

1 The relationship between the moderate-heavy boundary and critical speed in running.

2

3 **Abstract**

4 **Purpose**

5 Training characteristics such as duration, frequency, and intensity can be manipulated to
6 optimise endurance performance, with an enduring interest in the role of training intensity
7 distribution to enhance training adaptations. Training intensity is typically separated into three
8 zones, which align with the moderate, heavy, and severe intensity domains. While estimates of
9 the heavy-severe intensity boundary, i.e., the critical speed (CS) can be derived from habitual
10 training, determining the moderate-heavy boundary or first threshold (T1) requires testing,
11 which can be costly and time-consuming. Therefore, the aim of this review was to examine the
12 percentage at which T1 occurs relative to CS.

13 **Results**

14 A systematic literature search yielded 26 studies with 527 participants, grouped by mean CS
15 into low ($11.5 \text{ km}\cdot\text{h}^{-1}$; 95% CI [11.2, 11.8]), medium ($13.4 \text{ km}\cdot\text{h}^{-1}$; 95% CI [13.2, 13.7]), and
16 high ($16.0 \text{ km}\cdot\text{h}^{-1}$; 95% CI [15.7, 16.3]) groups. Across all studies, T1 occurred at 82.3% of
17 CS (95% CI [81.1, 83.6]). In the medium and high CS groups, T1 occurred at a higher fraction
18 of CS (83.2% CS (95% CI [81.3, 85.1]) and 84.2% CS (95% CI [82.3, 86.1]), respectively)
19 relative to the low CS group (80.6% CS; 95% CI [78.0, 83.2]).

20 **Conclusions**

21 The study highlights some uncertainty in the fraction of T1 relative to CS, influenced by
22 inconsistent approaches in determining both boundaries. However, our findings serve as a
23 foundation for remote analysis and prescription of exercise intensity, although testing is
24 recommended for more precise applications.

25

26 **Keywords:** testing, monitoring, intensity domains, endurance training, exercise prescription

27

28 **Introduction**

29 Training characteristics including duration, frequency, and intensity can be manipulated to
30 maximise endurance performance.^{1,2} There is an enduring interest in the role of training
31 intensity distribution across different intensity "zones" to elicit distinct training adaptations as
32 well as helping to identify "best practice".^{1,3,4} Several approaches have been proposed to
33 delineate these zones, but most commonly they align with three distinct physiological domains:
34 moderate, heavy, and severe.⁵ Moderate-intensity is characterised by the rapid attainment of

35 oxygen uptake ($\dot{V}O_2$) steady state within 2-3 mins), and blood [lactate] is not substantially
36 elevated above resting levels.⁶ Heavy-intensity exercise is typified by delayed attainment of a
37 $\dot{V}O_2$ steady state, caused by the emergence of the slow component of $\dot{V}O_2$ kinetics, as well as
38 stable metabolite concentrations above resting values.⁷ The severe-intensity domain occurs
39 above the heavy-severe boundary, where a steady state is not attainable in respiratory and
40 metabolic responses, and given sufficient time eventually leads to the attainment of an
41 individual's maximum oxygen uptake ($\dot{V}O_{2max}$) and task failure.⁷ These domains are separated
42 by two distinct "thresholds", although these may behave more like phase transitions.⁸

43

44 The transition between the moderate and heavy domains (T1) is typically quantified as either
45 lactate threshold (LT),⁹ gas exchange threshold (GET),¹⁰ or the first ventilatory threshold
46 (VT1).¹¹ The demarcation of the heavy-severe boundary is typically represented by either
47 critical speed (CS),¹² maximum lactate steady state,⁹ or respiratory compensation point
48 (RCP).¹⁰ There is some conjecture as to the most accurate representation of the heavy-severe
49 domain boundary.¹³⁻¹⁷ In essence, the heavy-severe boundary represents the greatest work rate
50 at which a metabolic steady state can occur which is conjectured to be most appropriately
51 captured by CS.¹⁶ Indeed, it has been proposed that the CS may be the most appropriate method
52 of determining the heavy-severe boundary.^{16,18} Furthermore, estimates of the CS, and its
53 analogy for cycling, critical power, can be derived from habitual training data or a set of time
54 trials.¹⁹⁻²¹ Importantly, these approaches do not necessarily require costly and time-consuming
55 laboratory-based testing, thus permitting remote determination which may be more accessible
56 for amateur runners.¹⁹ The latter is an important distinction given that the determination of T1
57 as LT necessitates capillary blood sampling, whereas GET and VT1 require an online gas
58 analyser. If T1, without specific testing, can be expressed as a percentage of CS, this would
59 enable more accessible exercise intensity prescription across all exercise intensity domains, or
60 the remote monitoring of training intensity distribution.

61

62 Despite considerable attention being directed towards CS, the relationship between T1 and CS
63 during running has not been systematically studied. To address this limitation, the aim of this
64 study was to conduct a systematic review and quasi meta-analysis to determine the percentage
65 at which T1 occurs relative to CS. It has previously been observed that the heavy and severe
66 domains become compressed in elite endurance athletes.²² Therefore, a further aim was to
67 examine whether the percentage at which T1 occurs relative to CS differs between fitness
68 levels.

