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Research Note

Effect of insertion process on biceps tendon reconstruction in BASHTI technique: An in-vitro study

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BASHTI technique;
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Fixation strength;
Insertion process;
Insertion frequency.

Abstract. Bone And Site Hold Tendon Inside (BASHTI) implant-less technique is proposed as an alternative to conventional tendon repair methods. This study aims to evaluate the strength of this technique under biceps loading conditions with different fixation strategies. Twelve specimens with bovine tendons and Sawbones were constructed using two different insertion methods; in Group 1, 4 samples were prepared using a hand-hammer with a hitting frequency of 300 Beats Per Minute (BPM), while Group 2 included eight specimens with insertion using an auto-hammer applying a frequency of 3600 BPM. Both of the groups were tested under cyclic loading, followed by a pull-out until the failure. All the samples completed the cyclic step without failure. At the pull-out step, for Group 1, the strength and stiffness were 251 ± 31 N and 10.3 ± 0.8 N/mm, respectively, while these values were 183 ± 35 N and 10.5 ± 3.0 N/mm, respectively, for Group 2. It was concluded that the BASHTI structure for biceps tendon reconstruction had a proper strength and the insertion process had no effect on its behavior under cyclic loading. It was also proved that variations in the insertion frequency significantly affected the maximum strength of the structure (p-value = 0.038). Still, its influence on the stiffness was insignificant (p-value = 0.91).

1. Introduction

Damage to long or short head biceps tendons, i.e., dominant tendons in the arm, can cause significant shoulder pain, loss of arm strength, and restricted arm motion. Hence, it has been of great importance to investigate the appropriate methods to repair the damaged tissue and restore the main functionalities of the biceps. According to the research conducted by Voleti et al. [1], the Long Head tendon of the Biceps (LHB) is more at risk from injury. There are several surgical treatment methods such as biceps tenotomy and biceps tenodesis for biceps tendon reconstruction. In the tenotomy, the tendon is cut and heals by itself in the humerus over time. In this case, the function of the repaired biceps tendon would be acceptable, but the arm's appearance might change. According to a report from Colliton and Scheiderer [2], in the biceps tenodesis method, the tendon's damaged part is removed and two or more simple sutures are used to anchor the remaining portion of the tendon next to the bone. Although these two methods have yielded promising results, the biceps tenodesis method has been found

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superior from a cosmetic point of view based on the studies of Aflatooni et al. [3] and MacDonald et al. [4].

The conventional methods for biceps tendon repair have some side effects. Several studies have attempted to reduce these drawbacks. For example, according to Hammarstedt et al. [5], in the bone-tunnel approach, a suture passing through a tunnel in the bone is used to hold the tendon next to the bone. The cortical endo-button method utilizes a button and a suture to fix the tendon in the right place based on Snir et al. [6]. Also, Amouyel et al. [7] and Daneshvarhashjin et al. [8] used an ordinary or conical interference screw for fixing reconstruction. An interference screw was found as the most reliable fixation method for biceps tendon reconstruction in terms of maximum strength and equivalent stiffness in the cadaveric shoulder by Buchholz et al. [9] and Sethi et al. [10] and animal shoulder models by Ramos and Coelho [11]. Also, Park et al. [12] demonstrated that this method was better than Suture Anchor (SA) in terms of residual pain after surgery for biceps tendon reconstruction on patients. On the other hand, in a research study on the application of a cadaveric model by Hong et al. [13] and in-vivo research on patients by Olsen et al. [14], SA and interference screw methods had the same ultimate failure load. Still, the SA method had significantly larger cyclic and failure displacement values and the interference screw was stiffer than SA due to the study of Tashjian and Henninger [15].

Comparison between SA and bone-tunnel methods on a cadaveric model in terms of failure force (i.e., the force at the tendon displacement of 10 mm) in the research of Pereira et al. [16] indicated that SA repairs with an average failure force of 56.7 N were weaker than bone-tunnel repairs that yielded the failure force of 73.8 N. However, the interference screw fixation was associated with some disadvantages such as high cost (according to Laupattarakasem et al. [17]), bone tunnel enlargement [18–20], tendon rotation (based on Saithna et al. [21]), bone resorption [22], tendon tearing [23], intra-articular inflammation (due to research by Barber [24]), limitation of the ability to move (as is observed in Hirschmann et al. [25]), and interruption in post-surgical Magnetic Resonance Imaging (MRI) [26].

