EFFECT OF REPAIR ORIENTATION ON THE DISTAL BICEPS TENDON

by

Tyler J. Madonna

B.S. in Mechanical Engineering, University of Pittsburgh, 2012

Submitted to the Graduate Faculty of

Swanson School of Engineering in partial fulfillment

of the requirements for the degree of

Master of Science in Mechanical Engineering

University of Pittsburgh

2017

UNIVERSITY OF PITTSBURGH

SWANSON SCHOOL OF ENGINEERING

This thesis was presented

by

Tyler J. Madonna

It was defended on

March 1, 2017

and approved by

Mark Carl Miller Ph.D., Associate Research Professor, Department of Mechanical Engineering and Materials Science

Christopher Schmidt MD, Assistant Research Professor, Department of Orthopaedic Surgery

Qing-Ming Wang Ph.D., Professor, Department of Mechanical Engineering and Materials Science

Thesis Advisor: Patrick Smolinski, Ph.D., Associate Professor, Department of Mechanical Engineering and Materials Science

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Tyler J. Madonna, M.S.

University of Pittsburgh, 2017

The goal of the project was to quantify the effect of tendon orientation on the distal biceps tendon's ability to generate supination torque, as measured by the moment arm. The anatomic orientation was defined as the external rotation of the tendon before inserting onto the radial tuberosity. The hypothesis was that an anatomic orientation repair would recreate a native tendon moment arm, while a non-anatomic orientation repair would impact the moment arm.

Isometric supination torque was measured for the native distal biceps tendon, anatomically oriented repaired tendon, and non-anatomically oriented repair tendon in 8 cadaveric specimens. A computer controlled testing apparatus, which exerted known loads on the biceps tendon, was developed to measure isometric supination torque generated in the wrist of cadaveric elbows.

During testing the biceps tendon was loaded and the generated supination torque was measured at three rotational positions: 60° pronation, neutral, and 60° supination.

Forearm rotational positional significantly affected the moment arm but tendon orientation did not significantly affect the moment arm. The native tendon orientation had a mean moment arm of 8.22 ± 1.71, 9.56 ± 1.77, and 5.49 ± 1.41 mm in 60° pronation, neutral, and 60° supination, respectively. The anatomic repair tendon orientation had a mean moment arm of 8.41 ± 2.02, 9.61 ± 2.02, and 5.42 ± 1.35 mm in 60° pronation, neutral, and 60° supination,

respectively. The non-anatomic repair tendon orientation had a mean moment arm of 8.30 ± 1.83, 9.45 ± 1.85, and 5.31 ± 1.38 mm in 60° pronation, neutral, and 60° supination, respectively.

Biomechanically, these findings suggest that tendon orientation had no effect on the moment arm. However, the effects of orientation on healing are not understood and it is not suggested that surgeons ignore the tendon orientation during repair. The results of this project could allow surgeons to better understand how distal biceps tendon orientation in surgical repairs affects function, which would lead to improved surgical techniques.

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PREFACE

First, I would like to thank my advisors for their guidance and support: Dr. Chris Schmidt, Dr. Patrick Smolinski, and Dr. Mark Miller. I could not have asked for better mentors as my time as a graduate student. I would also like to thank the graduate students and orthopedic fellows for their help conducting the experiments: Sean Delserro, Michael Smolinski, Brandon Brown, Dr. Stephen Lui, and Dr. Joe Styron. Finally, I would like to thank all my friends and family for their support and encouragement.

1.0 INTRODUCTION

1.1 MOTIVATION

This study involves the surgical repair of ruptures of the distal biceps tendon. Rupture of the distal biceps tendon from the radial tuberosity is a relatively rare injury that mostly occurs in the dominant arm of middle-aged males [1, 2]. The injury occurs in 1.2 of 100,000 patients with the most common mechanism of injury involving a sudden eccentric loading to the flexed forearm [3, 4].

Common surgical procedures include the one and two incision repair techniques. The one and two incision repair technique reattach the tendon to the anterior or posterior surface of the tuberosity, respectively [5]. Although studies have examined the effect of attachment position of the tendon on functional outcome, no studies have examined the orientation of the tendon.

1.2 GOALS

The goal of this project was to quantify the effect of the distal biceps tendon orientation on forearm supination and flexion strength. The results of this project could allow surgeons to better understand how distal biceps tendon orientation in surgical repairs affects function which would lead to improved surgical techniques.

2.0 BACKGROUND

2.1 ANATOMIC DEFINITIONS

The human body can be oriented in many different positions. Thus, a standard set of terms exists to alleviate confusion when describing anatomical features. Anatomical positions and directions are defined in reference to a standard anatomical position, shown in Figure 1. The standard anatomical position for humans consists of an individual standing with arms hanging at the side. The head and hands (palms) are facing forward.

The anatomic directions are defined in reference to the standard anatomical position. The terms anterior and posterior are used to describe the front and the back of the body, respectively. Superior and inferior are used to describe an objects relation to the head. Superior is closer to the head and inferior is closer to the feet. Medial and lateral are used to describe an object's relation to the vertical midline of the body. Medial is closer to the midline and lateral is farther from the midline. For example, the left ear is lateral to the left eye and the nose is medial to the left eye. Distal and proximal are usually used to describe location on the extremities. Proximal is closer to the trunk and distal is farther from the trunk. The shoulder is proximal to the elbow and the wrist is distal to the elbow. Rotation toward the midline and away from the midline are known as internal and external rotation, respectively.

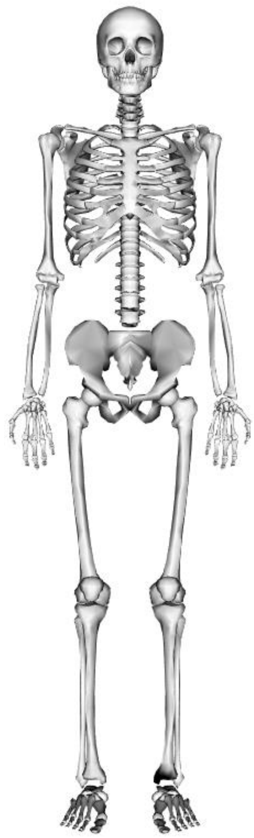

Figure 1. Human skeleton in the standard anatomical position [6]

2.2 ELBOW ANATOMY

The anatomical focus of this research is the arm, specifically the elbow. The arm is comprised of three bones: radius, ulna, and humerus. The radius is the bone situated on the lateral side of the forearm. The ulna is the bone located medially to the radius. The humerus is the bone of the upper arm whose proximal end serves as the ball joint of the shoulder. The three bones of the arm have four articulations: humeroradial, humeroulnar, proximal radioulnar, distal radioulnar. The arm bones and relevant articulations are shown in Figure 2.

The humeroradial and humeroulnar articulations allow the angle between the humerus and the forearm to increase and decrease. The motions that decrease and increase this angle are known as flexion and extension, respectively.

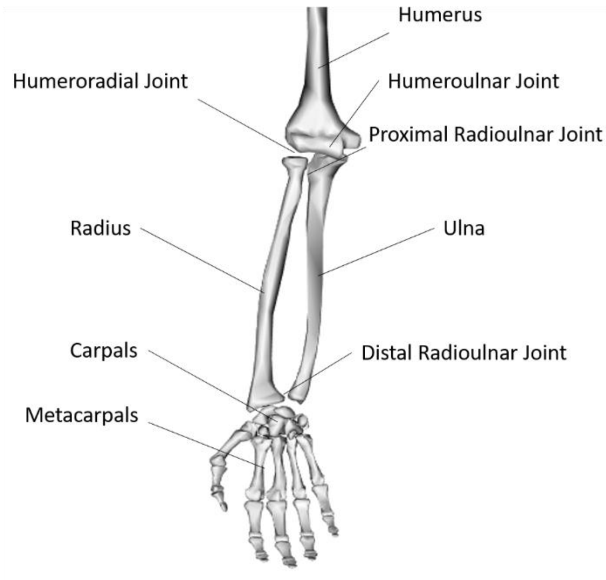

Figure 2. Bones and joints of the arm [6]

The proximal and distal radioulnar articulations allow rotation of the radius around the ulna. The motions that turn the palm anteriorly and posteriorly are known as supination and pronation, respectively. These motions are shown in Figure 3.

