findings in this study as this analysis was more rudimentary in nature due to lack of sample sizes bowling data was aggregated thus losing the between format comparison. Moreover, it is unclear from coaching and players accounts (McGrath, 2010, Pont, 2006, Woolmer et al., 2008) if performers complete the bowling event at higher intensities in shorter formats of the game. In batting specific research it is noted there is little difference between OD and MD matches for frequency, duration and time spent in high intensity activities when scoring centuries (Duffield and Drinkwater, 2008). Considering anecdotal evidence, it is possible that within an OD match a bowler, knowing that there is a limit to the number of overs that can be bowled could lead to extra physical effort, conscious or sub consciously, occurring in this specific cohort. The similarity between OD and MD cricket for VMU data may be linked to this generic activity count being developed to capture information at lower intensity as would be found within health related research. Therefore, the data stream may not being sensitive enough due to the capture rate (18Hz) of the BioHarness™ device not being sufficient for activity being monitored.

Literature has identified OD cricket as a more physically intense format in comparison to MD probably due to greater incidence of higher intensity activity and less recovery time between these episodes in the shorter format (Duffield and Drinkwater, 2008, Petersen et al., 2010). Specifically, fast bowlers have been reported to cover more distance sprinting (e.g. moving at $> 5.01 \text{ m}\cdot\text{sec}^{-1}$) and complete more repeated sprints in this shorter match format (Petersen et al., 2010, Petersen et al., 2011b). Although this current study did not measure distances covered during bowling, the mean run up velocity (Table 27) for fast-medium bowlers in this study was $19.9 \text{ km}\cdot\text{h}^{-1}$ ($5.5 \text{ m}\cdot\text{sec}^{-1}$), a figure which is comparable to other research (see Table 1), and this finding relates to the repeated sprinting evidence previously mentioned (Petersen et al., 2010, Petersen et al., 2011b). Linking to the earlier coaching point of consistency during bowling performance, variation in run up velocity between OD and MD matches were not substantiated as this specific run up data was collected in training, though peak acceleration is noted as being significantly higher during bowling for OD matches in this research. Whether performers bowl with more intensity during OD matches or if fielding activities completed during bowling events account for the increases in peak acceleration identified in this

study are, due to the nature of data collection, not confirmed from this research. The increases in peak acceleration data would imply that greater intensity of activity has been completed and though high intensity activity is considered anaerobic in nature, the repeated nature of this activity would also stimulate a cardio-vascular response in the recovery period, post-sprinting, which may explain the increased heart rate responses from this shorter format of the game (McArdle et al., 2009, Petersen et al., 2010, Petersen et al., 2011b, Rudkin and O'Donoghue, 2008).

Generally, there appeared to be a trend of higher accelerometry values during bowling in OD cricket albeit these differences were not all statistically significant (Table 31). Despite the aforementioned differences in timings for OD and MD matches, an axis which did not appear to support this trend of higher values in the shorter format was the sagittal axis. Absolute values were very similar ($< 2 \text{ ct.episode}^{-1}$) and initially appear to provide little indication as to the match format being played. Interestingly, during bowling episodes the values were higher in the posterior direction in comparison to the anterior which, may seem contrary to what would be expected but this outcome could be explained by the nuances of the bowling action. As described in section 2.4.2.4, bowling starts from a relatively rhythmical run up and prior to release of the ball there are large braking forces especially as the front foot lands and allows the ball to be delivered (Figure 4) (Davies and Collins, 2012, Ferdinands, 2008). This technical element of the bowling action may increase the posterior forces registered during bowling activity. When a match state comparison is made for data generated on the sagittal axis, data from the between over episodes (i.e. non bowling) are over $100 \text{ ct.episode}^{-1}$ lower in the posterior direction when compared to bowling episodes. The sagittal anterior data presents similar values in both bowling and between over states therefore suggesting the possible importance of sagittal posterior axis in fast-medium bowling. Clearly the sagittal axis may warrant further investigation with comparisons of bowling styles, efficiency of delivery, injury occurrence and performance over a longer term being considered.

An axis which presents interesting results is the lateral axis (Table 31). The lateral left axis was significantly higher for MD cricket while lateral right axis was significantly higher in OD cricket, so requires further consideration. The bowling action is a complex series of extensions, rotations and flexion's of the trunk therefore creating different forces at different points of the bowling action (Bartlett et al., 1996, Ferdinands, 2008, Woolmer et al., 2008). It may be possible to posit a similar argument as previously noted with regards to increased intensity of OD cricket which may explain the higher right lateral forces identified in the shorter format of cricket. Additionally, with MD overs being longer in duration when compared to OD cricket (see 7.3.2) this could account for a higher count per episode for the left lateral axis and therefore some of the differences between the data

sets. When comparing the two sets of data on the lateral axis there appears to be higher occurrence of force in the left direction (i.e. a higher count) during bowling. Within a right arm bowling action, the left lateral side can be a point of high flexion during the delivery (Figure 4) (Davies and Collins, 2012, Ferdinands, 2008). This could account for this general finding of an increased count in comparison to the right lateral axis though as previously mentioned, the capture rate of the Bioharness™ is not sufficient to isolate the data to such a point in time. It is suggested that left lateral forces would be consistent when bowling as all bowlers were right handed, well trained in completing the same task, albeit with minor technical differences. When comparing bowling data to the between over data on the lateral axes (Table 31 and 32), somewhat confusingly, the differences noted during bowling episodes are seen again (i.e. right higher in OD, left higher MD) suggesting that the MD format has a lateral left force which is consistently higher than OD cricket. Interestingly, the between over lateral axis data is 40-60 ct.episode⁻¹ lower when compared to the equivalent bowling data. During the between over episodes, both axes present similar data values (i.e. they are within 10 ct.episode⁻¹) emphasising that bowling elicits greater lateral forces. In summary, based on the aforementioned data the lateral axes are seemingly both involved in the bowling action though it is inconclusive as to why MD cricket presents consistently higher lateral left values, this clearly warrants further investigation. It is acknowledged that this research has a small sample size and data capture rate (18 Hz) is not high therefore the occurrence of statistical anomalies should also be considered.

When considering the bowling related HR data (Table 35) to previous literature, absolute and relative values are lower than have been reported in simulated bowling research. Burnett et al. (1995) reported absolute values of 163 ± 11 beats.min⁻¹ and peak values of 176 ± 12 beats.min⁻¹ (relative to age 80.3% and 84.7% respectively). Duffield et al. (2009) reported post-over mean HR of 162 ± 9 beats.min⁻¹ and slightly lower values are reported by Delvin et al. (2002) (154 ± 15 beats.min⁻¹) though no age related relative values were provided. It appears, in comparison to the data captured in-match using the Bioharness™ system, that simulated bowling research has presented a higher absolute and relative HR values. The results of this study are partially supported by Petersen et al (2010) who reports fast bowlers mean HR during Twenty-Twenty (T20) cricket are 133 ± 12 beats.min⁻¹ which are lower than simulated bowling events and more comparable to the data reported for MD and OD formats. Moreover, Johnstone et al. (2008) report similar data from a fast-medium bowler with HR mean during a 6 over first-class OD match (137 ± 19 beats.min⁻¹). Petersen et al. (2010) does highlight the nuances of T20 may explain variations in HR and also these HR data include between over episodes within the mean HR calculation which may account for the lower values. The lower HR values reported from in-match events clearly suggests there is a need to

understand the activity and movement patterns for these events. There is a need for a review of physiological profiles for fast-medium bowlers and cricket performers generally across the main formats of the game. Possible reasons for these differences between simulated and in-match data will be discussed later in the section.

A previously unreported data point in other literature (Burnett et al., 1995, Devlin et al., 2001, Duffield et al., 2009) is HR minimum which could be a key point of information as it was significantly lower in MD format with a medium to large Effect Size (ES) (Table 35). MD cricket presented lower minimum values during bowling which would corroborate with previous research which has identified this form of cricket as being less physically intense (Petersen et al., 2010). The lower minimum HR during MD bowling is explained by lower VMU and peak acceleration (i.e. activity) values. Additionally, it would appear there is more time for the performer recover within a MD match as bowling and between over episodes have been identified as being of longer duration. The reduced activity and increased recovery associated with MD cricket would allow HR values to recover more readily and therefore could provide an additional rationale for the other HR values being lower in MD cricket. When consecutive overs descriptive data are analysed, HR minimum increases from over 1 to over 7 ($HR_{\min} + 8 \text{ beat}\cdot\text{min}^{-1}$; $HR_{\text{minage}} + 4.2 \%$) suggesting a mild reduction in cardio-vascular capacity to recover as the bowling activity continues (Figure 34). This increase in HR minimum was non-significant but this theme appears contrary to previous research (Duffield et al., 2009, Noakes and Durandt, 2000) and the efficacy of increasing cardio-vascular stress as bowling continues should be investigated further during match conditions. Although the latter consecutive overs data was aggregated across formats, the HR minimum could help the coach to objectively assess performer's ability to recover allowing an insight in to the physiological state of the bowler.

An interesting HR value for the OD format was absolute and age-related maximum HR (Table 35). Absolute HR_{\max} difference was significantly higher (i.e. $2 \text{ beats}\cdot\text{min}^{-1}$), while the latter age related difference was $< -1 \%$ and considered not significant. Although the in-match literature base is very small and the two other studies being compared are not directly equivalent being from T20 (Petersen et al., 2010) and OD (Johnstone et al., 2008), this study's finding linked to maximum HR may be contrary to the data presented. Those aforementioned research studies present a $\sim 10 \text{ beat}\cdot\text{min}^{-1}$ higher peak HR for the more intense T20 cricket in comparison to the OD format (Petersen et al., 2009a, Petersen et al., 2010). This study reports $< 2 \text{ beats}\cdot\text{min}^{-1}$ higher absolute difference and the age-related difference is negligible in the more intense OD format. It appears that further clarification is needed on the value of HR maximums, relative and absolute, but within this research the age-related variable appears not to be suitable for exercise scientists and coaches to investigate differentiation of physiological work across OD and MD cricket.

When considering the two pre and post HR points assessed during bowling, hypotheses 3 and 4 were not supported (see 7.2.10.1). HR_{10r} presented similar values (OD, 28 beats.min⁻¹, MD 28 beats.min⁻¹) across both match formats which does not support earlier assumptions of the increased cardio-vascular stress of OD cricket. HR_{60r} noted higher values in MD cricket in comparison to OD (OD, 41 beats.min⁻¹, MD, 45 beats.min⁻¹) cricket suggesting MD format has a higher cardio-vascular cost 60 seconds after bowling. Although not statistically significant, so caution should be applied to any interpretation, these trends seen are counter to the original hypotheses postulated and appear contrary to the higher HR values reported so far in OD cricket. Based on the limited evidence available it has been demonstrated that more distance is covered at a greater intensity by performers in OD cricket (Petersen et al., 2010, Petersen et al., 2011b). Therefore similar values for HR_{10r} and higher HR_{60r} value in the less active/intense MD format seems surprising especially when other absolute and relative HR values were higher in OD cricket. For the coach, having a chance to immediately assess the physiological state of a performer pre or post bowling seems attractive on a tactical level. Therefore, to assess the value of these two data points further investigation was completed across 7 consecutive overs. This data was aggregated but from this analysis there does appear to be a more logical theme for these two HR data points in line with other HR data being reported, with a gradual increasing cardio-vascular cost to bowling as activity continues (Figure 34). Specifically for the pre and post measures, there is a -10 beat.min⁻¹ increase from over 1 (HR_{10r} , 23 beats.min⁻¹, HR_{60r} , 38 beats.min⁻¹) to over 7 (HR_{10r} 34 beats.min⁻¹, HR_{60r} , 47 beats.min⁻¹). The increases in HR presented were deemed non-significant which, in a statistical sense, is similar with Duffield and colleagues (2009) findings related to over to over HR changes in a simulated bowling event. When consecutive over bowling accelerometry data is assessed (Appendices 4, Figure 31, 32), data remains relatively constant throughout the bowling episode suggesting that performers are maintaining the same intensity of activity but at a increasing cost to the cardio-vascular system. Therefore, this trend in HR data again suggests an increasing cardio-vascular cost for fast-medium bowling as the bowling spell continues as players are unable to recover back to the original baseline HR levels from over 1.

Interestingly, as seen with other HR values reported previously, the largest increase in consecutive overs for HR_{10r} was between over 1 and over 2 (+6 beats.min⁻¹) which may demonstrate that performers are not physiologically prepared prior to activity/performance commencing. There is some evidence to support this finding from simulated bowling events. Duffield et al., (2009) noted the main increase in core body temperature is immediately following the 1st over bowled and also data presented by the same researchers (Figure 6) appears to show a similar trend of increasing HR from over 1 to over 2. Accelerometry data for the same 7 consecutive overs presents a relatively consistent view of activity reiterating the notion identified in coaching literature (Pont, 2006,

Woolmer et al., 2008) that these participants are highly skilled bowlers with rhythmical consistent movement pattern during bowling. These results may highlight the difficulties of in-match preparation in that completing “practice” (i.e. warm up) activity that prepares the cardio-vascular system for performance in a dynamic competitive situation is hard to achieve. There are claims that cricket is sometimes slow to progress its exercise science practices (Buchanan, 2008) and even though match characteristics may not allow, coaches and captains should plan bowling changes in advance so players can have time to be in the optimal physiological state prior to bowling. Further research using similar mobile monitoring technology may eventually permit the coach to be aware if players are physiologically ready to bowl and not potentially be using the first over bowled as a “warming up” event. Clearly the latter could give the batting team a distinct advantage if bowlers are unable to produce desired velocity or direction of delivery from the start. Although the data presented contrary results when comparing OD and MD, these unique relative data points, HR_{10r} and HR_{60r}, should be investigated further as understanding the cardio-vascular responses pre and post bowling and how these values may change across match formats could be important for coaches in understanding short and long term performance.

The analysis completed in this research was focussed on splitting data captured in different match formats (i.e. OD and MD) while most previous simulated bowling research does not make that distinction. The evidence presented clearly identifies a division between OD and MD cricket based on the accelerometry and subsequent changes in HR data of performers. Differences in HR values between this research and simulated events could be linked to a number of reasons. The simulated type of research, although useful in generating a starting point for exercise scientists in this area, is ecologically flawed as cricket has 3 distinct match formats (MD, OD, T20) which require specific physiological performance data on each. There is now emerging objective time-motion data presented on distances covered in-matches which confirms that T20, OD and MD cricket formats have different characteristics (Petersen et al., 2009a, Petersen et al., 2010, Petersen et al., 2011b). This higher accelerometry values identified in this research corroborates those latter findings on MD and OD matches. Without this bespoke information it is difficult for strength and conditioning coaches and sports medicine professionals to be effective in their interventions and formulate training and recovery schedules.

In summary, the evidence from this bowling data suggests there is a trend of increased activity, shorter recovery time and therefore higher cardio-vascular workload for fast-medium bowlers in OD cricket. This information will be valuable for sports science support teams with regards to planning workloads, organising bespoke between match training schedules, monitoring of fatigue and injury occurrence.