Bone And Site Hold Tendon Inside (BASHTI) technique has been suggested as an organic implantless fixation method to minimize the disadvantages of conventional methods by Bashti et al. [27]. In this method, the bone plug (i.e., auto-graft) is utilized for tendon fixation instead of the interference screw or any other implants. Biazzo et al. [28] demonstrated that use of a bone plug to fix the tissue would cause the healing process to accelerate while the operational costs would decrease. With no external implant inside the body, chances of allergies and MRI misrepresentations would significantly decrease. Recent studies on the BASHTI technique by Borjali et al. [29] and Nourani et al. [30] on Anterior Cruciate Ligament (ACL) reconstruction have indicated that the method is feasible and the result is reasonable. According to Moeinnia et al. [31] and Mohseni et al. [32], the fixation strength of the BASHTI method was significantly affected by the geometrical parameters of the fixation such as tendon and bone plug diameters.

BASHTI is an innovative popular method for soft tissue fixation. Almost all the previous studies on this technique have been conducted for ACL reconstruction. On the other hand, the effects of different dynamical parameters on the biomechanical properties including the ultimate failure load and the equivalent stiffness of fixation are the main focus of this study. Hence, this study aims to:

- Implement the BASHTI technique for biceps tendon reconstruction;
- Investigate the effect of insertion process on the biomechanical properties of this fixation technique.

2. Material and methods

2.1. Material preparation

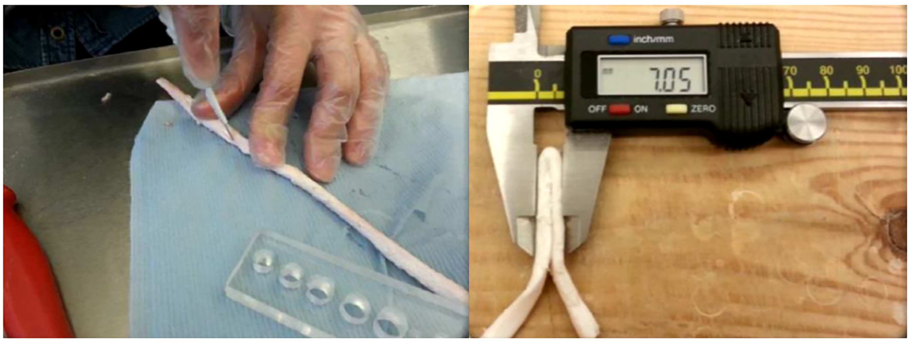
Polyurethane block from Sawbones (Pacific Research Laboratories, Malmo, Sweden) with a density of 240 kg/m^3 (15 pounds per cubic foot) was used to simulate the bicipital region groove in the proximal humerus bone. The blocks were considered to have similar biomechanical properties as the humerus cancellous bone based on Saithna et al. [21] (Figure 1(a)). Meanwhile, bovine digital tendons were used to represent the human LHB tendon. The tendons were harvested from bovine feet shortly after being slaughtered and frozen freshly at -20°C. Studies from Chizari et al. [33] and Snow et al. [34] demonstrated that the tendon maintenance up to 48 hours post-mortem would not affect its mechanical properties, provided it be frozen at -20°C or below (Figure 1(b)).

Following a report from Chizari et al. [33], the tendon was thawed at room temperature and kept moist during the test using water spray to maintain its mechanical properties. Tendons were trimmed to the size and the geometric parameters of all the samples were kept the same. The tendon was then looped in a double-strand fashion with a diameter of 7 mm (Figure 2(a) and (b)).

Meanwhile, the Sawbones block was mapped into equal square (45 mm * 45 mm) sections (Figure 3(a)) and then, in the middle of each section, a tunnel was created using a custom-made cannulated drill bit and the core bone was extracted (Figure 3(b)). The diameters of the tunnel and core bone were 10 and 8.3 mm, respectively. The core bone was then chamfered and its length was sized to 20 mm (Figure 4).

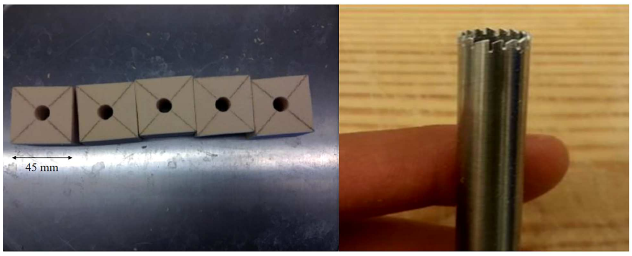
(a) (b)

Figure 1. (a) Typical polyurethane foam block. (b) Digital tendons harvested from bovine feet.