69

70 **Methods**

71 *Search Strategy*

72 A systematic search was conducted to identify relevant papers in two scientific databases:
73 PubMed and Scopus. The focus of this review was on journal articles published in English that
74 described measures of both CS and T1. Articles published up to 28th February 2023 were
75 reviewed originally, with an updated search taking place on 3rd April 2024. Title, abstract and
76 keyword search fields were searched using the following search strategy:

77

78 ("critical speed") OR ("critical velocity") AND (("run") OR ("running"))

79

80 *Screening Procedure*

81 The selection process consisted of four steps using PRISMA guidelines: 1) duplicates were
82 removed after combining results from the two databases; 2) an initial title and abstract screen
83 was performed by independent reviewers (SM and TC); 3) two independent reviewers (SM
84 and BH) read the full texts based on the inclusion/exclusion criteria detailed below. References
85 of all included studies were checked for additional studies that could be included. At all stages,
86 conflicting decisions were adjudicated by a third reviewer (BH at stage 2, and DM at stage 3).
87 Studies were included if they met the following inclusion criteria: 1) CS was reported, 2) either
88 GET, LT1, or VT1 was reported, 3) participants were 18+, 4) written in the English language.
89 Studies were excluded if they: 1) did not meet the inclusion criteria above, 2) were book
90 chapters, review articles, case studies, letters, short communications, conference proceedings
91 or other non-peer-reviewed literature, 3) reported on animal subjects, and 4) did not examine
92 running.

93

94 *Data Extraction*

95 Data were extracted by BH, SM, DM, and EM using a customised form to ensure
96 standardisation. Information from each article included: sample size, participant training level,
97 age, sex, protocol used to determine CS, CS, protocol used to determine T1, and speed which
98 elicited T1. Where studies divided participants into subgroups, the mean values from the
99 subgroups were extracted separately for further analysis. Where T1 or CS was not reported,
100 but the relative position of it relative to the CS or T1 was, this percentage was used to calculate
101 the mean speed at either CS or T1 for the group. Where T1 or CS was reported in a figure, the
102 authors were contacted to confirm the values required.

103

104 ***Statistical Analysis***

105 Following data extraction, the mean percentage at which T1 occurred relative to CS was
106 calculated. Prior to this, each study was checked for normality of data distribution. None of the
107 included studies stated that either T1 or CS data were skewed or not normally distributed. The
108 mean critical speed from each of the included articles were grouped into bins of equal size
109 ($0.49 \text{ km}\cdot\text{h}^{-1}$), which were then plotted against the cumulative frequency. The total number of
110 participants (n) of the included articles were divided into three to form cut-offs (i.e., $n/3$ and
111 $2n/3$). If the cut-off coincided with a bin, then all articles up to and including the bin were
112 included. These cut-offs were then applied to group studies into low ($\leq 12 \text{ km}\cdot\text{h}^{-1}$), medium
113 ($>12 \text{ km}\cdot\text{h}^{-1}$), and high CS ($>14 \text{ km}\cdot\text{h}^{-1}$) based on the cumulative frequency. Sample size
114 weighted means and 95% confidence intervals (95% CI) were calculated for CS in each group,
115 and overall. Furthermore, sample size weighted means and 95% CI were calculated for the
116 overall percentage of CS at which T1 occurred, and for the percentage of CS at which T1
117 occurred in each group. Hedge's g was used to calculate effect sizes between the percentage of
118 CS at which T1 occurred in the three groups. Data were visually displayed as forest plots using
119 Graphpad Prism (Prism 9, Graphpad Software, San Diego, CA).

120

121 **Results**

122 ***Search Results***

123 From a total of 1,243 articles identified in the original database search, 26 papers met the
124 inclusion criteria. No additional articles were identified through searches of reference lists. A
125 diagram outlining the screening procedure is given in Figure 1.

126

127 Figure 1 about here.

128

129 ***Participant Characteristics***

130 Table 1 gives participant characteristics of the included studies. The pooled weighted mean CS
131 across the included studies was $13.6 \text{ km}\cdot\text{h}^{-1}$ (95% CI [13.4, 13.8]). The CS of the low, medium,
132 and high CS subgroups was $11.5 \text{ km}\cdot\text{h}^{-1}$ (95% CI [11.2, 11.8]), $13.4 \text{ km}\cdot\text{h}^{-1}$ (95% CI [13.2,
133 13.7]), and $16.0 \text{ km}\cdot\text{h}^{-1}$ (95% CI [15.7, 16.3]), respectively. Thirteen of the included studies
134 tested only male participants,^{18,23-34} six of the studies tested a mixture of males and females,³⁵⁻

135 ⁴⁰ with only one recruiting solely female participants.⁴¹ Six studies did not report the sex of the
136 participants.⁴²⁻⁴⁷

137

138 Table 1 about here.

139

140 ***Study Characteristics***

141 Of the approaches used to estimate CS, nine studies used a series of constant work rate trials
142 (CWR),^{18,23,26,31,33,35,36,39,46} eight used the three minute all out test (3MT),^{27,28,30,34,40-42,45} six
143 used time trials (TT),^{25,32,37,38,43,44} two studies used an intermittent 3MT protocol,^{24,47} and one
144 study compared both CWR and TT trials.²⁹ Ten studies reported GET,^{23,26-28,35,37,40-42,45} nine
145 reported LT1,^{18,25,32,33,38,39,44,46,47} and seven reported VT1^{24,29-31,34,36,43} as T1. Further
146 methodological details of the included studies are summarised in Table 2.

