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Katherine L. Mardula for the degree of Master of Science in Mechanical Engineering presented on December 3, 2013.

Title: R_EHand: ReEngineering the Human Hand with Differential Mechanisms to Improve Hand Function After Tendon-Transfer Surgeries

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Since the 1970s, tendon-transfer surgeries have been routinely performed for a variety of conditions such as stroke, paralysis, spinal atrophy, trauma, and birth defects. The surgery involves rerouting a tendon from a disabled muscle and directly suturing it to a functioning muscle in order to partially restore hand function. This direct suture between the donor muscle and the recipient tendons directly couples the movement of all the joints actuated by the recipient tendons, leading to reduced hand function in physical interaction tasks such as grasping, a key aspect for activities of daily living. The tendon-transfer surgery for high median-ulnar palsy is used as an example in order to present a new approach to tendon-transfer surgery, where implanted passive engineering mechanisms are used to attach the donor muscle to the recipient tendons. This thesis provides evidence through cadaver studies to support the hypotheses that hand function is improved through increased adaptive finger movement, reduced required donor muscle actuation force, and enables grasping at low forces on the object when compared with the suture based procedure.

R$_E$Hand: ReEngineering the Human Hand with Differential Mechanisms to Improve Hand Function After Tendon-Transfer Surgeries

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"This is the real secret of life – to be completely engaged with what you are doing in the here and now. And instead of calling it work, realize it is play."

– Alan Wilson Watts

CONTRIBUTION OF AUTHORS

Chapter 5 is a conference paper which I wrote with co-author, Thane Somers. Thane Somers provided the matlab code to report the forces from the six-axis force sensor.

TABLE OF CONTENTS

Page

1 Introduction 1

1.1 Hypotheses . . . 1

1.2 Introduction to Chapter 2: Implanted Engineering Mechanisms Improve Finger Movement Post Tendon-Transfer Surgery for High Median-Ulnar Palsy . . . 3

1.3 Introduction to Chapter 3: Implanted Differential Mechanisms Improve Hand Function after Tendon-Transfer Surgery: A Cadaver-Based Study . . . 3

1.4 Introduction to Chapter 4: Results for All Four Spheres from Cadaver Studies . . . 3

1.5 Introduction to Chapter 5: Implanted Adaptive Mechanism Enables Grasping at Lower Forces After Tendon-Transfer Surgery: A Cadaver-Based Study . . . 4

1.6 Introduction to Chapter 6: Preliminary R_EDesign Ideas . . . 4

1.7 Contents of Appendix . . . 4

2 Implanted Engineering Mechanisms Improve Finger Movement Post Tendon-Transfer Surgery for High Median-Ulnar Palsy
Submitted to 2014 American Society of Biomechanics 5

2.1 Introduction . . . 6

2.2 Background . . . 8

2.2.1 The tendon transfer surgical procedure . . . 8

2.2.2 Adaptive coupling mechanisms in robotic hand design . . . 9

2.3 Applying adaptive mechanisms to tendon-transfer surgery . . . 10

2.4 Methods . . . 10

2.4.1 Experimental set-up . . . 11

2.4.2 Analysis . . . 12

2.5 Results . . . 13

2.6 Discussion and Future Work . . . 16

3 Implanted Differential Mechanisms Improve Hand Function after Tendon-Transfer Surgery: A Cadaver-Based Study

TABLE OF CONTENTS (Continued)

Page

Submitted to The Journal of Hand Surgery November 2013 18
3.1 Introduction 19
3.2 Materials and Methods 21
3.2.1 Analysis 23
3.3 Results 26
3.3.1 Hypothesis I: Pulley-based procedure reduces actuation force requirement when compared with the suture-based procedure 27
3.3.2 Hypothesis II: Adaptive finger movement in the proposed procedure 27
3.4 Discussion 28
3.5 Acknowledgements 31
3.6 References 31

4 Results for All Four Objects 34
4.1 Hypothesis I: Pulley-based procedure reduces actuation force requirement when compared with the suture-based procedure 35
4.2 Hypothesis II: Adaptive finger movement in the proposed procedure . 35
4.2.1 Ball 1 38
4.2.2 Ball 2 38
4.2.3 Ball 3 38
4.2.4 Ball 4 39

5 Introduction to Chapter 5: Implanted Adaptive Mechanism Enables Grasping at Lower Forces After Tendon-Transfer Surgery: A Cadaver-Based Study
Submitted to 2014 American Society of Biomechanics 40
5.1 Introduction 40
5.2 Methods 41
5.2.1 Analysis 42
5.3 Results and Discussion 43

6 Mechanism Design 46
6.1 Customer Needs 46

TABLE OF CONTENTS (Continued)

Page

6.2 Design Concepts 47

7 Conclusion 49

7.1 Summary of Results 49

7.2 Hypothesis I 49

7.3 Hypothesis II 50

7.4 Hypothesis III 50

7.5 Future Work 50

Bibliography 50

Appendices 55

A Significance Calculations 56

B Pulley Design 62

C Experimental Set Up 65

D All Design Concepts 73

LIST OF FIGURES

Figure Page

2.1 (a) Schematic representation of the hand anatomy showing the muscles and the rerouting that occurs in a tendon-transfer procedure of the FDP and ECRL. (b) Schematic representation of the conventional procedure with arrows indicating the directional movement caused by donor muscle contraction. The fingers do not close in completely around the object because of coupled finger movement. (c) Schematic representation of the proposed procedure with the hierarchical pulley system, arrows indicate direction of movement caused by donor muscle contraction. Here the fingers are able to close completely around the object due to adaptive movement enabled by the pulley system. (d) A hierarchical pulley system constructed with off-the-shelf components and implanted in the cadaver forearm for the experimental test. 6

2.2 Passive adaptive mechanisms used in robotic hands. (a) Depiction of the grasping process with an adaptive coupling mechanism. One finger makes contact, then the other makes contact while the first is stationary ending with both fingers having full contact with the object. The (b) the seesaw and (c) pulley design for underactuation. (d) An example of an underactuated robotic finger with two degrees of freedom and one actuator. 9

2.3 The experimental set up, PIP joint angle graphs for proposed and conventional procedures and cadaver hand demonstrating adaptive grasp. (a) Experiment set up (not all cameras shown). (b) Adaptive graph around sphere with proposed procedure. Index finger continues to move while other fingers have contact. Lines drawn over markers where joint angles were calculated. 'X' indicates finger contact. (c) Subject 1 with proposed procedure PIP joint angles, $\bar{\theta}_{pip}$ over time, $\bar{t}$.(d) Subject 1 with conventional procedure $\bar{\theta}_{pip}$ over $\bar{t}$. (e) Subject 3 with proposed procedure $\bar{\theta}_{pip}$ over $\bar{t}$. (f) Subject 3 with conventional procedure $\bar{\theta}_{pip}$ over $\bar{t}$. 11

LIST OF FIGURES (Continued)

Figure — Page

3.1 (a) Hand musculature and tendons and tendon-transfer surgery for high median-ulnar nerve palsy, where tendons are transferred from the FDP to the Extensor carpi radialis longus (ECRL) muscle. (b) Current tendon-transfer procedure using sutures. (c) The proposed procedure using a pulley mechanism. (d) Prototype pulleys implanted in cadaver forearm for study. 20

3.2 (a)Proposed experimental set-up for evaluating post-surgery grasp capability. (b) Initial pulley design for concept test. (c) Marker placement illustration on finger tip, distal interphalangeal joint, proximal interphalangeal joint, metacarpal phalangeal joint and carpometacarpal joint. (d) Pulley-based procedure cadaver hand grasping stemmed ball. 23

3.3 Time history profiles of example subjects for a specific trial showing the summation of joint angles and actuation force profiles for the suture based procedure and pulley based procedure. Contact times of the fingers are indicated. 24

3.4 Summation of joint angles for each finger calculated from motion capture data for each joint. 25

3.5 Illustration of the grasping process through each identified phase of finger contact. Finger contact identified with a darker line. (a) Suture based procedure. (b) Pulley-based procedure. 26

3.6 Mean actuation force across trials at full contact for each procedure and each subject. Pulley-based procedure has a lower muscle actuation force for all trials than the suture-based procedure. . . . 27

4.1 Mean actuation force across trials at full contact for each procedure and each subject for all four objects. Pulley-based procedure has a lower muscle actuation force for all trials than the suture-based procedure. P-value for all balls is 10^{-7} 36

LIST OF FIGURES (Continued)

Figure Page

5.1 a) Hand musculature and tendons and tendon-transfer surgery for high median-ulnar nerve palsy, where tendons are transferred from the FDP to the Extensor carpi radialis longus (ECRL) muscle. (b) Current tendon-transfer procedure using sutures. (c) The pulley-based surgical procedure in a cadaver arm. (e)Wireframe drawing of experimental setup using a six axis force sensor under the object with cadaver arm placed around object. Extensor carpi radialis longus actuated with linear servo. 41

5.2 Mean grasp forces across all trials at full finger contact for each procedure and subject for all four balls. The mean grasp force for the pulley-based procedure is lower than for the suture-based procedure in most trials. 44

5.3 Average direction of force for all balls with 95% confidence interval imposed on wireframe drawing of hand grasping ball. Suture based procedure force direction is $322.1° \pm 2.3°$ and the pulley based procedure is $319.7° \pm 2.2°$. 45

6.1 Design selection matrix used to assess eight designs established in brainstorming sessions. Design images in Appendix D 47

6.2 Rendered simplified pulley design. 48

LIST OF TABLES

Table Page

2.1 Summary of finger movement and behavior for the test interval. Normalized and actual time specified for the stationary period and rate of change of PIP joint angle change for the test period. Stationary periods are characterized by a threshold of 0.4. 14

3.1 Hypothesis II: Summation of joint angle change. Mean summation of joint angle change, $\sum\bar{\theta}_c$, for each finger that has made contact with the object and $\sum\bar{\theta}_{nc}$ for each finger that has not made contact with the object for pulley based procedure and suture based procedure. Similar numbers indicate similar movement in the fingers, whether in contact or not. ^{a} p-value $< 10^{-7}$, ^{b} p-value $< 10^{-6}$, other values were not significantly different in joint angle change. 28

4.1 Number of trials and segments analyzed for each ball. 34

4.2 Number of trials and segments analyzed for each ball. 35

4.3 Hypothesis II: Summation of joint angle change. Mean summation of joint angle change, $\sum\bar{\theta}_c$, for each finger that has made contact with the object and $\sum\bar{\theta}_{nc}$ for each finger that has not made contact with the object for pulley based procedure and suture based procedure. Similar numbers indicate similar movement in the fingers, whether in contact or not. $^{a-e}$ indicates values that are not significant (p-value is over 0.05). 37

5.1 Mean grasp force ratio $(\frac{G_{pulley}}{G_{suture}})$ for each ball across all subjects. A ratio less than 1 signifies that grasp forces are lower for the pulley-based procedure as compared to the suture-based procedure. . . . 43

LIST OF APPENDIX FIGURES

Figure Page

A.1 University of Washington Medicine statistics on patients.http://www.uwmedicine.org/global/about/Pages/default.aspx. 58

A.2 US News Best Hospitals and Orthopedics. http://health.usnews.com/best-hospitals/rankings/orthopedics 59

A.3 American Hospital Association Fast Facts on US Hospitals. http://www.aha.org/research/rc/stat-studies/fast-facts.shtml . 60

A.4 Bureau of Labor Statistics U.S. Department of Labor, News Release: Nonfatal Occupational Injuries and Illnesses Requiring Days Away from Work, 2011. Released: Novemeber 8, 2012. USDL-12-2204. . 61

B.1 Proximal pulley design used in cadaver experiments 63

B.2 Distal pulley design used in cadaver experiments 64

C.1 Wireframe drawing of experimental set up for April 2013 cadaver experiments. 66

C.2 Photo with labels of experimental set up for April 2013 cadaver experiments. Linear servo and load cell are not visible in photo. . . 67

C.3 Drawing of fixture to secure six-axis force sensor for test set up. . . 68

C.4 Drawing of Ball 1 69

C.5 Drawing of Ball 2 70

C.6 Drawing of Ball 3 71

C.7 Drawing of Ball 4 72

D.1 Passive Springs: Allows compliance within the tendons when the donor muscle contracts and a finger makes contact, the springs compress allowing all fingers to make contact. 74

D.2 Loose Pulleys: A similar design to hierarchical pulley system with different ideas on pulley placement. 75

LIST OF APPENDIX FIGURES (Continued)

Figure | Page

D.3 Simplified Pulleys: A passive pulley system with view moving parts that are more integrated. 76

D.4 Linkage Systems: Similar to a see-saw design, the linkages can rotate around a fixed point for adaptive movement. 77

D.5 Planetary Gears: Gears rotate allowing translation movement. . . . 78

D.6 Soft Hydraulics: Maleable tubes with hydraulics to produce tendon force. 79

D.7 Rigid Hydraulics: A rigid hydraulic system translates forces through internal pressure. 80

D.8 Cams/ Clutch: Forces amplified or absorbed with moving cams as fingers make contact with object. 81

LIST OF APPENDIX TABLES

Table — Page

A.1 Copy of Sources attached. *Considering Harborview Medical Center, Northwest Hospital and Medical Center, Valley Medical Center and University of Washington Medical Center as one facility for reporting purposes. **Extrapolated from present data. 56

A.2 Cost of tendon transfer surgeries based on total hospital cost based on CPT codes (table A.3) and statistics from the Bureau of Labor Statistics 56

A.3 University of Washington Department of Orthopaedics and Sports Medicine number of Tendon Transfers / Tenodesis sorted by CPT codes for 2012 Fiscal Year. `https://ocm.ama-assn.org/OCM/CPTRelativeValueSearch.do` 57

Chapter 1: Introduction

Tendon-transfer surgeries are performed to restore partial hand function after stroke, paralysis, spinal muscle atrophy, nerve or muscle trauma and congenital disorders [1–5]. The procedure reroutes one or more tendons from a dysfunctional muscle to a functioning muscle[2, 3]. The tendons from a dysfunctional muscle are called the recipient tendons, and the functioning muscle is called the donor muscle. The donor muscle controls the movement originally created by the dysfunction muscle, but does not always restore complete hand function [1–5]. In this work, I focus on at least fifteen procedures where multiple tendons are rerouted to a single donor muscle [1, 3]. One muscle actuating the movement of multiple tendons couples the movement created by the rerouted tendons.