7.4.3 Between Over

It has been highlighted in section 2.4.3 that in-match analysis provides an insight in to specific areas of performance that have been over looked by other bowling research. This research identified previously unreported between over episodes in the literature, which may provide a unique insight in to the physiological state of performers during the match, prior to bowling another over.

General trends for accelerometry and HR between over data (Table 32 and 36) were for higher values to be produced within OD cricket which appear consistent with the bowling data presented previously. Specifically, higher peak acceleration and marginally higher VMU values from the OD format were not considered to be statistically significant but, these activity counts were accumulated from shorter between over durations. Linked to the increased activity counts, HR data presented significantly higher values in OD matches with medium to large ES for all variables apart from HR maximum. These results appear to support earlier findings that the OD format involves increased physical activity in shorter time periods and therefore produces a greater cardio-vascular response in the performers.

As highlighted extensively, bowling and between over events are shorter in OD cricket but more relevantly for this match state scoring rate is significantly higher in the shorter format (See section 7.3.1), a result which is comparable to other match data (ICC, 2013). Anecdotal evidence suggests that traditionally, bowlers are placed in fielding positions where there may be less activity to complete in order to facilitate recovery between overs. The higher run rate identified within OD cricket may require bowlers to complete more fielding activity between overs in comparison to MD cricket and this appears to be supported by higher VMU and peak acceleration data within the OD format (Table 32).

Further specific analysis continues to present interesting data across the two match formats with relative and absolute values for minimum HR presenting significant higher values in OD ($HR_{min} +13 \text{ beats}\cdot\text{min}^{-1}$, $HR_{minage} +5.8\%$) with medium to large ES. Between over periods have been shown to be episodes where less activity (in comparison to bowling) occurs (Table 32) and therefore most recovery for fast-medium bowlers occurs. Previous research (Petersen et al., 2010) has suggested fast bowlers in MD format have a longer recovery ratio (MD, $38 \pm 3 \text{ secs}^{-1}$; OD, $25 \pm 7 \text{ secs}^{-1}$) which would permit the cardio-vascular system to return to and remain on or near baseline levels. This reduced activity and enhanced recovery period is important for the bowler if optimal performance is sought in the next bowling episode.

Previous bowling related research (Burnett et al., 1995, Devlin et al., 2001) is more accustomed to presenting maximum HR values during bowling, which clearly are of interest, but these values should be coupled with activity values and other cardio-vascular responses to fully understand the players' physiological status. For example, absolute and age related HR maximum bowling values reduce by 12.3% and 16.3% in OD cricket and, 15.9% and 22.4% in MD cricket respectively when compared to equivalent between over minimum values (Tables 35 and 36). These data again demonstrate the higher physiological stress faced by the bowler in OD cricket and corroborate the seemingly greater opportunity to recover during MD cricket. Moreover, these values could be monitored over a season to assess long term physiological status and may provide an additional tool for the strength and conditioning coach when considering fatigue and/or overtraining.

When comparing accelerometry between over to bowling data (Table 31 and 32) it is possible to highlight specific data sets which may be more aligned with bowling and therefore potentially more use to the coach and strength and conditioning coach. Assessing OD format as an example, data for VMU, peak acceleration, lateral axes, sagittal posterior axis were between 42-62% lower during the between over activities. Data captured on the vertical axis and sagittal anterior axis varied by <3% between these two match states. This latter overview highlights where the greatest changes in accelerometry force may occur during the bowling and non-bowling activity which may make further research in this area more focussed. With further investigation, bowlers' between over HR and accelerometry values could be related to each format of the game and be an interesting point of reference for exercise scientists when monitoring workload or injury incidence in cricket.

As discussed in 2.4.3.3, on the very rare occasions between over activity is identified within wider simulated bowling research it could be claimed the behaviour incorporated and described is somewhat mechanical in nature and without a physiological rationale. For example, within the paper by Duffield et al., (2009), who acknowledges concerns over validity of their protocol, a rare overview of simulated fielding activities is provided which required players to walk 10 meters as their bowling partner delivered the ball and 20 m runs were completed twice in the over. Though this description of a process is a definite improvement on early simulated research presented (Burnett et al., 1995) and provides some evidence for replication by other scholars, at face-value it appears a consistent repetitive protocol and it is not clear if it was linked to any physiological marker. Petersen et al. (2010) intimated from data collected in-match using GPS technology, the between over episode was not a standardised period, describing sprints or clusters of sprints occasionally occurring but disappointingly the paper did not detail how much distance was covered during these phases. Data presented in this research shows (Figure 34) a trend of increasing between over cardio-vascular cost as a bowling spell continues, with HR data increasing, albeit non-significantly, between 6 - 9% from

over 1 to over 7. When accelerometry data (VMU and peak acceleration) is considered during the same period a significant difference in activity between overs was noted (Figure 32). This outcome reflects the real variability of between over episodes supporting the findings of Petersen et al. (2010) that this period is non-standardised with respect to activity that occurs. The latter result does continue to question the validity of simulated bowling studies which fail to consider the activity and cardio-vascular variability in the between over period. Practically, this unique over-to-over analysis could be of interest to coaches and exercise scientists alike in order to assess changes in micro level recovery (i.e. between overs) or longer term across different match scenarios.

In summary, this between over data has presented a first glimpse at in-match physiological responses and activity levels which future research could utilise to optimise performance across all formats of the game. This data may have previously not been considered by sports science support teams but now can be monitored and related to optimising performance both short and long term.

7.4.4 Fielding

In comparison to the other match states fielding data presented the lowest HR (Table 37) suggesting, that within this research, this specific activity provokes the lowest cardio-vascular stress in fast-medium bowlers. Petersen et al. (2010; 2011b) confirms that fielding is a less demanding activity than bowling with performers in this role covering less total distance (MD fielder ~15 vs bowler ~22.6 km; OD, fielder ~10.8 vs bowler ~13.4 km). Moreover, the latter research also identifies in comparison to fast bowling, the fielding activity completes fewer absolute sprints and high intensity activities per hour.

All HR values were significantly lower in MD cricket and the biggest relative and absolute differences between the match formats were seen for HR_{min} (-12 beats.min⁻¹) and HR_{minage} (-6.1%) supporting the consideration that HR minimum may provide a unique insight in to physiological stress. Considering age related HR data, an example of the decreased cardio-vascular stress associated with fielding can be seen when bowling and fielding data are compared. A 14.3% and 16.5% decrease from bowling to fielding activities for age related HR values is found in OD and MD matches respectively (Tables 35 and 37). These data could provide a better understanding of player physiological status if monitored longer term by the strength and conditioning coach possibly leading to improved training prescription.

With the exception of sagittal anterior axis, accelerometry data (Table 33) presents an overriding trend of higher values within the OD format which is more interesting considering the OD match occurs over a shorter duration. Data values for fielding are the highest due to the extended period performers were completing that specific task. Considering the data noted in earlier sections, VMU and peak acceleration present a consistent picture with significantly higher values attained in OD cricket. Due to the wide variety of roles and movement patterns that occur within fielding it is unclear why sagittal anterior axis presents higher counts in the MD format. Large standard deviations associated with this data suggest that there is a high variation of activity occurring. This is consistent with variation in data reported by Petersen et al. (2011b) and is explained by the variety of fielding positions and activity that may occur in the game.

In summary, this current study provides a distinctive insight in to the fielding role completed by fast-medium bowlers with seemingly a greater cardio-vascular response on the performer in OD cricket when compared to MD cricket due to increased activity levels. Physiological monitoring during fielding is in its infancy and more data is required to build a comprehensive picture of the cardio-vascular and activity profile of this period. All performers in the team complete the fielding role so understanding its requirements seems fundamental in establishing the evidence base for cricket. Sports science support teams should now monitor how performers with higher physical workloads (i.e. fast-medium bowlers) compare to other team members during OD and MD matches and continue to enhance bespoke recovery and training strategies for players.

7.4.5 Association between Bowling Performance and Physiological Data

To the authors' best knowledge, this is the first research to attempt to assess if there is an association with physiological data collected by a mobile monitoring device and cricket sporting performance. Overall, this exploratory investigation did not demonstrate that the variables selected were related to bowling performance possibly due to in-match events which may have influenced the outcomes. Therefore, this indicates that sporting performance is multi-factorial with not one single marker dictating the outcome of performance.

7.4.6 Accelerometry data and bowling performance

Results indicate there were no significant relationships between accelerometry data and bowling performance. Therefore, hypotheses 14 to 20 were not supported (see 7.2.10.1). Significant

differences for between over lateral left axis data were reported with higher values occurring when a low number of runs were scored in the subsequent over. A rationale for these results will be presented in 7.4.8.

7.4.7 Heart rate and bowling performance

This study suggests there were no significant positive relationships between HR data and bowling performance. This latter outcome was true for both the match states of bowling and between over. Therefore hypotheses 10 – 13 were not supported (see 7.2.10.1). During bowling, additional analysis initially identifies a significant difference for age related HR data and performance but follow up analysis failed to reveal where this difference was. The latter result may have been a result of a reduction in the critical value due to Bonferroni correction or a more complicated contrast of the groups than originally completed (Field and Miles, 2010, Newell et al., 2010, O'Donoghue, 2012). Between overs, there were significant differences for absolute and age related HR values when low and medium runs were scored. The higher HR value was reported when lower runs were scored in the subsequent over. A rationale for these results will be presented in 7.4.8. There were no other significant differences found across the HR data.

7.4.8 Bowling performance and Bioharness™ data

As an innovative part to the research the overriding premise was to consider if fluctuations in HR and/or accelerometry data captured by the Bioharness™ during bowling or the between over episodes were related to actual performance. The results indicate that there are no associations between the data. The two significant differences for the between over data reported a higher HR and left lateral axis values occurring when lower runs were scored in the subsequent over. These results are difficult to rationalise as it would be more logical for lower cardio-vascular stress and less activity between over leading to improved performance, but this results suggests the opposite outcome.

The lack of association between HR and accelerometry data and bowling performance is likely to be explained by the many uncontrollable factors that exist during the data collection period (i.e. in-match). Although many established controls were implemented within the research (see 7.2.4) there were other factors which were not controllable due to the nature of research setting and these will be highlighted further within the next section.

This research linked the runs scored per over to bowling accuracy which although at face value is logical, has its limitations in a competitive sporting environment (see 7.4.9). The wider research assessing accuracy and bowling performance have been completed in a simulated environment. Portus et al. (2000) reported a change in technique within bowlers during an 8 over spell of bowling which rationally may affect accuracy. A decrease in bowling accuracy with increasing dehydration has also been posited (Devlin et al., 2001) though Duffield et al. (2009) did not record any differences in accuracy over two spells of bowling but did indicate increases in perceptual fatigue. It appears the mechanisms associated with bowling accurately during a spell of bowling are multifaceted and still not well understood partly due to different research designs and participants being utilised. The previous research is completed within a simulated environment and undoubtedly the relationship between data would be more complex within a competitive match situation. This innovative study's strength was its use of new monitoring technology, the participant sample and ecological validity of collecting data in a competitive match. The field based setting with which these elements are within may have partially led to the lack of relationships in data or differences reported not permitting logical explanation. Limited relationships in data are due, in part, to sporting performance being multi-factorial with not one underlining factor being entirely responsible for the outcome of performance.

7.4.9 Limitations to the wider study

There are certain aspects that may have influenced the outcomes presented or need clarifying to place the results in context. The following section aims to discuss limitations of the chapter.

Accelerometry data was deemed precise and reproducible (Chapters 3-6), but the data capture rate of this variable in the Bioharness™ may have limited the quality of data presented. Sampling at 18 Hz was an insufficient rate to capture the specifics of the bowling movement and delivery leading to some data being distorted in the time period specified. The individual delivery of each ball took ~3.6 sec⁻¹ though the Bioharness™ reported this same event over a longer period of time (e.g. ~5 sec⁻¹) due to the slower sampling rate. Variations in this data set may well be presented differently if a higher capture rate that meets the Nyquist criterion is used. The latter criterion states "*sampling frequency must be twice the frequency of the highest frequency movement*" (cited Chen and Bassett, 2005. p491). It is suggested that frequency of movement in the arms could be near 25 Hz therefore a minimum sampling rate for accelerometry data to capture bowling activity comprehensively could near 50 Hz which is an issue future issue developers of monitoring equipment and researchers should consider (Chen and Bassett, 2005).

Bowling related HR values reported in this research were different to simulated events previously reported. Some of these differences were due to differences in research design (i.e. between over activity) as discussed previously. Another possible limitation related to the HR data was linked to the data smoothing which was applied. Polynomial smoothing could have influenced the HR data set as any smoothing technique which is designed to remove extreme values may affect the final value presented. The HR data captured with this version of the Bioharness™ (version 1) was, at times, influenced by EMG or movement artefacts during periods of higher velocity movement. Further research should use newer versions of the Bioharness™ and reassess its capacity to capture HR at higher velocities ($> 12 \text{ km.h}^{-1}$). It is thought worth noting that within this research context due to the nuances of the sport a lot of the data collection was captured at $<10 \text{ km.h}^{-1}$ at which the Bioharness™ reported very good reliability and validity. An additional reason for differences in HR data between simulated and in-match could be linked to the participants used in each respective research. As discussed in Section 2.4.3.3, accessing high quality performance level fast-medium bowlers is not always possible. Table 1 reported that only one other study (Duffield et al., 2009) used first-class performers as participants and then, as in this research, it was a small sample number. Performers from different playing standards may well have differing training and fitness qualities which will influence run up velocities, bowling speeds and recovery rates, and therefore will affect HR data presented.

Participants pre-match preparation was difficult to control though all performers agreed to maintain hydration status, avoid alcohol and caffeine, the actual monitoring of this at each match was not possible and therefore an element of trust was assumed. Hydration checks using a valid and reliable urine osmolality device (see 7.2.4) were completed pre-match though further assessment throughout the days play was not always possible due to limited access to performers at times. Additionally related to participants' pre-match status, the previous day's activity levels/routine was not considered within the data analysis which future research may want to factor in. With an increasing volume of matches being scheduled bowlers could be playing 5 or 6 consecutive days of competitive cricket and the accumulation of fatigue may affect data collected. Embryonic evidence on this issue suggests players suffer a 9% decrement in endurance fitness over a season (Petersen et al., 2010). Researchers should seek to assess how physiological status of performers changes short term through different match formats and longer term over a season. This type of data may enhance player preparation further improving performance.

Within this study it is acknowledged that the environmental conditions when the data were collected could also influence bowlers' physiological performances. All data were collected in UK spring/ early

summer time at temperatures below the threshold of 27°C set. With UK seasonal changes in weather, the environmental temperature could differ day to day by 5-10°C, individual bowlers may not adapt to this change due to acclimatisation process taking 5 to 10 days. If temperatures increased by 10°C in a 24 hour period it is possible that bowlers physiological responses may be artificially high in the unacclimatised state they are in (Astrand et al., 2003, Garrett et al., 2011, Powers and Howley, 2007). Future research could control this area further by collecting data within a specified temperature range rather than having a maximum figure to consider. Depending on the temperature range selected and longevity of the research period, the latter idea may limit the volume of data collected but may be possible in countries where more stable weather patterns occur.