147

148 Table 2 about here.

149

150 ***First Threshold as a Fraction of CS***

151 Across all studies, T1 occurred at 82.3 % CS (95% CI [81.1, 83.6]). In the low, medium, and
152 high CS groups, T1 occurred at 80.6% CS (95% CI [78.0, 83.2]), , 83.2% CS (95% CI [81.3,
153 85.1]), and 84.2% CS (95% CI [82.3, 86.1]), respectively. These data are summarised in Figure
154 2. Hedge's *g* revealed small effect sizes for the percentage at which T1 occurred in the medium
155 CS group (*g* = 0.296) and high CS group (*g* = 0.227) compared to the low CS group. A trivial
156 effect size was noted in the percentage of at which T1 occurred in the medium CS group
157 compared to the high CS group (*g* = 0.076).

158

159 Figure 2 and 3 about here.

160

161 **Discussion**

162 In this systematic review and meta-analysis, we have found that T1 occurs at 82.3% CS (95%
163 CI [81.1, 83.6]). However, this was associated with a relatively large variance between studies
164 and fitness levels, discussed below. Importantly, the fraction at which T1 occurred relative to
165 CS seemed to be dependent on the fitness level, with small increases in runners with moderate
166 or high CS. This is in accordance with previously reported observations in very highly trained
167 runners, where both the heavy and severe domains tend to be compacted towards the speed
168 associated with $\dot{V}O_{2max}$.^{22,48} The findings suggest that the heavy domain tends to be more

169 compressed than that of the severe domain. However, the high CS group had a relatively
170 modest pooled mean CS ($16.0 \text{ km}\cdot\text{h}^{-1}$) in comparison to the previously estimated CS of elite
171 runners ($21.0 \text{ km}\cdot\text{h}^{-1}$).^{49,50} Therefore, this phenomenon may only be evident in those with
172 exceptionally high CS.

173

174 The fraction at which T1 occurs relative to CS appears to be elevated compared to that observed
175 in cycling (i.e., critical power),⁵¹ which is consistent with previous comparisons between
176 exercise modalities.⁵² Previously, a “critical intensity” has been demonstrated, whereby
177 metabolic rate and blood lactate are not significantly different between running at CS and
178 cycling at critical power.⁵³ Therefore, this difference is likely due to the position of T1 relative
179 to the peak incremental test work rate and may be linked to the larger $\dot{V}\text{O}_2$ slow component
180 associated with cycling.^{52,54} It has been posited previously that in participants with little cycling
181 experience, extraneous energetic cost may be due to gripping handlebars or unnecessary torso
182 movement at submaximal work rates.⁵² However, differences in muscle contraction regimen,
183 and lesser elastic energetic contribution in cycling,⁵⁵ are more significant contributors to the
184 greater $\dot{V}\text{O}_2$ slow component associated with cycling when compared to running.

185

186 It is notable that only one of the included studies reported both T1 and CS that were comparable
187 ($< 2\%$ difference),³⁰ thus supporting previous conclusions that VT1 and critical power are
188 unique work rates.⁵¹ The incongruent findings reported by Kuo et al.³⁰ are likely due to
189 differences in temperature between the initial incremental test to determine VT1 (mean
190 temperature: 22.0°C) and the 3MT (mean temperature: 34.7°C) conducted outdoors on a track.
191 Therefore, it is likely that environmental conditions will affect the fraction at which T1 occurs
192 relative to CS, possibly by depressing estimates of CS. Therefore, it is recommended that
193 environmental factors are considered when using this approach.

194

195 The large pooled standard deviation demonstrates a degree of uncertainty in where T1 occurs
196 relative to CS. This may be due to inconsistent approaches used to determine both the T1 and
197 CS. There was substantial variation in the fraction at which T1 relative to CS was evident
198 when using different methods. Measures of LT occurred at 87.7% CS (95% CI [86.2, 89.3]),
199 whereas gas-based measures resulted in a lower fraction of CS (GET: 79.5% CS (95% CI [77.3,
200 81.8]), VT: 81.7% CS (95% CI [79.4, 84.1])). Indeed, ventilatory and lactate performance
201 parameters have been shown to differ during graded exercise tests in running.^{56,57} Furthermore,
202 the studies that reported LT used a variety of different criteria to determine LT including 1

203 mmol/L above baseline, speed at 2 mmol/L, and a “sustained increase above baseline”. The
204 determination of CS has also previously been shown to be dependent on the methods
205 selected.^{19,58} Therefore, some consideration is warranted by practitioners about how they wish
206 to define both T1 and CS. However, in the current approach, the variation of T1 as a fraction
207 of CS is comparable to previously reported error and sources of biological variability in other
208 thresholds.^{59,60} It should also be recognised that although this is a practical approach, the
209 relative position of thresholds may depend on numerous factors including age,^{61,62}
210 anthropometry,⁶³ sex,^{64,65} and training phase.³⁹ Such factors were not considered substantively
211 in the current review, but may provide an interesting avenue for further research. Furthermore,
212 due to the scope of the review the findings cannot be extrapolated to other factors which may
213 influence adaptations to training including heart rate, perceived exertion values, and ventilatory
214 measures.