Based on records of the United States American Hospital Association and US News Report, there are over 20,000 upper-extremity tendon transfer procedures in the United States annually(see table A.1), costing over $200 million (table A.2). In addition, 22% of hand surgeries performed in the military are tendon transfer surgeries[6] and have been extensively used since World War II [7].

The tendon-transfer surgery for high median ulnar palsy is studied to examine creating adaptive tendon movement for improving hand function after tendon-transfer surgeries that reroute multiple recipient tendons to one donor muscle.

1.1 Hypotheses

The improvement of hand function provided by the adaptive mechanism when compared with the suture-based procedure will be tested with the following hypotheses:

Hypothesis I: The pulley-based procedure will lead to more adaptive finger movement than the suture-based procedure during a grasping task. Adaptive finger movement reduces finger slip on the grasping object and allows more fingers to make contact on the object leading to a more secure grasp. (Chapter 2, 3 and 4)

Hypothesis II: The pulley-based procedure will require smaller muscle actuation forces than the suture-based procedure to establish full contact. Affirmation of this hypothesis indicates that a patient will need less strength to grasp an object. (Chapter 3 and 4)

Hypothesis III: The pulley-based procedure will reduce the force applied to the object during the grasping process until all fingers have made contact on the object compared to the forces on the object with the suture-based procedure. Reducing the force during the grasp ensures that the object isn't pushed away during the grasping process and allows all fingers to make contact at low forces before increasing the grasp force. The direction of total force will be the same for the pulley and suture based procedures, and pointed toward the thumb. (Chapter 5)

Cadaver arms are used to test the hypotheses based on standard in the field [1, 3, 8–10]. Studies have also shown that cadaveric tissue histology is similar to live tissue, and is a viable option for testing [11]. Another study identifies that the muscle architecture of cadavers differs from live muscles, but has the qualities of cadaveric muscle fall between a life muscles relaxed and contracted phase [12]. This study relies on tendon tissue, rather than the muscles. Based on standard within surgical research and similar histology, using cadaver arms is deemed acceptable for these experiments.

1.2 Introduction to Chapter 2: Implanted Engineering Mechanisms Improve Finger Movement Post Tendon-Transfer Surgery for High Median-Ulnar Palsy

Chapter 2 presents a paper submitted to the 2014 American Society of Biomechanics focusing on hypothesis I. This paper is based on results from cadaver studies held in August 2012 at Harbor View Medical Center, part of University of Washington's Medical Center which provide a proof of concept for an off-the-shelf hierarchical pulley system. The pulley system allows the fingers to close around an object and reduces finger slip after tendon-transfer surgery compared to the suture-based procedure.

1.3 Introduction to Chapter 3: Implanted Differential Mechanisms Improve Hand Function after Tendon-Transfer Surgery: A Cadaver-Based Study

Chapter 3 presents a journal paper submitted to Journal of Hand Surgery addressing hypothesis I and II. The analysis is of a cadaver study performed in April 2013 with six cadaver arms. This paper provides evidence in support of hypothesis I and hypothesis II for a large raised sphere (ball 4).

1.4 Introduction to Chapter 4: Results for All Four Spheres from Cadaver Studies

This chapter parallels the analysis in Chapter 3 to support hypothesis I and II with the results of all four spheres for the subjects in the cadaver study.

1.5 Introduction to Chapter 5: Implanted Adaptive Mechanism Enables Grasping at Lower Forces After Tendon-Transfer Surgery: A Cadaver-Based Study

Chapter 5 presents a paper submitted to the 2014 American Society of Biomechanics supporting hypothesis III. The cadaver studies in April 2013 are further analyzed to determine the grasp force on the object from a six-axis force sensor placed under the spheres. This paper was co-authored with Thane Somers.

1.6 Introduction to Chapter 6: Preliminary R_EDesign Ideas

The initial design process for improving the adaptive mechanism is shown in chapter 6. The criteria required for the device is described for all stakeholders (surgeon, patient, manufacturer and physical therapist) and evaluated for ten designs. The top three designs were distinguished and the top design was prototyped.

1.7 Contents of Appendix

Appendix A included the statistics that were used to extrapolate information from University of Washington Medical Center to the entire US. The pulley design used in cadaver experiments for this thesis is shown in appendix B. The manufactured drawings for the experimental test setup and drawings for objects used in cadaver studies are detailed in appendix C. Appendix D shows the design concepts generated for future designs of the adaptive mechanism.

Chapter 2: Implanted Engineering Mechanisms Improve Finger Movement Post Tendon-Transfer Surgery for High Median-Ulnar Palsy

Submitted to 2014 American Society of Biomechanics

Since the 1970s, tendon-transfer surgeries have been routinely performed for a variety of conditions such as stroke, paralysis, spinal atrophy, trauma, and birth defects. The surgery involves rerouting a tendon from a disabled muscle and directly suturing it to a functioning muscle in order to partially restore hand function. This direct suture between the donor muscle and the recipient tendons directly couples the movement of all the joints actuated by the recipient tendons, leading to reduced hand function in physical interaction tasks such as grasping–a key aspect for activities of daily living. The tendon-transfer surgery for high median-ulnar palsy is used as an example in order to present a new approach to tendon-transfer surgery, where implanted passive engineering mechanisms are used to attach the donor muscle to the recipient tendons. Specifically, the extensor carpi radialis longus is used as the donor muscle to actuate the flexor digitorum profundus tendons to enable flexion of all the fingers. Through cadaver studies, it is shown that the new procedure will improve hand function in the activities of daily living by enabling the fingers to adapt independently to the object shape during the grasping process as well as reduce the finger slipping on the object surface once a power grasp is established.

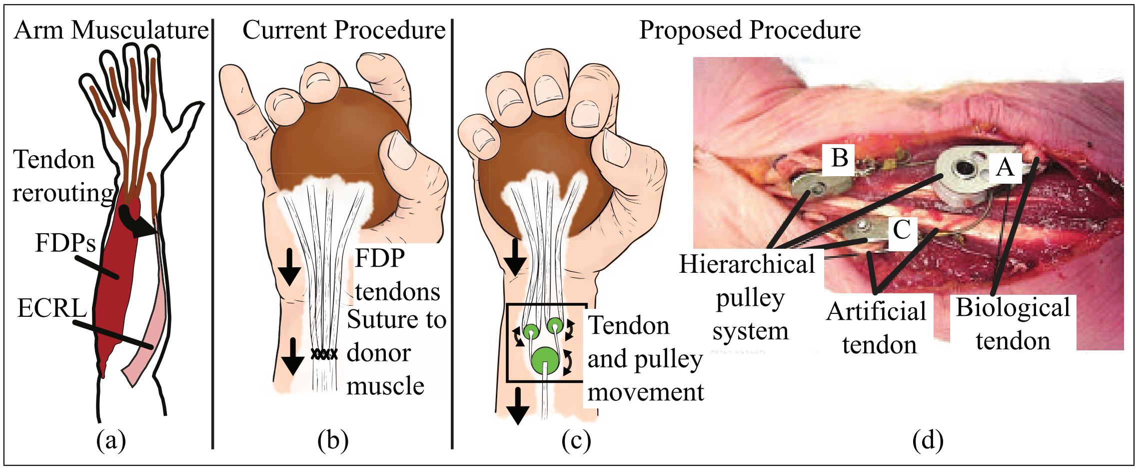

Figure 2.1: (a) Schematic representation of the hand anatomy showing the muscles and the rerouting that occurs in a tendon-transfer procedure of the FDP and ECRL. (b) Schematic representation of the conventional procedure with arrows indicating the directional movement caused by donor muscle contraction. The fingers do not close in completely around the object because of coupled finger movement. (c) Schematic representation of the proposed procedure with the hierarchical pulley system, arrows indicate direction of movement caused by donor muscle contraction. Here the fingers are able to close completely around the object due to adaptive movement enabled by the pulley system. (d) A hierarchical pulley system constructed with off-the-shelf components and implanted in the cadaver forearm for the experimental test.

2.1 Introduction

Based on records of the United States American Hospital Association, there are over 65,000 upper-extremity tendon transfer procedures in the United States annually. These surgeries are conducted to partially restore hand function for a variety of conditions such as stroke, paralysis, spinal muscle atrophy, nerve or muscle trauma, and congenital disorders [8]. The surgical procedure, well-established since the 1970s, involves re-routing one or more tendons from an affected muscle and directly suturing it to a functioning donor muscle [2, 13], so that the donor muscle's contraction produces the required joint movement.

However, a fundamental aspect of tendon-transfer surgery has gone unaddressed. A single donor muscle is often directly sutured to multiple recipient tendons. For example, take the case of tendon-transfer surgery for high median-ulnar palsy, a severe condition that affects the ulnar and median nerves of the hand. Among high median-ulnar palsy's many effects, it disables the flexor digitorum profundus (FDP) muscle, which flexes all four fingers. Thus, high ulnar-median palsy results in an inability to completely close the fingers, leading to weak grasp strength.

In order to restore finger flexion capability, the current surgical procedure is to suture all the FDP tendons driving flexion in all four fingers to a functioning donor muscle (for example, the extensor carpi radialis longus (ECRL), see Fig. 2.1a) [1, 2, 4]. While the direct suture is a simple method of attachment, it results in directly coupling the movement of the distal joints of all four fingers. This is adequate if the fingers are closed in free space, as when making gestures and hand movements, but this direct suture method prevents the fingers from adapting independently during physical interaction tasks. Specifically, when the fingers close on an object during a grasping process, all the other fingers would also stop before making contact since motion of all the fingers are coupled (see Fig. 2.1b). Thus, the direct-suture attachment method results in poor multi-finger power/enveloping grasping ability and may require the patient to use unnatural wrist and arm movements to complete the grasp. Since the ability to perform power grasps is a fundamental aspect of the activities of daily living [14], such as when holding or grasping onto objects when feeding, post-surgery hand function is fundamentally impeded (see Fig. 2.1b).

In this paper, the tendon-transfer surgery for high median-ulnar palsy is used to explore the development of a new tendon-transfer surgical procedure that uses implanted passive miniature engineering mechanisms, such as a hierarchical pulley system, for attaching the donor muscle to the recipient tendons (see Fig. 2.1c). It is expected that the engineering mechanism will enable the joints actuated by the recipient tendons to adapt independently during physical interaction tasks without losing the advantages of the conventional surgical procedure. Specifically, with the adaptive mechanism in place, the fingers would close as the donor muscle contracts. If any finger made contact, the pulleys would spin to allow the other fingers to continue to close, enabling the fingers to wrap around the object and improving post-surgery hand grasping function in the activities of daily living (see Fig. 2.2a).

Cadaver experiments were used to compare finger movement after the conventional and proposed surgery. These experiments show that the implanted adaptive mechanisms improve grasp capability based on: (1) independent finger movement when establishing contact with an object and (2) minimize finger slipping on the object surface during the contact stage of the grasping process.

2.2 Background

2.2.1 The tendon transfer surgical procedure

Even though there are thirty-eight muscles in the forearm and the hand, only a small set of muscles may satisfy the requirements of a donor muscle for a particular tendon-transfer surgery [8, 13, 15–20]. Many factors determine the choice of a donor muscle for a tendon-transfer surgery, including muscle excursion, force, sarcomere length, and angle of routing, together significantly limiting the available choice. While data from surgical outcomes on patients [21], cadaver studies, and simulation [9, 10, 22–26] have been used to fine tune tendon transfer procedures, surgeries are often chosen based on the surgeon's expertise [2, 4, 5, 21].

This experiment focuses on a tendon-transfer procedure for high median-ulnar palsy called the modified Brand procedure. The modified Brand procedure uses a tendon-graft that is split into four slips to connect the ECRL, a wrist extensor muscle, with the four FDP tendons (Fig. 2.1a) [3, 4, 27, 28]. The ECRL choice as a donor muscle helps maintain balance of the wrist with the ratio of forces applied by the extensor and flexor muscles [2]. The extensor carpi radialis brevis (ECRB), another extensor muscle, continues to provide wrist extension capability. Drawbacks with this procedure, such as adhesions of the tendons, potential clawing,

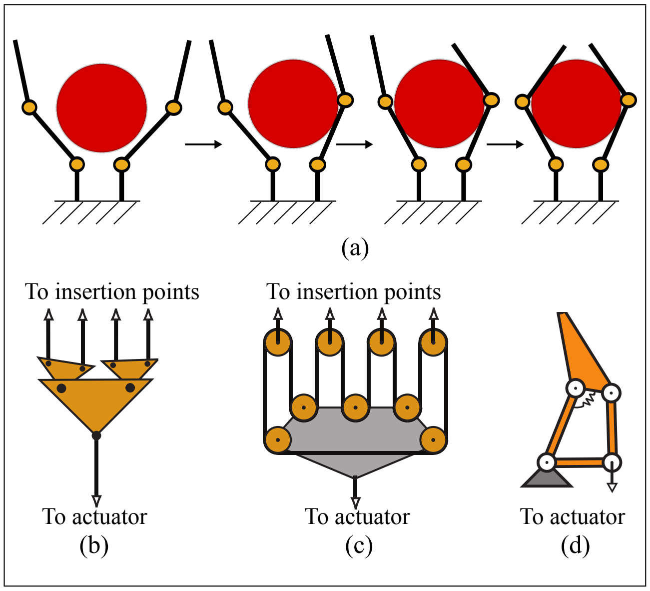

Figure 2.2: Passive adaptive mechanisms used in robotic hands. (a) Depiction of the grasping process with an adaptive coupling mechanism. One finger makes contact, then the other makes contact while the first is stationary ending with both fingers having full contact with the object. The (b) the seesaw and (c) pulley design for underactuation. (d) An example of an underactuated robotic finger with two degrees of freedom and one actuator.

wrist angulation, have been addressed [29]. However, the coupled movement of the fingers from having one muscle control all four fingers has not been addressed.

2.2.2 Adaptive coupling mechanisms in robotic hand design

The robotics and prosthetics community has been developing robot hands for over thirty years with the goal of achieving the dexterity of the human hand [30–34]. Traditionally, designers have chosen one motor per joint to keep actuation simple. However, this results in bulky hands that need extensive sensing modalities to provide input to the many actuators. Recently, the robotics community has explored the design of underactuated hands – hands with fewer actuators than degrees of freedom. While underactuation leads to reduced weight and size, the key benefit is the adaptive movement of hand joints during the grasping process (see Fig. 2.2a). At the core of underactuated robotic hands are passive adaptive coupling mechanisms that belong to the class of differential mechanisms, the same as those utilized in automobiles, which allow wheels driven by the same drive shaft to rotate at differing rates. The adaptive coupling mechanisms are used to route power from one actuator across multiple fingers, enabling the fingers to adapt independently to external contact, improving grasping behavior (see Fig. 2.2a) [30, 35–38]. Several types of adaptive mechanisms have been utilized in robotic hand design such as pulleys or seesaw mechanisms, each with specific benefits (see Figs. 2.2b, 2.2c and 2.2d) [39].