The performance criteria in this study of runs per over was selected as it is the universal marker of bowling performance in cricket and the data is collected objectively by official scorers. There are though limitations of using this objective measure as within the match episodes, tactics or state of play could have had a large influence on how the bowler performed. Being professional cricketers will have meant bowling under team instructions which may well have affected performance as opposed to it being affected by accumulation of physiological stresses linked to the match. For example, whether the performer continues to bowl a longer extended spell may well be linked to a tactical decision within the match. This is even more so within OD matches where limits on overs bowled exist and it is common place for fast-medium bowlers to have 2 or 3 shorter spells regardless of how effectively they are performing. Using runs scored per over is a well-established performance indicator within cricket culture but it is a gross measure of performance and does not account for the nuances of the game. Using runs scored per over works on the premise that the more runs scored from the over the worse the bowling performance. This may not always be the case as for example, it is possible that the batter scores runs off a bowler from a mistake or false shot (i.e. edging the ball for 4 runs) when actually the bowler had “performed” well during that period of play. Alternative or a combination of factors could be utilised to generate a performance indicator which may still include runs per over but also includes such issues as the quality of batters scoring the runs (i.e. specialist batters or lower order), the time of match (i.e. first session or last, day 1 or day 3), and if the runs scored were purposeful (i.e. not edges). Moreover, there are other video based performance analysis methods which could assess bowling performance based on where the ball is pitched (Moore et al., 2012), which future research could consider and link to in-match physiological monitoring.

The consecutive overs and performance related analysis did provide a unique and interesting overview of in-match bowling performance and confirmed the ability of the Bioharness™ to provide

good quality information. The aggregation of data needed to construct the 7 consecutive overs data meant that differentiation between MD and OD data was not possible. The combining of data for the Bioharness™ and sporting performance analysis was exploratory in nature but more detailed analysis with respect to match formats may have highlighted associations not identified in this across-format analysis. Future in-match research should seek to amass a larger sample size and assess HR and accelerometry responses from the different formats of the game to continue to identify the requirements of each.

The accelerometry data captured has been presented as absolute counts relative to specific match episodes and has produced good intra-episode comparative data. Previous bowling research had not defined the commencement or cessation of bowling or between over episodes therefore this was formulated based on accelerometry activity values (VMU) and run-up velocities. Comparisons with other research were restricted by the latter and future research within cricket bowling should agree criteria for different match episodes. Additionally, the discrete match episodes within the study were not directly comparable as there were distinct timings for OD and MD match states therefore some relationships between data sets may have been occluded. Future work in this area should present activity relative to time (counts per hour/min⁻¹) which may provide an indication of the intensity of activity to support the absolute figure captured.

The limited sample size in this research study restricts the generic application of the results. Although 10 participants volunteered for this specific study after data management and processing, this figure reduced to 7. The latter figure does appear small but is comparable to other bowling research (Table 1) and considering the number of English first-class players available, the research study may have accessed approximately 10% of the population of professional fast-medium bowlers. Researching within professional sport restricts the absolute number of participants in the study as teams may have other commitments which influence their ability to be part of the data collection. Limited participant numbers may lead to statistical anomalies which mean caution should be applied to some findings, therefore the continuation of research to confirm findings in the area should be encouraged.

7.5 Conclusions

In conclusion, this study has successfully used physiological mobile monitoring technology to assess performance in professional sport. The Bioharness™ device has been able to provide a new body of information which should positively facilitate coaches and strength and conditioning specialists' knowledge of fast-medium bowlers. The data captured clearly distinguishes between OD and MD cricket and it is clear that the former format has a greater physiological cost to fast-medium bowlers. Moreover, this research has presented a unique between over data set which has previously been overlooked and confirms that this non-bowling period elicits a higher physiological cost to the fast-medium bowler. It is reported there is a lack of time within busy playing schedules for high performance cricketers to complete physical conditioning (Petersen et al., 2010). Moreover, it has also been reported that when training occurs it is not always meeting the demands of the game (Petersen et al., 2011a). This research provides additional evidence for strength and conditioning coaches to plan evidence based training thereby using the limited time they have with performers more effectively. There are clearly opportunities to further explore data comparing and combining HR and accelerometry values across different match states in order to identify critical variables which may improve player preparation and/or recovery. Moreover, this type of data could be used to assess if players reach minimal thresholds of work within a match situation which could then influence the type of recovery or additional training which needs to be completed. With regards to the Bioharness™ and playing performance, there were no clear links established on this occasion which may have been due to the complexities of collecting data in a competitive match situation set within a background of professional sport.

From the data presented in this study there is a clear avenue for other applied researchers to continue this work identifying single or multiple data streams which can be used to enhance and optimise sporting performance. Coaches require more applied data which can be related and used to improve sporting performance. The use of physiological mobile monitoring technology is permitting ecologically valid data to be captured from competitive sporting situations providing an insight in to unseen performance data. With further advances in monitoring technology coupled with crickets continuing acceptance of the role of science to develop more effective players, exercise scientists should continue to research the area in order to confirm the multi format physiological profiles for fast-medium bowling before moving to other key roles in the team.

Chapter 8 - Conclusions and recommendations

8.1 Conclusions

Sports coaches are requesting more accessible applied research (Gore et al., 1993; Achten and Jeukendrup, 2003; Williams and Kendall, 2007), so further optimisation of performance can occur. Recent developments in mobile monitoring technology is permitting data capture from within competitive match scenarios which can reveal previously inaccessible data, some of which could be used to enhance performance. The aim of this research was to assess the effectiveness of the Bioharness™ mobile monitoring device in professional sporting performance.

The research project had five studies each with associated aims; First, an appreciation and value of the physiological profile of professional cricketers was considered. The aim of this first study was to assess the anthropometrical and physiological profile of a professional cricket team and identify differences between on-field playing positions (Johnstone and Ford, 2010). Second, a mobile monitoring device was identified for possible use but the precision of measurement needed to be confirmed in controlled conditions. This second study aim was to assess the validity of each variable measured in the Bioharness™ in relation to criterion measures within a physically active laboratory situation (Johnstone et al., 2012a). Third, reproducibility of data was considered of each variable in the Bioharness™ device within a physically active laboratory situation (Johnstone et al., 2012b). Fourth, research moved to testing in a less controlled arena with the aim was to assess the reliability and validity of each variable measured in the Bioharness™ within a physically active field based setting (Johnstone et al., 2012c). The final study utilised the mobile monitoring device in a professional sporting environment over three cricket season's. The aims were two fold, (1) to develop a performance profile of professional fast-medium bowlers across different forms of competitive cricket through measuring in-match physiological responses using the Bioharness™ mobile monitoring device, and (2) to investigate the relationship between cricket bowling performance and physiological data captured by the Bioharness™ mobile monitoring device from professional cricket fast-medium bowlers during competition.

Study one confirmed that there is incomplete peer reviewed information on the anthropometrical and physiological profile of professional cricketers and also the fast bowling role. As different formats of the game develop more position specific specialist players will be required, with these specialist elements will partly be based on their physiological attributes. Strength and conditioning specialists require clear, applied, reliable and valid data on players to develop enhanced bespoke programmes which allow for improvements in performance. Differences between playing positions may emerge further as cricket engages with exercise science, and therefore the identification of specific positional requirements provides practitioners with increased customised training programme designs. The

data collected in study 1, although informative for the coach, did not provide a dynamic applied view of performance. Use of mobile monitoring technology may provide a better understanding of the physiological responses of players' in a match situation which in turn could present new performance indicators on players. Access to previously unseen in-match data could help to optimise 'cricket-specific' conditioning programmes leading ultimately to raising playing standards to even higher levels. Additionally longer term, the Bioharness™ may assist technical coaches to make tactical decisions based on real match data being streamed from a wireless monitoring device though limitations associated with this area have been noted in this work. If new mobile monitoring technology is adopted by the coach and sports science support staff it is essential that the methods used to obtain such physiological data are as accurate, reproducible, and ecologically valid as possible.

Study two started the precision of measurement phase and suggested that, with prior understanding of data limitations, the Bioharness™ has proved to be a valid multivariable monitoring device within ambulatory laboratory testing. Accelerometry (ACC) and Posture (P) variables presented strong data which relates to the advanced piezoelectric technology used. Heart rate (HR) and Breathing Frequency (BF) data captured during high intensity activities should be considered with the understanding that the validity of this data could be influenced by artefacts at treadmill velocities of $\geq 10 \text{ km}\cdot\text{h}^{-1}$. It was noted that further development of infra-red Skin Temperature (ST) technology within the device should be considered. The Bioharness™ device is designed to enable naturalistic physiologically based monitoring to occur across differing free movement scenarios without the need for obtrusive invasive equipment. The design limitations associated with incorporating multi-variable monitoring within a device, which must be unobtrusive to the wearer, may place some limitations on the effectiveness of the functioning of individual elements. Free movement physiological data, which the Bioharness™ aims to capture, is inherently variable (Welk et al ., 2004), so the next progression for the device is assessment of its reliability and if that latter process produces appropriate data, further testing in a less controlled field based setting should occur, allowing for a more comprehensive appreciation of its capacities in the mode of use it was intended to be used.

Study three continued the investigation within a laboratory setting assessing reproducibility of data from the Bioharness™. When considering all data, the Bioharness™ can be considered a reliable device within the limitations reported within this study. Within subject reliability data was very strong suggesting the fit of the device on different individuals could be an important factor in attaining consistent data especially for HR and BF. Being able to access a reliable and valid monitor which measures a range of physiological variables simultaneously in free living conditions will allow for further invaluable understanding of human performance in a variety of environments.

Having established the reliability and validity of the Bioharness™ system within a laboratory setting, it was a logical next stage in the progression of the research project is to assess the validity and reliability of the Bioharness™ in a less controlled field based environment better reflecting the environment in which the device has been designed to operate within. Study four confirmed the Bioharness™ ACC and HR variables demonstrate relative reliability and validity in the field based environment. BF variable appears to present more variable data and may need further development to be effective in the wider active or sporting environment. It is clear that there is scope for more applied research to be completed, using up-to-date technology within a variety of sports or activities, which will allow a clearer understanding of the key performance variables to be gained (Bartlett, 2006). The research in chapters 4, 5, and 6 assessing the reliability and validity of the Bioharness™ has now provided an indication of which variables are suitable to use for analysis of sporting performance in fast-medium bowlers. The next phase of the research was to use the system during competitive sporting performance and assess if data collected from the device can assist coaches and players with their physical preparation and actual performance.

Study five captured data using the Bioharness™ in the professional sport arena. Analysing fast-medium bowlers over three seasons within a first-class county squad, this study has successfully used the Bioharness™ to assess performance in professional sport. The Bioharness™ device has been able to provide a new body of information which should positively facilitate coaches and strength and conditioning specialists' knowledge of fast-medium bowlers. The data captured clearly distinguishes between OD and MD cricket and it is clear that the former format has a greater physiological cost to fast-medium bowlers. Moreover, this research has presented a unique between over data set which has previously been overlooked and in comparison to fielding, confirms that this non-bowling period elicits a higher physiological cost to the fast-medium bowler. There are clearly opportunities to explore further in to similar data, comparing and combining HR and accelerometry data across different match states in order to identify critical variables which may improve player preparation and/or recovery. With regards to the exploratory investigation on Bioharness™ and playing performance, there were no clear links established on this occasion which may have been due to the complexities of collecting data in a competitive match situation set within a background of professional sport. Therefore, it is suggested that not one single variable will be solely responsible for sporting performance per se, especially in the game situation that involves complex tactical decision making.

In summary, this research project has resulted in seven contributions to the scientific literature. First, the profile of professional cricketers confirmed the emerging physiological differentiation between playing positions and the limitations in the literature related to field based data for coaches which would enable more effective physical preparation of professional players. Second, a review of the literature on the athletic profile of fast bowling has been constructed and disseminated to applied practitioners identifying future avenues of applied and in-match research. Third, the reliability, validity and limitations of the Bioharness™ have been reported in a laboratory and also field based environment allowing exercise scientists to understand the data from the device further. Fourth, within sporting performance the Bioharness™ has identified a difference in cardio-vascular and accelerometry based responses in OD and MD professional cricket. Fifth, the Bioharness™ has identified differences in cardio-vascular and accelerometry based responses in different match states during professional cricket. The practical application from this information is the necessity for different requirements with regards to physical preparation for different formats of the game. Sixth, the Bioharness™ has attempted to explore relationships between physiological responses and bowling performance in-match using professional cricket players providing a starting point for other researchers in the area. Finally, the organisation and processing of the large data sets from the field environment in to usable sport specific output has been described in chapter 7 which is, to the authors knowledge, unique in the literature.

Based on work completed in chapters 4, 5 and 6, not all of the 5 variables within the Bioharness™ were utilised and assessed in chapter 7 though it is clear that data captured by the device has successfully identified unique and valuable information for exercise scientists, strength and conditioning specialists and cricket coaches. Therefore, with an appreciation of limits noted within this thesis, the Bioharness™ monitoring device used within this research is effective for use in a professional sport setting.

8.2 Recommendations

From the data presented in this study it is clear that the Bioharness™ is permitting ecologically valid data to be captured from competitive sporting situations. Other applied researchers should continue this work with the same or equivalent technology, within cricket and other sports, to identify inaccessible data which could progress sports performance.

As further advancements are made with mobile monitoring technology researchers should continue to assess precision of measurement and reliability using robust procedures. New devices should also be tested at higher running velocities and within field based situations which replicate competitive sport. Additionally, mobile technology must be unobtrusive and adhere to local sporting governing body regulations, permitting the performer to continue to compete within the sport while data is collected.

This research has analysed single individual data streams (i.e. HR) when relationships between multiple or combination of data streams could be developed to enhance and optimise sporting performance. Combining HR values with accelerometry data may lead to the construction of a “physical stress” index which relates to or even assists in monitoring workload effectively.

It has been identified that coaches require more applied data which can be used to improve sporting performance. It is yet to be established if coaches are aware or feel able to view and use real time data that the technology is generating. It is important that coaches engage and use the technology or embed it within sport science support teams. Also it is important exercise scientists work with the coach and make data generated by mobile monitoring technology accessible and purposeful for all concerned. These issues need confirming otherwise future research could be purely an academic exercise in number generation.

With crickets continuing acceptance of the role of science to develop more effective performers there are further opportunities to use mobile monitoring technology in the sport. Cricket still lags behind with regards to literature presenting player specific profiles across different formats of the game. Exercise scientists should continue to develop this research area in order to confirm the multi format profiles (T20, OD, MD) for fast-medium bowling before and other key roles in the team.