215

216 **Practical Applications**

217 The findings provide a basis on which remote analysis and prescription of training zones can
218 be performed in runners of a range of abilities. To utilise these findings, we have included a
219 table to outline appropriate factors to approximate T1 from CS (Table 3). However, given the
220 large pooled standard deviation values, caution is warranted when using this approach, and
221 separate testing may be needed for both boundaries to ensure precise prescription. Indeed,
222 greater nuance is especially warranted when prescribing exercise for high level or elite athletes.

223

224 Table 3 about here.

225

226 **Conclusions**

227 In conclusion, this systematic review and quasi meta-analysis reveals that T1 occurs at
228 approximately 82.3% of CS in runners, with this occurrence influenced by fitness levels.
229 Notably, the heavy domain is more compressed in runners with high CS. Environmental
230 conditions may affect T1 relative to CS, introducing uncertainties. The study provides a
231 foundation for remote analysis and training zone prescription in runners, but caution is advised
232 due to large pooled standard deviation, and precise testing for accurate prescription,
233 particularly for high-level athletes, is recommended. Further work could explore the potential
234 to model T1 relative to CS based on factors such as sex, age, and anthropometry, and training
235 status.

236

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239

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Table 1. Participant characteristics of included studies							
	Sample Size	Sex	Description	Age	$\dot{V}O_{2\max}$ ($\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$)	CS ($\text{km}\cdot\text{h}^{-1}$)	T1 ($\text{km}\cdot\text{h}^{-1}$)
Ade et al (2014) ³⁵	71	40 M, 31 F	Healthy adults	23 (5)	48.0 (7.9)	11.9 (2.2)	8.2 (1.6)
Balasekaran et al. (2023) ⁴⁶	12	NR	Endurance-trained	32 (7)	57.6 (5.4)	15.0 (1.4)	13.4 (1.6)
Balasekaran et al. (2023) ^{46*}	9	NR	Sprint-trained	27 (9)	51.1 (3.6)	11.5 (0.8)	10.5 (0.8)
Bosquet et al (2006) ²³	17	M	Middle- and long-distance runners	23 (3)	66.5 (7.3)	16.1 (1.9)	13.6 (1.7)
Florence et al (1997) ³⁶	12	6 M, 6 F	Marathon runners	29(4)	45.0-75.0	16.0 (1.7)	14.5 (1.7)
Follador et al (2021) ³⁷	42	31 M, 11 F	Recreational runners	32 (6)	52.5 (6.6)	14.0 (2.0)	12.1 (2.0)
Fukuda et al (2011) ²⁴	14	M	Collegiate hockey and rugby players	21 (2)	51.2 (2.8)	17.3 (1.1)	10.1 (1.5)
Galbraith et al (2014) ²⁵	14	M	Highly-trained endurance runners	28 (8)	69.8 (6.3)	17.7 (1.8)	15.7 (1.2)
Hogg et al (2018) ^{38*}	12	8 M, 4 F	Recreationally active	30 (9)	54.0 (5.8)	12.5 (0.1)	10.0 (1.2)
Hogg et al (2018) ^{38*}	12	8 M, 4 F	Recreationally active	30 (9)	54.0 (0.7)	12.5 (0.1)	9.7 (1.5)
Hunter et al (2021) ²⁶	10	M	Recreationally trained runners	29 (10)	53.0 (5.0)	14.2 (1.5)	11.5 (1.6)
Kalva-Filho et al. (2024) ⁴⁷	14	NR	Futsal players	21 (2)	41.0 (8.9)	10.1 (1.1)	9.4 (0.7)
Kramer et al (2018) ²⁷	15	M	Soccer players	23 (3)	50.5 (4.0)	14.3 (1.9)	11.3 (1.2)
Kramer et al (2019) ²⁸	14	M	Field athletes	21 (2)	44.1 (4.3)	13.6 (2.0)	10.5 (1.3)
Kramer et al (2020) ⁴²	43	NR	Athletic (soccer: n = 16; rugby: n = 14; hockey: n =	23 (4)	50.0 (8.6)	13.5 (1.8)	11.1 (1.3)