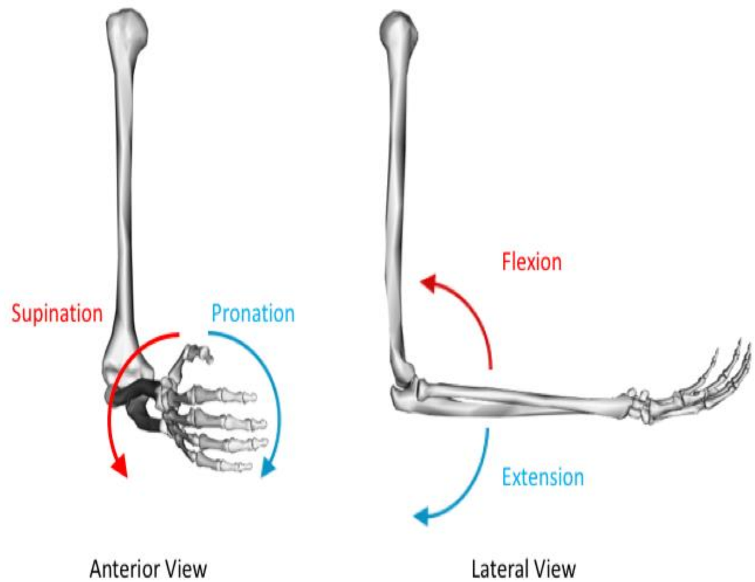

Figure 3. Motions of the forearm [6]

Many muscles are involved in the motion of the elbow and forearm, shown in Figure 4. These muscles are necessary for the motions of flexion, extension, supination, and pronation. The main muscles involved in flexion are the biceps brachii, brachialis, brachioradialis, and the pronator teres, while the triceps brachii is the main muscle involved in extension. The biceps brachii and the supinator muscle supinate the forearm, while the pronator teres and the pronator quadratus pronate the forearm.

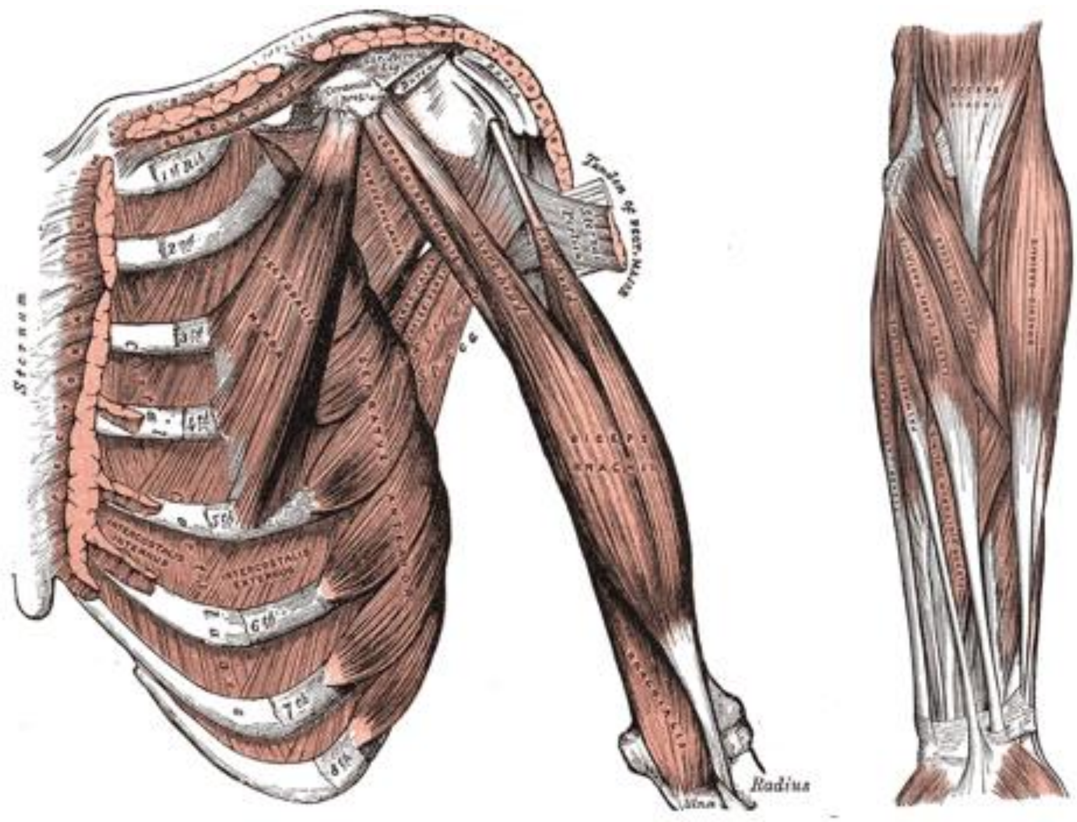

Figure 4. Muscles of the upper arm and forearm [7]

2.3 BICEPS BRACHII ANATOMY

The biceps brachii functions to flex the elbow and to supinate the forearm. The biceps is composed of two separate sections that originate proximally from two separate points. The long head of the biceps is lateral to the short head. The long head of the biceps originates from the supraglenoid tubercle while the short head originates from the coracoid process of the scapula. Both the long head and short run parallel to the anterior aspect of the humerus. Distally, the two heads form the distal biceps tendon that inserts onto the posterior aspect of the radial tuberosity. Before insertion, the tendon externally rotates so that the long head portion inserts proximal to the short head portion [8]. This tendon rotation before the insertion is defined in this thesis as the tendon orientation. The tendon orientation is shown in Figure 5.

As the forearm pronates, the distal biceps tendon wraps around the radial tuberosity creating a cam effect. The radial tuberosity cam allows the biceps to create a torque about the radius. Thus, the cam effect gives the biceps the ability to supinate the arm.

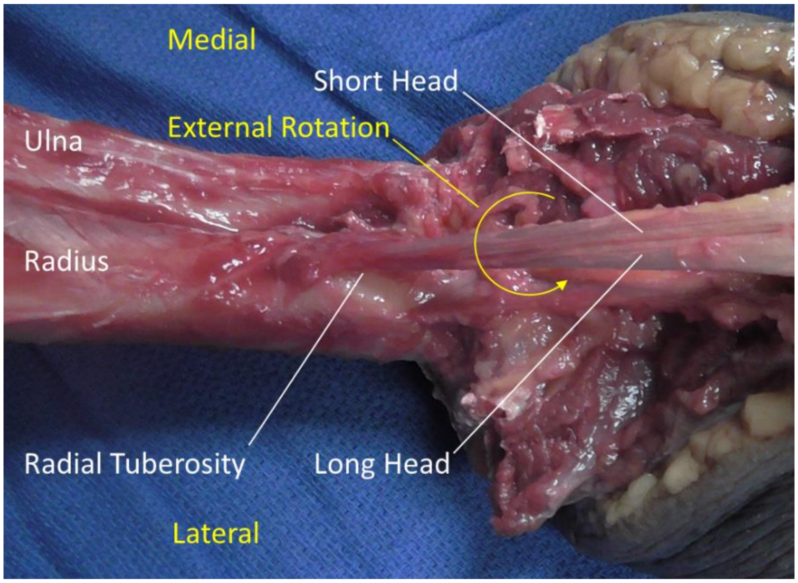

Figure 5. The distal biceps tendon orientation

2.4 DISTAL BICEPS INJURIES

Rupture of the distal biceps tendon from the radial tuberosity is a relatively rare injury, occurring in 1.2 of 100,000 patients and representing about 3% of injuries to the biceps [3, 4, 9]. The injury mostly occurs in the dominant arm of middle-aged males between 40 and 50 years of age [1, 2]. The injury often involves a sudden eccentric loading to the flexed, supinated forearm such as during lifting activities [3, 4, 10].

Complete ruptures are usually associated with a deformity to the anterior upper arm known as a reverse Popeye sign. This deformity is caused by proximal retraction of the biceps muscle [11]. Patients often report pain, swelling, and cramping around the elbow, as well as weakness in supination [12-14].

Patients who smoke have been shown to have a 7.5 times greater risk of a distal biceps tendon rupture [3]. Use of anabolic steroids and statins has also been shown to increase risk of distal biceps rupture [15]. Arterial supply and mechanical impingement could also contribute to the occurrence of tendon rupture [2].