2.3 Applying adaptive mechanisms to tendon-transfer surgery

The proposed procedure for the tendon-transfer surgery for high median-ulnar palsy is to use a hierarchical pulley mechanism to attach the donor muscle to the recipient tendons (see Fig. 2.2c). All other surgical aspects remain the same as the conventional procedure. The key idea is that the adaptive mechanism will enable the fingers to independently close around the object and form a stable grasp (see Fig. 2.1c). An adaptive mechanism is expected to improve the grasp of the hand by enabling all the fingers to make contact with the object independently and reducing the propensity to slip off the object.

2.4 Methods

Experiments were conducted with cadavers to examine the ability of the hierarchical pulley mechanisms to enable the fingers to close completely on the object and the ability of the fingers to maintain the grasp as the actuation increased.

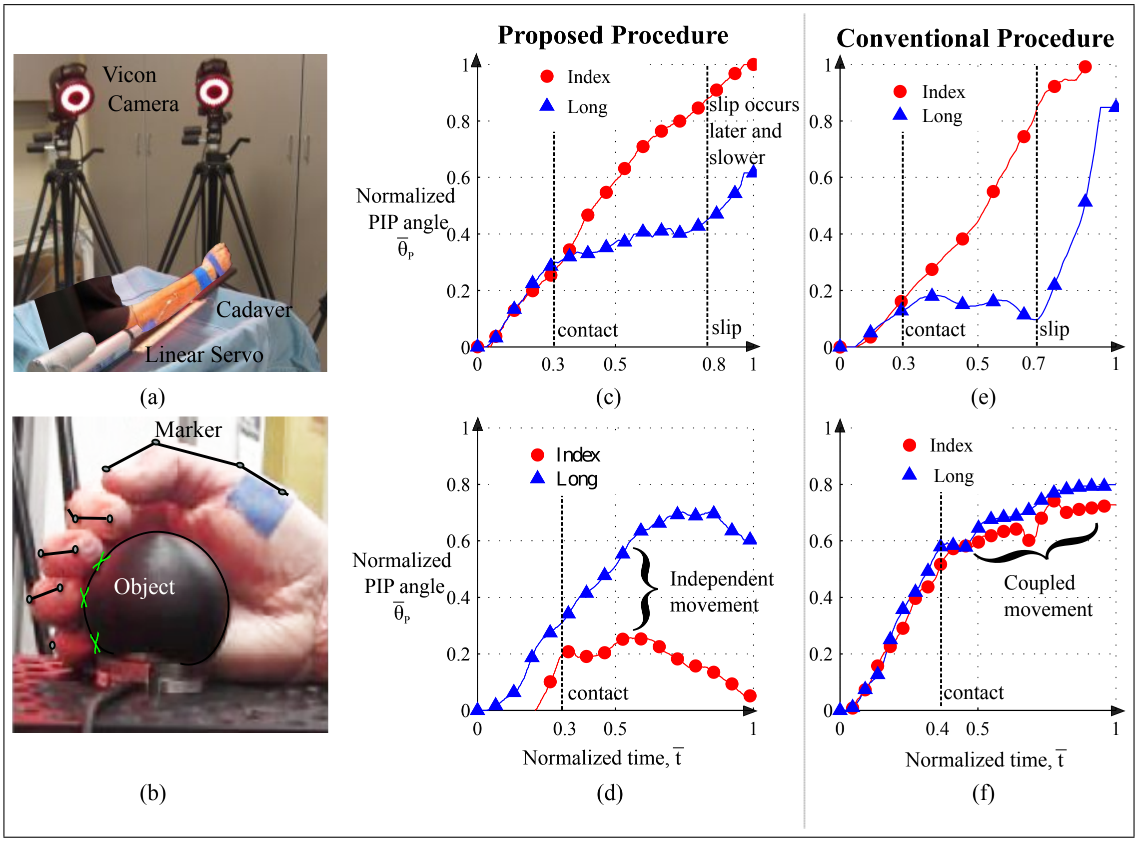

Figure 2.3: The experimental set up, PIP joint angle graphs for proposed and conventional procedures and cadaver hand demonstrating adaptive grasp. (a) Experiment set up (not all cameras shown). (b) Adaptive graph around sphere with proposed procedure. Index finger continues to move while other fingers have contact. Lines drawn over markers where joint angles were calculated. 'X' indicates finger contact. (c) Subject 1 with proposed procedure PIP joint angles, $\bar{\theta}_{pip}$ over time, $\bar{t}$.(d) Subject 1 with conventional procedure $\bar{\theta}_{pip}$ over $\bar{t}$. (e) Subject 3 with proposed procedure $\bar{\theta}_{pip}$ over $\bar{t}$. (f) Subject 3 with conventional procedure $\bar{\theta}_{pip}$ over $\bar{t}$.

2.4.1 Experimental set-up

The conventional tendon-transfer procedure and the proposed tendon-transfer procedure were conducted on three fresh-frozen cadaver right arms. The arm was secured to a horizontal test platform with the ulnar side along the table surface and the radial side away from it. The fingers were positioned at rest, with the sphere attached to the table surface in front of the palm (see Figs. 2.3a, 2.3b).

In the conventional procedure, the ECRL tendon was routed through the ulna and radial bones and directly sutured to the origin of all four FDP tendons with a "baseball" stitch and "end to side" technique. The proposed procedure was performed with the same donor muscle, but the ECRL tendon was stitched to the hierarchical pulley adaptive mechanism at pulley A (see Figs. 2.1c and 2.1d). The FDP tendon of the ring and small finger were stitched together and wrapped around pulley C, while the index and long finger were stitched together and wrapped around pulley B. Both pulleys were attached with a cable wrapped around pulley A. The ECRL tendon was then cut from the muscle belly and attached to a linear servo to produce tendon excursion. The linear servo moved 2.5mm each time the experimenter pressed a button. Even after the fingers closed in and the object was in the grasp, servo actuation was continued until the fingers slipped off the object, in order to see how stable the fingers were on the object (see Figs. 2.3a and 2.3b). Four-millimeter reflective markers were placed on the hand at the finger tips, the PIP, DIP, and MCP joints. In addition, markers were placed to indicate the ulnar and radial sides of the hand. A Vicon Workstation(http://www.vicon.com/) recorded the reflective marker points at 60 Hz using six cameras.

2.4.2 Analysis

The MCP, PIP, and DIP joint angles were calculated through vector analysis using the 3D marker coordinates. The markers on the ring and little fingers were occluded due to the arm posture. Thus, all the analysis was done on the index and long finger. The PIP joint angle, θ_p, captured the key aspect of the finger flexion during the grasping process and was used for the analysis. Angle and time data from each cadaver was normalized using the maximum angle, $\theta_{p,max}$, through which the PIP joints travelled across all fingers and both procedures,

$$\theta_{p,max} = \max\{\theta_{p,i}, \theta_{p,l}\},$$

during the grasping process. Normalized PIP angles were computed as:

$$\bar{\theta}_{p,i/l} = \frac{\theta_{p,i/l} - \theta_{p,i/l,min}}{\theta_{p,max} - \theta_{p,i/l,min}},$$

where $\bar{\theta}_{p,i/l}$ represents the normalized PIP joint angle for the index or long finger, $\theta_{p,i/l}$ the PIP joint angle for the index or long finger, and $\theta_{p,i/l,min}$ the minimum angle for the index or long finger during the grasping process. The normalized time is computed as

$$\bar{t} = \frac{t - t_s}{t_e - t_s}$$

where $\bar{t}$ represents the normalized time, t_s the state time of the trial, and t_e the end time of the trial. This normalized analysis is particularly useful in context of grasping, since the finger closing behavior is highly dependent on external factors, such as object shape and position. The finger movement and stopping point may differ across tests. Thus, it is difficult to compare absolute joint angles between trials and samples and the normalized angles were used. The slope, $\bar{m}$, of the joint angle change over time for each finger is computed through a moving average of the normalized slope, $m_{i/l}$, with a window size of 7. The normalized slope is computed:

$$m_{i/l} = \frac{\bar{\theta}_{i/l,t+5} - \bar{\theta}_{i/l,t}}{\Delta t}$$

where $\bar{\theta}_{i/l,t+5}$ is the normalized angle five steps forward in time. All significance tests on slopes were conducted using t-tests at the $p = 0.05$ level to identify significant events during the grasping process.

2.5 Results

The time history of the normalized joint angles of the index $\bar{\theta}_{p,i}$ and long finger $\bar{\theta}_{p,l}$ for the proposed and conventional procedures for subject 1 and subject 3 of the cadaver samples are shown in Figs. 2.3c, 2.3d, 2.3e and 2.3f. Three clear events of the grasping process were noticed:

Table 2.1: Summary of finger movement and behavior for the test interval. Normalized and actual time specified for the stationary period and rate of change of PIP joint angle change for the test period. Stationary periods are characterized by a threshold of 0.4.

Proced.	Subject	Finger	Time, t		Normalized Slope, $\bar{m}$		PIP Angle, θ_p(deg)		
			Absolute (sec)	Normalized, $\bar{t}$	Magnitude	Characterization	Initial	Final	$\Delta\theta_p$
Pulley	1	Index	0.0 : 12.5	0.0 : 1.0	1.0	initial movement	34.8	82.0	47.2
		Long	0.0 : 3.8	0.0 : 0.3	1.0	initial movement	41.0	55.3	14.3
			3.8 : 10.0	0.3 : 0.8	0.0	stationary	55.3	61.1	5.8
			10.0 : 12.5	0.8 : 1.0	0.8	slip	61.1	70.1	9.0
	2	Index	0.0 : 6.3	0.0 : 0.5	0.9	initial movement	39.4	59.6	20.2
			6.3 : 10.3	0.5 : 0.8	0.0	stationary	59.6	60.2	0.6
			10.3 : 11.5	0.8 : 0.9	1.4	slip	60.2	66.7	6.5
		Long	0.0 : 3.8	0.0 : 0.3	1.6	initial movement	39.5	61.0	21.5
			3.8 : 7.5	0.3 : 0.6	0.0	stationary	61.0	61.2	0.2
			7.5 : 11.4	0.6 : 0.9	0.9	slip	61.2	72.3	11.1
	3	Index	2.5 : 3.8	0.2 : 0.3	2.0	initial movement	46.2	54.5	8.3
			36.8 : 10.0	0.3 : 0.8	0.0	stationary	54.5	53.1	-1.4
		Long	0.0 : 8.8	0.0 : 0.7	1.0	initial movement	32.4	62.8	30.4
			8.8 : 12.75	0.7 : 1.0	0.0	stationary	62.8	59.0	-3.8
Suture	1	Index	0.0 : 7.3	0.0 : 1.0	1.0	initial movement	42.0	82.1	40.0
		Long	0.0 : 4.0	0.0 : 0.3	1.0	initial movement	44.2	50.7	6.5
			4.0 : 5.3	0.3 : 0.7	0.0	stationary	50.7	47.8	-2.9
			5.3 : 7.3	0.7 : 1.0	1.2	slip	47.8	75.7	27.9
	2	Index	4.0 : 5.3	0.3 : 0.4	1.7	initial movement	60.3	68.5	8.2
			5.3 : 13.3	0.4 : 1.0	0.0	stationary	68.5	65.0	-3.5
		Long	2.8 : 4.0	0.2 : 0.3	3.6	initial movement	57.4	74.8	17.4
			4.0 : 13.3	0.3 : 1.0	0.0	stationary	74.8	80.7	5.9
	3	Index	0.0 : 7.3	0.0 : 0.4	1.3	initial movement	41.0	62.8	21.8
			7.3 : 18.2	0.4 : 1.0	0.0	stationary	62.8	69.3	6.5
		Long	0.0 : 7.3	0.0 : 0.4	1.2	initial movement	34.8	52.5	17.7
			7.3 : 18.2	0.4 : 1.0	0.0	stationary	52.5	60.7	8.2

1. The time a finger contacted the object
2. The time a finger became stationary
3. The time a finger slipped off the object

These critical events of the grasping process were identified with significant changes in the slope $\bar{m}$ during the grasping process. Table 3.1 gives the slopes and the times when different events took place.

Conventional Procedure

In the conventional procedure, the time periods that each digit was stationary depended on all the other digits being stationary, which indicates coupled movement. From Table 3.1 Subject 1 had a slope $\bar{m}_l = 1.2$ from $0.7 \leq \bar{t} \leq 1.0$ the period after the contact period. Both fingers for subject 2 were stationary from $0.4 \leq \bar{t} \leq 1.0$. Subject 3 shows coupled movement with the index and long fingers being stationary $0.4 \leq \bar{t} \leq 1.0$. The slopes of the initial movement were similar ($\bar{m}_i = 1.3$ and $\bar{m}_l = 1.2$).

Proposed Procedure

Subject 1 had a slope $\bar{m}_l = 0.8$ from $0.8 \leq \bar{t} \leq 1$ for the long finger, 30% less slope than the conventional procedure. Independent movement for the proposed procedure on subject 2 is shown with the independent stationary periods for the index finger interval $0.5 \leq \bar{t} \leq 0.8$ and long finger interval $0.3 \leq \bar{t} \leq 0.6$. Subject 2 also has a differing slope for the index finger ($\bar{m}_i = 1.4$ from $0.8 \leq \bar{t} \leq 0.9$) and the long finger ($\bar{m}_l = 0.9$ from $0.6 \leq \bar{t} \leq 0.9$) for the proposed procedure. Subject 3 shows independent movement with stationary index finger on the interval $0.3 \leq \bar{t} \leq 0.8$ and stationary long finger $0.7 \leq \bar{t} \leq 1.0$. Initial movement for subject 3 vary for the proposed procedure with slopes $\bar{m}_i = 2$ and $\bar{m}_l = 1$ for the index and long finger.

2.6 Discussion and Future Work

Two distinct aspects of finger movement were noticed between the conventional and proposed procedure for high median-ulnar palsy tendon transfer surgery: (1) finger movement when establishing contact and (2) finger slip during contact. Finger movement when establishing contact is critical because it indicates how the fingers close around the object, the type of grasp the fingers produce, and the forces they can apply on the object. Ideally, all fingers must continue to close even after one finger makes contact to adequately grasp an object. Also, a finger that slips off the object after contact is established with a rapid change in angle is an indicator for a low quality grasp.