			5; mixed martial arts: n = 4; track athletes: n = 4)				
Kramer et al (2020) ^{42*}	25	NR	Non-athletic (gym-based training: n = 14; recreational running: n = 8; recreational CrossFit: n = 3)	25 (3)	48.3 (7.6)	10.8 (2.0)	9.1 (2.1)
Kranenberg et al (1996) ²⁹	9	M	Highly trained runners	26 (5)	67.7 (4.1)	17.4 (1.2)	16.6 (1.4)
Kuo et al (2017) ³⁰	12	M	Sprinters	21 (2)	55.0 (1.0)	11.4 (0.5)	11.2 (0.3)
Myrkos et al. (2023) ³⁹	24	9M, 15F	Recreationally active	21 (3)	57.7 (7.6)	12.0 (1.5)	10.1 (1.2)
Nimmerichter et al (2017) ³¹	16	M	Trained endurance athletes	30 (7)	63.6 (6.9)	13.5 (1.3)	9.6 (0.9)
Nixon et al (2021) ¹⁸	10	M	Well-trained competitive (runners n=7, triathletes n=3)	23 (5)	63.0 (4.0)	16.4 (1.3)	14.5 (1.2)
Perez et al. (2024) ⁴⁰	10	7M, 3F	Middle-distance runners	19.3 (1.7)	60.3 (5.1)	18.3 (1.1)	14.6 (0.7)
Pettitt et al (2012) ⁴¹	14	F	Collegiate distance runners	19 (1)	54.8 (3.3)	15.9 (1.5)	14.0 (0.8)
Ruiz-Alias et al (2022) ⁴³	15	NR	Athletes	31 (10)	66.3 (7.2)	16.6 (1.6)	13.7 (1.3)
Schnitzler et al (2010) ³²	29	M	Moderately trained athletes	25 (7)	NR	13.1 (0.7)	12.2 (0.5)
Silva et al (2005) ⁴⁴	11	NR	Physically active adults	21 (2)	48.9 (5.8)	12.0 (1.8)	11.1 (1.7)
Smith et al (2001) ³³	8	M	Recreationally active subjects	28 (5)	54.9 (3.2)	14.4 (1.1)	11.6 (0.9)
Sperlich et al (2014) ³⁴	15	M	Well-trained runners	25 (5)	71.1 (11.6)	14.6 (1.6)	12.5 (1.3)
Thomas et al (2020) ^{45*}	9	NR	Moderately active, non-athletic	23 (4)	46.2 (6.6)	10.1 (1.9)	8.9 (3.3)

Thomas et al (2020) ^{45*}	9	NR	Moderately active, non-athletic	23 (3.79)	44.2 (5.4)	11.2 (1.7)	9.4 (2.5)
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446 NR: not reported. Duplicate study titles with asterisks represent subgroups within studies.
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	Ramp Protocol of T1 (Start speed, increments)	Determination of T1	CS Protocol	Surface
Ade et al (2014) ³⁵	IND, 1 min stages, 0.5 km·h ⁻¹ increments	GET	Four T _{lim} trials at 90-120% s $\dot{V}O_{2max}$	Treadmill
Balasekaran et al. (2023) ⁴⁶	40-60% $\dot{V}O_{2max}$, 4 min stages, 4-5% $\dot{V}O_{2max}$ increments	LT1	Minimum of two-to-three T _{lim} trials at 110-140% s $\dot{V}O_{2max}$	Treadmill
Bosquet et al (2006) ²³	10 km·h ⁻¹ , 2 min stages, 1 km·h ⁻¹ increments	GET	Four T _{lim} trials at 95, 100, 105, 110, and 120% of s $\dot{V}O_{2max}$	Treadmill
Florence et al (1997) ³⁶	7.9 km·h ⁻¹ , 1 min stages, 0.7 km·h ⁻¹ increments	VT1	Four T _{lim} trials at velocities from 13.0-21.6 km·h ⁻¹	Treadmill
Follador et al (2021) ³⁷	8 km·h ⁻¹ , 1 min stages, 1.1 km·h ⁻¹ increments	GET	Three TTs for 1200, 2400, and 3600 m	GXT treadmill TTs track
Fukuda et al (2011) ²⁴	10 km·h ⁻¹ , 2 min stages, 2 km·h ⁻¹ increments until 16 km·h ⁻¹ then, 1 min stages, 1 km·h ⁻¹ increments until 18 km·h ⁻¹ then, 1 min stages 2% gradient increments	VT1	Intermittent critical velocity test	Treadmill