2.5 TORQUE

Torque is the mathematical expression of the tendency of a force to cause a rotation of a body. Mathematically, the torque vector, $\vec{\tau}$, is a vector about a point defined as the cross product of the position vector, $\vec{r}$, and the force vector, $\vec{F}$, as given in Equation 1.

$$\vec{\tau} = \vec{r} \times \vec{F} \qquad (1)$$

The position vector is a vector from the point about which the moment is being computed to a point on the force line of action. By the definition of the cross product, the magnitude of the torque vector, $|\vec{\tau}|$, can be written as:

$$|\vec{\tau}| = |\vec{r}||\vec{F}| \sin\theta \qquad (2)$$

where,

$|\vec{\tau}|$ - magnitude of the torque vector

$|\vec{r}|$ - magnitude of the position vector

$|\vec{F}|$ - magnitude of the force vector

θ - angle between the position vector and the force vector

By rearranging Equation 2, the moment arm can be defined mathematically. The moment arm, d, is shown in Equation 3. The moment arm is the perpendicular distance between the moment axis and the force vector's line of action.

$$d = \frac{|\vec{\tau}|}{|\vec{F}|} = |\vec{r}| \sin\theta \qquad (3)$$

For application to the distal biceps and forearm, the position vector, $\vec{r}$, is a vector from the axis of rotation of the forearm to the radial tuberosity and the force vector, $\vec{F}$, is the biceps vector. A cross-section of the radius outlining these components is shown in Figure 6.

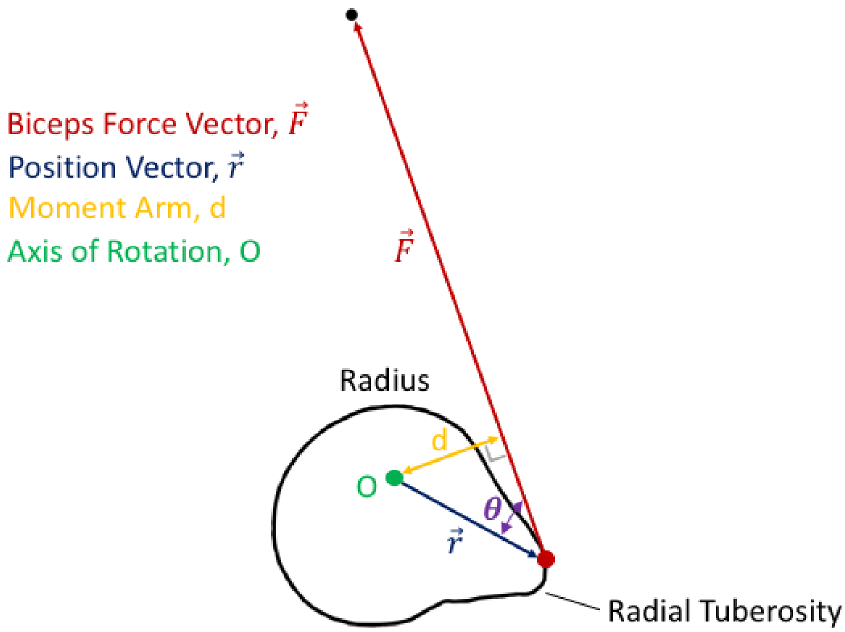

Figure 6. Cross-section of the radius showing the application of torque in supination

2.6 PREVIOUS BICEPS MOMENT ARM WORK

The moment arm is the perpendicular distance between the forearm axis of rotation and the biceps' line of action. Several groups have indirectly measured the moment arm and used it to study biceps mechanics.

In 1995, Murray et al. showed in a cadaveric study that the moment arms of the various elbow muscles varied as a function of elbow flexion and forearm rotation angle. The moment arms were determined by fitting a third order polynomial best fit curve to the tendon displacement and joint angle data. The study resulted in a maximum biceps moment arm in male specimens of 1.36 cm and occurring at 85º elbow flexion and approximately 0º forearm supination [16].

In 2001, Haugstvedt et al. used a simulator to load the supinator and pronator muscles of the forearm in eight cadaveric specimens. The simulator utilized a torsional load cell to measure the axial torque across the wrist, a rotary potentiometer to measure the metacarpal position region relative to the ulna, and pneumatic actuators to load the muscles. The elbow was placed in 90º flexion and each muscle was ramp loaded while the wrist torque was recorded. Each muscle was tested in 10º increments over the entire forearm rotation range of motion. The moment arm was determined by calculating the slope of the linear wrist torque vs. muscle load relationship. Haugstvedt et al found that the biceps can generate a supination torque approximately four times greater than the supinator muscle. The maximum biceps moment arm was measured to be about 1.2 cm at approximately 20º supination [17].

In 2010, Schmidt et al. used an elbow simulator to test the effect of distal biceps reattachment location on supination torque in six cadaveric specimens. The simulator utilized a torsional load cell to measure supination torque, actuators to load the biceps muscle, and a moveable carriage to properly align the forearm rotation axis to the torque sensor axis. The elbow was placed in 90º flexion and the biceps was loaded to 67 N while the forearm torque was recorded. Each reattachment site was tested isometrically at 60º pronation, neutral, and 60º supination. The moment arm was determined by calculating the slope of the best-fit linear regression line fitted to the forearm torque vs. biceps load data. The group found that reattaching the tendon to the center axis of the anterior aspect of the tuberosity produced lower moment arms in 60º supination (-97%) and neutral (-27%) compared to the native insertion [18].

3.0 METHODS

3.1 OVERVIEW

The goal of this experiment was to indirectly determine the moment arm of the distal biceps tendon by applying a known load to the biceps and measuring the generated torque at the wrist.

Isometric supination torque was measured using eight cadaveric specimens. The specimens were mounted in an elbow simulator, which consisted of a computer controlled linear actuator to apply known biceps force. The forearm was rotated and fixed at three positions: 60° pronation, neutral and 60° supination. The biceps tendon was loaded and the generated torque at the wrist was measured for the native tendon attachment. The tendon insertion site was then transected, reattached, and tested in anatomic and non-anatomic repair orientations. The torque vs. load data was plotted to determine the bicep moment arm for each tendon attachment. A two-way repeated measure analysis of variance (ANOVA) was used for statistical analysis.

3.2 TESTING APPARATUS

An apparatus capable of measuring isometric forearm torque was developed for this project. The final assembly is shown in Figure 7 and Figure 8. The apparatus consisted of an L-shaped 80/20® extruded aluminum frame mounted to a material testing system (MTI-1K, Measurements

Technology Inc.). The frame included an adjustable clamp to grasp the humerus of the specimen. The material testing system included a force load cell (MLP-75, Transducer Techniques LLC) connected to a vertically moving, computer controlled actuator. The 80/20® frame included two adjustable pulleys to route a 100 lb test line from the load cell to the biceps tendon, while reproducing the anatomical biceps vector.

The end of the frame supported an adjustable carriage that could translate, rotate, and lock into place. A torque load cell (TRT-50, Transducer Techniques LLC) was attached to the carriage to measure forearm torque. A torque transfer shaft was attached to the torque load cell using a coupling. The transfer shaft freely rotated within the coupling but could be locked into a rotational position using a set screw. The transfer shaft angle was measured using an attached rotary potentiometer (GL100-10K0-M340, Novotechnik). An adjustable arm with a universal joint was used to connect the transfer shaft to a distal radius mounting plate. The final assembly allowed the forearm to rotate and lock into different rotational positions. The design offered enough flexibility and adjustment to handle anatomic variability in the cadaveric specimens.