For the proposed procedure, the fingers show adaptive movement by moving independently even while establishing contact (see Fig. 2.3c, 2.3d and Table 3.1). The adaptive movement of the fingers enabled by the implanted adaptive coupling mechanism enables the hand to grasp objects that are varied in size and shape increasing the quality of the grasp. This experiment has demonstrated adaptive movement in grasping a sphere and is expected to apply to other objects as well. Differing time intervals of stationary fingers show that even when one finger is not moving the other one continues to close, enabling the finger to establish a stable grasp. In the proposed procedure, the fingers slipped off the object at different rates and at different times, further emphasizing adaptive movement for the two fingers.

The adaptive coupling mechanism decreases the slip rate of fingers off of the object, indicating a higher grasp quality than with the conventional procedures indicating that the grasps using the adaptive mechanism can sustain larger gripping forces.

Further studies will be performed in the near future with the following modifications to the current experiments. Smaller pulleys will be implanted that fit within the forearm more effectively. The sphere will be placed on a 6-axis force sensor to measure the X, Y, and Z forces in addition to the torques applied by the grasp on the object. This will help evaluate the stability of the grasp by directly measuring force balance. A larger sample size of cadaver arms will also be used to evaluate performance across a larger sample set.

Chapter 3: Implanted Differential Mechanisms Improve Hand Function after Tendon-Transfer Surgery: A Cadaver-Based Study

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Purpose: **To investigate a new tendon-transfer surgical procedure that implants passive a hierarchical pulley system for attaching multiple tendons to a single donor muscle in place of the current technique that directly sutures the tendons to the donor muscle. This new pulley-based procedure is expected to improve hand function when compared with the current suture-based procedure in physical-interaction tasks.**
Methods: **The tendon-transfer surgery for high median-ulnar palsy is exemplar for this study. The pulley-based and suture-based procedures were conducted on six cadaver hands. Post-surgery finger movement and actuation force were measured in a grasping task. Cadaver fingers closed around a stemmed sphere by pulling the ECRL tendon with a linear servo. A five-camera motion capture system measured finger movement, and a single-axis load cell measured the actuation force applied by the servo.**
Results: **When compared with the suture-based procedure, the pulley-based procedure: (i) required 55% less actuation force to close the fingers around the object; (ii) improved the fingers individual adaptation to the objects shape during the grasping process and reduced finger slip on the object. There was no difference between the two procedures in finger movement before the fingers contacted the ball. However, once some fingers contacted the ball during the grasping process, the pulleys reduced the slip of fingers ($2.99°0.28°$ total movement after contact) that were in contact with the ball when compared with the conventional procedure ($6.22°0.66°$ total movement after contact).**

Conclusions: **Using an implanted differential mechanism for attaching tendons to muscles in the tendon-transfer surgery for high median-ulnar palsy improves hand function in grasping tasks when compared with the current procedure. This indicates the need to explore the use of implanted differential mechanisms in other hand surgeries as well.**
Type of Study/ Level of Evidence: **Therapeutic Study**

3.1 Introduction

Tendon-transfer surgeries are performed to partially restore hand function for a variety of conditions such as stroke, paralysis, spinal muscle atrophy, nerve or muscle trauma, and congenital disorders.[1−5] The surgical procedure involves re-routing one or more tendons from an affected muscle and directly suturing it to a functioning donor muscle.[2,3] Based on records of the United States American Hospital Association, there are over 20,000 upper-extremity tendon transfer procedures in the United States annually. Also, 22% of hand surgeries performed in the military are tendon transfer surgeries[6] and have been extensively used since World War II.[7]

In at least fifteen types of tendon-transfer surgeries, a single donor muscle is directly sutured to multiple recipient tendons.[1,3] One such procedure is the tendon-transfer surgery for high median-ulnar palsy, a condition where all four flexor digitorum profundus (FDP) muscles are paralyzed, preventing the fingers from completely closing.[2] The current procedure to restore finger flexion for this condition (the modified Brand procedure[2]) sutures all four FDP tendons to the extensor carpi radialis longus (ECRL) (see Fig. 1b).[1−4] However, this procedure has a drawback. The suture directly couples the movement of all four fingers and prevents the fingers from adapting (conforming) individually to an objects shape during grasping tasks[1,3,8,9] limiting the activities of daily living and long term patient wellness.[10−13] Specifically, even if one finger makes contact with the object during the grasping process, it is forced to flex when the other fingers close on the object.

The tendon-transfer surgery for median-ulnar palsy is used to investigate a new

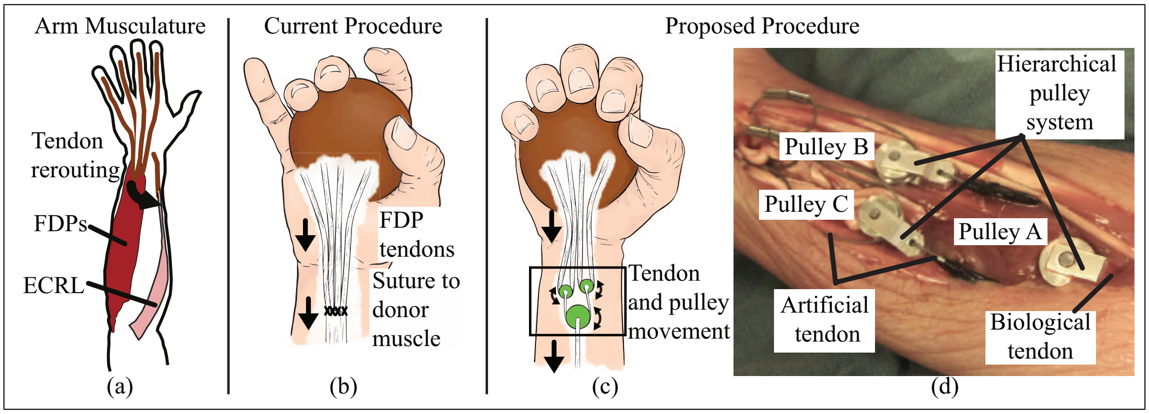

Figure 3.1: (a) Hand musculature and tendons and tendon-transfer surgery for high median-ulnar nerve palsy, where tendons are transferred from the FDP to the Extensor carpi radialis longus (ECRL) muscle. (b) Current tendon-transfer procedure using sutures. (c) The proposed procedure using a pulley mechanism. (d) Prototype pulleys implanted in cadaver forearm for study.

surgical procedure that uses a hierarchical pulley system for attaching the donor muscle to the recipient tendons in place of the direct suture to address the drawback relating to the coupling of finger movement (see Fig. 1c, 1d). Inspiration for applying these mechanisms in hand surgery comes from their successful implementation in robotic hand design[14] for routing forces and movement from a single motor to multiple digits (see [15] for other examples). When used in the human hand, the pulleys are expected to enable the joints actuated by the recipient tendons to adapt independently during grasping tasks while retaining advantages of the suture-based surgical procedure. The additional passive degrees of freedoms offered by the pulleys (translation and rotation inside the forearm) are expected to enable each finger to adaptively close around an object (see Fig. 1b). Adaptability in grasping is quantified as the relative movement of fingers that have not contacted the object compared with movement of fingers that contacted the object.[16]

The improved post-surgery hand function resulting from using a pulley system to attach the tendons to a donor muscle instead of the suture will be tested using two hypotheses based on cadaver experimental data:

Hypothesis I. The pulley-based procedure reduces actuation force requirement when compared with the suture-based procedure.
Hypothesis II. The pulley-based procedure improves adaptability of finger movement in a grasping task compared to the suture-based procedure.

3.2 Materials and Methods

Both the suture-based and pulley-based tendon-transfer procedures were conducted on six cadaver arms, four right (subjects 1-4) and two left (subjects 6 and 7), with mean age of 90.6 ± 2 years. The arm was secured with bone screws to a horizontal test rig with the ulnar side along the table surface (see Figure 2a). The fingers were set in their rest position. A 3.5 cm diameter sphere on top of a 2.5 cm height stem and attached to the table surface was placed in front of the palm. The experiment is not intended to analysis grasp quality, so the palm and thumb were not wrapped around the object. A stemmed sphere was used to increase diversity in finger movement around the object. This increased adaptive finger movement for a better assessment of the two procedures.

Movement of the cadaver fingers was created using a linear servo that pulled on the ECRL tendon, thus acting as the ECRL muscle. A single-axis load cell was placed between the linear servo and the ECRL tendon in order to measure the actuation force applied. For each arm, the suture-based procedure was performed first and the finger movement during a grasping task measured. Then the pulley-based procedure was performed and finger movement measured on that arm. In the suture-based procedure, the ECRL tendon was routed through the ulna and radial bones and directly sutured to the origin of all four FDP tendons with an ”end to side technique2. The ECRL tendon was cut from the muscle belly and attached to the linear servo to produce tendon excursion.

The differential mechanism used in these experiments consisted of three pulleys arranged in a hierarchical fashion with a single proximal pulley attached to two distal pulleys (see Fig 1c, Fig 2b). In this prototype, the proximal pulley had a diameter of 20 mm and was 10 mm thick, weighing 4.6 grams. The distal pulleys were 15 mm in diameter and 10 mm thick, weighing 3.7 grams. The pulley-based procedure was performed with the ECRL tendon stitched to a cable attached to proximal pulley A of the hierarchical pulley mechanism (see figure 5.1c and 5.1d). The ring and small finger FDP tendons were stitched to a cable wrapped around distal pulley C, while the index and long finger tendons were stitched to a cable wrapped around distal pulley B. The heads of both pulleys were attached with a cable and wrapped around pulley A. While the prototypes were made of aluminum for cost and manufacturability, future versions will be made of bio inert material and have a thinner profile. The cables were made of pre-strained 0.86 mm nylon-coated stainless steel.

Data streams from the single axis load cell, motion-capture system, and linear servo were synchronized using National Instruments Labview (http:// www.ni.com/ labview/) software. Each time the experimenter pressed the actuation button, the linear servo moved 1.8mm. The total servo travel never surpassed the ECRLs optimal fiber excursion length of 8.1 cm, never exceeding the maximum ECRL force of 304 N.[17] Servo actuation was continued until the fingers had reached full grasp or a maximum of 150 N in actuation force was reached.

Four-millimeter reflective markers were placed on the hand at the finger tips, distal interphalangeal (DIP) joints, proximal interphalangeal (PIP) joints, metacarpal phalangeal (MCP) joints, and carpometacarpal (CMC) joints (see figure 3.2c). A five-camera motion-capture system (OptiTrack – http:// www.naturalpoint.com/ optitrack/) recorded the marker positions at 30 Hz. A separate video camera was also used to record each trial. After each trial, the servo was reset while keeping the ECRL tendon taut, and the fingers were manually returned to the rest position. An average of 5 ± 2 trials were conducted for each cadaver and each procedure. Data was only considered when all parameters were met (sufficient motion capture data, arm movement in test apparatus, suture break out, fingers reset properly).

Note that in this work, investigation on each cadaver involved first conducting the suture-based procedure and then conducting the pulley-based procedure, and the sutured section of tendon was removed before the pulley-based procedure was

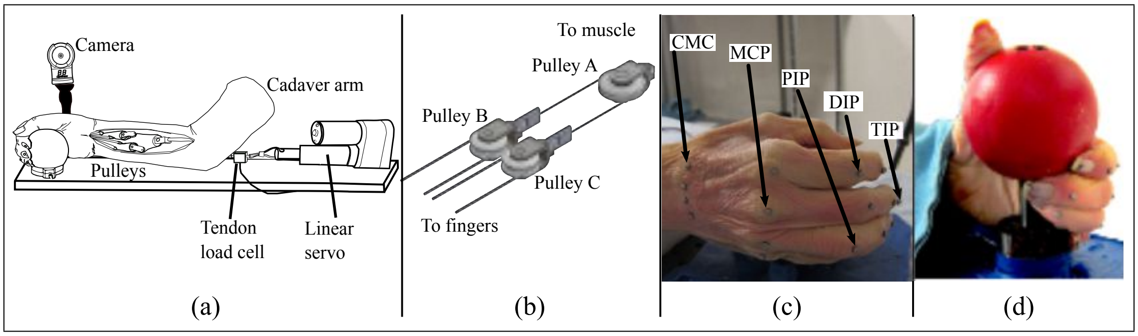

Figure 3.2: (a)Proposed experimental set-up for evaluating post-surgery grasp capability. (b) Initial pulley design for concept test. (c) Marker placement illustration on finger tip, distal interphalangeal joint, proximal interphalangeal joint, metacarpal phalangeal joint and carpometacarpal joint. (d) Pulley-based procedure cadaver hand grasping stemmed ball.

performed. The suture-based procedure was performed first to ensure that the tendon lengths were sufficient to route the ECRL tendon. The cadavers were thawed for a minimum of twenty-four hours and had reached a steady-state temperature before the first procedure was conducted on them. It is unlikely that the order of procedures would have affected the results.