Galbraith et al (2014) ²⁵	IND, 4 min stages, 1 km·h ⁻¹ increments	LT1	Three TTs for 1200, 2400, and 3600 m	GXT treadmill TTs track
Hogg et al (2018) ³⁸	IND, 4 min stages, 1 km·h ⁻¹ increments	LT1	Three TTs for 1200, 2400, and 3600 m	GXT treadmill TTs track
Hunter et al (2021) ²⁶	8 km·h ⁻¹ , 0.5 min stages, 0.5 km·h ⁻¹ increments	GET	Four T _{lim} trials at 60% Δ, 70% Δ, 80% Δ and 100% s $\dot{V}O_{2max}$	Treadmill
Kalva-Filho (2024) ⁴⁷	8 km·h ⁻¹ , 3 min stages, 0.5 km·h ⁻¹ increments	LT1	3MT (intermittent protocol)	Futsal pitch
Kramer et al (2018) ²⁷	8 km·h ⁻¹ , 1 min stages, 1 km·h ⁻¹ increments	GET	3MT	GXT treadmill 3MT track
Kramer et al (2019) ²⁸	8 km·h ⁻¹ , 1 min stages, 1 km·h ⁻¹ increments	GET	3MT	GXT treadmill 3MT track
Kramer et al (2020) ⁴²	IND, 1 min stages, 0.8 km·h ⁻¹ increments	GET	3MT	GXT treadmill 3MT track
Kranenberg et al (1996) ²⁹	IND, 2 min stages until VT1, 0.8 km·h ⁻¹ increments, then 1 min stages, 0.8 km·h ⁻¹ increments, then 1 min stages, 2% gradient increments	VT1	Three TTs for 907, 2267.5, and 4081.5 m Three TTs for 3, 7, and 13 min	Track Treadmill
Kuo et al (2017) ³⁰	10.4 km·h ⁻¹ , 1 min stages, 0.65 km·h ⁻¹ increments until 14.3 km·h ⁻¹ , then 1% gradient increments	VT1	3MT	GXT treadmill 3MT track
Myrkos et al. (2023) ³⁹	8 km·h ⁻¹ , 3 min stages, 1.5 km·h ⁻¹ increments	LT1	Three T _{lim} trials at 90, 100, and 110% peak treadmill speed	Treadmill

Nimmerichter et al (2017) ³¹	6 km·h ⁻¹ , 1 min stages, 0.5 km·h ⁻¹ increments	VT1	Three T _{lim} trials at 70% Δ, and 98% and 110% of s $\dot{V}O_{2max}$	Treadmill
Nixon et al (2021) ¹⁸	IND, 3 min stages, 1 km·h ⁻¹ increments	LT1	Four T _{lim} trials at 90%, 95%, 100% and 105% s $\dot{V}O_{2max}$	Treadmill
Perez et al. (2024) ⁴⁰	12.0 km·h ⁻¹ (M) and 11.8 km·h ⁻¹ (F), 1 min stages, 0.8 km·h ⁻¹ increments	GET	3MT	GXT treadmill 3MT track
Pettitt et al (2012) ⁴¹	10.4 km·h ⁻¹ , 1 min stages, 0.64 km·h ⁻¹ increment until 14.21 km·h ⁻¹ , then 1 min stags, 1% gradient increments	GET	3MT	GXT treadmill 3MT track
Ruiz-Alias et al (2022) ⁴³	9 km·h ⁻¹ , 3 min stages, 1 km·h ⁻¹ increments	VT1	Two TTs for 3 and 9 min	Treadmill
Schnitzler et al (2010) ³²	11 km·h ⁻¹ , 4 min stages, 0.5 km·h ⁻¹ increments	LT1	Three TTs for 3, 6, and 12 min	GXT treadmill TTs track
Silva et al (2005) ⁴⁴	IND, 3 min stages, 0.5 km·h ⁻¹ increments	LT1	Two TTs for 3000 and 500m	GXT treadmill TTs track
Smith et al (2001) ³³	IND, 4 min stages, 1.0 km·h ⁻¹ increments	LT1	Four T _{lim} trials at 100, 105, 110, 120% s $\dot{V}O_{2max}$	Treadmill
Sperlich et al (2014) ³⁴	7 km·h ⁻¹ , 1 min stages, 1.0 km·h ⁻¹ increments	VT1	3MT	GXT treadmill 3MT track
Thomas et al (2020) ⁴⁵	IND, 1 min stages, 0.8 km·h ⁻¹ increments	GET	3MT	GXT treadmill 3MT track

455 3MT: three minute all out test, CS: critical speed, GXT: graded exercise test, GET: gas exchange threshold, LT1: first lactate threshold, IND:
456 Individualised start speed, T1: first threshold, TT: time trial, T_{lim}: time to task failure, VT1: first ventilatory threshold, s $\dot{V}O_{2max}$: speed which
457 elicited $\dot{V}O_{2max}$, M: male, F: female.
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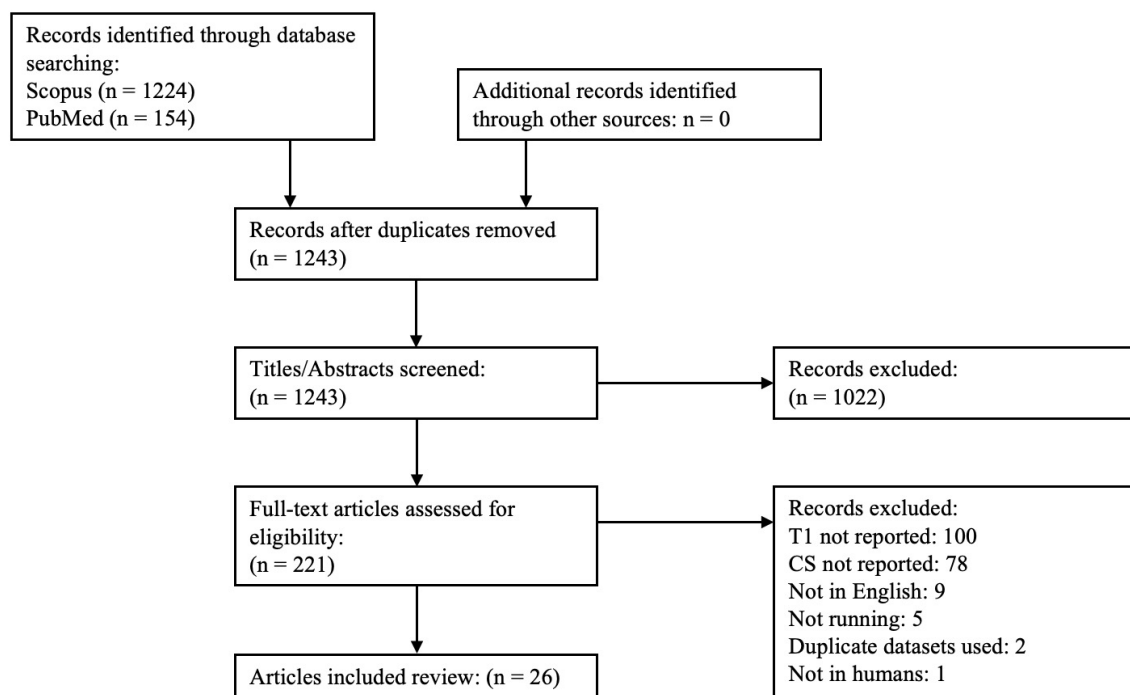
459 Table 3. Suggested multiplication factors for level of runner