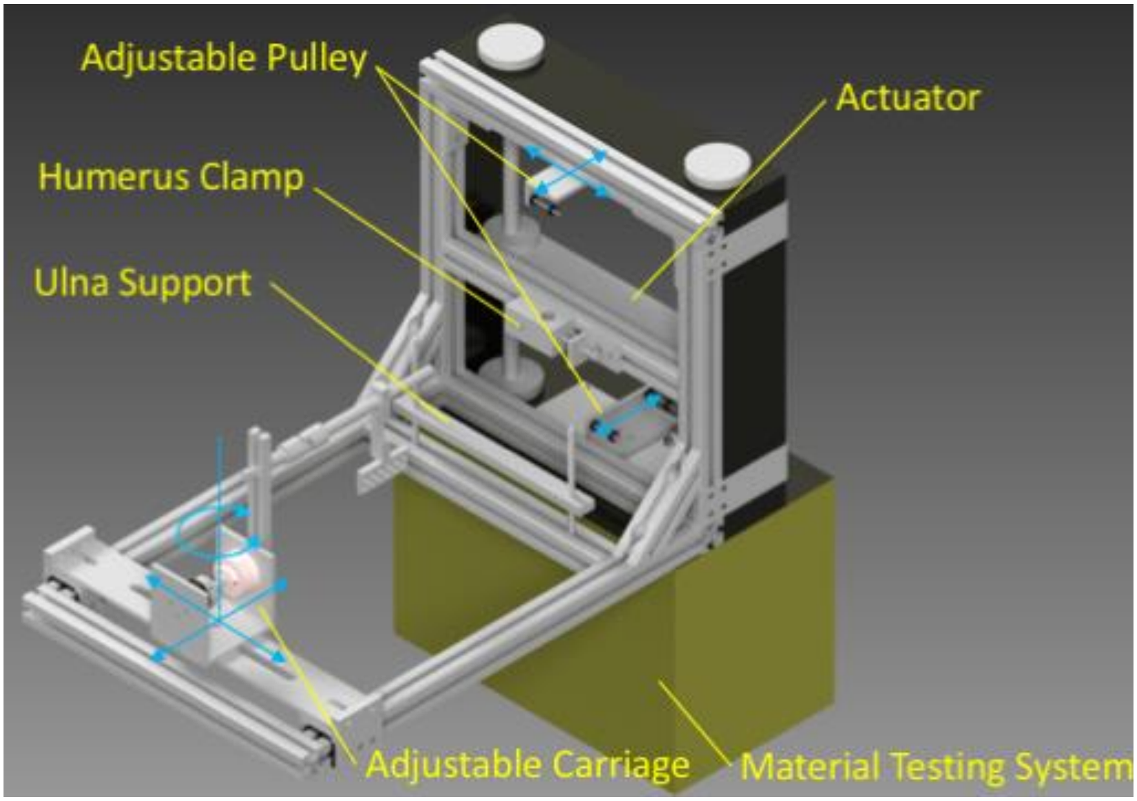

Figure 7. 3D model of the testing apparatus

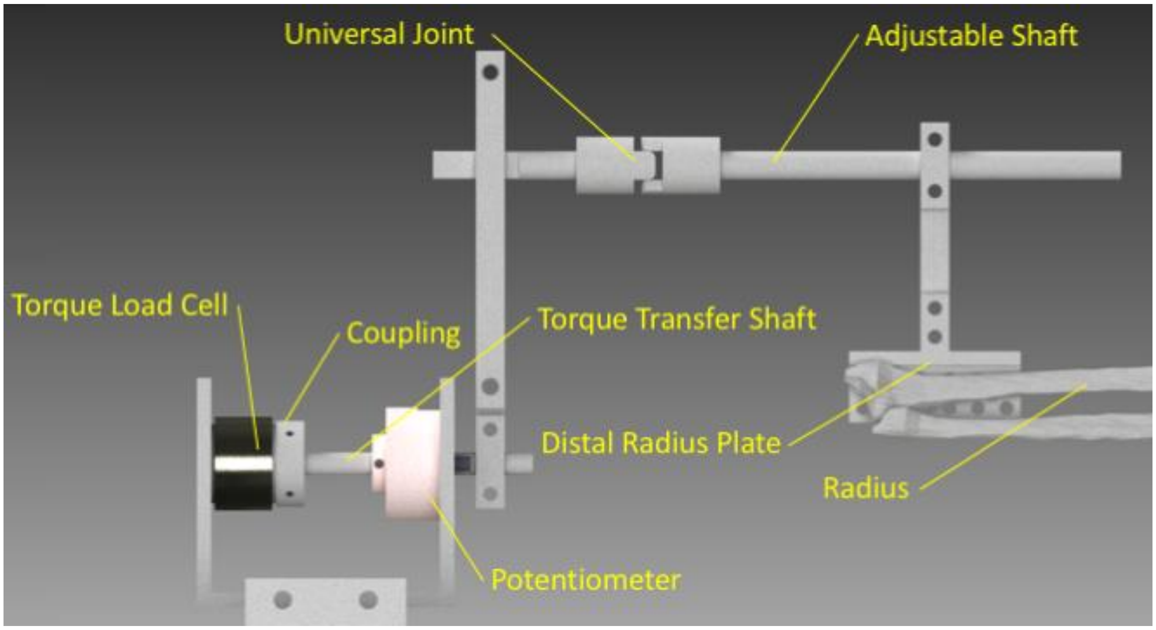

Figure 8. 3D model of the adjustable carriage

3.3 DATA ACQUISITION

Determination of the moment arm required simultaneous capture of the biceps load and the forearm torque. The outputs of the force and torque load cells were each connected to a signal conditioner (DPM-3, Transducer Techniques LLC). The outputs of the rotary potentiometer were connected into a 5-volt voltage divider circuit to create an analog signal ranging from 0 – 5 V.

The outputs of the signal conditioners and voltage divider were connected to an analog-to-digital (A/D) converter (USB-6008, National Instruments). The A/D converter was connected to a computer running Matlab. A program was written in Matlab to acquire the data and to provide real-time plotting of the supination torque and biceps load during testing. A schematic of the data acquisition is shown in Figure 9. The Matlab script to acquire the data can be found in Appendix 1.

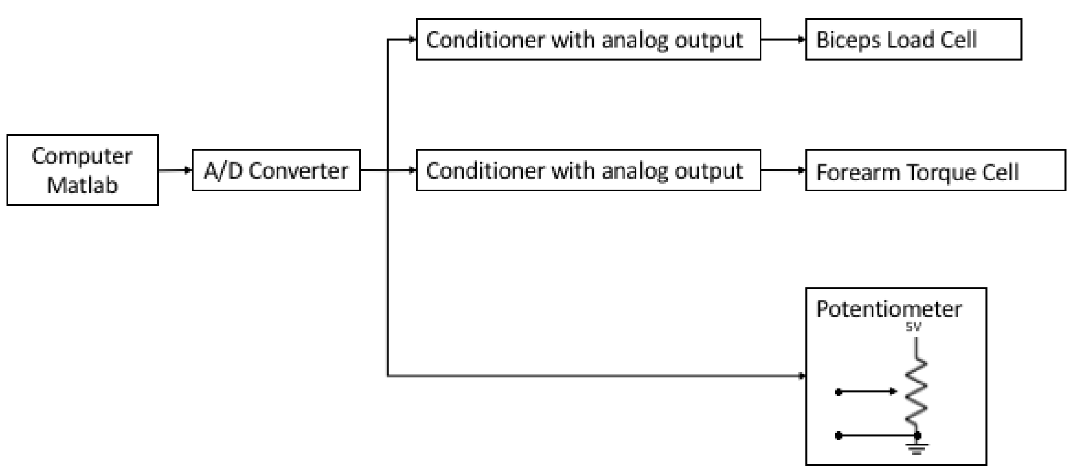

Figure 9. Schematic of the data acquisition setup

3.4 CADAVERIC SPECIMENS

A total of eight male upper-extremity cadaveric specimens average age of 61 years (range: 48 – 75), were used. Each specimen included the full arm from the hand to the scapula. Specimens with a medical history of rheumatoid arthritis or degenerative joint disease were excluded. Prior to the day of testing, each specimen was allowed to thaw 12 hours at room temperature and kept moist with normal saline.

3.5 CADAVERIC SPECIMEN PREPARATION

The distal biceps tendon of each specimen was isolated and the arm was disarticulated at the wrist. The soft tissue of the forearm was removed leaving interosseous membrane and the elbow joint capsule intact. A Krackow locking loop stitch was placed into the distal biceps musculotendinous junction using 2-0 Fiberwire suture (Arthrex, Inc., Naples, FL). With the elbow in 90° flexion, the free end of the suture was pulled tight and placed on the midpoint, known as Point A, between the coracoid process and the bicipital groove. The measurements between the radial tuberosity and Point A, shown in Figure 10, were recorded to reproduce the anatomical biceps vector. The arm was transected midhumerus before beginning the experiment.