3.2.1 Analysis

3.2.1.1 Actuation Force

To analyze the force required by the ECRL to grasp the sphere, the actuation force applied by the servo was recorded at the point where all fingers made contact with the ball for each trial by the single-axis load cell. The actuator force measured for each procedure and subject were averaged across the trials, such that Fsi represented the mean actuator force for the i-th subject for the suture-based procedure, and Fpi the mean actuator force for the i-th subject for the pulley-based procedure. The ratio $R_{fi} = \frac{F_{pi}}{F_{si}}$ of the mean actuation forces between the two procedures was computed for each subject,i, in order to test hypothesis I. It was expected that

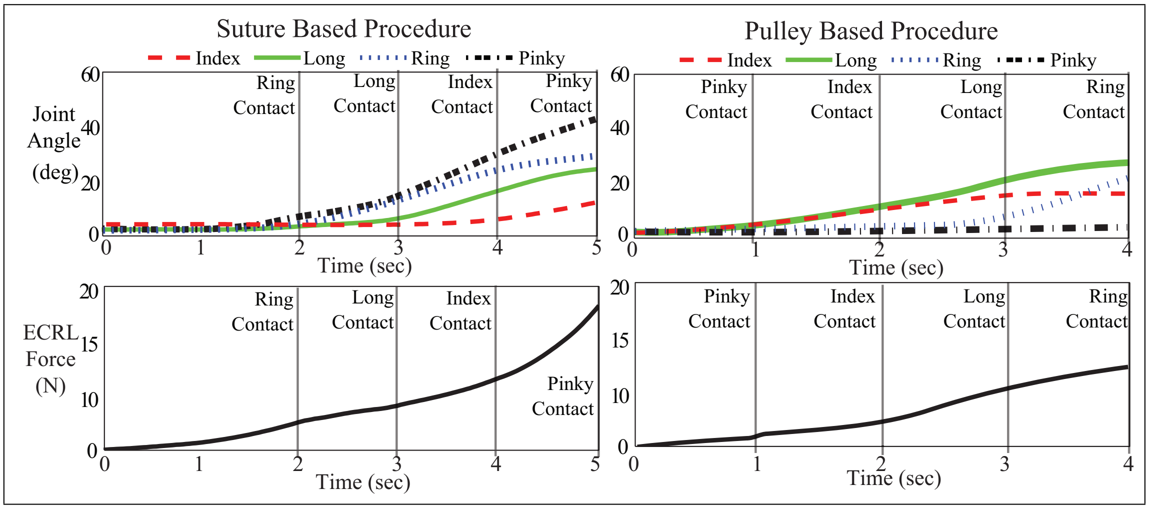

Figure 3.3: Time history profiles of example subjects for a specific trial showing the summation of joint angles and actuation force profiles for the suture based procedure and pulley based procedure. Contact times of the fingers are indicated.

this ratio would be less than one ($R_{fi} < 1$), given that the pulley system in the pulley-based procedure enables the fingers to better adapt to the object surface with reduced muscle force. The ratio of forces R_{fi} was averaged across all subjects to compute R_F. Statistical significance of the ratio data was tested with a one-sided paired t-test.

The force is measured when all fingers that make contact on the ball have made contact (shown by example trial in 3.3). During each trial the servo mechanism was pulled beyond the point that all fingers made contact on the ball to a cut off force, but data beyond the point that all fingers made contact with the ball was not analyzed.

3.2.1.2 Finger Movement during Grasping

The finger movement during a trial was processed using the OptiTrack Motive motion capture software to create time history data of each of the joint angles for each finger. Each fingers movement during the grasping process was quantified as

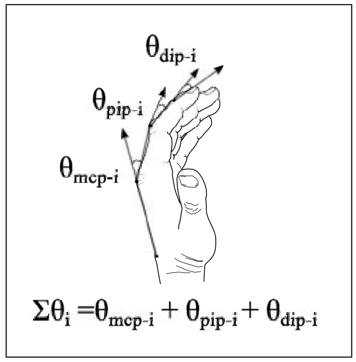

Figure 3.4: Summation of joint angles for each finger calculated from motion capture data for each joint.

the sum of movement of all the joints ($\sum \theta_i = \theta_{MCP-i} + \theta_{PIP-i} + \theta_{DIP-i}$, where i specifies the finger, see figure 3.4). The digital videos were analyzed to note the time that each finger contacted the ball, which defined the stages of the grasping process.

The grasping process during each trial was split into four phases based on the sequence of fingers making contact: phase 1: Beginning movement to first finger contact; phase 2: period between first finger contact and second finger contact; phase 3: period between second contact and third contact; phase 4: period between third finger contact and fourth finger contact (full contact). An example with each segment illustrated is shown for subject 6 in figure 3.5. Note that in some trials, some fingers make contact with the object at the same time. Such trials would have fewer grasping phases.

For each of the grasping phases, the summation of the changes in joint angles, $\sum \theta_c$, for the fingers that established contact and the fingers that had not established contact, $\sum \theta_{nc}$, were computed (shown in figure 3.4) for each segment of time. It was expected that$\sum \theta_c$ would be lower for the pulley-based procedure when compared with the suture-based procedure and that $\sum \theta_c$ for would be less than$\sum \theta_{nc}$ the pulley-based procedure.

This would indicate two things: (i) less slip of the fingers on the object during the grasping process, and (ii) better adaptability of the fingers to the objects shape

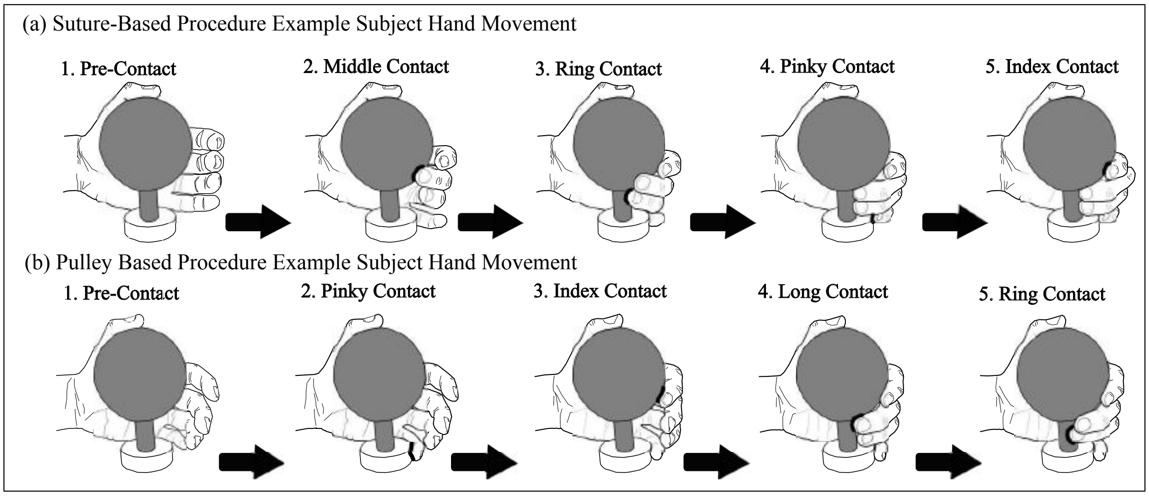

Figure 3.5: Illustration of the grasping process through each identified phase of finger contact. Finger contact identified with a darker line. (a) Suture based procedure. (b) Pulley-based procedure.

during the grasping process. For the suture-based procedure, $\sum \theta_c$ is expected to be equal to $\sum \theta_{nc}$, showing coupled finger movement through the grasping process. The finger movement for the fingers that have not yet contacted the ball $\sum \theta_c$ will also be compared for the suture-based procedure and pulley-based procedures, in order to verify that the pulleys do not obstruct finger movement. Statistical significance was determined with an independent sample t-test.

3.3 Results

A total of 29 trials for the suture-based procedure and 32 trials for the pulley-based procedure were analyzed across all of the subjects. Trials were omitted if the motion capture data could not be trajectorized due to marker occlusion or confusion. This is because the markers placed on the fingers can come very close to each other during the grasping process. The variance between subjects is not analyzed because of insufficient amount of trials.

3.3.1 Hypothesis I: Pulley-based procedure reduces actuation force requirement when compared with the suture-based procedure

Figure 3.6 shows the mean actuation force required for establishing full contact between the fingers and the object for the pulley-based and the suture-based procedure. A paired t-test showed that the actuation force required following the pulley-based procedure was significantly lower than the force required for the suture-based procedure for each subject (mean of the ratio of forces across the subjects for ball 4 $R_F = 0.55 \pm 0.12, p - value : 0.03$).

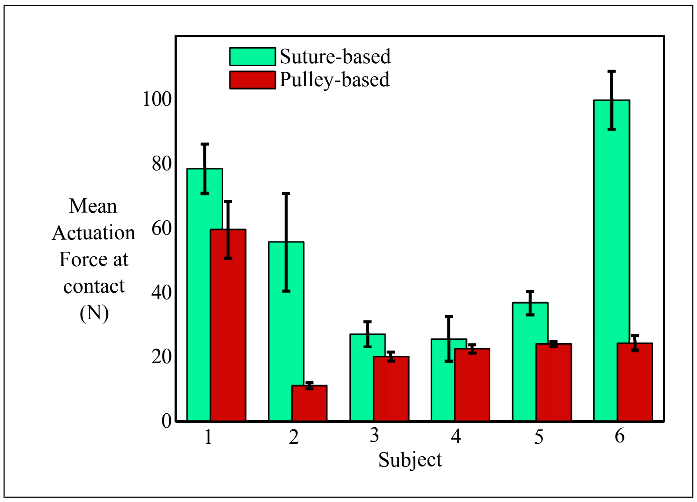

Figure 3.6: Mean actuation force across trials at full contact for each procedure and each subject. Pulley-based procedure has a lower muscle actuation force for all trials than the suture-based procedure.

3.3.2 Hypothesis II: Adaptive finger movement in the proposed procedure

For the 32 trials for the pulley-based procedure, there were 73 phases during the grasping process between the time when finger(s) made contact on the object and the subsequent finger(s) made contact (compared to an expected 96 if all fingers

Table 3.1: Hypothesis II: Summation of joint angle change. Mean summation of joint angle change, $\sum\bar{\theta}_c$, for each finger that has made contact with the object and $\sum\bar{\theta}_{nc}$ for each finger that has not made contact with the object for pulley based procedure and suture based procedure. Similar numbers indicate similar movement in the fingers, whether in contact or not. [a] p-value $< 10^{-7}$, [b] p-value $< 10^{-6}$, other values were not significantly different in joint angle change.

Procedure	Contacted finger average angle change (deg ± s. error)	Not yet contacted finger average angle change (deg ± s. error)
Pulley-based	$2.99°(0.28°)^{a,b}$	$6.42°(0.57°)^{a}$
Suture-based	$6.22°(0.66°)^{b}$	$6.14°(0.75°)$

touch at separate times). The 29 trials for the suture-based procedure had 55 phases during the grasping process (compared to 87 expected). The remaining phases could not be analyzed due to incomplete motion-capture data. The joint angle changes for both procedures for fingers in contact with the object and for fingers that had not yet made contact with the object are presented in Table 3.1.

The pulley-based procedure mean joint angle changes were $\sum\bar{\Delta}\theta_c = 2.99° \pm 0.28°$ and $\sum\bar{\Delta}\theta_{nc} = 6.42° \pm 0.57°$, were significantly different $(p - value < 10^{-7})$. The suture-based procedure mean joint angle changes, $\sum\bar{\Delta}\theta_c = 6.22° \pm 0.66°$ and $\sum\bar{\Delta}\theta_{nc} = 6.14° \pm 0.75°$, were not significantly different (p value: 0.9). The mean values of $\sum\bar{\Delta}\theta_c$ across all six subjects for the pulley-based procedure were significantly less $(p - value < 10^{-6})$ than the suture-based procedure.

3.4 Discussion

Since grasping is a fundamental aspect of daily living, the benefits of tendon-transfer surgery need to be quantified in the context of grasping tasks where the fingers physically interact with the environment. However, prior work evaluates post-surgery hand function only qualitatively[1,18] or quantitatively for finger and wrist movement in free space without external contact[9,17]. The experiments in this paper begin to address this issue by quantitatively confirming our hypotheses that the pulley-based procedure leads to better grasping capability when compared with the suture-based procedure.

A key aspect of the grasping process is that it is difficult to predict or ensure which finger will make first contact with the object and where on the object it will make contact due to uncertainty in hand position or object shape. A healthy person overcomes this uncertainty through control over individual finger flexion. However, this is a significant issue for those with disabilities, since they may not have individualized control of finger flexion and they may be re-learning to use their musculature after a tendon-transfer surgery. This happens in the case of patients following the current suture-based procedure for high median-ulnar palsy. Since the suture couples finger flexion, the fingers do not adapt individually to the objects shape, resulting in the patient having to perform awkward wrist and arm movements to ensure a secure grasp. As the results show, the pulley-based procedure enables the joints actuated by the recipient tendons to adapt individually (through translation and rotation of the pulleys within the arm) during grasping tasks without losing the advantages of the suture-based surgical procedure. This enables a more natural hand grasping motion post-surgery.

In terms of hypothesis I, the pulley-based procedure enables the fingers to use 55% of the actuation force required following the suture-based procedure. The pulley system enables each of the fingers to make contact on the ball with low muscle force. In contrast, the suture-based procedure couples the movement of the fingers. Thus, if multiple fingers make contact with the object in a staggered fashion, then the muscle force must stretch the tendons of the fingers that have already established contact with the object in order to close the fingers that have not yet made contact. Not only does this require greater muscle strength from the patient, but repeated stretching of the finger tendons will lead to poor hand function long-term. Another potential benefit of the reduced force requirement after the pulley-based procedure is that it increases the number of potential muscle donors; that is, a weaker muscle could be used as a donor muscle as well. Finally, the variation in the force required to close the fingers is also significantly lower for the pulley-based procedure. This indicates that the patient would be able to use a consistent actuation force for grasping following the pulley-based procedure when compared with the suture-based procedure, making it easier to use the muscle following surgery. The pulley-based procedure has potential to minimize the difference between individual finger tip forces during the grasping process, which will lead to a better grasp. This will be explored in future experiments.

In terms of hypothesis II, the pulley-based procedure leads to significantly better adaptive finger movement in terms of enabling the fingers to individually wrap around the object even when actuated by just one muscle. This can be understood through four major comparisons between the pulley-based and suture-based procedure based on the summation of joint angles of the finger(s) that make contact with the object and those that did not make contact (see table 1). First, for the pulley-based procedure, the mean joint angle change for those fingers that make contact $\sum \Delta\theta_c$ is significantly lower than the mean joint angle change for the fingers that have not contacted $\sum \Delta\theta_{nc}$. This comparison shows that the fingers that made contact are moving much less than the fingers that did not make contact. Second, mean joint angle change for the suture-based procedure $\sum \Delta\theta_c$ is similar to the mean joint angle change for the fingers that have contacted, showing that the fingers have coupled movement even after contact has been made. Third, the mean joint angle change for those fingers that make contact, $\sum \Delta\theta_c$, across all six subjects for the pulley-based procedure was significantly less than for the suture-based procedure. This indicated that the fingers that made contact after the pulley-based procedure do not slip as much on the object as the fingers after the suture-based procedure. Fourth, the fingers that did not make contact for the pulley-based and suture-based procedure have a similar change in joint angles indicating that the fingers are moving the same distance between the two procedures and the pulley-based procedure does not degrade the ability to move the fingers. To summarize these findings over the entire trial, the first finger to make contact on the ball moved 3°on average over each contact phase, which is

9°of movement over the entire trial. The first finger to make contact on the ball through the suture-based procedure moved 6°on average for each contact phase, which is over 18°of movement over the entire trial.