(a) (b)

Figure 2. (a) Trimming and resizing tendons to obtain the desired diameter. (b) Measuring the double-strand diameter using a digital caliper.



(a) (b)

Figure 3. (a) Sawbones artificial bone block mapped into equal square sections. (b) The tunnel drilled using a cannulated drill bit with an outer diameter of 10 mm and an inner diameter of 8.3 mm.

2.2. In-vitro model construction

Twelve BASHTI components were made for assembly. To assemble the components, the tendon in the double-strand form was passed through the tunnel and the core bone was placed between the tendon strands and pushed inside the tunnel maintaining a 5 mm gap from both the top and bottom of the tunnel (Figure 5).

Figure 4. An extracted core bone with a length of 30 mm (right one). Chamfered core bone with a sized length of 20 mm (left one).

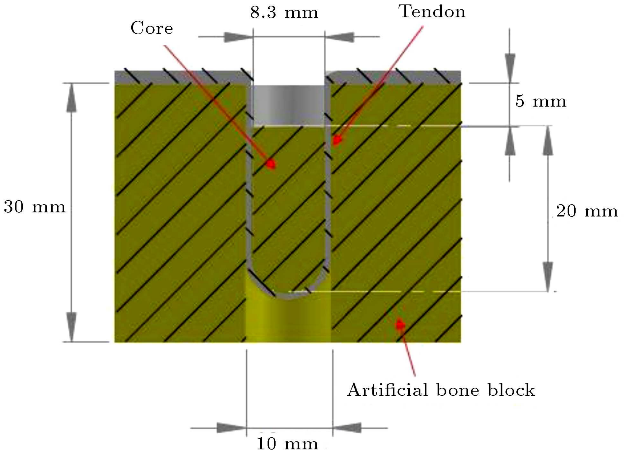


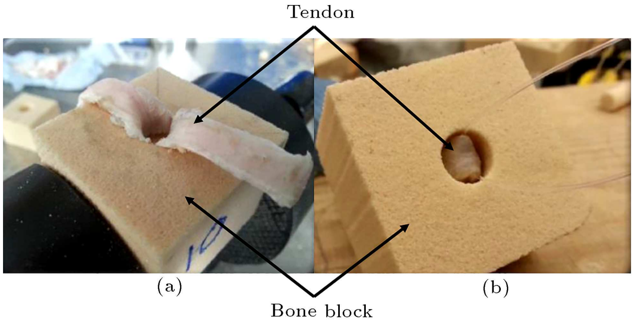
Figure 5. Illustration of the assembled BASHTI specimen prepared for the experimental study.

(a) (b)

Figure 6. Process to insert the core bone inside the tunnel: (a) Group 1: hand power hammer and (b) Group 2: electrical auto-hammer.

Since the tendon's initial diameter and the core bone together were greater than the tunnel's outer diameter, a considerable force was needed to insert the core bone inside the tunnel properly. To maintain a pretension on the tendon during the core bone insertion, the tendon was kept under tension with a load of about 20 N (Figure 6(a)).

To carry out the experiments, the specimens were divided into two groups. In Group 1, the insertion process was performed using a manual hammer with a beat rate lower than 300 BPM. Four samples were built in this group (Figure 6(a)). In Group 2, core bones were inserted into the tunnels with the aid of an automated hammer with a constant beat rate of 3600 BPM (Figure 6(b)). An attempt was made to apply the same impact load value at each beat of the hammer for both of the groups. Eight samples were made in this group. The number of specimens in each group was determined so that the standard deviation on the average failure load was within 15% of the average failure load to ensure the repeatability of results. All the samples in both groups were used to investigate the biomechanical properties of fixations (Figure 7(a) and (b)). The specimens were kept moist during the preparation of the experimental study.



(a) (b)

Figure 7. Two views of a prepared BASHTI specimen: (a) Top view and (b) bottom view.

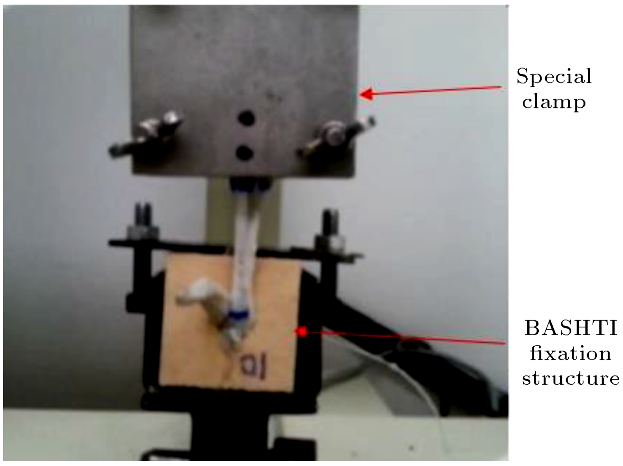


Figure 8. Specimen setup using a specially designed clamp.