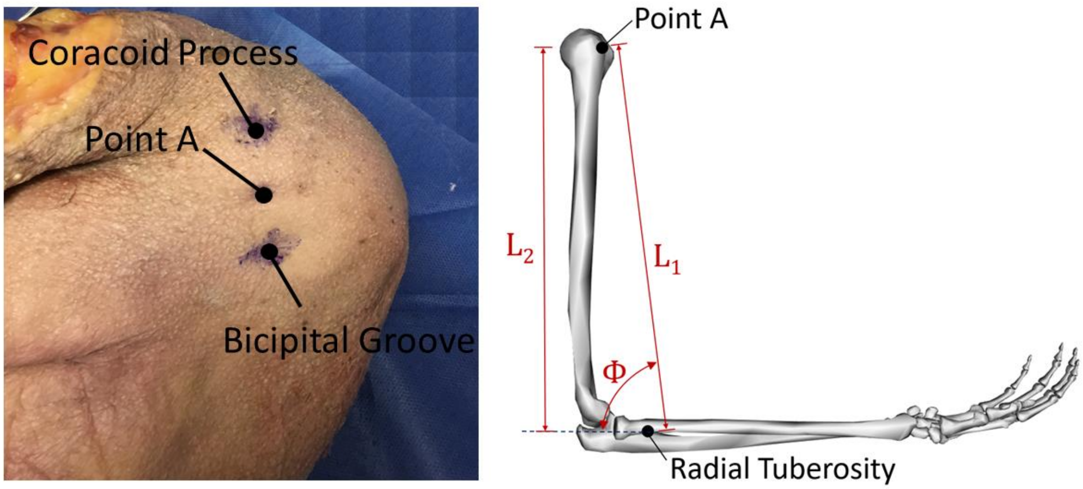

Figure 10. Anatomical measurements to reproduce the biceps vector

3.6 TENDON ORIENTATION

Three tendon orientations were tested in this experiment: native, anatomic repair, and non-anatomic repair. The native tendon orientation is defined as the intact tendon with an external rotation moving distally to the radial tuberosity, shown in Figure 5. The anatomic repair is defined as a repaired tendon with a native-like externally rotated orientation, while the non-anatomic repair is defined as a repaired tendon with an internally rotated orientation. The anatomic and non-anatomic repair are shown in Figure 11.

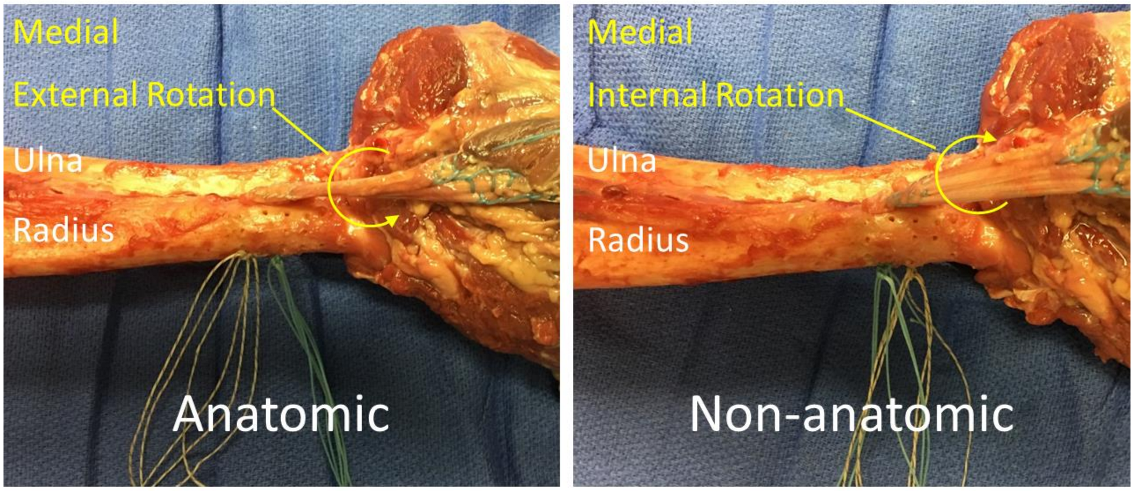

Figure 11. Anatomic and non-anatomic repair orientations

3.7 REPAIR PROCEDURE

Following the native orientation test, the distal biceps was removed from its attachment on the radial tuberosity. Three holes were drilled though the radius (bicortical) with a 2 mm drill bit. The location of the holes was determined by placing a central hole through the center of the native tendon insertion before drilling proximal and distal holes that spanned the tendon footprint. Krackow locking loop stitches using 2-0 Fiberwire (Arthrex, Inc., Naples, FL) were placed individually through the distal tendon heads. The sutures were passed through the drill holes and tied over bone bridges opposite the radial tuberosity. The repair was performed in this manner to enable testing of the tendon in two separate repair orientations.

3.8 TEST PROTOCOL

Before each supination test, a mounting plate was attached to the distal radius. The specimen was mounted in the elbow simulator with the humerus and ulna fixed to the frame at 90° of flexion, shown in Figure 12. The adjustable arm was attached to the distal radius mounting plate. A line was drawn on the distal radial ulnar joint from the radial styloid to the ulnar styloid. The reference neutral rotational position of the forearm was defined when the line was vertical, shown in Figure 13. The suture on the proximal end of the distal biceps tendon was attached to an actuator using 100 lb test line. The forearm was rotated and locked into each of the three angular positions: 60° supination, neutral, and 60° pronation. The supinated and pronated positions were found using the potentiometer and the reference neutral rotational position. For forearm angle, the biceps tendon was loaded to 67 N (15 lbs) and the torque was measured at the distal forearm. The distal biceps tendon was transected and surgically reattached using the repair technique outlined in Section 3.7. The supination test protocol was carried out for the native, anatomic repair, and non-anatomic repair tendon orientations. The test order for the anatomic and non-anatomic repairs were randomized using the rand function in Matlab.

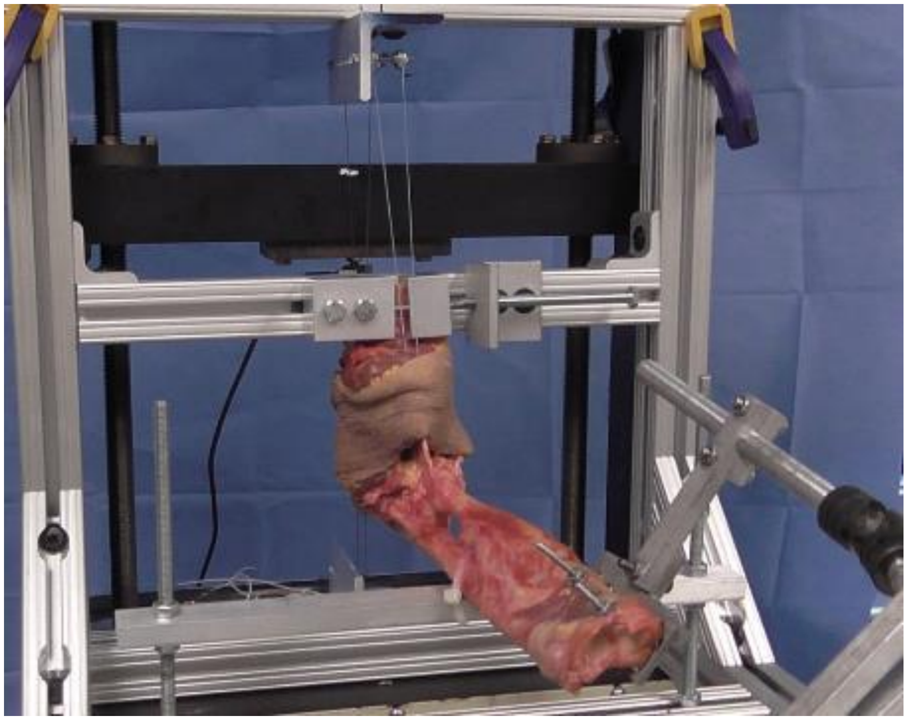

Figure 12. A specimen mounted to the elbow simulator in 90° flexion

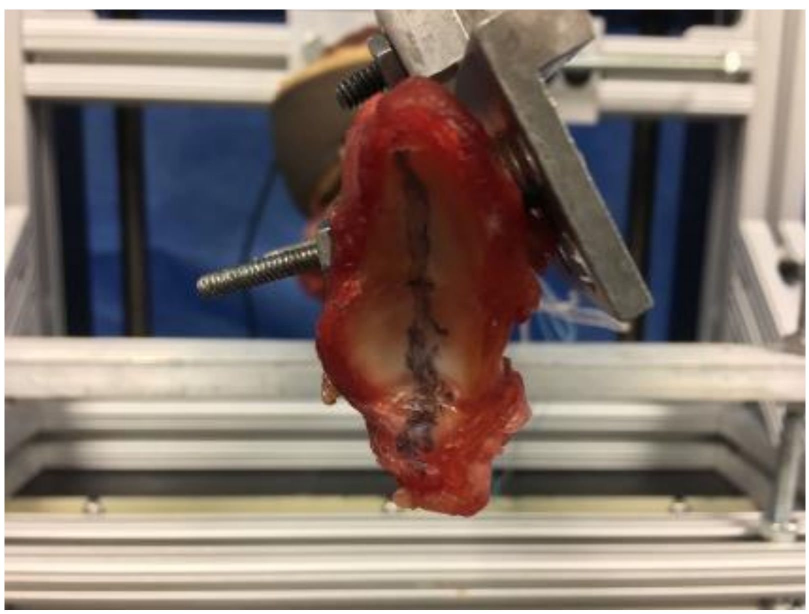

Figure 13. The reference neutral rotational position of the forearm

3.9 DATA ANALYSIS

A linear regression line was fitted to the torque vs. load data for each test as shown by Figure 14. The moment arm was defined as the absolute value of the slope of the regression line. The moment arm was averaged over the three trials taken at each angular position. The Matlab script to calculate the moment arm can be found in Appendix 2.