These promising results show the pulley-based tendon transfer surgery improves hand function after tendon-transfer surgery. However, more work is required to prepare it for long-term in vivo use. First, when the pulley-based procedure is used in clinical practice, biocompatible materials that reduce fibrosis and methods for attaching biological and artificial tendons would be required. There are encouraging results from biomaterials groups[19] and surgical companies for making attachments between synthetic and biological material (http://www.ortotech.com/). Future work will include conducting an examination of the grasp force on the object, using a larger number of cadaver samples, and improving mechanism design.

3.5 Acknowledgements

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Chapter 4: Results for All Four Objects

The results for the actuation forces (hypothesis I) and adaptive finger movement (hypothesis II) for all four balls are described in this chapter. Table 4.1 identifies the number of trials and phases of finger contact within the grasp sequence. Trials were omitted if the motion capture data could not be trajectorized due to marker occlusion or confusion. This is because the markers placed on the fingers can come very close to each other during the grasping process. An ideal grasp has three phases where each finger to contact the object makes contact at a separate time. However, many of the trials have fingers contacting at the same time or not contacting at all, which changes the number of phases in the grasping sequence for each ball.

Table 4.1: Number of trials and segments analyzed for each ball.

Ball	Procedure	Trials	Phases
1	Pulley	35	85
1	Suture	31	75
2	Pulley	38	84
2	Suture	34	78
3	Pulley	29	69
3	Suture	29	76
4	Pulley	32	73
4	Suture	29	55
Avg	Pulley	33.5± 1.9	77.8±4.0
Avg	Suture	30.8±1.3	71.0±5.4

Table 4.2: Number of trials and segments analyzed for each ball.

Sphere	Force Ratio, $R_F = \frac{pulley force}{suture force}$	p-value
1	0.53 (0.11)	0.02
2	0.70 (0.09)	0.04
3	0.48 (0.07)	0.03
4	0.55 (0.12)	0.03
mean	0.57(0.05)	$< 10^{-7}$

4.1 Hypothesis I: Pulley-based procedure reduces actuation force requirement when compared with the suture-based procedure

Figure 4.1 shows the mean actuation force required for establishing full contact between the fingers and the object for the pulley-based and the suture-based procedure. A paired t-test showed that the actuation force required following the pulley-based procedure was significantly lower than the force required for the suture-based procedure for each subject and all balls. The mean force ratio of pulley-based actuation force over suture-based actuation force, R_F, and p-value for all balls is shown in table 4.2. The mean ratio of pulley-based procedure over the suture based-procedure actuation force for all subjects and all four balls is $R_F = 0.57 \pm 0.05$ ($p < 10^{-7}$).

4.2 Hypothesis II: Adaptive finger movement in the proposed procedure

The joint angle changes for both procedures for fingers in contact with the object and for fingers that had not yet made contact with the object are presented in Table 4.3 for all subjects and all four objects.

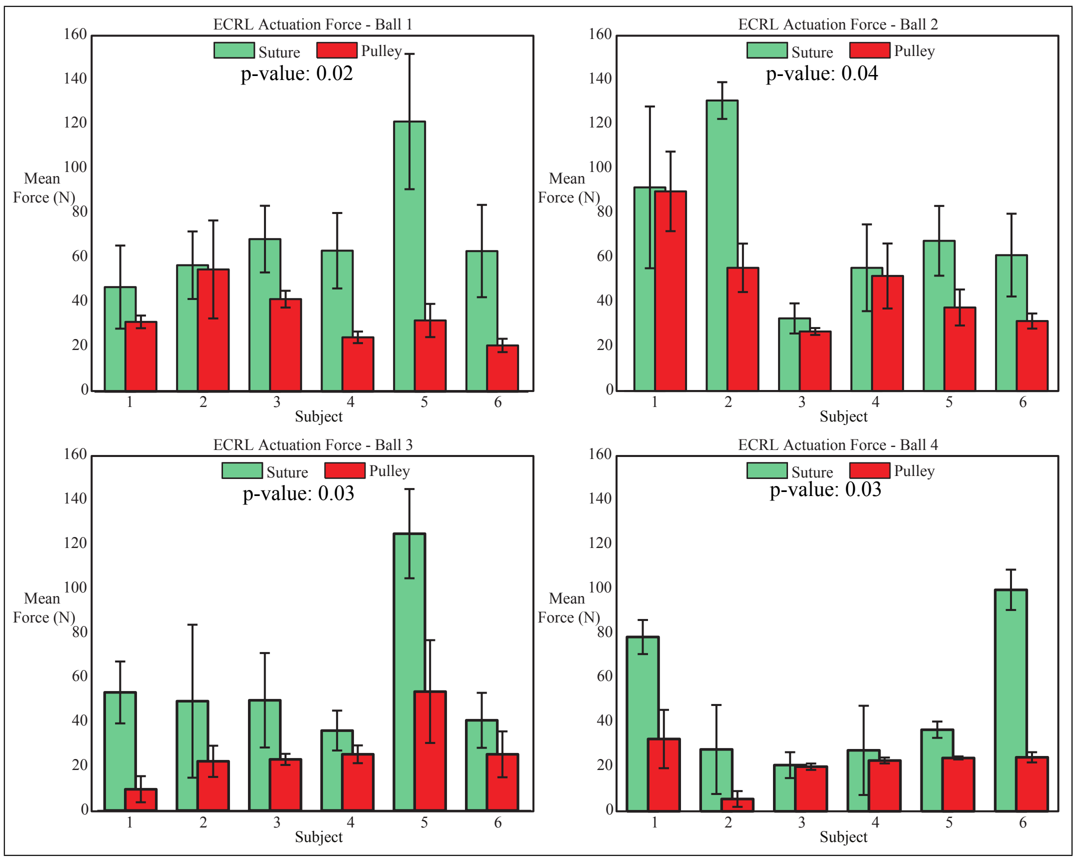

Figure 4.1: Mean actuation force across trials at full contact for each procedure and each subject for all four objects. Pulley-based procedure has a lower muscle actuation force for all trials than the suture-based procedure. P-value for all balls is 10^{-7}

Table 4.3: Hypothesis II: Summation of joint angle change. Mean summation of joint angle change, $\sum\bar{\theta}_c$, for each finger that has made contact with the object and $\sum\bar{\theta}_{nc}$ for each finger that has not made contact with the object for pulley based procedure and suture based procedure. Similar numbers indicate similar movement in the fingers, whether in contact or not. $^{a-e}$ indicates values that are not significant (p-value is over 0.05).

Ball #	Procedure	Contacted finger average angle change (deg ± s. error)	Not yet contacted finger average angle change (deg ± s. error)
Ball 1	Pulley	4.42°(0.43°)	6.10°(1.14°)
	Suture	7.50°(0.61°)	9.81°(0.66°)
Ball 2	Pulley	4.35°(0.46°)	9.05°(0.65°)
	Suture	7.29°(0.61°)^{a}	7.04°(0.66°)^{a}
Ball 3	Pulley	3.17°(0.30°)^{b}	3.50°(0.37°)^{b}
	Suture	4.31°(0.50°)^{c}	5.59°(0.47°)^{c}
Ball 4	Pulley	2.99°(0.28°)	6.42°(0.57°)^{d}
	Suture	6.69°(0.63°)^{e}	6.43°(0.68°)^{d,e}

4.2.1 Ball 1

The pulley-based procedure mean joint angle changes were $\sum\bar{\Delta}\theta_c = 4.42° \pm 0.43°$ and $\sum\bar{\Delta}\theta_{nc} = 6.10° \pm 1.14°$, were not significantly different (p-value: 0.2). The suture-based procedure mean joint angle changes, $\sum\bar{\Delta}\theta_c = 7.50° \pm 0.76°$ and $\sum\bar{\Delta}\theta_{nc} = 9.81° \pm 0.69°$, were significantly different (p value: 0.03). Reasons for similar finger movement between the touching fingers and fingers that have not yet made contact may be related to the minimal overall movement of the fingers. The suture based procedure had significantly different movement, but the change in joint angles was large for the fingers in contact and the fingers not in contact with the ball. Ball 2 is 2.5 cm in diameter without a stem, minimizing the difference between each finger's movement. A key result from this object is that the pulley-based procedure had less movement for the fingers that made contact. The mean values of $\sum\bar{\Delta}\theta_c$ across all six subjects for the pulley-based procedure were significantly less (p-value: 0.02) than the suture-based procedure.

4.2.2 Ball 2

The pulley-based procedure mean joint angle changes were $\sum\bar{\Delta}\theta_c = 4.35° \pm 0.46°$ and $\sum\bar{\Delta}\theta_{nc} = 9.05° \pm 0.65°$, were significantly different (p-value: $< 10^{-4}$). The suture-based procedure mean joint angle changes, $\sum\bar{\Delta}\theta_c = 7.29° \pm 0.61°$ and $\sum\bar{\Delta}\theta_{nc} = 7.04° \pm 0.66°$, were not significantly different (p value: 0.8). The mean values of $\sum\bar{\Delta}\theta_c$ across all six subjects for the pulley-based procedure were significantly less (p-value: $< 10^{-4}$) than the suture-based procedure.

4.2.3 Ball 3

The pulley-based procedure mean joint angle changes were $\sum\bar{\Delta}\theta_c = 3.17° \pm 0.30°$ and $\sum\bar{\Delta}\theta_{nc} = 3.50° \pm 0.37°$, were not significantly different (p-value: 0.5). The suture-based procedure mean joint angle changes, $\sum\bar{\Delta}\theta_c = 4.31° \pm 0.50°$ and $\sum\bar{\Delta}\theta_{nc} = 5.59° \pm 0.47°$, were not significantly different (p value: 0.06). Reasons for similar finger movement between the touching fingers and fingers that have not yet made contact may be related to the minimal overall movement of the fingers. Ball 3 is 3.5 cm in diameter, minimizing the difference between each fingers movement. A key result from this object is that the pulley-based procedure had less movement for the fingers that made contact. The mean values of $\sum \bar{\Delta}\theta_c$ across all six subjects for the pulley-based procedure were significantly less (p-value: 0.05) than the suture-based procedure.

4.2.4 Ball 4

The pulley-based procedure mean joint angle changes were $\sum \bar{\Delta}\theta_c = 2.99° \pm 0.28°$ and $\sum \bar{\Delta}\theta_{nc} = 6.42° \pm 0.57°$, were significantly different (p-value: $< 10^{-7}$). The suture-based procedure mean joint angle changes, $\sum \bar{\Delta}\theta_c = 6.69° \pm 0.63°$ and $\sum \bar{\Delta}\theta_{nc} = 6.43° \pm 0.68°$, were not significantly different (p value: 0.8). The mean values of $\sum \bar{\Delta}\theta_c$ across all six subjects for the pulley-based procedure were significantly less (p-value: $< 10^{-6}$) than the suture-based procedure. While the mean values of $\sum \bar{\Delta}\theta_{nc}$ were not significantly different (p-value: 0.99) indicating that the finger movement between the two procedures is similar for the fingers that have not made contact with the object.

Chapter 5: Introduction to Chapter 5: Implanted Adaptive Mechanism Enables Grasping at Lower Forces After Tendon-Transfer Surgery: A Cadaver-Based Study

Submitted to 2014 American Society of Biomechanics

5.1 Introduction

Based on American Hospital Association and US News records, there are over 20,000 upper-extremity tendon transfer procedures are performed in the US annually to partially restore hand functionality for patients with a variety of conditions, such as stroke, trauma, congenital defects [8]. Tendon-transfer surgeries restore hand function by rerouting tendons from a dysfunctional muscle and suturing them to a functioning donor muscle [2, 13]. In tendon-transfer surgery for high median-ulnar palsy, which disables the flexor digitorum profundus (FDP) muscle, all four tendons of the FDP are directly sutured to the extensor carpi radialis longus muscle (ECRL) to restore finger flexion (see figure 5.1a for musculature and 5.1b for procedure) [1, 2, 4]. This suture-based procedure couples the movement of all fingers, preventing individual fingers from conforming to an object's shape while grasping without increasing the muscle force and stretching the tendons, severely limiting activities of daily living. During the grasping process, one finger makes contact on the object first and the ECRL must then exert more force to stretch the contacted finger's tendon to close the remaining fingers on the object [2]. An increase in ECRL actuation force propagates through the tendons to the finger tips. An increased grasp force on the object being held requires more strength, can push the object away and risks crushing the object.

A simple implanted engineering mechanism, in this particular study a hierarchical pulley mechanism shown in figure 5.1c, is used to attache the ECRL to the recipient tendons. It is hypothesized that the pulley-based procedure will enable

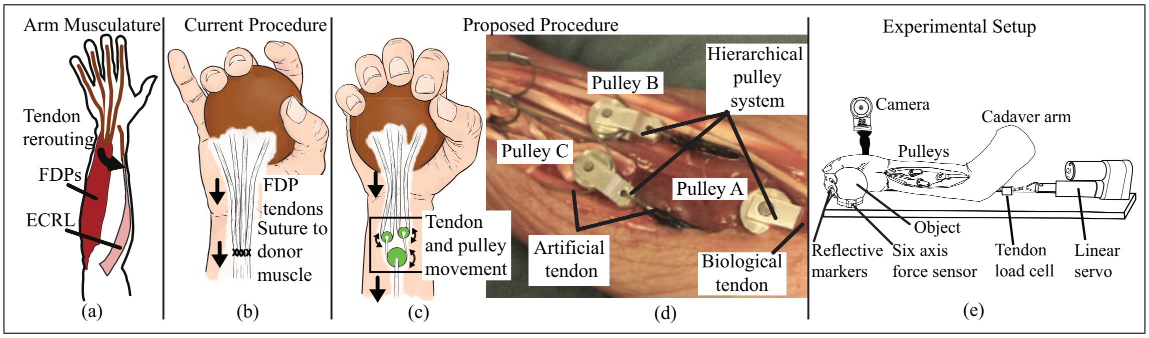

Figure 5.1: a) Hand musculature and tendons and tendon-transfer surgery for high median-ulnar nerve palsy, where tendons are transferred from the FDP to the Extensor carpi radialis longus (ECRL) muscle. (b) Current tendon-transfer procedure using sutures. (c) The pulley-based surgical procedure in a cadaver arm. (e)Wireframe drawing of experimental setup using a six axis force sensor under the object with cadaver arm placed around object. Extensor carpi radialis longus actuated with linear servo.

the fingers to conform to the object's shape as compared to the currently used suture-based procedure. When one finger makes contact with the object, the pulleys rotate within the forearm allowing the remaining fingers to close on the object without increasing the ECRL actuation force until all fingers have established contact on the object. Results from this study support hypothesis III that the pulley system is expected to reduce force during the grasping process until all fingers have made contact on the object compared to the forces on the object with the suture-based procedure with the force direction pointing toward the thumb in both cases.