2.3. Mechanical testing

According to Thigpen et al. [35], Ramos and Coelho [11], Saithna et al. [21], and Lacheta et al. [36], to simulate the post-operation conditions in the first few weeks following a biceps surgery and examine the fixation strength of the specimens, a two-step tensile loading was applied to the samples using a custom-made clamp (Figure 8). In the first step of loading, a force-controlled periodic load between 10 N and 70 N with a frequency of 0.5 Hz was applied to the structure for 100 cycles (i.e., it was assumed that the patient would slow flexion and extension of the arm up to 100 times in the first week after surgery). In the second step of loading, a displacement-controlled single-cycle load with a 500 mm/min speed until failure was applied to the specimen. Those samples that successfully passed the first loading step without failure were immediately considered for the second loading step. Permanent displacement resulting from the periodic loading in the specimen was controlled before the second step of loading. Also, the applied force and corresponding displacement in the tendons were recorded in all the samples.

2.4. Statistical analysis methods

This study used the Student's t-distribution to calculate the confidence interval of all the results. Also, all the dispersions were calculated with 95% confidence. The two groups of samples differed only in terms of the insertion process. So, there was only one parameter that could affect the results. This study used an unpaired Student's t-test because there were two groups of samples. A p-value lower than 0.05 was considered statistically significant.

3. Results

All the specimens of both groups completed the cyclic loading step without any kind of failure, and there was no significant difference between the results of the two groups in this loading step. There were two modes of failure in the specimens after reaching the maximum shear strength. These failure modes include: (a) fixation failure in which the core bone and tendon slipped out of the tunnel (Figure 9(a)) and (b) tendon rupture (Figure 9(b)).

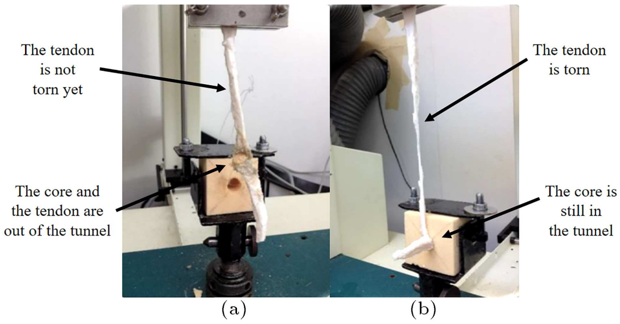


Figure 9. Two modes of failure observed and recorded for all specimens: (a) Fixation failure and (b) tendon rupture.

In Group 1, a manual hammer was utilized to insert the core bone into the tunnel with a lower than 300 BPM beat rate. The results of this group are summarized in Table 1. On the other hand, Group 2 tests utilized an automatic hammer with a constant beat rate of 3600 BPM. The results of this group are demonstrated in Table 2. The results are the maximum shear load, fixation failure load, and cyclic displacement of the tendon at the end of the periodic loading step, pull-out displacement of the tendon from the beginning of the second loading step up to the maximum load, fixation failure mode, and Average Pull-out Stiffness (APS) of the fixation.

As shown in Figure 10 (i.e., the load-displacement graph of the second loading step for sample no. 1 in

Table 1. Results of Group 1 tests. All samples completed the first loading step without any failure.

Test no.	**Max. shear load (N)**	**Fixation failure load (N)**	**Cyclic displacement (mm)**	**Pull-out displacement (mm)**	**Failure mode**	**APS (N/mm)**
1	286	210	3.7	20.4	Fixation	10.6
2	214	195	3.6	9.4	Tendon	15.3
3	238	210	3.2	15.0	Fixation	11.2
4	265	190	4.0	15.7	Fixation	12.4
	251±50	**201±16**	**3.6±0.5**	**15.1±7.2**	–	**12.4±3.3**

Table 2. Results of Group 2 tests. All samples completed the first loading step without any failure.