	CS	Multiplication Factor to Approximate T1
Low CS	$\leq 12 \text{ km}\cdot\text{h}^{-1}$	CS * 0.806
Medium CS	12.01-14 $\text{km}\cdot\text{h}^{-1}$	CS * 0.832
High CS	$> 14 \text{ km}\cdot\text{h}^{-1}$	CS * 0.842

460 T1: first threshold, CS: critical speed.

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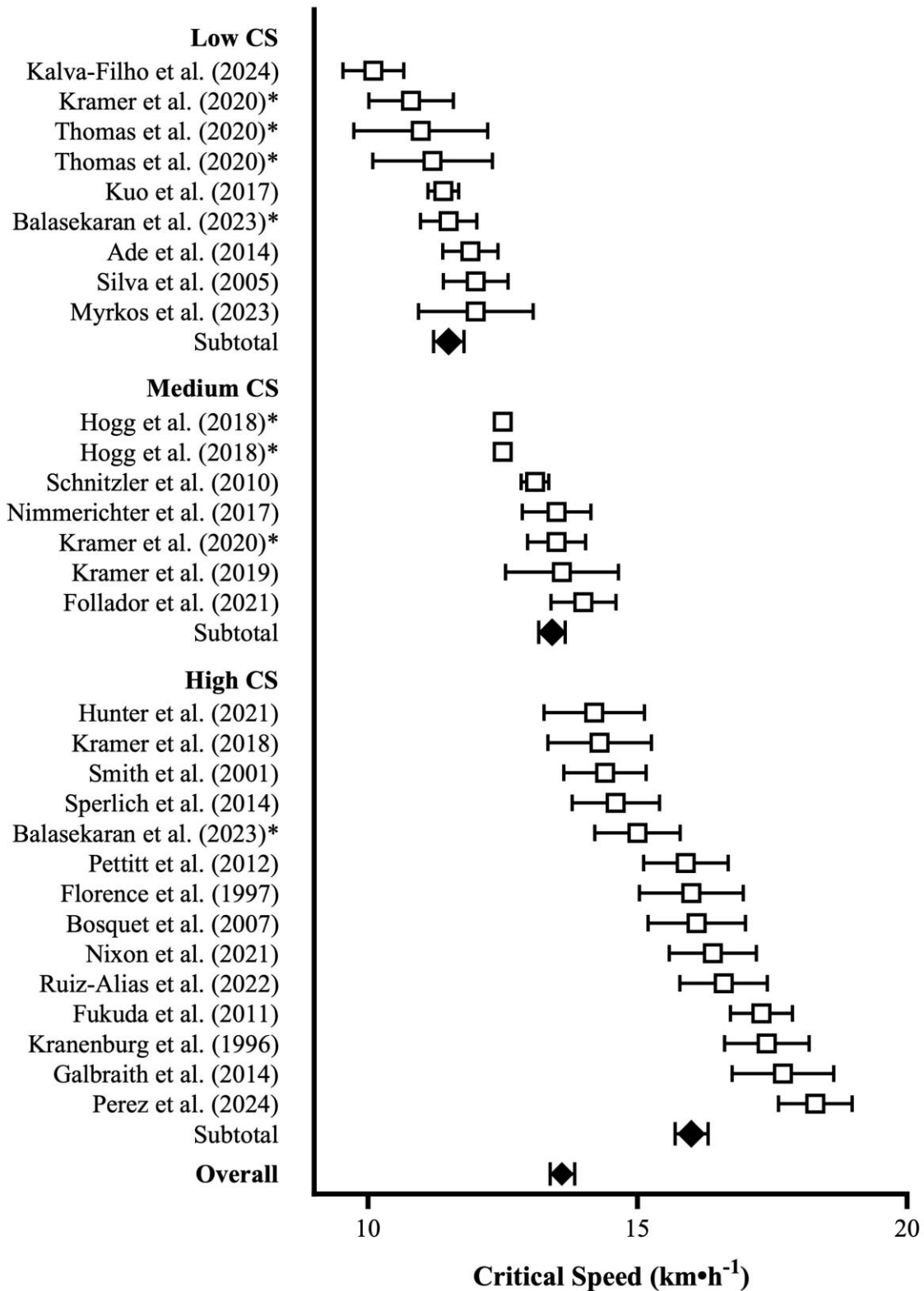
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464 Figure 1. Flow diagram of the search strategy.