5.2 Methods

The suture and pulley procedures were performed sequentially on 6 cadaver arms. In the suture-based procedure, the ECRL tendon was rerouted through the ulna and radial bones and directly sutured to all four FDP tendons. For the pulley-based procedure, the ECRL tendon was sutured to a proximal pulley of a hierarchical pulley system, connected to two distal pulleys. The index and long FDPs are sutured around one distal pulley and the ring and pinky FDP tendons are sutured around the second. The arm was secured with bone screws to a horizontal test platform positioned to grasp one of four spheres: a 2.5 cm diameter sphere, a 2.5 cm sphere with a stem, a 3.5 cm diameter sphere and a 3.5 cm sphere with a stem. Each sphere was screwed to a six-axis force sensor to measure grasp force. The ECRL tendon was actuated with a linear servo. A digital video camera filmed each trial. The footage was used to distinguish when all of the fingers have made contact with the object. The experimental set up is shown in figure 5.1e.

5.2.1 Analysis

To analyze the magnitude of the grasp force on each sphere, the force applied to the force sensor was recorded as each subject's fingers closed on each sphere. The force resulting from a full grasp with all fingers contacting the sphere for each procedure for each subject was averaged across all trials. For the i-th subject, the mean grasp force is represented as $\mathrm{G_{si}}$ for the suture-based procedure and $\mathrm{G_{pi}}$ for the pulley based procedure. The ratio of the mean grasp forces, $R_{gi} = \frac{G_{pi}}{G_{si}}$, is used to compare the grasp forces between the two procedures for each subject. These ratios were averaged across all subjects to find the mean ratio, $\mathrm{R_g}$ for each ball and across all subjects and all balls to find an overall ratio, $\mathrm{R_G}$. It was hypothesized that the ratios would be less than one ($R_{gi} < 1$) as the pulley system allows the fingers to adapt independently to the ball, lowering the force the fingers must apply to form a complete graphs. In addition to force magnitude, the direction of force was assessed for each trial at full contact. Standard error was computed for all ratios and a one-sided paired t-test was used to test the statistical significance of the data.

Ball	Grasp force ratio(s. error)	p-value
1	0.40(0.15)	0.018
2	0.45(0.03)	0.062
3	0.25(0.04)	0.004
4	0.48(0.12)	0.033
mean	0.39(0.05)	<0.001

Table 5.1: Mean grasp force ratio ($\frac{G_{pulley}}{G_{suture}}$) for each ball across all subjects. A ratio less than 1 signifies that grasp forces are lower for the pulley-based procedure as compared to the suture-based procedure.

5.3 Results and Discussion

Figure 5.2 shows the mean grasp forces, G_{si} and G_{pi}, for each subject on each ball after establishing a full grasp. For each ball, the mean grasp force ratio between the pulley-based procedure and suture based procedure is shown in Figure 5.1. A paired t-test across all balls and subjects showed that the grasp force resulting from the pulley-based procedure is significantly lower than with the suture-based procedure, with an average ratio of $0.39 \pm .05$ ($p < .001$).

The direction of the force on the ball is pointed toward the thumb in both procedures (see figure 5.3). This confirms that the pulley based procedure doesn't effect the direction of force that the fingers apply to an object. The angle is measured with the origin pointing toward the MCP joint. For the suture-based procedure, the direction of force for all balls and all subjects is $322.1° \pm 2.3°$ with 95% confidence. The pulley-based procedure force direction is $319.7° \pm 2.2°$ with 95% confidence. Further studies will be conducted to determine the force contribution of each individual finger.

The grasp force on an object following the pulley-based tendon-transfer procedure is 39% of the force created with the currently practiced suture-based procedure. To form a full-contact grasp with the suture-based procedure, the actuating muscle must stretch the tendon of the previously contacted fingers in order to move the next finger to contact. This causes the already contacted fingers to ap-

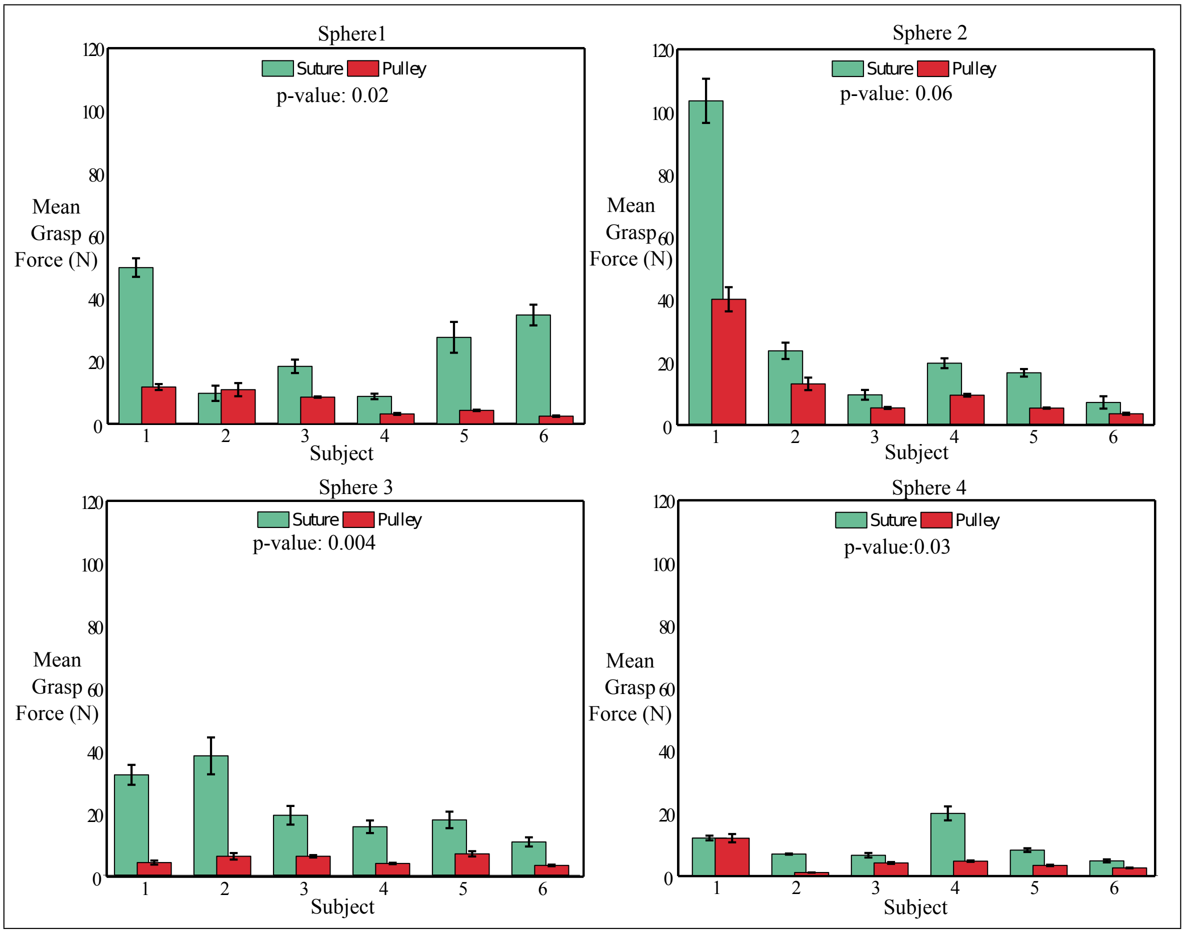

Figure 5.2: Mean grasp forces across all trials at full finger contact for each procedure and subject for all four balls. The mean grasp force for the pulley-based procedure is lower than for the suture-based procedure in most trials.

ply excessive force to object. Using implanted pulley's de-couples the forces each finger applies to a grasped object, allowing each finger to independently contact the object without applying excessive force.

This shows that the pulley-based procedure leads to significantly better adaptive finger forces when grasping an object when actuated by one muscle compared to the currently used tendon-transfer procedure. Most importantly, the reduced

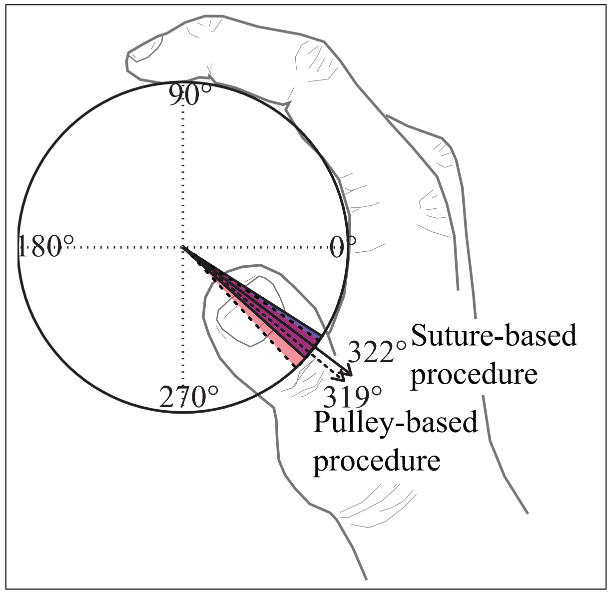

Figure 5.3: Average direction of force for all balls with 95% confidence interval imposed on wireframe drawing of hand grasping ball. Suture based procedure force direction is $322.1° \pm 2.3°$ and the pulley based procedure is $319.7° \pm 2.2°$.

grasp force increases a patients ability to create a stable grasp, particularly on delicate objects that require fine force control in all fingers. This improves patient quality-of-life by improving hand performance in everyday grasping tasks. Additionally, less stretching of the tendons reduces wear, improving hand function long-term.

The major limiting factor of this study is the number of cadaver arms used. More testing is needed to account for biological variability. Additionally, grasp force was only measured by the hand as a whole. Measuring the force applied by each finger would give a more accurate assessment of when full contact has been reached and would allow better comparisons to be made between the pulley-based, suture-based, and normal hand function. Other future work includes examining the angle of grasp force, improving the device's biocompatibility, and optimizing it for long-term, in-vivo use.

Chapter 6: Mechanism Design

A hierarchical pulley system was used for primary testing, but has several drawbacks. It is unfavorable to have several moving parts implanted with in the human body because of tissue fibrosous, irritation of the surrounding tissues, the size of the device, and the exposed elements. Brainstorming sessions yielded eight design concepts (all eight shown in appendix D) which were compared and evaluated through the customer requirements.

6.1 Customer Needs

The following design requirements were established to judge design concepts based on the needs of the patient, surgeon, physical therapist and manufacturer:

1. Robust to tangling up in arm
2. Actuation of multiple digits
3. Biocompatible
4. Long Lifetime
5. One muscle as an input
6. Dimensions fit into average arm (internally)
7. Reduce forces required by muscle
8. Ability to apply different tensions on tendons
9. Small amount of moving parts
10. Low cost

Please fill in the box lining up the stakeholder to the description with a rating for the importance of that device description from 1 to 5. 1 is very important, 3 is neutral, 5 is unimportant.								
	Design Concept Pool (numbers coorelate to Slide number)							
Customer Requirements	1. Passive Springs	2. Loose Pulleys	3. Simplified Pulleys	4. Linkage Systems	5. Planetary Gears	6. Soft Hydraulic	7. Rigid Hydraulic	8. Cams/ Clutch
Dimensions fit into average arm (internally)								
Small amount of moving parts								
Low cost								
Low Weight								
Long Lifetime								
One muscle as an input								
Actuation of multiple digits								
Ability to apply different tensions on tendons								
Reduce forces required by muscle								
Robust to tangling up in arm								
Minimal amount of tools required to manufacture implant								
Biocompatible								

Figure 6.1: Design selection matrix used to assess eight designs established in brainstorming sessions. Design images in Appendix D

11. Low Weight

12. Minimal amount of tools required to manufacture implant

6.2 Design Concepts

The highest ranking design found through the design selection matrix (shown in Table 6.2) based on the customer requirements is a simplified pulley system that looks like a smiley face (all eight design concepts are shown in appendix D).

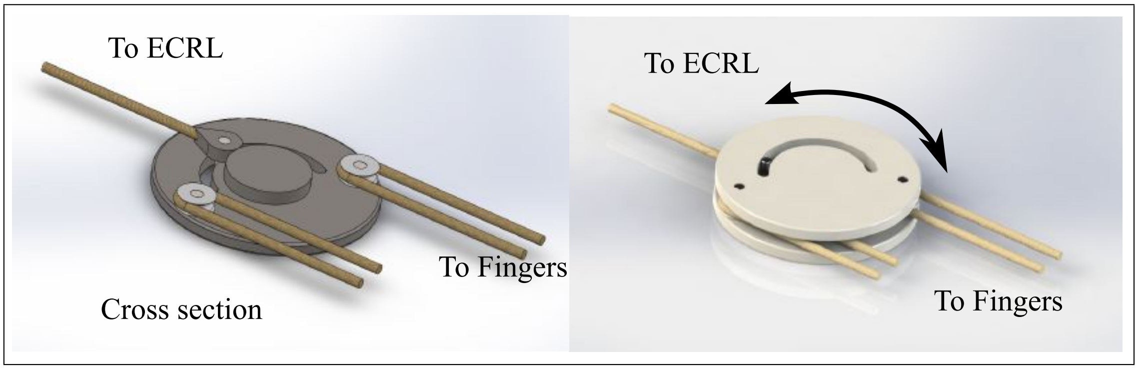

Figure 6.2: Rendered simplified pulley design.

The simplified pulley system is one unit. Two rotating pins at the top of the circle attach to the FDP tendons, serving as the distal pulleys for the hierarchical pulley system. These pins allow the FDP tendons to rotate if one finger makes contact before a different finger. The device translates within the forearm and the whole unit rotates when a finger makes contact. The rotation is enable by the slot with a pin that is connected to the ECRL tendon. The current prototype is made with the biocompatible material ultra-high-molecular-weight-polyethylene (UHMW).

Chapter 7: Conclusion

7.1 Summary of Results

Hand function can be improved with implanting an adaptive mechanism into the forearm, similar to the hierarchical pulley mechanism studied based on the hypotheses below:

Hypothesis I: The pulley system will lead to more adaptive finger movement then the suture-based procedure during a grasping task.
Hypothesis II: The pulley system will require smaller muscle actuation forces than the suture-based procedure to establish full contact.
Hypothesis III: The pulley system will enable lower force applied to the object during the grasping process until all fingers have made contact on the object compared to the forces on the object with the suture-based procedure.