Test no.	**Max. shear load (N)**	**Fixation failure load (N)**	**Cyclic displacement (mm)**	**Pull-out displacement (mm)**	**Failure mode**	**APS (N/mm)**
1	225	220	2.6	7.8	Fixation	19.9
2	126	110	6.0	11.0	Tendon	5.1
3	263	260	2.8	7.5	Fixation	25.7
4	234	225	2.4	9.0	Fixation	18.2
5	130	125	5.1	7.4	Fixation	8.1
6	163	163	2.8	5.1	Fixation	18.2
7	155	155	3.4	6.9	Tendon	12.3
8	170	160	4.2	9.9	Fixation	10.1
	183±43	**177±44**	**3.7±1.1**	**8.1±1.5**	–	**14.7±5.8**

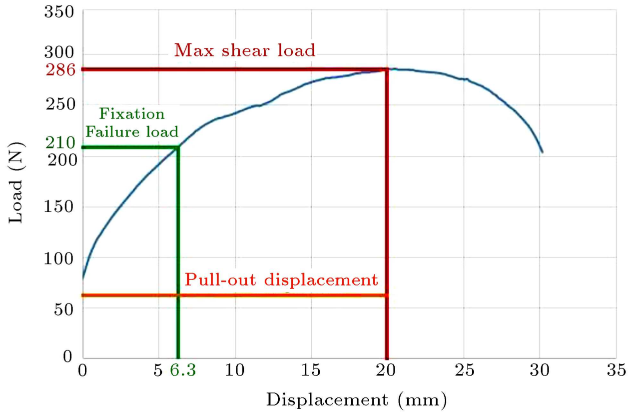


Figure 10. The load-displacement graph for Test No. 1 in Group 1. The maximum shear load, fixation failure load, and pull-out displacement of the sample are shown.

Group 1), the maximum shear strength of a sample was the maximum load tolerated during the second loading step. On the other hand, based on previous studies on biceps tendon repair by Pereira et al. [16], this fixation failed when its displacement from the beginning of the cyclic loading step reached 10 mm. The failure load of samples was the maximum load endured until the tendon displacement from the beginning of the first loading step reached 10 mm. For example, according to Table 1, the cyclic displacement of Test No. 1 of Group 1 was 3.7 mm. When the second loading step's displacement reached 6.3 mm, the applied load would be the failure load (Figure 10). Also, the APS value was the average slope of the load-displacement graph from the beginning of the second step loading up to the maximum load, defined using Eq. (1):

$$APS = \frac{\text{Maximum shear load} - 70\ (\text{N})}{\text{Pullout displacement}}, \qquad (1)$$

where 70 N was the maximum load of the periodic loading step.

As shown in Table 1, the failure mode of 75% of the specimens in Group 1 was the fixation failure (i.e., the tendon slipped out of the structure, Figure 9(a)). One specimen's failure mode (i.e., Test No. 2) was the tendon rupture that might result from tendon damage during the tendon harvest and trimming procedure. Also, 75% of the specimens in Group 2 failed due to fixation failure (Figure 11). Hence, the insertion method did not affect the repaired biceps tendon's failure mode using the BASHTI technique.

According to the results reported in Tables 1 and 2 and also, the box plots of distribution results associated with Groups 1 and 2 presented in the Appendix (Figures A.1 to A.5), the maximum shear strength of specimens in Group 1 was 37% higher than the value for Group 2. Use of an unpaired Student's t-test to analyze these results revealed that the maximum shear strength of these fixations was significantly affected by the insertion method (p-value = 0.037). On the other hand, the average fixation failure load in Group 1 was just 14% more than that for the specimens in Group 2. This difference was found insignificant based on the statistical analysis (p-value = 0.396). Also, the analyses showed that the cyclic displacement was almost independent of the insertion process (p-value = 0.976). However, displacement at the pull-out loading step was significantly influenced by the insertion process so that the samples in Group 1 samples yielded more pull-out displacement values (p-value = 0.003). Although the average APS value for Group 2 samples was 19% more than that in the specimens in Group 1, the results implied that the APS was almost independent of insertion frequency (p-value = 0.534). Figure 12 describes the methods used in this study step by step with a summary of the obtained results.

4. Discussion

All specimens in both groups completed the cyclic loading step without any failure, and there was no significant difference between the displacement of samples in the two groups (p-value = 0976). By comparing