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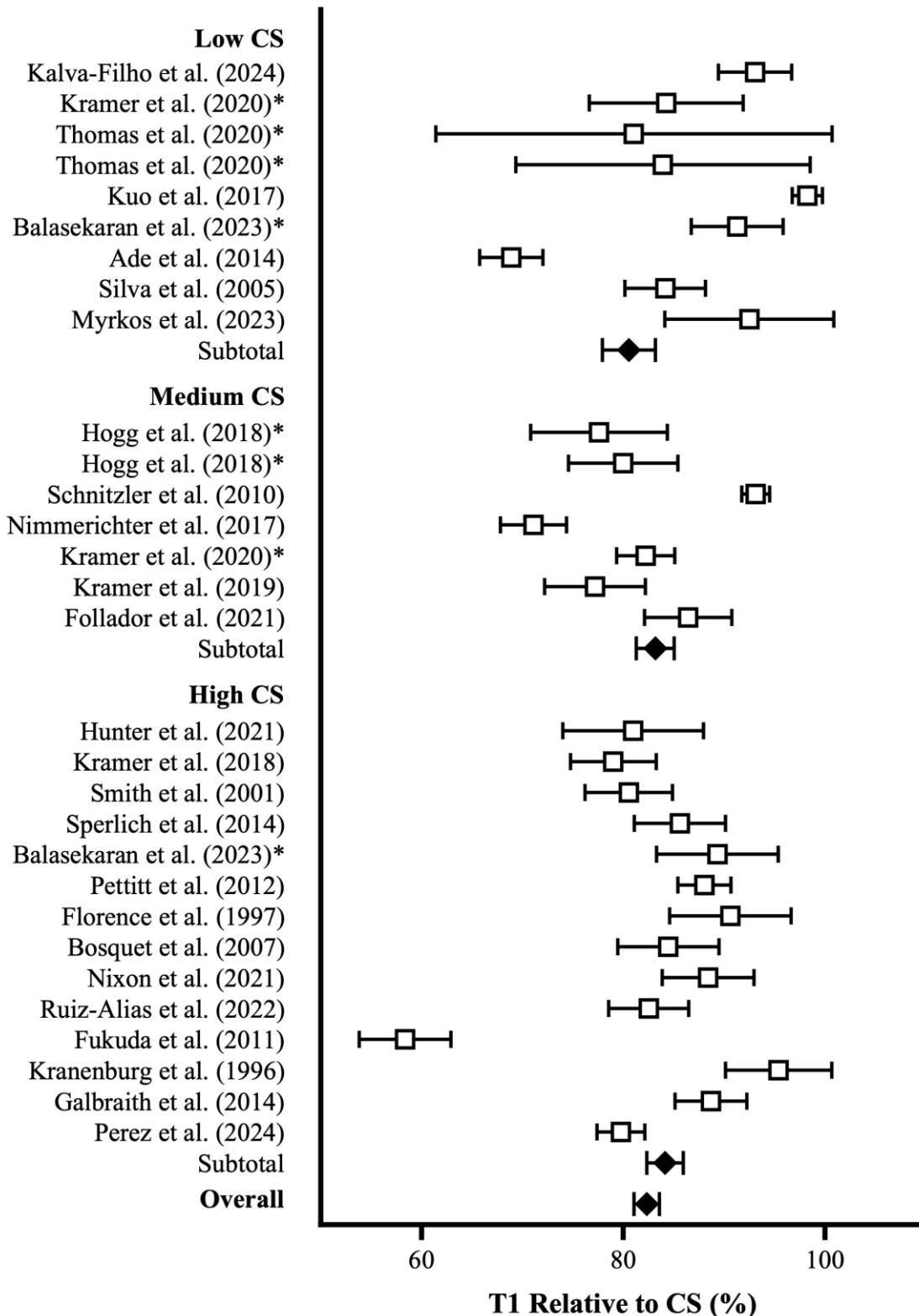
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Figure 2. Forest plot of the included studies for critical speed (CS). The white squares and error bars represent the mean and 95% CI of the study. The black diamonds and error bars represent the pooled mean CS and 95% CI for either the subgroups or overall. Duplicate study titles with asterisks represent subgroups within studies.



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 475 Figure 3. Forest plot of the included studies for the percentage at which T1 occurred relative
 476 to CS. The white squares and error bars represent the mean and 95% CI of the study. The
 477 black diamonds and error bars represent the pooled mean percentage at which T1 occurred
 478 relative to CS and 95% CI for either the subgroups or overall. Duplicate study titles with
 479 asterisks represent subgroups within studies.
 480