A two-way repeated measure ANOVA was used to determine if tendon orientation and forearm position significantly affect the moment arm of the biceps with significance if $p < 0.05$. All moment arm data sets were tested for and met the assumptions of normality and sphericity using Kolmogorov-Smirnov ($p > 0.05$) and Mauchly's test ($p > 0.05$), respectively.

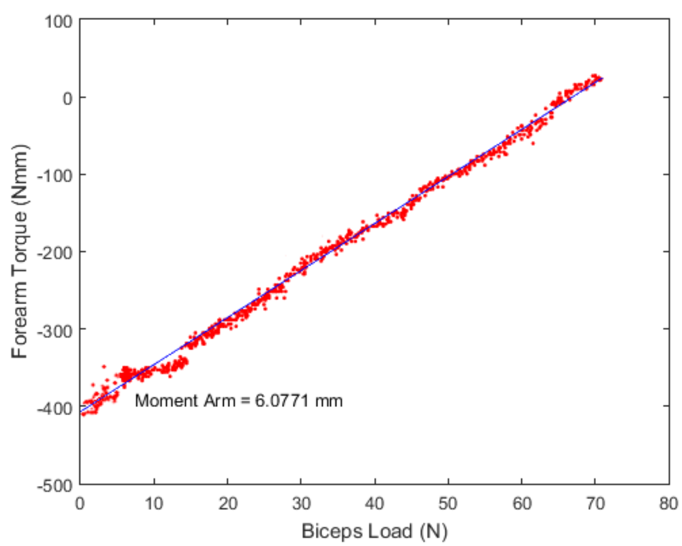

Figure 14. A linear regression line fitted to forearm torque vs. biceps load data

4.0 RESULTS

4.1 GROSS OBSERVATIONS

The distal biceps tendon appeared normal in all specimens. Each tendon inserted slightly posterior to the highest point (apex) of the radial tuberosity in a ribbon-like form. At 60° pronation, there appeared to be full wrapping of the biceps tendon around the apex of the tuberosity. As the forearm supinated a decrease in tendon wrapping occurred with little to no wrapping occurring at 60° supination. The wrapping appeared to be very similar in the anatomic and non-anatomic orientations, shown in Figure 15. The wrapping gave observational evidence to the cam effect of the radial tuberosity to produce supination torque [5].

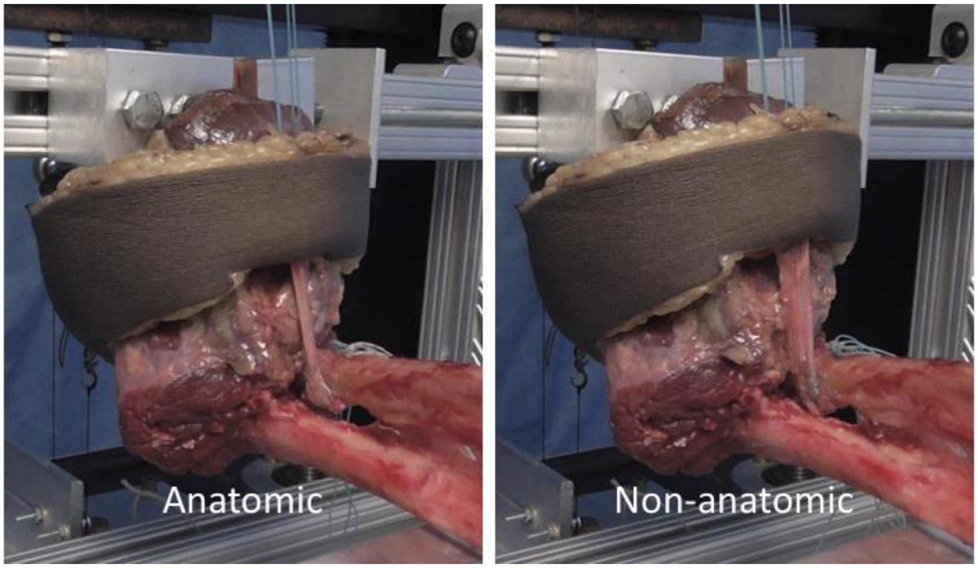

Figure 15. Tendon wrapping around the tuberosity in various repair orientations

All anatomic and non-anatomic repairs appeared to insert into the posterior aspect of the radial tuberosity. However, the anatomic repair seemed to insert in a ribbon-like form, like the native tendon, while the non-anatomic repair seemed to bunch at the tendon-bone interface. The bunching occurred throughout forearm rotation and only occurred at an unloaded biceps state. The non-anatomic tendon appeared to become ribbon-like at approximately 10 N of biceps force. The bunching effect is shown in Figure 16.

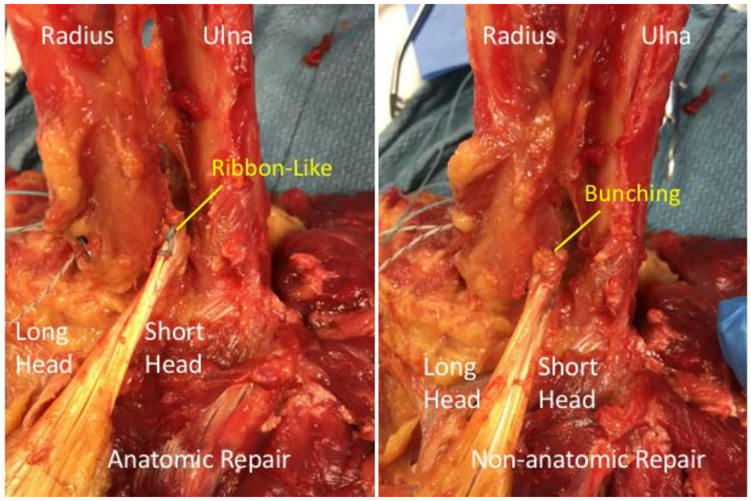

Figure 16. Non-anatomic repair tendon bunching at the tendon-bone interface

4.2 MOMENT ARM RESULTS

The ANOVA showed that forearm rotational positional significantly affect the moment arm ($p < 0.01$) but tendon orientation did not significantly affect the moment arm ($p > 0.352$). The native tendon orientation had a mean moment arm of 8.22 ± 1.71, 9.56 ± 1.77, and 5.49 ± 1.41 mm in 60° supination, neutral, and 60° pronation, respectively. A summary of the results is shown in Figure 17 and Table 1.

Reattachment of the biceps tendon in the anatomic orientation for the three rotational positions did not show a significant difference from the native tendon. The anatomic repair tendon orientation had a mean moment arm of 8.41 ± 2.02, 9.61 ± 2.02, and 5.42 ± 1.35 mm in 60° supination, neutral, and 60° pronation, respectively.

Reattachment of the biceps tendon in the non-anatomic orientation for the three rotational positions did not show a significant difference ($p = 0.351$) from the native or anatomic repair orientations. The non-anatomic repair tendon orientation had a mean moment arm of 8.30 ± 1.83, 9.45 ± 1.85, and 5.31 ± 1.38 mm in 60° supination, neutral, and 60° pronation, respectively. These results are comparable to both the native and anatomic repair results.