To conclude, there are a number of fundamental advancements between previous fast-medium bowling research (Duffield et al., 2009, Burnett et al., 1995, Devlin et al., 2001, Gore et al., 1993) and this study. In this research, data is being collected from in-match performances and compared to a competitive performance indicator using professional cricketers. Moreover, the in-match between

over data is also being assessed as this physiological stress or workload that the bowler may experience has yet to be investigated, and may have an effect on the next bowling performance. There are ample opportunities for researchers to build on the themes within this thesis. As Kolt (2012) noted, formats of cricket will further evolve, teams will continue to engage with sport science and coaches require higher performance from their performers, therefore applied research will be of paramount importance.

9. References

- ACHTEN, J. & JEUKENDRUP, E. (2003) Heart rate monitoring: Applications and limitations. *Journal of Sports Medicine*, 33, 517-538.
- AMASAY, T., ZODROW, K., KLINC, L., HESS, J. & KARDUNA, A. (2009) Validation of tri-axial accelerometer for the calculation of elevation angles. *International Journal of Industrial Ergonomics*, 39, 783-789.
- AMERICAN COLLEGE OF SPORTS MEDICINE (2000) *ACSM guidelines for exercise testing and prescription (6th Ed)*, Philadelphia, Lippincott, Williams and Wilkins.
- AMERICAN THORACIC SOCIETY (2003) ATS/ACCP Statement on Cardiopulmonary Exercise Testing. *American Journal of Respiratory and Critical Care Medicine*, 167, 211-277.
- ARMSTRONG, L. E., HERRERA SOTO, J. A., HACKER, F. T., CASA, D. J., KAVOURAS, S. A. & MARESH, C. M. (1998) Urinary indices during dehydration, exercise, and rehydration. *International Journal of Sports Nutrition*, 8, 345 - 355.
- ASKANZI, J., SILVERBERG, P. A., FOSTER, R. J., HYMAN, A. I., MILIC-EMILI, J. & KINNEY, J. M. (1980) Effects of respiratory apparatus on breathing pattern. *American Physiological Society*, 48, 577-580.
- ASTRAND, P., RODAHL, K., DAHL, H. & STROMME, S. (2003) *Textbook of work physiology*, Champaign, IL, Human Kinetics.
- ATKINSON, G. & NEVILL, A. M. (1998) Statistical methods for assessing measurement error (reliability) in variables relevant to sports medicine. *Sports Medicine*, 26, 217 - 238.
- ATKINSON, G. & NEVILL, A. M. (2001) Selected issues in the design and analysis of sport performance research. *Journal of Sports Sciences*, 19, 811 - 827.
- ATTWELLS, R. L., BIRRELL, S. A., HOOPER, R. H. & MANSFIELD, N. J. (2006) Influence of carrying heavy loads on soldiers' posture, movements and gait. *Ergonomics*, 49, 1527-1537.
- AUSTRALIAN BUREAU OF STATISTICS (1998) How Australians measure up. Australian Bureau of Statistics. accessed online [http://www.ausstats.abs.gov.au/ausstats/subscriber.nsf/0/CA25687100069892CA256889001F4A36/\\$File/43590_1995.pdf](http://www.ausstats.abs.gov.au/ausstats/subscriber.nsf/0/CA25687100069892CA256889001F4A36/$File/43590_1995.pdf) on June 25th 2012.
- AUSTRALIAN CRICKET BOARD (2012) High performance cricket. accessed online <http://www.cricket.com.au/about-us/high-performance-cricket?t=Staff> on June 10th 2012
- BARBERO-ALVAREZ, J. C., SOTO, V. M., BARBERO-ALVAREZ, V. & GRANDA-VERA, J. (2008) Match-analysis and heart rate of futsal players during competition. *Journal of Sports Sciences*, 26, 63-73.
- BARTLETT, R. (2003) The science and medicine of cricket: An overview and update. *Journal of Sports Sciences*, 21, 733 - 752.
- BARTLETT, R. (2006) Medicine and science in cricket. *Journal of Science and Medicine in Sport*, 9, 470 - 471.
- BARTLETT, R., STOCKILL, N., ELLIOTT, B. & BURNETT, A. (1996) The biomechanics of fast bowling in men's cricket: A review. *Journal of Sports Sciences*, 14, 403 - 424.
- BARTLETT, R., WHEAT, J. & ROBINS, M. (2007) Is movement variability important for sports biomechanists? *Sports Biomechanics*, 6, 223 - 243.
- BERNMARK, E. & WIKTORIN, C. (2002) A triaxial accelerometer for measuring arm movements. *Applied Ergonomics*, 33, 541-547.
- BIANCHI, G. & SORRENTINO, R. (2007) *Electronic filter simulation and design*, New York, USA, McGraw-Hill.
- BISHOP, D. (2008) An applied research model for the sports sciences. *Sports Medicine*, 38, 253 - 263.
- BISHOP, D., BURNETT, A., FARROW, D., GABBETT, T. & NEWTON, R. (2006) Sports science roundtable: Does sports science research influence practice? *International Journal of Sports Physiology and Performance*, 1, 161 - 168.

- BLAND, J. M. & ALTMAN, D. G. (1986) Statistical methods for assessing agreement between two methods of clinical measurement. *The Lancet*, 327, 307 - 310.
- BLAND, J. M. & ALTMAN, D. G. (2003) Applying the right statistics: analysis of measurement studies. *Ultrasound Obstet Gynecol*, 22, 85 - 93.
- BOBBERT, M. F., GERRISTEN, K. G., LITJENS, M. C. & VAN SOEST, A. J. (1995) Why is countermovement jump height higher than squat jump? *Medicine and Science in Sport and Exercise*, 29, 1402-1412.
- BOUDET, G. & CHAMOIX, A. (2000) Heart Rate Monitors and Abnormal Heart Rhythm Detection. *Archives of Physiology and Biochemistry* 108, 371-379.
- BRAGE, S., BRAGE, N., FRANKS, P. W., EKELUND, U. & WAREHAM, N. J. (2005b) Reliability and validity of the combined heart rate and movement sensor Actiheart. *European Journal of Clinical Nutrition*, 59, 561-570.
- BRAGE, S., WEDDERKOPP, N., FRANKS, P. W., ANDERSON, L. B. & FROBERG, K. (2003) Re-examination of validity and reliability of the CSA monitor in walking and running. *Medicine & Science in Sport & Exercise*, 35, 1447-1454.
- BROOKS, A. G., GUNN, S. M., WITHERS, R. T., GORE, C. J. & PLUMMER, J. L. (2005) Predicting walking METs and energy expenditure from speed or accelerometry. *Medicine & Science in Sport & Exercise*.
- BROWN, C. D. & WISE, R. A. (2007) Field tests of exercise in COPD: The six-minute walk test and the shuttle walk test. *Journal of Chronic Obstructive Pulmonary Disease*, 4, 217 - 223.
- BRUNTON, A., CONWAY, J. H. & HOLGATE, S. T. (2000) Reliability: what is it, and how is it measured? *Physiotherapy*, 86, 94 - 99.
- BUCHANAN, J. (2008) Jurassic Park revisited: Research meets the dinosaur. *Sport Health*, 26, 13.
- BUONO, M. J., JECHORT, A., MARQUES, R., SMITH, C. & WELCH, J. (2007a) Comparison of infrared versus contact thermometry for measuring skin temperature during exercise in the heat. *Physiological Measurement*, 28, 855-859.
- BURNETT, A., ELLIOTT, B. & MARSHALL, R. (1995) The effect of a 12-over spell on fast bowling technique in cricket. *Journal of Sports Sciences*, 13, 329 - 341.
- BURNHAM, R. S., MCKINLEY, R. S. & VINCENT, D. D. (2006b) Three types of skin-surface thermometers. *American Journal of Physical Medicine & Rehabilitation*, 85, 553-558.
- CAMPBELL, I. G., WILLIAMS, C. & LAKOMY, H. K. A. (2004) Physiological and metabolic responses of wheelchair athletes in different racing classes to prolonged exercise. *Journal of Sports Sciences*, 22, 449-456.
- CÁRDENAS, A. F., PON, R. K. & CAMERON, R. B. (2003) Management of streaming body sensor data for medical information systems. *Proceedings of METMBS*, p 186-191.
- CARLING, C., REILLY, T. & WILLIAMS, M. (2009) *Performance assessment for field sports*, Routledge, Oxon.
- CHARMARI, K., HACHANA, Y., AHMED, Y., GALY, O., SGHAIER, F., CHATARD, F., HUE, O. & WISLOFF, U. (2004) Field and laboratory testing in young elite soccer players. *British Journal of Sports Medicine*, 38, 191 - 196.
- CHEN, K. Y. & BASSETT, D. R. (2005) The technology of accelerometry-based activity monitors: current and future. *Medicine and Science in Sport and Exercise*, 37, s490 - 500.
- CHENY, M., ISSACSON, D. & NEWELL, J. (1999) Electrical Impedance Tomography. *Society for Industrial and Applied Mathematics*, 41, 85-101.
- CHO, H., KOO, S., LEE, J., CHO, H., KANG, D., SONG, H., LEE, J., LEE, K. & LEE, Y. (2009) Heart monitoring garments using textile electrodes for healthcare applications. *Journal of Medical Systems*, 1-13.
- CHRISTIE, C., TODD, A. & KING, G. (2007) Selected physiological responses during batting in simulated cricket work bout: A pilot study. *Journal of Science and Medicine in Sport*, 11, 581 - 584.
- CLARENBACH, C. F., SENN, O., BRACK, T., KOHLER, M. & BLOCH, K. E. (2005a) Monitoring of ventilation during exercise by a portable respiratory inductive plethysmography. *American College of Chest Physicians*, 128, 1282-1290.

- CRICINFO (2008) Most wickets in test career (Test matches). accessed online <http://stats.espncricinfo.com/ci/content/records/93276.html> on December 10th 2008
- CRICINFO (2012) Player profiles. accessed online <http://www.espncricinfo.com/ci/content/current/player/index.html> on May 10th 2012
- CRICINFO (2013) IPL Player list 2013 auction. accessed online <http://www.espncricinfo.com/indian-premier-league-2013/content/story/603194.html> on March 10th 2013
- CRONIN, J. & HANSEN, K. (2005) Strength and power predictors of sport speed. *Journal of Strength and Conditioning Research*, 19, 349 - 357.
- CROSBIE, J., VACHALATHITI, R. & SMITH, R. (1997) Patterns of spinal motion during walking. *Gait & Posture*, 5, 6-12.
- CURRELL, K. & JEUKENDRUP, A. E. (2008) Validity, reliability and sensitivity of measures of sporting performance. *Sports Medicine*, 38, 297 - 316.
- DANESHMANDI, H., RAHMANINIA, F., SHAHROKHI, H., RAHMANI, P. & ESMAEILI, S. (2010a) Shoulder joint flexibility in top athletes. *Journal of Biomedical Science and Engineering*, 3, 811 - 815.
- DAVIES, M. & COLLINS, S. (2012) *Bowling; How to play, coach and win*, London, Wisden.
- DE GROOT, J. F., TAKKEN, T., GOOSKENS, R. H. J. M., SCHOENMAKERS, M. A. G. C., WUBBELS, M., VANHEES, L. & HELDERS, P. J. M. Reproducibility of Maximal and Submaximal Exercise Testing in Normal Ambulatory and Community Ambulatory Children and Adolescents With Spina Bifida: Which Is Best for the Evaluation and Application of Exercise Training? *Physical Therapy*, 91, 267-276.
- DENNIS, R., FINCH, C. & FARHART, P. (2005) Is bowling workload a risk factor for injury to Australian junior cricket fast bowlers. *British Journal of Sports Medicine*, 39, 843 - 846.
- DENNIS, R., FINCH, C., MCINTOSH, A. & ELLIOTT, B. (2008) Use of field-based tests to identify risk factors for injury to fast bowlers in cricket. *British Journal of Sports Medicine*, 42, 477 - 482.
- DEPAULO & MCCOOL, F. D. (2002) Seminars in respiratory and critical care medicine. *Pulmonary Complications of Neuromuscular Diseases*, 23, 201-209.
- DEVLIN, L., FRASER, S., BARRAS, N. & HAWLEY, J. (2001) Moderate levels of hypohydration impairs bowling accuracy but not bowling velocity in skilled cricket players. *Journal of Science and Medicine in Sport*, 4, 179 - 187.
- DITTMAR, A., MEFFRE, R., DE OLIVEIRA, F., GEHIN, C. & DELHOMME, G. (2005) Wearable medical devices using textile and flexible technologies for ambulatory monitoring. *Engineering in Medicine and Biology Society, 2005. IEEE-EMBS 2005. 27th Annual International Conference of the. IEEE.*
- DOUGLAS, C., BECKER, S. M. & MARESH, C. M. (2007) Validity of devices that assess body temperature during outdoor exercise in the heat. *Journal of Athletic Training* 42, 333-342.
- DRUST, B., ATKINSON, G. & REILLY, T. (2008) Future perspectives in the evaluation of the physiological demands of soccer. *Sports Medicine*, 37, 783 - 805.
- DUFFIELD, R., CARNEY, M. & KARPPINEN, S. (2009) Physiological responses and bowling performance during repeated spells of medium-fast bowling. *Journal of Sports Sciences*, 27, 27 - 35.
- DUFFIELD, R. & DRINKWATER, E. (2008) Time motion analysis of Test and One-day-international cricket centuries. *Journal of Sports Sciences*, 26, 457 - 464.
- DUTHIE, G., PYNE, D. & HOOPER, S. (2003) Applied physiology and game analysis of rugby union. *Sports Medicine*, 33, 973 - 991.
- EASTON, C., FUDGE, B. W. & PITSILADIS, Y. P. (2007) Rectal, telemetry pill and tympanic membrane thermometry during exercise heat stress. *Journal of Thermal Biology*, 32, 78-86.
- EKELUND, U., POORTVLIET, E., YNGVE, A., HURTIG-WENNLÖV, A., NILSSON, A. & SJÖSTRÖM, M. (2001) Heart rate as an indicator of the intensity of physical activity in human adolescents. *European Journal of Applied Physiology*, 85, 244-249.
- ELLIOTT, B. (2000) Back injuries and the fast bowler in cricket. *Journal of Sports Sciences*, 18, 983 - 991.