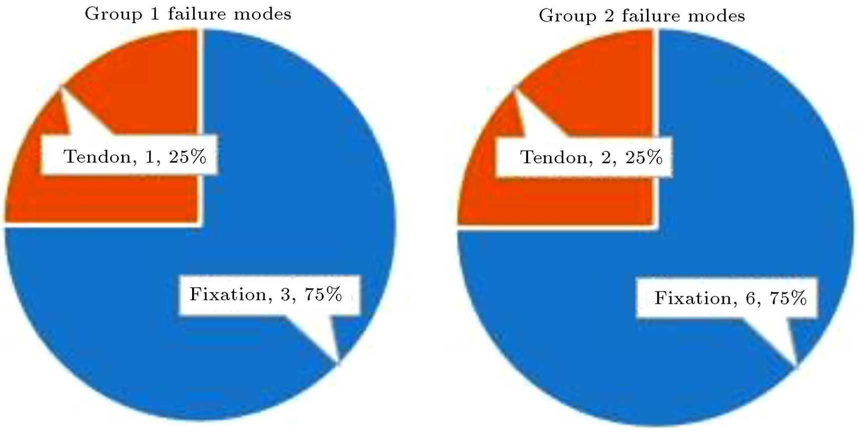


Figure 11. Failure modes in Groups 1 and 2 samples.

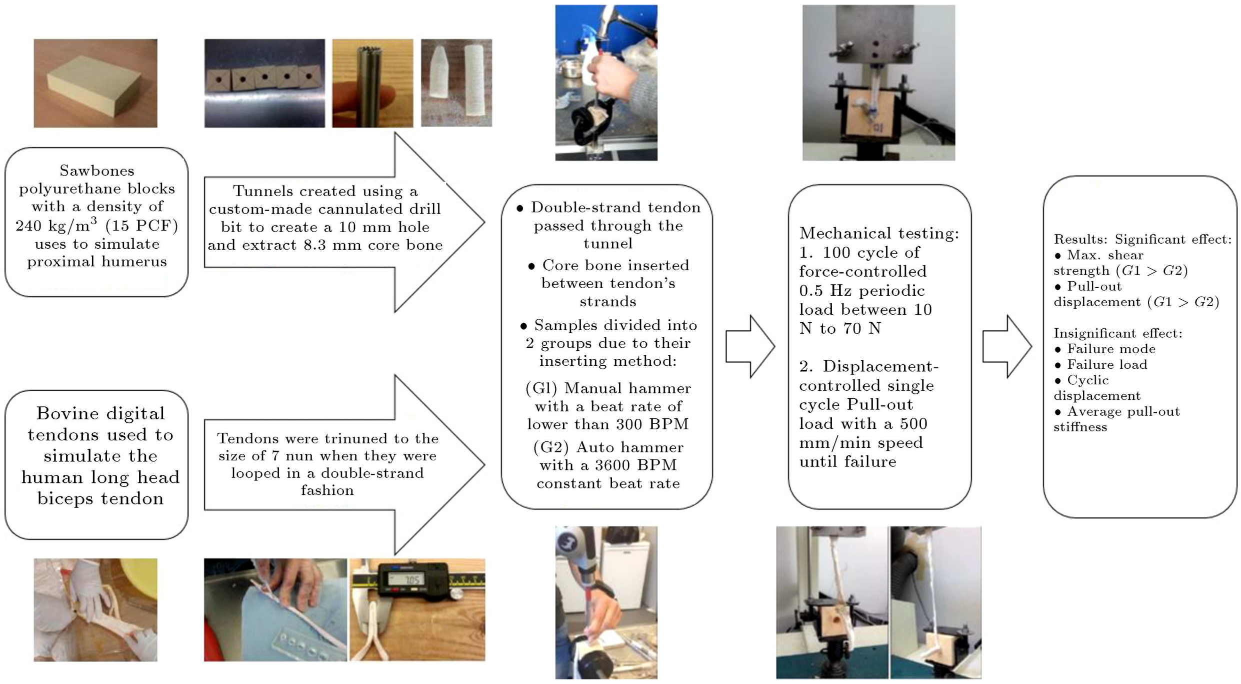


Figure 12. The flowchart of steps conducted in this study with a summary of the obtained results.

the results of the current work with those obtained from other methods in the literature such as those utilized by Hong et al. [13] and Mazzocca et al. [37], it could be observed that the repaired biceps tendon using the BASHTI technique had equal or lower cyclic displacements than samples reconstructed using bone-tunnel SA and interference screw methods. Therefore, it is suggested that the fixation structure of the BASHTI technique be acceptable for the after-surgery physiotherapy exercises. Also, it was shown that the change in the insertion process had no significant effect on the function of the fixation in this post-surgery period.

Figure 11 shows that the insertion process has no significant effects on the failure mode of repaired biceps tendons using the BASHTI technique. The single-cycle pull-out loading step results demonstrated a significant influence of the insertion process on the ultimate shear strength of the tested specimens. This loading step was applied to investigate the fixation function under unusual loading conditions after passing the post-surgical physiotherapy exercises such as lifting heavyweights. A low-frequency insertion process was observed to increase the maximum strength of repaired biceps tendons using the BASHTI technique. However, the failure load was not affected by the insertion frequency.