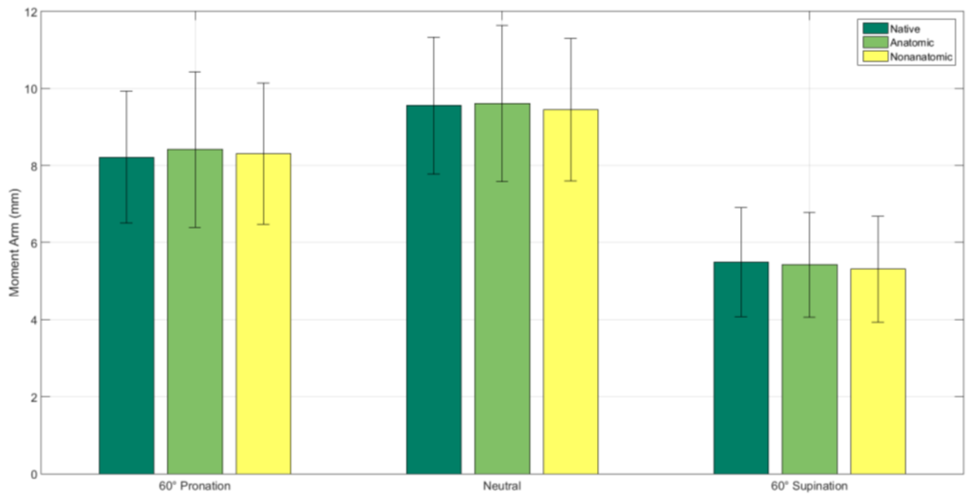

Figure 17. Summary of results for moment arm vs. forearm position

Table 1. Summary of results for moment arm vs. forearm position

	60° Pronation	Neutral	60° Supination
	Average ± Standard Deviation (mm)	Average ± Standard Deviation (mm)	Average ± Standard Deviation (mm)
Native	8.22 ± 1.71	9.56 ± 1.77	5.49 ± 1.41
Anatomic	8.41 ± 2.02	9.61 ± 2.02	5.42 ± 1.35
Non-anatomic	8.30 ± 1.83	9.45 ± 1.85	5.31 ± 1.38

5.0 DISCUSSION

The data analysis showed that forearm rotational positional significantly affected the moment arm ($p < 0.001$) but tendon orientation did not significantly affect the moment arm ($p > 0. 352$). The native tendon orientation had a mean moment arm of 8.22 ± 1.71, 9.56 ± 1.77, and 5.49 ± 1.41 mm in 60° supination, neutral, and 60° pronation, respectively. These findings compare well to previous literature that measured the moment arm. Schmidt et al. reported an average native moment arm of 8.0, 10.4, and 5.7 mm for 60° supination, neutral, and 60° pronation, respectively [18]. Haugstvedt et al. reported an approximate moment arm of 10, 11, and 2.5 mm for the same rotational positions [17]. This provides agreement with the results of this study.

Reattachment of the biceps tendon in the anatomic orientation for the three rotational positions did not show a significant difference in orientation from the native tendon. The anatomic repair tendon orientation had a mean moment arm of 8.41 ± 2.02, 9.61 ± 2.02, and 5.42 ± 1.35 mm in 60° supination, neutral, and 60° pronation, respectively. Schmidt et al. reported an average moment arm of 8.41, 10.41, and 6.24 mm and found no difference between the native and anatomic location repair [18]. These findings are comparable to the findings in this study and provide assurance that the tendon repairs were repaired to the intended anatomic location on the radial tuberosity.

Reattachment of the biceps tendon in the non-anatomic orientation for the three rotational positions did not show a significant difference in orientation ($p = 0.625$) from the native or anatomic repair orientations. The non-anatomic repair tendon orientation had a mean moment arm of 8.30 ± 1.83, 9.45 ± 1.85, and 5.31 ± 1.38 mm in 60° supination, neutral, and 60° pronation, respectively. These results are comparable to both the native and anatomic repair results. These results are also comparable to the native and anatomical repair reported by Schmidt [18].

Data analysis also showed that forearm rotational positional significantly affected the moment arm ($p < 0.05$) in all tendon orientations. This result agrees with the previous literature and add further validation to the methods used in this study [16, 18].

This biomechanical study showed no effect of tendon repair orientation on the supination moment arm. By applying the definitions of torque in Equation 1 and Equation 2, it can be deduced why no significance was found. For a given forearm rotational position, the position vector, $\vec{r}$, does not change. The position vector is defined from the axis of rotation of the forearm to the point on the surface of the radius where the biceps force is applied; the vector is largely defined by the anatomy of the radius and not the biceps tendon. The force vector, $\vec{F}$, is along the line of the biceps. In this study, the magnitude of the biceps force vector was controlled by the actuator and measured with the force load cell. By Equation 3 and the constant position vector, the direction of the force vector is the only way to change the moment arm. In an analogous example, axially twisting and loading a ribbon does not change the magnitude or direction of force. The results of this study suggest that changing the tendon orientation does not play a significant role in changing the biceps force vector for a given rotational position and therefore does not change the moment arm. The anatomy and vectors relating to the moment are outlined in Figure 18.

The twisting of the tendon produced a small torque about the axis of the biceps tendon. Changing the tendon from the anatomic to non-anatomic repair orientation changed the direction of torque. Since the torque is not about the axis of rotation of the forearm and is very small in magnitude, it had no effect on the moment arm.

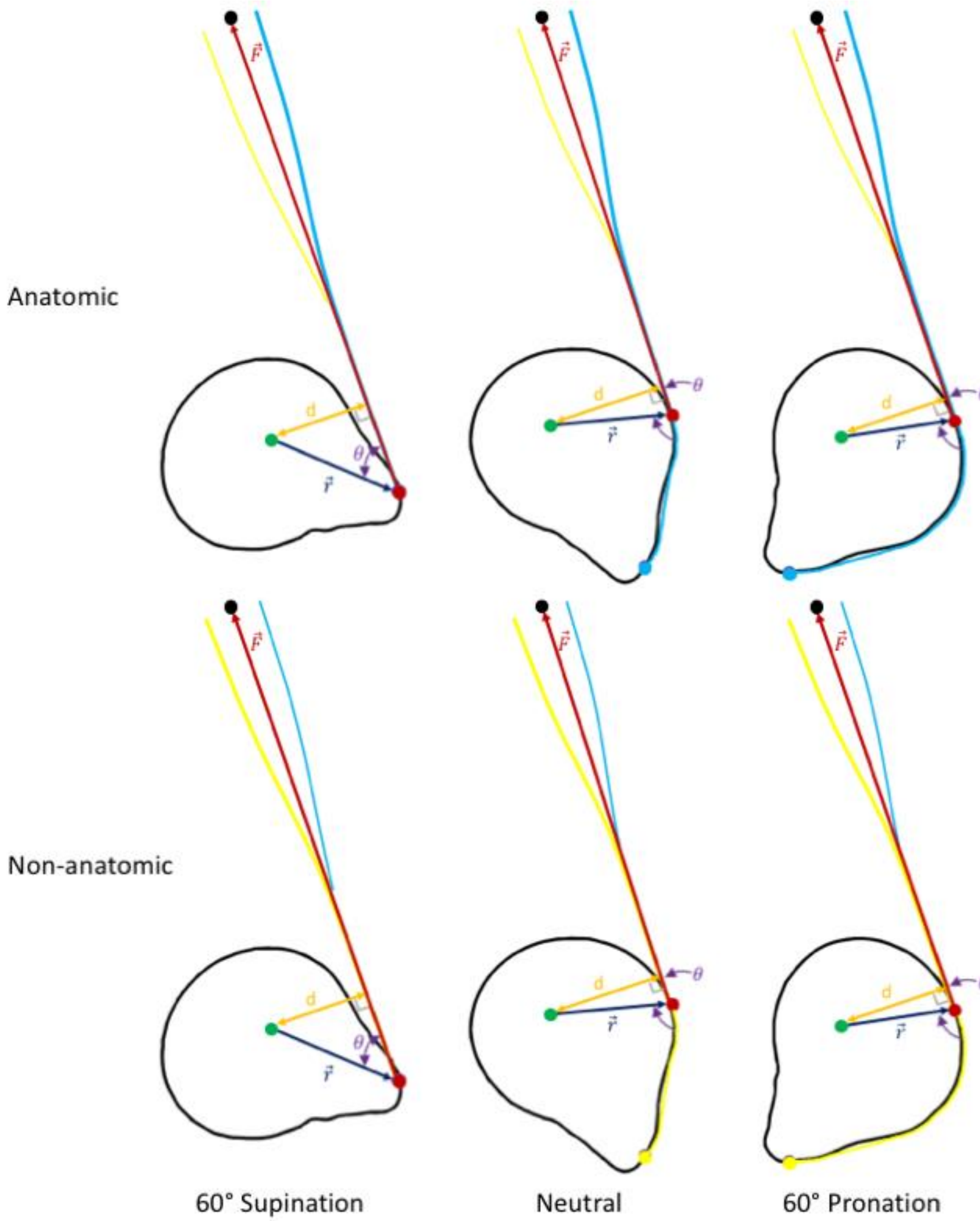

Figure 18. Torque related vectors for each orientation at various rotational positions. Right radius outline viewed from distal to proximal. Force vector (red), position vector (blue), moment arm (orange), medial edge of short head (light blue), lateral edge of long head (yellow).