- ELLIOTT, B., WALLIS, R., SAKURAI, S., LLOYD, D. & BESIER, T. (2002) The measurement of shoulder alignment in cricket fast bowling. *Journal of Sports Sciences*, 20, 507 - 510.
- ELLIOTT, B. C., FOSTER, D. H. & GRAY, S. (1986) Biomechanical and physical factors influencing fast bowling. *Australian Journal of Science and Medicine in Sport*, 18, 16 - 21.
- ENGEL, M. (2007) *Wisden cricketers almanac*, Johns Wisden and Co.
- ENGEL, M. (2012) *Wisden cricketers almanac*, Johns Wisden and Co.
- ENGLAND AND WALES CRICKET BOARD (2009) National cricket performance centre. accessed online <http://www.ecb.co.uk/ecb/national-cricket-performance-centre-loughborough/> on June 5th 2009
- ENGLAND AND WALES CRICKET BOARD (2012) ECB Sports science and medicine team. accessed online <http://ecb.co.uk/ecb/national-cricket-performance-centre-loughborough/science-medicine-management-group-smmg,720,BP.html> on June 10th 2012
- EQUIVITAL (2013) Equivital technology platform. accessed online <http://www.equivital.co.uk/technology> on May 20th 2013
- ERICKSON, R. S. (1999) The continuing question or how best to measure body temperature. *Critical Care Medicine*, 27, 2307-2310.
- ESTON, R. G., ROWLANDS, A. V. & INGLEDEW, D. K. (1998) Validity of heart rate, pedometry and accelerometry for predicting the energy cost of children's activities. *American Physiological Society*, 84, 362-371.
- FERDINANDS, R. (2008) Biomechanics and the art of bowling.
- FERDINANDS, R., KERSTING, U., MARSHALL, R. N. & STUELCKEN, M. (2010) Distribution of modern cricket bowling actions in New Zealand. *European Journal of Sport Science*, 10, 179-190.
- FIAMMA, M. N., SAMARA, Z., BACONNIER, P., SIMILOWSHI, T. & STRAUS, C. (2006) Respiratory inductive plethysmography to assess respiratory variability and complexity in humans. *Respiratory Physiology and Neurobiology*, 156, 234-239.
- FIELD, A. & MILES, J. (2010) *Discovering statistics using SPSS*, London, Sage.
- FINCH, C., ELLIOTT, B. & MCGRATH, A. (1999) Measures to prevent cricket injuries. *Sports Medicine*, 28, 263 - 272.
- FINNI, T., HU, M., KETTUNEN, P., VILAVOU, T. & CHENG, S. (2007) Measurement of EMG activity with textile electrodes embedded in to clothing. *Physiological Measurement*, 28, 1405 - 1419.
- FLETCHER, J. G. (1955) Calories and cricket. *The Lancet*, 1, 1165 - 1166.
- FOERSTER, F., SMEJA, M. & FAHRENBERG, J. (1999) Detection of posture and motion by accelerometry: a validation study in ambulatory monitoring. *Computers in Human Behavior*, 15, 571-583.
- FOSTER, C., DANIELS, J. T., DEKONING, J. T. & COTTER, H. M. (2006) Field testing of athletes. IN MAUD, P. J. & FOSTER, C. (Eds.) *Physiological Assessment of Human Fitness*. 2nd ed. Champaign, IL, Human Kinetics.
- FREESTON, J., FERDINANDS, R. & ROONEY, K. (2007) Throwing velocity and accuracy in elite and sub-elite cricket players: A descriptive study. *European Journal of Sport Science*, 7, 231-237.
- FRUIN, M. L. & WALBERG RANKIN, J. (2004) Validity of a multi-sensor armband in estimating rest and exercise energy expenditure. *Medicine & Science in Sport & Exercise*, 36, 1063-1069.
- GABBETT, T. (2002) Physiological characteristics of junior and senior rugby league players. *British Journal of Sports Medicine*, 36, 334 - 339.
- GAMELIN, F. X., BERTHOIN, S. & BOSQUET, L. (2006) Validity of Polar S810 heart rate monitor to measure R-R intervals at rest. *Medicine & Science in Sport & Exercise*, 38, 887-893.
- GANT, N., ATKINSON, G. & WILLIAMS, C. (2006b) The validity and reliability of intestinal temperature during intermittent running. *Medicine & Science in Sport & Exercise*, 38, 1926-1931.
- GARRARD, C. S. & EMMONS, C. (1986) The reproducibility of respiratory responses to maximum exercise. *Respiration*, 49, 94 - 100.

- GARRETT, A., REHRER, N. & PATTERSON, M. (2011) Induction and Decay of Short-Term Heat Acclimation in Moderately and Highly Trained Athletes. *Sports Medicine*, 41, 757-771.
- GARRETT, B. E. & GRIFFITHS, R. R. (2001) Intravenous Nicotine and Caffeine: Subjective and Physiological Effects in Cocaine Abusers. *Journal of Pharmacology and Experimental Therapeutics*, 296, 486-494.
- GLAZIER, P. S., PARADISIS, G. P. & COOPER, S. (2000) Anthropometric and kinematic influences on release speed in men's fast-medium bowling. *Journal of Sports Sciences*, 18, 1013 - 1021.
- GODSEN, R., CARROLL, T. & STONE, S. (1991) How well does Polar Vantage XL heart rate monitor estimate actual heart rate? *Medicine and Science in Sport and Exercise*, 23, S14.
- GOODIE, J. L., LARKIN, K. T. & SCHAUSS, S. (2000) Validation of the Polar heart rate monitor for assessing heart rate during physical and mental stress. *Journal of Psychophysiology*, 14, 159-164.
- GOODWIN, M. S., VELICER, W. F. & INTILLE, S. S. (2008) Telemetric monitoring in the behavioural sciences. *Behavior Research Methods*, 40, 328-341.
- GORE, C., BOURDON, P., WOOLFORD, S. & PEDERSON, D. (1993) Involuntary dehydration during cricket. *International Journal of Sports Medicine*, 14, 387 - 395.
- GROSSMAN, P. (2004) The Lifeshirt: A multi-function ambulatory system for monitoring health, disease and medical intervention in the real world. *Studies in Health Technology and Informatics*, 108, 133-141.
- GROSSMAN, P., SPOERLE, M. & WILHELM, F. H. (2006) Reliability of respiratory tidal volume estimation by means of ambulatory inductive plethysmography. *Biomedical Instrumentation & Technology*, 42, 193-198.
- GROSSMAN, P., WILHELM, F. H. & BRUTSCHE, M. (2010) Accuracy of ventilatory measurement employing ambulatory inductive plethysmography during tasks of everyday life. *Biological Psychology*, 84, 121-128.
- HAILSTONE, J. & KILDING, A. E. (2011) Reliability and validity of the Zephyr Bioharness to measure respiratory responses to exercise. *Measurement in Physical Education and Exercise Science*, 15, 293 - 300.
- HALE, T. (2003) *Exercise Physiology: A thematic approach*, Chichester, England, John Wiley and Sons Ltd.
- HANSSON, G., ASTERLAND, P., HOLMER, N. G. & SKERFVING, S. (2001a) Validity and reliability of triaxial accelerometers for inclinometry in posture analysis. *Medical and Biological Engineering and Computing*, 39, 405-413.
- HANSSON, G. A., ARVIDSSON, I., OHLSSON, K., NORDANDER, C., MATHIASSEN, S. E., SKERFVING, S. & BALOGH, I. (2006) Precision of measurements of physical workload during standardised manual handling. Part II: Inclinometry of head, upper back, neck and upper arms. *Journal of Electromyography and Kinesiology*, 16, 125 - 136.
- HARLEY, R. & DOUST, J. (1997) *Strength and fitness training for basketball: A sports science manual*, Leeds, UK, National Coaching Foundation.
- HARPER-SMITH, A. D., CRABTREE, D. R., BILZON, J. L. J. & WALSH, N. P. (2010) The validity of wireless ibuttons and thermistors for human skin temperature measurement. *Physiological Measurement*, 31, 95 - 114.
- HARVEY, G., MEIR, R., BROOKS, L. & HOLLOWAY, K. (2008) The use of body mass changes as a practical measure of dehydration in team sports. *Journal of Science and Medicine in Sport*, 11, 600-603.
- HEALEY, J. (2000) Future possibilities in electronic monitoring of physical activity. *Research Quarterly for Exercise and Sport*, 71, 137-145.
- HEILMAN, K. J. & PORGES, S. W. (2007) Accuracy of Lifeshirt (Vivometrics) in the detection of cardiac rhythms. *Biological Psychology*, 75, 300-305.
- HENDELMAN, D., MILLER, K., BAGGETT, C., DEBOLD, E. & FREEDSON, P. (2000) Validity of accelerometry for the assessment of moderate intensity physical activity in the field. *Medicine & Science in Sport & Exercise*, 32, 442-449.

- HERSLER, C., CONINE, T. A., NUNN, A. & HANNAY, M. (1992) Assessment of an infrared non-contact sensor for routine skin temperature monitoring: a preliminary study. *Journal of Medical Engineering and Technology*, 16, 117-122.
- HOPKINS, W. (2000a) A new view of statistics: Summarising data - Precision of measurement. accessed online www.sportsci.org/resource/stats/precision.html on March 12th 2008.
- HOPKINS, W. G. (2000b) Measures of reliability in sports medicine and science. *Sports Medicine*, 30, 1 - 15.
- HOPKINS, W. G. (2008) A new view on statistics. accessed online <http://sportsci.org/resource/stats> on February 9th 2008.
- HOPKINS, W. G., MARSHALL, S. W., BATTERHAM, A. M. & HANIN, J. (2009) Progressive statistics for studies in sports medicine and exercise science. *Medicine and Science in Sport and Exercise*, 41, 3 - 12.
- HOPKINS, W. G., SCHABORT, E. J. & HAWLEY, J. A. (2001) Reliability of power in physical performance tests. *Sports Medicine*, 31, 211 - 234.
- HOUGHTON, L. & DAWSON, B. (2012) Short report: Recovery jump performance after simulated cricket batting innings. *Journal of Sports Sciences*, 30, 1069 - 1072.
- HOUGHTON, L., DAWSON, B., RUBENSON, J. & TOBIN, M. J. (2011) Movement patterns and physical strain during a novel, simulated cricket batting innings (BATEX). *Journal of Sports Sciences*, 29, 801-809.
- INTERNATIONAL CRICKET COUNCIL (2009) About the ICC. accessed online http://icc-cricket.yahoo.net/the-icc/about_the_organisation/overview.php. on June 10th 2009
- INTERNATIONAL CRICKET COUNCIL (2013) International cricket council results. accessed online <http://www.icc-cricket.com/results> on December 1st 2013
- JOBSON, S. A., NEVILL, A. M. & ATKINSON, G. (2009) Choose your primary outcome variables with care. *Journal of Sports Sciences*, 27, 313 - 314.
- JOHNSTONE, J. A. & FORD, P. A. (2010) Physiological profile of professional cricketers. *Journal of Strength and Conditioning Research*, 24, 2900 - 2907.
- JOHNSTONE, J. A., FORD, P. A. & COUSINS, S. (2008) In-match heart rate responses of bowlers in elite cricket. *Journal of Sports Sciences*, 26, 94-95.
- JOHNSTONE, J. A., FORD, P. A., HUGHES, G., WATSON, T. & GARRETT, A. T. (2012a) Bioharness™ multivariable monitoring device: Part I. Validity. *Journal of Sports Science and Medicine*, 11, 400-408.
- JOHNSTONE, J. A., FORD, P. A., HUGHES, G., WATSON, T. & GARRETT, A. T. (2012b) Bioharness™ multivariable monitoring device: Part II. Reliability. *Journal of Sports Science and Medicine*, 11, 409-417.
- JOHNSTONE, J. A., FORD, P. A., HUGHES, G., WATSON, T., MITCHELL, A. C. S. & GARRETT, A. T. (2012c) Field based reliability and validity of Bioharness™ multivariable monitoring device. *Journal of Sport Science and Medicine*, 11, 443-452.
- KARLSSON, J. S., WIKLUND, U., BERGLIN, L., ÖSTLUND, N., KARLSSON, M., BÄCKLUND, T., LINDECRANTZ, K. & SANDSJÖ, L. (2008) Wireless Monitoring of Heart Rate and Electromyographic Signals using a Smart T-shirt. *Proc. of the IEEE Engineering in Medicine on-line* at <http://www.phealth2008.com/Events/papers/p7.pdf>.
- KENT, L., O'NEILL, B., DAVIDSON, G., NEVILL, A., ELBORN, J. S. & BRADLEY, J. M. (2009) Validity and reliability of cardiorespiratory measurements recorded by the LifeShirt during exercise tests. *Respiratory Physiology and Neurobiology*, 167, 162-167.
- KING, G. A., TORRES, N., POTTER, C., BROOKS, T. J. & COLEMAN, K. J. (2004) Comparison of activity monitors to estimate energy cost of treadmill exercise. *Medicine and Science in Sport and Exercise*, 36, 1244 - 1251.

- KINGSLEY, M., LEWIS, M. J. & MARSON, R. E. (2004) Comparison of Polar 810s and an Ambulatory ECG System for RR Interval Measurement During Progressive Exercise. *International Journal of Sports Medicine*, 26, 39-44.
- KISTEMAKER, J. A., DEN HARTOG, E. A. & DAANEN, H. A. M. (2006) Reliability of an infrared forehead skin thermometer for core temperature measurements *Journal of Medical Engineering and Technology*, 30, 252-261.
- KOCOGLU, H., GOKSU, S., ISIK, M., AKTURK, Z. & BAYAZIT, Y. A. (2002) Infrared tympanic thermometer can accurately measure the body temperature in children in an emergency room setting. *International Journal of Paediatric Otorhinolaryngology*, 65, 39-43.
- KOLT, G. S. (2012) It's just not cricket, or is it? *Journal of Science and Medicine in Sport*, 15, 189.
- KREBS, D. E., WONG, D., JEVSEVAR, D., RILEY, P. O. & HODGE, W. A. (1992) Trunk kinematics during locomotor activities. *Physical Therapy*, 72, 505-514.
- LAMBERT, M. & BORRESEN, J. (2006) A theoretical basis of monitoring fatigue: A practical approach for coaches. *International Journal of Sports Science and Coaching*, 1, 371-388.
- LAMBERTS, R., SWART, J., NOAKES, T. & LAMBERT, M. (2009) Changes in heart rate recovery after high-intensity training in well-trained cyclists. *European Journal of Applied Physiology*, 105, 705-713.
- LAMBERTS, R. P., LEMMINK, K., DURANDT, J. J. & LAMBERT, M. I. (2004) Variation in heart rate during sub-maximal exercise: Implications for monitoring and training. *Journal of Strength and Conditioning Research*, 18, 641 - 645.
- LAUKKANEN, R., M. T & VIRTANEN, P. K. (1998) Heart Rate Monitors: State of the Art. *Journal of Sports Science*, 16, 3-7.
- LEDGER, L., MERCIER, D., GADOURY, C. & LAMBERT, J. (1988) The multistage 20 meter shuttle run test for aerobic fitness. *Journal of Sports Sciences*, 6, 93 - 101.
- LEGER, L. & THIVIERGE, M. (1988) Heart Rate Monitors: Validity, stability and functionality. *The Physician and Sports Medicine*, 16, 143-151.
- LEINO, K., NUNES, S., VALTA, P. & TAKALA, J. (2001) Validation of a new respiratory inductive plethysmograph. *Acta Anaesthesiologica Scandinavica*, 45, 104-111.
- LEROUX, A., FUNG, J. & BARBEAU, H. (2002) Postural adaptation to walking on incline surfaces: I. Normal strategies. *Gait and Posture*, 15, 64-74.
- LLOYD, R., OLIVER, J., HUGHES, M. & WILLIAMS, C. (2008) Reliability and validity of field-based measures of leg stiffness and reactive strength in youths. *British Association of Sport and Exercise Sciences annual conference*. Brunel University, London, UK.
- LOCKIE, R. G., CALLAGHAN, S. J. & JEFFRIESS, M. D. (2013) Analysis of Specific Speed Testing for Cricketers. *Journal of Strength & Conditioning Research*.
- LOPES, P. & WHITE, J. (2006) Heart rate variability: Measurement methods and practical implications. IN MAUDS, P. J. & FOSTER, C. (Eds.) *Physiological Assessment of Human Fitness*. 2nd ed. Champaign, IL, Human Kinetics.
- LORAM, L. C., MCKINON, W., WORMGOOR, S., ROGERS, G. G., NOWAK, I. & HARDEN, L. (2005) Determinants of ball release speed in schoolboy fast-medium bowlers in cricket. *Journal of Sports Medicine and Physical Fitness*, 45, 483 - 490.
- LUKE, A., MAKI, K., BARKEY, N., COOPER, R. & MCGEE, D. (1997) Simultaneous monitoring of heart rate and motion to assess energy expenditure. *Medicine & Science in Sport & Exercise*, 29, 144-148.
- LYMBERIS, A. & DITTMAR, A. (2007) Advanced wearable health systems and applications. *Engineering in Medicine and Biology*, May, 29-33.
- MACFARLANE, D. J., PHILL, D., FOGARTY, B. A. & HOPKINS, W. G. (1989) The Accuracy and Variability of Commercially Available Heart Rate Monitors. *The New Zealand Journal of Sports Medicine*, 17, 51-53.
- MAGALHÃES, J., REBELO, A., OLIVEIRA, E., SILVA, J., MARQUES, F. & ASCENSÃO, A. (2010) Impact of Loughborough Intermittent Shuttle Test versus soccer match on physiological, biochemical and neuromuscular parameters. *European Journal of Applied Physiology*, 108, 39-48.