It should be noted that at the failure load, neither a repaired biceps tendon was torn nor did the block and tendon completely slip out of the tunnel, but the fixation did not maintain its original function. However, when the fixation reaches its maximum shear load, it means that one of the failure modes occurs and revision surgery is needed to fix the tendon again (see Figure 9). Also, according to Hong et al. [13] and Mazzocca et al. [37], it could be observed that the BASHTI fixation, which used a low-frequency insertion process, yielded a fixation structure with an equal or higher ultimate strength with respect to bone-tunnel, SA, and interference screw reconstruction methods. It is hypothesized that a higher frequency of insertion can cause micro-fractures on the core bone and reduce the ultimate strength of the fixation.

It was observed from the results that while a low-frequency insertion method yielded a higher maximum strength in the fixation, it significantly increased the pull-out displacement, too. The simultaneity of these two phenomena caused the average APS values of the two groups to remain almost unchanged. It was believed that the friction force between the tendon and the tunnel created by inserting the core bone inside was so high that the movement of the core bone inside the tunnel was very low. Therefore, the pull-out displacement up to the maximum load of the samples entirely resulted from tendon elongation. Based on Figure 10, the load-displacement curve has an increasing trend before the maximum shear load point and some fluctuations in the range of $8-15$ mm. The main trend resulted from the tendon elongation and tendon tissue properties and the fluctuations occurred because of local small movements of the core bone inside the tunnel. Based on a comparison of the APS values of this technique and other techniques including the method used by Hong et al. [13], it is shown that the BASHTI technique had lower stiffness and higher pull-out displacement than SA and interference screw techniques.

There were some limitations to this study. For example, bovine digital tendons were used instead of the human tendon because the latter was out of access for this study. Also, Sawbones' artificial bone blocks were used instead of human bone. In future studies, it is recommended that the technique be tested using a human cadaver model. Moreover, further study should be conducted to determine a correlation between the insertion beat rate and the fixation's biomechanical properties when the BASHTI technique is used. It is recommended that future studies evaluate the insertion process using an automated hammer with an adjustable beat rate and controlled frequencies.

5. Conclusions

In this study, the laboratory model samples of biceps tendon fixation using the Bone And Site Hold Tendon Inside (BASHTI) method were prepared using Sawbones artificial bone blocks with a density of 240 kg/m^3 (15 pounds per cubic foot) and bovine digital tendons. The experimental evaluation was conducted in two groups. Group 1 used a manual hammer with an uncontrolled beat rate of lower than 300 BPM to insert the core bone into the drilled bone tunnel. Group 2 utilized an automated hammer with a constant and controlled beat rate of 3600 BPM to construct the fixation. A two-step loading condition was applied to the specimens to simulate the post-surgical conditions. The first stage of loading was a force-controlled cyclic loading including 100 cycles between 10 N and 70 N with a frequency of 0.5 Hz, followed by a displacement-controlled single-cycle pull-out with a constant rate of 500 mm/min as the second step up to the failure of the tendon and/or fixation. Almost all the specimens completed the first step without failure. The second loading stage revealed that the BASHTI technique provided an acceptable level of strength to repair a biceps tendon with maximum strengths of 251±50 N and 183±43 N (95% confidence interval) for Groups 1 and 2, respectively. Considering the results obtained from both of the loading stages, the insertion method was proved to significantly affect the maximum shear strength and pull-out displacement of BASHTI structure (p-values = 0.037 and 0.003, respectively). However, its effects on the failure mode, failure load, cyclic displacement, and Average Pull-out Stiffness (APS) value of fixations were statistically insignificant (p-values = 0.396, 0.976, and 0.534, respectively). Therefore, the study suggests that the insertion process with a low beat rate will be more suitable for obtaining an acceptable fixation strength and preventing the fixation from needing revision surgery.

Abbreviations

LHB	The Long Head tendon of the Biceps
SA	Suture Anchor
BASHTI	Bone And Site Hold Tendon Inside
BPM	Beats Per Minute
APS	Average Pull-out Stiffness

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Appendix

The distribution of results in Groups 1 and 2 are shown in Figures A.1 to A.5.