The bunching effect of the tendon could have affected the wrapping of the tendon around the tuberosity. The bunching could have caused the tendon to fold over onto itself and not lay flat on the tuberosity. This would cause a change in direction of the biceps force and therefore affect the moment arm. Instead, gross observation showed that the tendon bunching effect did not occur at biceps loads greater than 10 N. The non-anatomic oriented tendon wrapped normally around the tuberosity. Although the tendon cross-sectional shape at the insertion is not symmetric, the lack of symmetry did not impede normal wrapping.

Previous literature has shown that the position of the distal biceps repair on the tuberosity has a significant effect on the supination mechanics of the forearm [18, 19]. Schmidt and Prud'homme-Foster have both recommended surgeons pay attention to repairing the tendon to the anatomical position to reduce the risk of losing supination torque through the full forearm range of motion. From a biomechanical perspective, surgeons should pay closer attention to the location of the tendon reattachment than to the orientation of the tendon.

The results of this study indicate that the repair orientation does not play a biomechanically significant role on the mechanics of supination. However, the testing was completed immediately after the repair of cadaveric specimens and did not consider the role of healing. Follow up studies would need to be completed in animal models or unpremeditated non-anatomic orientation repair recipients to test the effect of repair orientation on healing. Until the effects of orientation on healing are better understood, it is not suggested that surgeons ignore the tendon orientation during repair. Effects on healing are worth investigating because if the orientation has no effect even after the tendon has healed, then potential benefits include reduced surgery time and less time under anesthesia.

6.0 CONCLUSIONS AND FUTURE WORK

6.1 CONCLUSIONS

This biomechanical study provides support that the distal biceps tendon orientation does not play a significant role on the mechanics of supination. The research suggests that, from a biomechanical prospective, the surgeon should pay closer attention to the location of the tendon reattachment and less on the orientation of the tendon. However, due to the unknown effect of repair orientation on healing, non-anatomical biceps orientation repairs should still be avoided.

6.2 FUTURE WORK

Future work on this project could include a clinical follow up of patients with non-anatomical biceps orientations and are more than two years post-operative. The clinical follow up studies would include an isometric supination strength test at 60° pronation, neutral and 60° supination as well as a dynamic, constant torque supination test to evaluate endurance. Both tests would be measured bilaterally and injured vs. uninjured arms would be compared. These tests would be completed to evaluate the effects of repair orientation on supination after healing.

A clinical follow up would require the development of a method of identifying non-anatomical biceps orientations post-operatively. Such methods could include MRI or ultrasound techniques. Due to the unknown effect of repair orientation on healing, non-anatomical biceps orientation repair should not intentionally replace anatomical orientation repairs. Identification of patients with unintentional non-anatomical repairs would give clinicians and researchers data on the frequency of this procedure.

APPENDIX A

DATA ACQUISITION MATLAB CODE

```
% AcquireDataBicepsRepairOrientation
% Tyler Madonna
% 12/06/2016

clear;
clc;

% Raw voltage data gets collected in the vector 'data'
% Column 1 = data for analog input 0 (biceps load sensor)
% Column 2 = data for analog input 1 (distal forearm torque)
% Column 3 = data for analog input 2 (potentiometer)

% Calibration factors
biceps_load_sensor_cal_factor = 16.945; % N/V
forearm_torque_sensor_cal_factor = 293.29; % Nmm/V
forearm_load_sensor_cal_factor = 21.551; % N/V
rotation_pot_cal_factor = 67.341; % Deg/V

% Create a DAQ session
s = daq.createSession('ni');

% Set the three analog input channels
% Device number 'Dev1' can be found using the 'daq.getDevices' command
% Analog input channel 'ai1' can be found on the DAQ terminals
ch0 = s.addAnalogInputChannel('Dev1','ai0','Voltage');
ch1 = s.addAnalogInputChannel('Dev1','ai1','Voltage');
ch2 = s.addAnalogInputChannel('Dev1','ai2','Voltage');

% Set the input range for the three channels
ch0(1).Range = [-5 5];
ch1(1).Range = [-5 5];
ch2(1).Range = [-5 5];

% Set the terminal configuration so Matlab knows to use ground terminal as
% reference
% See https://www.mathworks.com/help/daq/ref/terminalconfig.html
```

```
ch0(1).TerminalConfig='SingleEnded';
ch1(1).TerminalConfig='SingleEnded';
ch2(1).TerminalConfig='SingleEnded';

% Set the data collection frequency (samples/sec) and duration (s)
s.Rate = 100;
s.DurationInSeconds = 15;

% Add a listener that gets notified every 40 data points
% On notify, create a plot of data vs. time
s.NotifyWhenDataAvailableExceeds = 40;
listener = s.addlistener('DataAvailable', ...
    @(s,event) plot(event.TimeStamps, biceps_load_sensor_cal_factor *
event.Data));

% Start the session
[data,time] = s.startForeground();

% % Plot forearm rotation vs. time
% plot(time, rotation_pot_cal_factor * data(:,3),'r.');
% xlabel('Time (s))');
% ylabel('Forearm rotation (deg)');
% mean(rotation_pot_cal_factor * data(:,3))

% % Plot forearm torque vs. biceps load
plot(biceps_load_sensor_cal_factor * data(:,1),
forearm_torque_sensor_cal_factor * data(:,2),'r.');
xlabel('Biceps load (N)');
ylabel('Forearm Torque (Nmm)');
```

APPENDIX B

MOMENT ARM CALCULATION MATLAB CODE

```
% GetMomentArm
% Tyler Madonna
% 12/06/2016

% Pass in the time and data vectors as parameters
function GetMomentArm(time, data)

% Set the evaluation time vector
eval_time = time;

% Set the evaluation biceps load vector using the calibration factor
biceps_load = 16.9450 * data(:,1);

% Set the evaluation forearm torque vector using the calibration factor
forearm_torque = 293.29 * data(:,2);

% Plot the raw forearm torque vs. biceps load data
plot(eval_time, biceps_load,'r.');

% Prompt the user to set the lower data limit.
% Eliminates the extra data when test doesn't start at exactly time=0s
lower_time_limit = dimensionFromInput('Enter the lower time limit in seconds:
');

% Find the lower biceps load indices within the data
lowerIndex = find(eval_time <= lower_time_limit);

% Remove all lower indices from the data
eval_time(lowerIndex) = [];
biceps_load(lowerIndex) = [];
forearm_torque(lowerIndex) = [];

% Prompt the user to set the upper data limit.
% Eliminates the extra data when test doesn't end when data acquistion ends
```

```
upper_time_limit = dimensionFromInput('Enter the upper time limit in seconds:
');

% Find the upper biceps load indices within the data
upperIndex = find(eval_time >= upper_time_limit);

% Remove all upper indices from the data
eval_time(upperIndex) = [];
biceps_load(upperIndex) = [];
forearm_torque(upperIndex) = [];

% Plot the new data vectors
plot(biceps_load, forearm_torque,'r.');

% Hold the plot
hold on;

% Fit a linear trendline to the data
p = polyfit(biceps_load, forearm_torque, 1);

% Create a representative trendline that can be display on a plot
trendX = linspace(0, max(biceps_load + 5),500);
trendY = polyval(p, trendX);

% Plot the trendline
plot(trendX, trendY, 'b-');

% Display the moment arm (slope of the trendline)
text(trendX(100), trendY(20), sprintf('Moment Arm = %0.4f mm', abs(p(1,1))));

end

% Get user input dimensions
% Return a double from the user input
function d = dimensionFromInput(s)
% Take user input
d = inputAsDouble(s);
% Make sure it's a double
while ~isNumber(d)
    % Prompt user again if it's not a double
    d = inputAsDouble(s);
end

end

% Is this a number?
% Returns a boolean
function b = isNumber(d)
b = ~isnan(d) || fix(d) == d;
end

% Create a double from the user input
% Returns a double or NaN
function d = inputAsDouble(s)
```

```
d = str2double(input(s, 's'));
end
```

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