- MANSINGH, A. (2006) Cricket and science. *Journal of Science and Medicine in Sport*, 9, 468 - 469.
- MASSIN, M., MAEYNS, K., WITHOFS, N., RAVET, F. & GÉRARD, P. (2000) Circadian rhythm of heart rate and heart rate variability. *Archives of Disease in Childhood*, 83, 179 -182.
- MATHIE, M. J., BASILAKIS, J. & CELLER, B. G. (2001) A system for monitoring posture and physical activity using accelerometers. *Engineering in Medicine and Biology Society, 2001. Proceedings of the 23rd Annual International Conference of the IEEE*.
- MATHIE, M. J., COSTER, A. C. F., LOVELL, N. H. & CELLER, B. G. (2003) Detection of daily physical activities using a triaxial accelerometer. *Medical & Biological Engineering & Computing*, 41, 296.
- MATSUKAWA, T., OZAKI, M., NISHIYAMA, T., IMANURA, M. & KUMAZAWA, T. (2000) Comparison of infrared thermometer with thermocouple for monitoring skin temperature *Critical Care Medicine*, 28, 532-536.
- MCARDLE, W., KATCH, F. & KATCH, V. (2005) *Essentials of exercise physiology*, Philadelphia, Lippincott Williams and Wilkins.
- MCARDLE, W. D., KATCH, F. L. & KATCH, V. L. (2009) *Exercise physiology: Nutrition, energy and human performance*, Philadelphia, Pen., Lippincott Williams and Wilkins.
- MCCOOL, F. D., WANG, J. & EBI, K. L. (2002) Tidal volume and respiratory timing derived from a portable ventilation monitor. *Clinical Investigations in Critical Care*, 122, 684-691.
- MCGRARTH, G. (2010) *Line and strength: The Glenn McGrath Story*, Australia, William Heinemann
- MCMORRIS, T. & GRAYDON, J. (2000) The effect of incremental exercise on cognitive performance. . *International Journal of Sport Psychology*, 31, 66-81.
- MEDBÄ, J. I., MAMEN, A., WELDE, B., HEIMBURG, E. V. & STOKKE, R. (2002) Examination of the Metamax I and II oxygen analysers during exercise studies in the laboratory. *Scandinavian Journal of Clinical & Laboratory Investigation*, 62, 585-598.
- MICHAELS, L. & CADORET, R. J. (1967) Day-to-day variability in the normal electrocardiogram. *British Heart Journal*, 29, 913 - 919.
- MINETT, G. M., DUFFIELD, R., KELLET, A. & PORTUS, M. (2012b) Effects of mixed-method cooling on recover of medium-fast bowling performance in hot conditions on consecutive days. *Journal of Sports Sciences*, DOI:10.1080/02640414.2012.709267.
- MINETT, G. M., DUFFIELD, R., KELLETT, A. & PORTUS, M. (2012a) Mixed-method pre-cooling reduces physiological demand without improving performance of medium-fast bowling in the heat. *Journal of Sports Sciences*, 30, 907-915.
- MOORE, A., TURNER, D. J. & JOHNSTONE, J. A. (2012) A preliminary analysis of team performance in English first-class Twenty-Twenty (T20) cricket. *International Journal of Performance Analysis in Sport*, 12, 188-207.
- MORGAN, D. & ALLEN, D. (2000) Early events in stretch-induced muscle damage. *Journal of Applied Physiology*, 87, 2007 - 2015.
- NATIONAL STATISTICS (2011) Health Survey for England 2010. The Health and Social Care Information Centre.
- NEUMANN, P., ZINSERLING, J. R., HAASE, C., SYDOW, M. & BURCHARDI, H. (1998) Evaluation of respiratory inductive plethysmography in controlled ventilation : Measurement of tidal volume and peep-induced changes of end-expiratory lung volume. *CHEST Journal*, 113, 443-451.
- NEVINS, R. J., DURDLE, N. G. & RASO, V. J. (2002) A posture monitoring system using accelerometers. *Electrical and Computer Engineering, 2002. IEEE CCECE 2002. Canadian Conference*, 2, p1087-1092.
- NEWELL, J., AITCHISON, T. & GRANT, S. (2010) *Statistics for Sport and Exercise Science: A practical approach* Malaysia, Pearson Education.
- NICHOLSON, G., COOKE, C., O'HARA, J. & SCHONFELD, A. (2009) Heart-rate of first-class cricket batsmen during competitive 50-over and 20-over match play. *Journal of Sports Sciences*, 27, s98.

- NOAKES, T. D. & DURANDT, J. J. (2000) Physiological requirements of cricket. *Journal of Sports Sciences*, 18, 919 - 929.
- NOAKES, T. D., LAMBERT, M. I. & GLEESON, M. (1998) Heart rate monitoring and exercise: Challenges for the future. *Journal of Sports Science*, 16, 105-106.
- NORTON, K., OLDS, T., OLIVE, S. & CRAIG, N. (1996) Anthropometry and sports performance. IN NORTON, K. & OLDS, T. (Eds.) *Anthropometrica*. Sydney, NSW, University of New South Wales Press.
- NUNAN, D., DONOVAN, G., JAKOVljeVIC, D. G. & HODGES, L. D. (2008) Validity and Reliability of Short-Term Heart Rate Variability from the Polar S810. *Medicine & Science in Sport & Exercise*, 41, 243-250.
- O'DONOGHUE, P. G. (2012) *Statistics for sport and exercise studies*, Oxon, Routledge.
- OAKLEY, B. & GREEN, M. (2001) The production of Olympic champions: International perspectives on elite sport. *European Journal of Sport Management*, 8, 83 - 102.
- OLIVER, J., ARMSTRONG, N. & WILLIAMS, C. (2008) Changes in jump performance and muscle activity following soccer-specific exercise. *Journal of Sports Sciences*, 26, 141 - 148.
- PARADISIS, G. P. & COOKE, C. B. (2001) Kinematic and postural characteristics of sprint running on sloping surfaces. *Journal of Sports Sciences*, 19, 149-159.
- PAYNE, W. R., HOY, G., LAUSSEN, S. P. & CARLSON, J. S. (1987) What research tells the cricket coach. *Sports Coach*, 10, 17-22.
- PEARSON, A. (2004) *SAQ for cricket*, London, A&C Black.
- PETERSEN, C., PORTUS, D. B. & DAWSON, M. R. (2009a) Quantifying positional movement patterns in Twenty20 cricket. *International Journal of Performance Analysis in Sport*, 9, 165-170.
- PETERSEN, C., PYNE, D., DAWSON, B., KELLET, A. & PORTUS, M. (2011a) Comparison of training and game demands of national level cricketers. *Journal of Strength and Conditioning Research*, 25, 1306 - 1311.
- PETERSEN, C., PYNE, D., DAWSON, B., PORTUS, M. & KELLET, A. (2010) Movement patterns in cricket vary by both position and game format. *Journal of Sports Sciences*, 28, 45 - 52.
- PETERSEN, C., PYNE, D., PORTUS, M. & DAWSON, B. (2009b) Validity and reliability of GPS units to monitor cricket-specific movement patterns. *International Journal of Sports Physiology and Performance*, 5, 381 - 391.
- PETERSEN, C., PYNE, D., PORTUS, M. & DAWSON, B. (2011b) Comparison of player movement patterns between 1-day and test cricket. *Journal of Strength and Conditioning Research*, 25, 1368 - 1372.
- PETERSEN, C., PYNE, D., PORTUS, M., KARPINEN, S. & DAWSON, B. (2009c) Variability in movement patterns during one day internationals by a cricket fast bowler. *International Journal of Sports Physiology and Performance*, 4, 278 - 281.
- PHILLIPS, E., PORTUS, M., DAVIDS, K., BROWN, N. & RENSHAW, I. (2010) Quantifying variability within technique and performance in elite fast bowlers: is technical variability dysfunctional or functional? IN PORTUS, M. (Ed. *Conference of Science, Medicine and Coaching in Cricket*. Gold Coast, Qld, Australian.
- PHILLIPS, E., PORTUS, M., DAVIDS, K. & RENSHAW, I. (2012) Performance accuracy and functional variability in elite and developing fast bowlers. *Journal of Science and Medicine in Sport*, 15, 182-188.
- PHILLIPS, N. (2007) Measuring flexibility. IN WINTER, E., JONES, A., DAVIDSON, R., BROMLEY, P. & MERCER, T. (Eds.) *British association of sport and exercise sciences sport and exercise physiology testing guidelines, Volume II: Exercise and clinical testing*. Oxon, Routledge.
- PIERPONT, G. L. & VOTH, E. J. (2004) Assessing autonomic function by analysis of heart rate recovery from exercise in healthy subjects. *The American Journal of Cardiology*, 94, 64-68.
- POLAR ELECTRO (1996) Method and system for measuring heartbeat rate using telemetric data transmission. USA. accessed online <https://www.google.com/patents/US5690119> on June 20th 2011.
- PONT, I. (2006) *The fast bowlers bible*, Wilt, UK, Crowood Press.

- PORTUS, M., MASON, B. R., ELLIOTT, B. C., PFITZNER, M. C. & DONE, R. P. (2004) Technique factors related to ball release speed and trunk injuries in high performance cricket fast bowlers. *Sports Biomechanics*, 3, 263 - 284.
- PORTUS, M., SINCLAIR, P., BURKE, S., MOORE, D. & FARHART, P. (2000) Cricket fast bowling performance and technique and the influence of selected physical factors during an 8 over spell. *Journal of Sports Sciences*, 18, 999 - 1011.
- POWELL, S. M., JONES, D. I. & ROWLANDS, A. V. (2003) Technical Variability of the RT3 Accelerometer. *Medicine & Science in Sports & Exercise*, 35, 1773-1778.
- POWELL, S. M. & ROWLANDS, A. V. (2004a) Inter-monitor Variability of the RT3 Accelerometer during Typical Physical Activities *Medicine & Science in Sports & Exercise*, 36, 324-330.
- POWERS, S. K. & HOWLEY, E. T. (2007) *Exercise physiology: Theory and application to fitness and performance*, New York, McGraw-Hill Intl.
- PYNE, D., DUTHIE, G., SAUNDERS, P., PETERSEN, C. & PORTUS, M. (2006) Anthropometric and strength correlates of fast bowling speed in junior and senior cricketers. *Journal of Strength and Conditioning Research*, 20, 620 - 626.
- R CORE TEAM (2013) R: A language and environment for statistical computing.
- RAMSBOTTOM, R., BREWER, J. & WILLIAMS, S. (1988) A progressive shuttle run test to estimate maximal oxygen uptake. *British Journal of Sports Medicine*, 22, 141 - 144.
- RANSON, C., BURNETT, A., KING, M., PATEL, N. & O'SULLIVAN (2007) The relationship between bowling action classification and three-dimensional lower trunk motion in fast bowlers in cricket. *Journal of Sports Sciences*, 26, 267 - 276.
- REILLY, T. (2007) *The science of training - Soccer*, Oxon, Routledge.
- REILLY, T., BANGSBO, J. & FRANKS, A. (2000) Anthropometric and physiological predispositions for elite soccer. *Journal of Sports Sciences*, 18, 669 - 683.
- RENNIE, K., ROWSELL, T., JEBB, S. A., HOLBURN, D. & WAREHAM, N. J. (2000) A combined heart rate and movement sensor: proof of concept and preliminary testing study. *European Journal of Clinical Nutrition*, 54, 409-414.
- RING, E. F. J. (2006) The historical development of thermometry and thermal imaging in medicine *Journal of Medical Engineering and Technology*. 30, 192-198.
- ROWLANDS, A. V., THOMAS, P. W., ESTON, R. & TOPPING, R. (2004) Validation of the RT3 triaxial Accelerometer for the Assessment of Physical Activity. *Medicine and Science in Sport and Exercise*, 36, 518 - 524.
- ROYAL, K., FARROW, D., MUJKA, I., HALSON, S., PYNE, D. & ABERNETHY, B. (2006) The effects of fatigue on decision making and shooting skill performance in water polo players. *Journal of Sport Sciences*, 24, 807-815.
- RUDKIN, S. T. & O'DONOGHUE, P. G. (2008) Time-motion analysis of first-class cricket fielding. *Journal of Science and Medicine in Sport*, 11, 604-607.
- RUPPERT, D., SHEATHER, S. J. & WAND, M. P. (1995) An effective bandwidth selector for local least squares regression. *Journal of the American Statistical Association*, 90, 1257-1270.
- SALTER, C. W., SINCLAIR, P. J. & PORTUS, M. R. (2007) The association between fast bowling technique and ball release speed: A pilot study of the within-bowler and between bowler approaches. *Journal of Sports Sciences*, 25, 1279 - 1285.
- SANDERCOCK, G. R., BROMLEY, P. D. & BRODIE, D. A. (2005) The reliability of short-term measurements of heart rate variability. *International Journal of Cardiology*, 103, 238 - 247.
- SAW, R., DENNIS, R. J., BENTLEY, D. & FARHART, P. (2011) Throwing workload and injury risk in elite cricketers. *British Journal of Sports Medicine*, 45, 805-808.
- SAWAKA, M. N. & YOUNG, A. J. (2006) Physiological systems and their responses to conditions of heat and cold. IN TIPTON, C. M. (Ed. *ACSM's Advanced Exercise Physiology*. Philadelphia, Lippincott Williams and Wilkins.
- SCHMUCKLER, M. (2001). What is ecological validity? A dimensional analysis. *Infancy*, 2, 4, 419-436.
- SCHLADER, Z., SIMMONS, S., STANNARD, S. & MUNDEL, T. (2011) Skin temperature as a thermal controller of exercise intensity. *European Journal of Applied Physiology*, 111, 1631-1639.