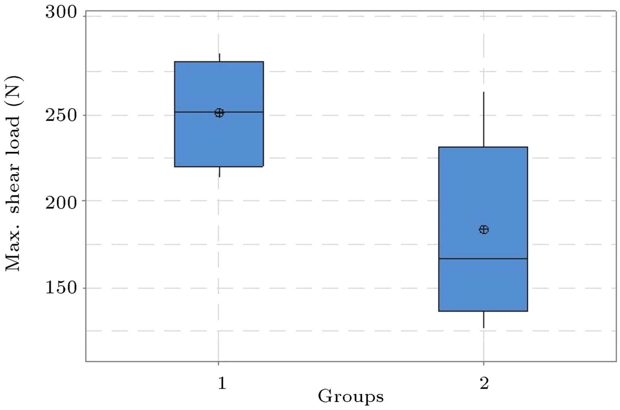

Figure A.1. Comparison of the maximum shear loads found for Groups 1 and 2.

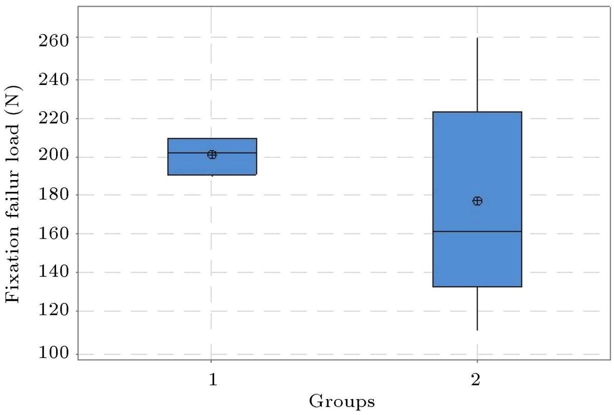

Figure A.2. Comparison of the fixation failure loads found for Groups 1 and 2.

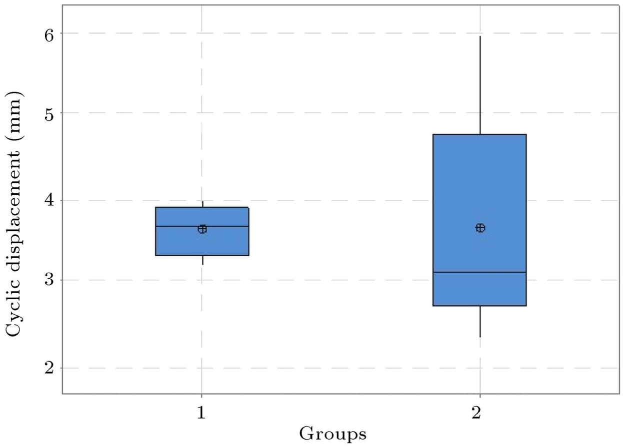

Figure A.3. Comparison of the cyclic displacements found for Groups 1 and 2.

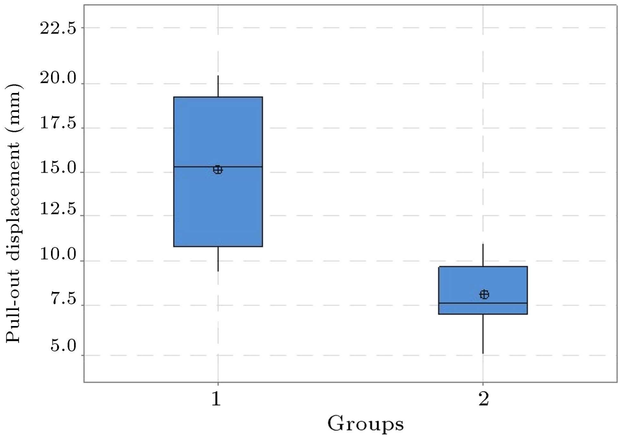

Figure A.4. Comparison of the pull-out displacements found for Groups 1 and 2.

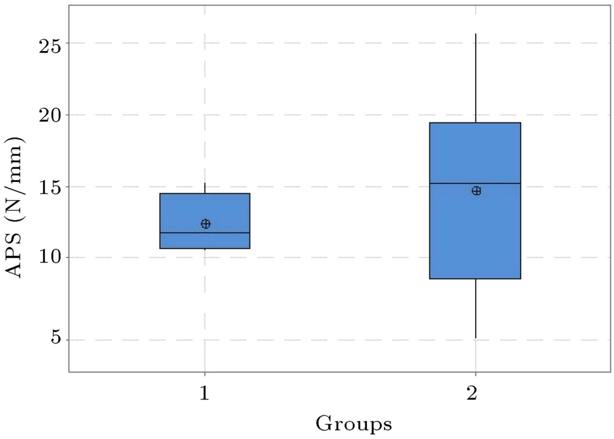

Figure A.5. Comparison of the APS values found for Groups 1 and 2.

Biographies

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