- SCHNEIDER, P. L., CROUTER, S. E., LUKAJIC, O. & BASSETT, D. J. (2003) Accuracy and Reliability of 10 Pedometers for measuring Steps over a 400-m Walk. *Medicine & Science in Sport & Exercise*, 35, 1779-1784.
- SEAWARD, B. L., SLEAMAKER, R. H., MCAULIFFE, T. & CLAPP, J. F. (1990) The precision and accuracy of a portable heart rate monitor. *Biomedical Instrumentation & Technology*, 24, 37-41.
- SIMPSON, R., MACHIN, G., MCEVOY, H. & RUSBY, R. (2006) Traceability and calibration in temperature measurement: a clinical necessity. *Journal of Medical Engineering and Technology*, 30, 212-217.
- SMITH, R., HARLEY, R. & STOCKILL, N. (2007) Sport specific procedures: Cricket. IN WINTER, E., JONES, A., DAVIDSON, R., BROMLEY, P. & MERCER, T. (Eds.) *British Association of Sport and Exercise Sciences; Sport and exercise physiology testing guidelines, Volume I: Sport testing*. Oxon, Routledge.
- STANTON, R., REABURN, P. R. & HUMPHRIES, B. (2004) The effect of short-term Swiss ball training on core stability and running economy. *Journal of Strength and Conditioning Research*, 18, 522-528.
- STAVEM, K., SAXHOLM, H. & SMITH-ERICHSEN, N. (1997) Accuracy of infrared ear thermometry in adult patients. *Intensive Care Medicine*, 23, 100-105.
- STECKLER, A. and MCLEROY, K. (2008). The importance of external validity. *American Journal of Public Health*, 98, 1, 9-10.
- STEWART, A. D. & ESTON, R. (2007) *Surface Anthropometry*, Oxon, Routledge.
- STRATH, S. J., SWARTZ, A. M., BASSETT, D. J., O'BRIEN, W. L., KING, G. A. & AINSWORTH, B. E. (2000) Evaluation of heart rate as a method for assessing moderate intensity physical activity. *Medicine & Science in Sport & Exercise*, 32, 465-470.
- STRETCH, R. (1991) Anthropometric profile and body composition changes in first-class cricketers. *South African Journal for Research in Sport, Physical Education and Recreation*, 14, 57 - 64.
- STRETCH, R., BARTLETT, R. & DAVIDS, K. (2000) Review of batting in men's cricket. *Journal of Sports Sciences*, 18, 931 - 949.
- STRETCH, R. & LAMBERT, M. (1999) Heart rate response of young cricket fast bowlers while bowling a six-over spell. *Sports Medicine*, 6, 15 - 19.
- STUELCKEN, M., PYNE, D. & SINCLAIR, P. (2007) Anthropometric characteristics of elite fast bowlers. *Journal of Sports Sciences*, 25, 1587 - 1597.
- TALIEP, M. S., PRIM, S. K. & GRAY, J. (2010) Upper Body Muscle Strength and Batting Performance in Cricket Batsmen. *The Journal of Strength & Conditioning Research*, 24, 3484-3487
10.1519/JSC.0b013e3181e7261b.
- TANAKA, H., MONAHAN, K. D. & SEALS, D. R. (2001) Age-predicted maximal heart rate revisited. *Journal of the American College of Cardiology*, 37, 153-156.
- TERBIZAN, D. J., DOLEZAL, B. A. & ALBANO, C. (2002) Validity of seven commercially available heart rate monitors. *Measurement in Physical Education and Exercise Science*, 6, 243-247.
- THOMAS, J. R., NELSON, J. K. & SILVERMAN, S. (2005) *Research methods in physical activity*, Champaign, Il, Human Kinetics.
- THOMAS, J. R., NELSON, J. K. & SILVERMAN, S. (2010) *Research methods in physical activity*, Champaign, Il, Human Kinetics.
- THORSTENSSON, A. L. F., NILSSON, J., CARLSON, H. & ZOMLEFER, M. R. (1984) Trunk movements in human locomotion. *Acta Physiologica Scandinavica*, 121, 9-22.
- TOMICH, G. M., FRANÇA, D. C., DIÓRIO, A. C. M., BRITTO, R. R., SAMPAIO, R. F. & PARREIRA, V. F. (2007) Breathing pattern, thoracic-abdominal motion and muscular activity during three breathing exercises. *Brazilian Journal of Medical and Biological Research*, 40, 1409-1417.
- TORTORA, G. J. & GRABOWSKI, S. R. (2003) *Principles of Anatomy and Physiology*, New York, USA, John Wiley & Sons.
- TROST, S. G., MCIVER, K. L. & PATE, R. (2005) Conducting accelerometry based activity assessments in field based research. *Medicine & Science in Sport & Exercise*, 37, 531 - 543.

- TROST, S. G., WARD, S. M., MOOREHEAD, S. M. & WATSON, P. D. (1998) Validity of the computer science and applications (CSA) activity monitor in children. *Medicine and Science in Sport and Exercise*, 30, 629 - 633.
- VALTA, P., TAKALA, J., FOSTER, R., WEISSMAN, C. & KINNEY, J. M. (1992) Evaluation of respiratory inductive plethysmography in the measurement of breathing pattern and peep-induced changes in lung volume. *CHEST Journal*, 102, 234-238.
- VANDERFORD, M., MEYERS, M., SKELLY, W., STEWART, C. & HAMILTON, K. (2004) Physiological and sport specific skill responses of Olympic youth soccer athletes. *Journal of Strength and Conditioning Research*, 18, 334 - 338.
- VANHELST, J., ZUNQUIN, G., THEUNYNCK, D., MIKULOVIC, J., BUI-XUAN, G. & BEGHIN, L. (2009) Equivalence of accelerometer data for walking and running: Treadmill versus on land. *Journal of Sports Science*, 27, 669-675.
- VELTINK, P. H., BUSSMANN, H. J., DE VRIES, W., MARTENS, W. J. & VAN LUMMEL, R. C. (1996) Detection of static and dynamic activities using uniaxial accelerometers. *Rehabilitation Engineering, IEEE Transactions on*, 4, 375-385.
- VENTURNI, C., ANDRÉ, A., AGUILAR, B. & GIACOMELLI, B. (2006) Reliability of two evaluation methods of active range of motion in the ankle of healthy individuals. *Acta Fisiatrica*, 13, 39 - 43.
- VUORI, I. (1998) Experience of heart rate monitoring in observational and interventional studies. *Journal of Sports Science*, 16, 25-30.
- WAJCIECHOWSKI, J., GAYLE, R., ANDREWS, R. & DINTIMAN, G. (1991) The accuracy of radio telemetry heart rate monitor during exercise. *Clinical Kinesiology*, 45, 9-12.
- WAND, M. (2013) Kern Smooth: Functions for kernel smoothing for Wand and Jones (1995).R package version 2.23-10. accessed online <http://CRAN.R-project.org/package=KernSmooth> on May 1st 2013
- WEBSTER, J. & ROBERTS, J. (2011) Determining the effect of cricket leg guards on running performance. *Journal of Sports Sciences*, 29, 749-760.
- WELK, G. J. (2005) Principles of design and analyses for the calibration of accelerometry-based activity monitors. *Medicine & Science in Sport & Exercise*, 37, 501-511.
- WELK, G. J., BLAIR, S. N., WOOD, K., JONES, S. & THOMPSON, R. W. (2000) A comparative evaluation of three accelerometry-based physical activity monitors *Medicine & Science in Sport & Exercise*, 32, 489-497.
- WELK, G. J., SCHABEN, J. A. & MORROW, J. R. (2004) Reliability of accelerometry-based activity monitors: A generalizability study. *Medicine & Science in Sport & Exercise*, 36, 1637-1645.
- WELLS, K. & DILLON, E. (1952) The sit and reach: A test of back and leg flexibility. *Research Quarterly*, 23, 115 - 118.
- WESTERTERP, K. R. (2009) Assessment of physical activity: a critical appraisal. *European Journal of Applied Physiology*, 105, 823-828.
- WILLIAMS, K. R. & CAVANAGH, P. R. (1987) Relationship between distance running mechanics, running economy, and performance. *The American Physiological Society*, 63, 1236-1245.
- WILLIAMS, S. J. & KENDALL, L. (2007) Perceptions of elite sports coaches and sports scientists of the research needs for elite coaching practice. *Journal of Sports Sciences*, 25, 1577 - 1586.
- WILMORE, J. & COSTILL, D. (2005) *Physiology of sport and exercise*, Champaign, IL, Human Kinetics.
- WINTER, E. M., ESTON, R. G. & LAMB, K. L. (2001) Statistical analyses in the physiology of exercise and kinanthropometry. *Journal of Sports Sciences*, 19, 761 - 775.
- WITT, J. D., FISHER, J. R. K., GUENETTE, J. A. & CHEONG, K. A. (2006a) Measurement of exercise ventilation by a portable respiratory inductive plethysmograph *Respiratory Physiology and Neurobiology*, 154, 389-395.
- WOLF, G. K. & ARNOLD, J. H. (2005) Non-invasive assessment of lung volume: Respiratory inductance plethysmography and electrical impedance tomography. *Critical Care Medicine*, 33, 163-169.
- WONG, W. Y. & WONG, M. S. (2008) Detecting spinal posture change in sitting positions with tri-axial accelerometers. *Gait & Posture*, 27, 168-171.

- WOOLMER, R., NOAKES, T. & MOFFETT, H. (2008) *Bob Woolmer's art and science of cricket*, New London, Holland Pubs.
- WORMGOOR, S., HARDEN, L. & MCKINON, W. (2010) Anthropometric, biomechanical, and isokinetic strength predictors of ball release speed in high performance cricket fast bowlers. *Journal of Sports Sciences*, 28, 957-965.
- YU-CHIAO, C. (2005) An infrared thermometer and a method for determining a temperature. EP Patent 1,530,034.
- ZAKERI, I., ADOLPH, A. L., PUYAU, M. R., VOHRA, F. A. & BUTTE, N. F. (2008) Application of cross-sectional time series modelling for the prediction of energy expenditure from heart rate and accelerometry. *Journal of Applied Physiology*, 104, 1665-1673.
- ZEBALLOS, J., COTES, J., FAIRBARN, M. S. & CRAPO, R. O. (2003) Reference values for cardiopulmonary exercise testing. IN WEISMAN, I. M. (Ed. *American Thoracic Society statement on cardiopulmonary exercise testing*).
- ZEPHYR TECHNOLOGY (2010) The Bioharness™ accessed online <http://www.zephyranywhere.com/products/> on July 10th 2010
- ZEPHYR TECHNOLOGY (2012) Bioharness™. accessed online <http://www.zephyranywhere.com/products/bioharness-3/> on September 1st 2012
- ZEPHYR TECHNOLOGY (2013) Bioharness™ 3 (Products). accessed online <http://www.zephyranywhere.com/products/> on February 23rd 2013

Appendices

1. Confirmation of ethical clearance
 - Physiological assessment of elite cricketers LS3/2/09P and LS3/2/09P(R1)
 - Reliability and validity of the Bioharness™ monitoring equipment LS3/11/09P
 - Field based reliability and validity of the Bioharness™ monitoring equipment LS1/10/10P
2. Participants hydration status (Osmolarity) during data collection
3. Example Bioharness™ screen shot from bowling event confirming bowling periods from accelerometry VMU
4. Descriptive data from consecutive bowling analysis
5. Extended SPSS output for relationships between Bioharness™ data and bowling performance

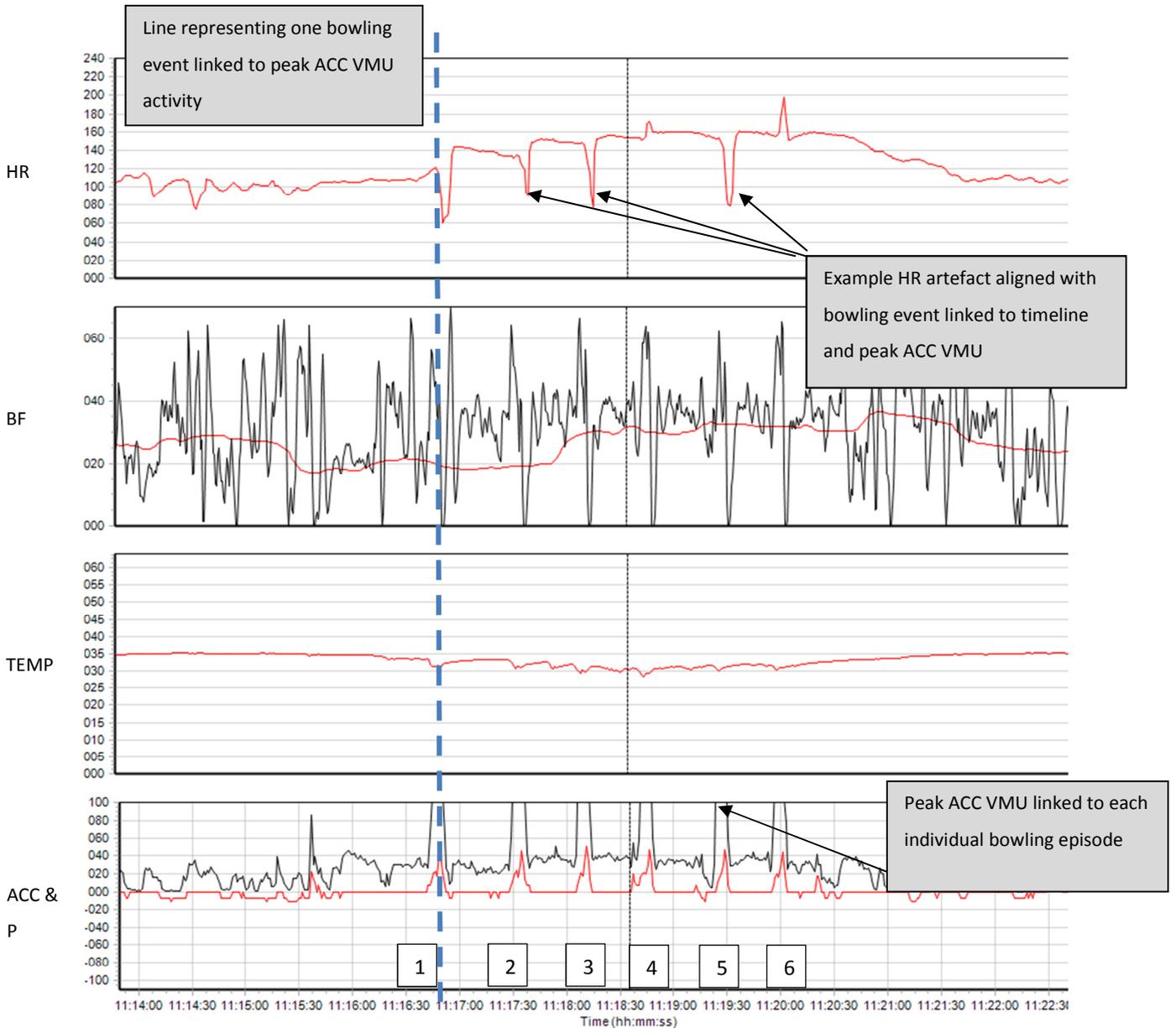
Appendix 1 – Ethics confirmation

Appendix 2 – Hydration data for fast-medium bowlers (n = 30 matches)

Descriptives ^a				
			Statistic	Std. Error
Mass pre match	Mean		95.84	2.329
	95% Confidence Interval for Mean	Lower Bound	90.72	
		Upper Bound	100.97	
	5% Trimmed Mean		96.26	
	Median		97.05	
	Variance		65.074	
	Std. Deviation		8.067	
	Minimum		80	
	Maximum		104	
	Range		25	
	Interquartile Range		7	
	Skewness		-1.246	.637
	Kurtosis		.928	1.232
	Osmo check pre match	Mean		541.67
95% Confidence Interval for Mean		Lower Bound	397.39	
		Upper Bound	685.94	
5% Trimmed Mean		545.19		
Median		485.00		
Variance		51560.606		
Std. Deviation		227.070		
Minimum		170		
Maximum		850		
Range		680		
Interquartile Range		430		
Skewness		.237	.637	
Kurtosis		-1.032	1.232	
second osmo check		Mean		777.50
	95% Confidence Interval for Mean	Lower Bound	586.12	
		Upper Bound	968.88	
	5% Trimmed Mean		780.00	
	Median		830.00	
	Variance		90729.545	
	Std. Deviation		301.213	
	Minimum		200	
	Maximum		1310	
	Range		1110	
	Interquartile Range		238	

	Skewness		-.490	.637
	Kurtosis		.772	1.232
third osmo check	Mean		623.33	65.601
	95% Confidence Interval for Mean	Lower Bound	478.95	
		Upper Bound	767.72	
	5% Trimmed Mean		613.15	
	Median		665.00	
	Variance		51642.424	
	Std. Deviation		227.250	
	Minimum		330	
	Maximum		1100	
	Range		770	
	Interquartile Range		340	
	Skewness		.505	.637
	Kurtosis		.154	1.232
	mass end of match	Mean		94.88
95% Confidence Interval for Mean		Lower Bound	89.75	
		Upper Bound	100.00	
5% Trimmed Mean			95.27	
Median			96.25	
Variance			64.946	
Std. Deviation			8.059	
Minimum			79	
Maximum			104	
Range			25	
Interquartile Range			9	
Skewness			-1.128	.637
Kurtosis			.697	1.232
a. player = bowl				

Appendix 3: Example Bioharness™ raw data output from bowling event



6 bowled deliveries identified by the ACC

Appendix 4 – Descriptive data from consecutive overs analysis

Table A1; Descriptive statistics (mean \pm SD) for heart rate in absolute (beat.min⁻¹) and relative (%) heart rate (HR) values during 7 consecutive overs

Table A2; Descriptive statistics (mean \pm SD) for heart rate in absolute (beat.min⁻¹) and relative (%) heart rate (HR) values during 7 consecutive between over episodes

Table A3; Descriptive statistics (Median \pm Inter Quartile Range) for cumulative accelerometry data (ct.episode¹) variables during 7 consecutive overs

Table A4; Descriptive statistics (Median \pm Inter Quartile Range) for cumulative accelerometry data (ct.episode¹) during 7 consecutive between over episodes

Table A1; Descriptive statistics (mean \pm SD) for heart rate in absolute ($\text{beat}\cdot\text{min}^{-1}$) and relative (%) heart rate (HR) values during 7 consecutive overs

	Consecutive Over No						
	1	2	3	4	5	6	7
	M \pm SD	M \pm SD	M \pm SD	M \pm SD	M \pm SD	M \pm SD	M \pm SD
HR _{10r}	23.40 \pm 13.37	29.33 \pm 14.83	27.13 \pm 11.24	27.92 \pm 13.18	28.93 \pm 13.28	29.63 \pm 10.61	33.78 \pm 13.30
HR _{60r}	38.20 \pm 16.90	44.82 \pm 17.13	44.04 \pm 16.65	44.44 \pm 15.57	49.97 \pm 15.33	46.93 \pm 17.37	47.28 \pm 19.79
HR	135.45 \pm 17.92	138.64 \pm 19.28	139.65 \pm 15.91	140.30 \pm 15.76	143.50 \pm 15.40	143.49 \pm 13.46	141.94 \pm 15.94
HR _{age}	69.80 \pm 9.54	71.50 \pm 10.67	72.10 \pm 9.14	72.45 \pm 9.13	74.15 \pm 8.80	74.03 \pm 8.24	73.21 \pm 9.20
HR _{max}	147.30 \pm 18.69	149.64 \pm 19.21	152.27 \pm 16.52	152.46 \pm 16.60	153.76 \pm 16.13	154.70 \pm 14.36	150.90 \pm 16.67
HR _{maxage}	75.96 \pm 9.99	77.17 \pm 10.34	78.60 \pm 9.254	78.71 \pm 9.38	79.47 \pm 9.07	79.92 \pm 8.33	78.17 \pm 9.44
HR _{min}	115.41 \pm 16.68	119.57 \pm 16.99	118.68 \pm 13.31	119.08 \pm 13.05	120.91 \pm 12.29	122.56 \pm 10.20	123.26 \pm 10.90
HR _{minage}	59.70 \pm 8.95	61.87 \pm 9.20	61.47 \pm 7.61	61.65 \pm 7.13	62.73 \pm 7.08	63.33 \pm 6.35	63.92 \pm 7.46

Tabular report; Absolute values: HR_{10r} = heart rate 10 seconds before bowling relative to baseline heart rate, HR_{60r} = heart rate 60 seconds after bowling relative to base line heart, HR = Heart rate, HR_{max} = Heart rate maximum, HR_{min} = Heart rate minimum. Relative values: HR_{age} = Heart rate relative to age, HR_{maxage} = Heart rate maximum relative to age, HR_{minage} = Heart rate minimum relative to age

Table A2; Descriptive statistics (mean \pm SD) for heart rate in absolute ($\text{beat}\cdot\text{min}^{-1}$) and relative (%) heart rate (HR) values during 7 consecutive between over episodes

	Consecutive Between Over No						
	1	2	3	4	5	6	7
	M \pm SD	M \pm SD	M \pm SD	M \pm SD	M \pm SD	M \pm SD	M \pm SD
HR	119.22 \pm 12.27	124.25 \pm 13.13	122.72 \pm 11.00	123.76 \pm 12.56	125.57 \pm 10.62	127.51 \pm 13.74	128.35 \pm 13.05
HR _{age}	61.55 \pm 6.73	64.03 \pm 7.02	63.31 \pm 6.08	63.91 \pm 6.89	64.72 \pm 6.12	65.67 \pm 7.05	66.32 \pm 5.66
HR _{max}	143.51 \pm 19.45	149.37 \pm 18.24	149.04 \pm 19.11	148.84 \pm 18.64	152.79 \pm 15.95	154.15 \pm 16.42	151.44 \pm 15.86
HR _{maxage}	74.13 \pm 10.35	76.98 \pm 9.64	76.96 \pm 10.65	76.96 \pm 10.47	78.96 \pm 9.21	79.73 \pm 8.32	79.11 \pm 6.28
HR _{min}	106.78 \pm 12.02	110.28 \pm 12.97	109.23 \pm 10.42	110.53 \pm 12.52	112.33 \pm 11.07	115.17 \pm 13.93	118.02 \pm 14.66
HR _{minage}	55.32 \pm 6.42	57.01 \pm 6.80	56.51 \pm 5.29	57.31 \pm 6.68	58.03 \pm 6.43	59.60 \pm 7.28	61.77 \pm 7.55

Tabular report; Absolute values: HR = Heart rate, HR_{max} = Heart rate maximum, HR_{min} = Heart rate minimum. Relative values: HR_{age} = Heart rate relative to age, HR_{maxage} = Heart rate maximum relative to age, HR_{minage} = Heart rate minimum relative to age

Table A3; Descriptive statistics (Median ± Inter Quartile Range) for cumulative accelerometry data (ct.episode⁻¹) variables during 7 consecutive overs

	Consecutive Over No						
	1	2	3	4	5	6	7
	Mdn ± IQR	Mdn ± IQR	Mdn ± IQR	Mdn ± IQR	Mdn ± IQR	Mdn ± IQR	Mdn ± IQR
VMU	116.22 ± 22.47	115.43 ± 20.42	115.71 ± 24.33	113.63 ± 13.70	110.15 ± 15.85	108.28 ± 16.01	114.74 ± 19.63
Acceleration	231.04 ± 43.12	227.00 ± 51.59	230.31 ± 50.28	226.93 ± 24.55	220.92 ± 30.97	223.01 ± 32.98	235.96 ± 45.49
Vertical x	-378.55 ± 43.58	-375.00 ± 84.60	-392.75 ± 73.73	-384.69 ± 46.18	-355.30 ± 50.83	-373.18 ± 24.52	-376.77 ± 50.05
Lateral y left	123.35 ± 38.50	122.20 ± 29.06	123.81 ± 38.74	118.84 ± 24.94	120.28 ± 38.82	120.60 ± 29.50	121.42 ± 39.98
Lateral y right	-94.24 ± 107.45	-93.99 ± 23.78	-101.70 ± 22.63	-92.19 ± 22.99	-90.53 ± 21.87	-93.59 ± 20.77	-93.56 ± 44.76
Sagittal z anterior	54.17 ± 15.56	53.49 ± 16.18	55.70 ± 23.84	56.62 ± 15.53	53.18 ± 20.55	57.99 ± 12.69	55.74 ± 17.33
Sagittal z posterior	-153.47 ± 36.65	-153.55 ± 36.74	-154.56 ± 29.97	-151.57 ± 19.43	-147.36 ± 31.19	-146.70 ± 38.46	-155.31 ± 16.09

Tabular report: VMU = Vector Magnitude Units, the combined value of 3 axis, Peak acceleration = maximum 3-axis acceleration, Peak Vertical (x) = peak value on vertical axis, Min Vertical (x) = minimum value on vertical axis, Peak Lateral (y) = peak value on lateral axis, Min Lateral (y) = minimum value on lateral axis, Peak Sagittal (z) = peak value on the sagittal axis, Min value (z) = minimum value on the sagittal axis

Table A4; Descriptive statistics (Median ± Inter Quartile Range) for cumulative accelerometry data (ct.episode⁻¹) during 7 consecutive between over episodes

	Consecutive Between Over No						
	1	2	3	4	5	6	7
	Mdn ± IQR	Mdn ± IQR	Mdn ± IQR	Mdn ± IQR	Mdn ± IQR	Mdn ± IQR	Mdn ± IQR
VMU	66.23 ± 20.66	62.50 ± 21.90	57.64 ± 15.53	63.45 ± 19.26	72.08 ± 22.84	72.42 ± 25.21	53.10 ± 21.61
Acceleration	136.35 ± 43.24	130.50 ± 55.24	117.12 ± 33.84	125.94 ± 41.38	144.16 ± 60.22	158.28 ± 52.50	110.22 ± 41.86
Vertical x	-378.35 ± 67.82	-346.94 ± 82.33	-350.79 ± 99.27	-365.25 ± 48.40	-405.29 ± 160.36	-391.31 ± 68.60	-351.45 ± 83.03
Lateral y left	62.97 ± 27.36	64.66 ± 29.08	53.14 ± 35.75	54.98 ± 33.13	72.06 ± 31.15	73.63 ± 30.73	56.66 ± 33.23
Lateral y right	-56.54 ± 26.33	-57.59 ± 23.46	-51.77 ± 16.37	-61.118 ± 26.56	-67.70 ± 19.96	-53.48 ± 38.84	-40.44 ± 30.76
Sagittal z anterior	53.47 ± 20.19	48.46 ± 29.21	52.12 ± 29.15	52.29 ± 38.63	58.67 ± 31.55	49.34 ± 36.52	56.42 ± 48.21
Sagittal z posterior	-63.42 ± 48.28	-70.47 ± 34.40	-51.14 ± 29.86	-59.39 ± 54.81	-72.92 ± 40.79	-71.48 ± 32.00	-54.67 ± 41.77

Tabular report: VMU = Vector Magnitude Units, the combined value of 3 axis, Peak acceleration = maximum 3-axis acceleration, Peak Vertical (x) = peak value on vertical axis, Min Vertical (x) = minimum value on vertical axis, Peak Lateral (y) = peak value on lateral axis, Min Lateral (y) = minimum value on lateral axis, Peak Sagittal (z) = peak value on the sagittal axis, Min value (z) = minimum value on the sagittal axis

Appendix 5. Heart rate and Accelerometry Correlations

Correlations			runs per over sub
Spearman's rho	runs2	Correlation Coefficient	-.028
		Sig. (2-tailed)	.701
		N	195
	runs per over sub	Correlation Coefficient	1.000
		Sig. (2-tailed)	
		N	225
hr602		Correlation Coefficient	.093
		Sig. (2-tailed)	.209
		N	186
hr102		Correlation Coefficient	.061
		Sig. (2-tailed)	.400
		N	195
hrmax2		Correlation Coefficient	.053
		Sig. (2-tailed)	.460
		N	195
hrmaxage2		Correlation Coefficient	.101
		Sig. (2-tailed)	.161
		N	195
hrmin2		Correlation Coefficient	-.053
		Sig. (2-tailed)	.460
		N	195

	N	195
hrminage2	Correlation Coefficient	-.023
	Sig. (2-tailed)	.745
	N	195
hrmean2	Correlation Coefficient	.055
	Sig. (2-tailed)	.445
	N	195
hrmeanage2	Correlation Coefficient	.017
	Sig. (2-tailed)	.812
	N	195
vmutot2	Correlation Coefficient	-.069
	Sig. (2-tailed)	.342
	N	193
peakaccel2	Correlation Coefficient	-.077
	Sig. (2-tailed)	.285
	N	195
minx2	Correlation Coefficient	.086
	Sig. (2-tailed)	.230
	N	195
peakx2	Correlation Coefficient	-.049
	Sig. (2-tailed)	.492
	N	195
miny2	Correlation Coefficient	.169*
	Sig. (2-tailed)	.019
	N	195
peaky2	Correlation Coefficient	.088
	Sig. (2-tailed)	.221
	N	195

minz2	Correlation Coefficient	.004
	Sig. (2-tailed)	.959
	N	195
peakz2	Correlation Coefficient	.058
	Sig. (2-tailed)	.424
	N	195

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).