7.2 Hypothesis I

Adaptive finger movement was improved with the pulley-based procedure based on a lesser amount of slip off the object and generally more movement for the fingers that have not made contact with the object. The cadaver studies show that the fingers in contact with the object move less than the fingers that are not yet in contact with the ball. This demonstrates that finger slip occurs less with the pulley system than in the suture-based procedure. These components improve grasp quality, leading patients to grab objects easier, improving use of the hand.

7.3 Hypothesis II

Smaller actuation forces from the donor muscle were required to establish full contact on the object. The average ratio of the pulley-based procedure over the suture-based procedure was 0.57 with 95% confidence ($p=10^{-7}$) for all four objects and all six subjects. A smaller actuation force allows a weaker donor muscle to be transfered as well as allowing a lower grade muscle to be a donor. Reduction in required force also means reduction in energy required to perform a grasping task, helping the patient to return to tasks of daily living.

7.4 Hypothesis III

During the grasping process, smaller grasp forces are desired to form a stable grasp on the object. Larger grasp forces can cause the object to move during the grasping process and change the hand position on the object unintentionally. Once all fingers make contact with the object the grasp force is able to increase on the object. The grasp force on an object following the pulley-based tendon-transfer procedure is 39% of the force created with the currently practiced suture-based procedure. A smaller force during the grasping process on the object indicates less energy used and a more secure grasp.

7.5 Future Work

This thesis confirms a proof of concept and led to the patenting process. Further work includes further cadaver studies to determine finger tip forces on the object and determine grasp quality in terms of the epsilon metric. Mechanism design will be improved to a smaller, lighter, more compact device and will be tested with biocompatible coatings in vitro to determine longevity and compatibility.

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APPENDICES

Appendix A: Significance Calculations

Table A.1: Copy of Sources attached. *Considering Harborview Medical Center, Northwest Hospital and Medical Center, Valley Medical Center and University of Washington Medical Center as one facility for reporting purposes. **Extrapolated from present data.

	UW Medicine Hospitals [fig A.1]	US Registered Hospitals [fig A.3]	Orthopedic Hospitals [fig A.2]
Facilities	1*	5724	1650
Admitted Patients	65,000	34,843,085	10,043,866**
Upper Extremity TT Procedures	123		19,006**

Table A.2: Cost of tendon transfer surgeries based on total hospital cost based on CPT codes (table A.3) and statistics from the Bureau of Labor Statistics

Tendon Transfer Average Cost	$833	
Hospital Services	$1800	
Anethesia Services	$1087	
Phyical Therapy Costs (12 visits, $200 each)	$2400	
Hospital Cost per patient		$6120
Avg Lost work DaysA.4	18	
Avg Hourly Wage	$25	
Lost wages per patient		$3600
Total Cost for 20,000 patients		$194,395,574

Table A.3: University of Washington Department of Orthopaedics and Sports Medicine number of Tendon Transfers / Tenodesis sorted by CPT codes for 2012 Fiscal Year. `https://ocm.ama-assn.org/OCM/CPTRelativeValueSearch.do`

CPT	CPT Description	#	UW Cost Each	UW Cost Total	Nat. Avg. Cost Each	Nat.Avg Cost Total
24301	MUSC/TENDON XFER,ARM/ELBOW,SINGLE	7	$801.94	$5613.58	$753.61	$5275.27
24320	TENOPLASTY,ELB-SHLDR,MUSC XFER,SINGL	0	$837.54	$0	$787.29	$0
24330	FLEXORPLASTY,ELBOW	0	$771.45	$0	$724.01	$0
24331	FLEXORPLASTY,ELBOW W EXTENSOR ADVANCEMENT	0	$843.23	$0	$729.74	$0
24340	REPAIR OF BICEPS TENDON AT ELBOW	1	$665.04	$665.04	$622.28	$622.28
25300	FUSION TENDONS WRIST,FINGR FLEXORS	4	$743.51	$2974.04	$695.77	$2783.08
25301	FUSION TENDONS WRIST,FINGR EXTENSORS	4	$693.03	$2772.12	$648.48	$2593.92
25310	TRANSPLANT FOREARM/WRIST TENDON	79	$667.52	$52734.08	$622.96	$49213.84
25312	XPLANT FOREARM TENDON,W TENDON GRFT	2	$772.58	$1545.16	$724.01	$1448.02
26471	FUSION FINGER TENDONS,PIP JT STABIL	8	$675.28	$5402.24	$619.22	$4953.76
26474	FUSION FINGER TENDONS,DIP JT STABIL	0	$650.81	$0	$596.76	$0
26480	TRANSPLANT HAND TENDON	4	$831.15	$3324.6	$760.41	$3041.64
26483	TRANSPLANT/GRAFT HAND TENDON	0	$922.73	$0	$848.87	$0
26485	TRANSPLANT PALM TENDON	1	$922.73	$922.73	$813.49	$813.49
26489	W/ FREE TENDON GRAFT, EACH TENDON	0	$1022.9	$0	$944.14	$0
26490	REVISE THUMB TENDON	2	$861.62	$1723.24	$796.82	$1593.64
26492	THUMB TENDON TRANSFER,GRAFT	0	$958.76	$0	$888	0
26494	HYPOTHENAR MUSC TRANSFER	0	$871.11	$0	$805.32	0
26496	REVISE THUMB TENDON,OTHR	4	$926.48	$3705.92	$857.38	$3429.52
26497	FINGER TENDON TRANSFER,4-5 FINGRS	0	$933.49	$0	$865.55	$0
26498	FINGER TENDON TRANSFER,2-5 FINGRS all 4 fingers	2	$1228.32	$2456.64	$1145.89	$2291.78
26499	CORRECTION CLAW FINGER, OTHER METHODS	0	$895.99	$0	$829.82	$0
26510	THUMB TENDON TRANSFER	5	$656.7	$3283.5	$601.53	$3007.65
	Totals	123		$87,123		$81,068

UW Medicine

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UW Medicine's Mission

UW Medicine's mission is to improve the health of the public by advancing medical knowledge, providing outstanding primary and specialty care to the people of the region, and preparing tomorrow's physicians, scientists and other health professionals.

UW Medicine owns or operates **Harborview Medical Center**, **Northwest Hospital & Medical Center**, **Valley Medical Center**, **University of Washington Medical Center**, a network of nine **UW Neighborhood Clinics** that provide primary care and secondary care, the physician practice **UW Physicians**, the **UW School of Medicine** and **Airlift Northwest**. In addition, UW Medicine shares in the ownership and governance of Children's University Medical Group and **Seattle Cancer Care Alliance**, a partnership among UW Medicine, **Fred Hutchinson Cancer Research Center** and **Seattle Children's**.

Our faculty includes 3 living Nobel Prize winners (5 in our history), 35 Institute of Medicine members, 32 National Academy of Sciences members and 13 Howard Hughes Medical Institute investigators.

Patient Care

Our hospitals, Harborview Medical Center, Northwest Hospital & Medical Center, Valley Medical Center and UW Medical Center together have about 65,000 admissions and about 1.6 million outpatient and emergency room visits each year. UW Medicine provides our patients with the latest in medical discovery, diagnoses and treatments. Our physicians treat patients, as well as conduct scientific research and teach the next generation of medical professionals.

People

- More than 25,000 employees contribute to the mission of UW Medicine.
- The School of Medicine has approximately 2,300 employed faculty members and more than 4,600 clinical faculty across the WWAMI program who teach medical students, residents and post-doctoral fellows.
- UW Medicine has approximately 4,500 students and trainees across a broad range of undergraduate, professional, and post-graduate programs.

Education

The five-state WWAMI regional medical educational network, serving Washington, Wyoming, Alaska, Montana and Idaho, is widely considered the best academic model for the training and placing of physicians in underserved communities.

UW School of Medicine has been ranked as one of the top primary-care medical school in the country since 1994. In addition, UW Medicine teaching programs are ranked among the best in the country in the 2013 rankings by *U.S. News & World Report.*

- Family medicine (No. 1 for 22 consecutive years)
- Rural medicine (No. 1 for 22 consecutive years)

Figure A.1: University of Washington Medicine statistics on patients.http://www.uwmedicine.org/global/about/Pages/default.aspx.

Top-Ranked Hospitals for Orthopedics

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Orthopedics is made up of 1,650 hospitals. All are experienced in treating difficult cases — a hospital is listed only if at least 320 inpatients in need of a high level of expertise in this specialty were treated there in 2009, 2010 and 2011 or if enough specialists recommended the hospital for such patients. The top 50 hospitals are ranked, based on score. The rest are listed alphabetically.

How We Rank Hospitals
See All Specialty Rankings

HOSPITAL SEARCH

Hospital Name
Hospital name
Location
City, State or ZIP Within 25 Miles
Find Hospitals

American Hospital Association

RANKINGS DATA BEHIND THE RANKINGS

Showing 1–10 of 1649

National Rank	Hospital	U.S. News Score
#1	**Hospital for Special Surgery** New York, NY See Orthopedics scorecard Ranked in New York metro area and New York	100.0 / 100
#2	**Mayo Clinic** Rochester, MN See Orthopedics scorecard Ranked in Minnesota	91.1 / 100
#3	**Cleveland Clinic** Cleveland, OH See Orthopedics scorecard Ranked in Cleveland metro area and Ohio	74.3 / 100
#4	**Massachusetts General Hospital** Boston, MA See Orthopedics scorecard Ranked in Boston metro area and Massachusetts	70.5 / 100

Figure A.2: US News Best Hospitals and Orthopedics. http://health.usnews.com/best-hospitals/rankings/orthopedics

Our vision is of a society of healthy communities where all individuals reach their highest potential for health

American Hospital Association

Fast Facts on US Hospitals

Fast Facts on US Hospitals

View the Fast Facts as a PDF file here.

The American Hospital Association conducts an annual survey of hospitals in the United States. The data below, from the 2011 annual survey, are a sample of what you will find in AHA Hospital Statistics, 2013 edition. The definitive source for aggregate hospital data and trend analysis, AHA Hospital Statistics includes current and historical data on utilization, personnel, revenue, expenses, managed care contracts, community health indicators, physician models, and much more.

AHA Hospital Statistics is published annually by Health Forum, an affiliate of the American Hospital Association. Additional details on AHA Hospital Statistics and other Health Forum data products are available at www.ahadataviewer.com. To order AHA Hospital Statistics, call (800) AHA-2626 or click on www.ahaonlinestore.com.

For further information or customized data and research, call the AHA Resource Center at (312) 422-2050 for one-stop service.

Total Number of All U.S. Registered * Hospitals	5,724
Number of U.S. **Community** ** Hospitals	4,973
Number of Nongovernment Not-for-Profit Community Hospitals	2,903
Number of Investor-Owned (For-Profit) Community Hospitals	1,025
Number of State and Local Government Community Hospitals	1,045
Number of Federal Government Hospitals	208
Number of Nonfederal Psychiatric Hospitals	421
Number of Nonfederal Long Term Care Hospitals	112
Number of Hospital Units of Institutions (Prison Hospitals, College Infirmaries, Etc.)	10
Total Staffed Beds in All U.S. Registered * Hospitals	924,333
Staffed Beds in Community** Hospitals	797,403
Total Admissions in All U.S. Registered * Hospitals	36,564,886
Admissions in Community** Hospitals	34,843,085
Total Expenses for All U.S. Registered * Hospitals	$773,546,800,000

Figure A.3: American Hospital Association Fast Facts on US Hospitals. `http://www.aha.org/research/rc/stat-studies/fast-facts.shtml` for 2011 should not be compared to prior year data. See footnote 4 on table 18 for the list of categories that comprise MSDs.

Five occupations had more than 11,000 MSDs. (See table 18 and table C.) Of these occupations, nursing assistants had the highest count at 25,010. Heavy and tractor-trailer truck drivers had the greatest median days away from work with 21 days.

For all occupations, the back was injured in 42 percent of the MSD cases and required a median of 7 days to recuperate. The most severe MSDs occurred to the shoulder, requiring a median of 21 days for the worker to return to work, but accounted for only 13 percent of the MSDs.

Table C. Median number of days away from work and percent of total musculoskeletal disorders (MSDs) by selected occupations and selected part of body, all ownerships, 2011

Selected occupation	Selected part of body							
	Median days away from work by							
	Total	Shoulder	Back	Abdomen	Arm	Wrist	Leg	Multiple body parts
All occupations	11	21	7	20	18	17	15	12
Nursing assistants	6	7	5	8	8	5	6	7
Laborers and freight- stock- and material movers- hand	12	30	7	25	10	15	20	6
Janitors and cleaners- except maids and housekeeping cleaners	8	21	6	20	20	10	19	14
Heavy and tractor-trailer truck drivers	21	35	13	25	29	15	27	70
Registered nurses*	8	13	7	6	14	5	17	6
	Percent of total MSDs							
All occupations	100.0	13.2	41.8	4.7	4.8	5.9	10.7	4.7
Nursing assistants	100.0	12.6	54.8	1.1	3.0	3.8	6.1	7.9
Laborers and freight- stock- and material movers- hand	100.0	15.7	44.3	7.0	4.6	4.1	7.0	3.9
Janitors and cleaners- except maids and housekeeping cleaners	100.0	11.7	48.5	5.3	4.4	3.1	7.7	3.6
Heavy and tractor-trailer truck drivers	100.0	16.4	35.5	6.7	7.1	2.4	14.1	4.7
Registered nurses*	100.0	13.0	52.9	0.8	2.2	2.4	6.6	9.2

*2010 Standard Occupational Classification

Worker characteristics

Worker characteristics include age, gender, race or ethnic origin, and length of service with the employer at the time of the incident. (See tables 6, 7, 8, 10 and 14.)

Age. Workers age 65 and over had a greater number of median days away from work than their younger counterparts--requiring a median of 14 days to recuperate before returning to work. For all ownerships the number of days away from work cases for most age groups remained relatively unchanged from the previous year, except for workers age 16-19 and 45-54 where the number of cases decreased 11 percent and 3 percent, respectively. The incidence rate for workers age 16-19 decreased to 109 cases per 10,000 full-time worker (from 117 in 2010). For workers age 45-54, the incidence rate per 10,000 full-time workers increased to 221 for state government workers and to 223 for local government workers; while it decreased for private sector workers to 111. (See table 6.)

6

Figure A.4: Bureau of Labor Statistics U.S. Department of Labor, News Release: Nonfatal Occupational Injuries and Illnesses Requiring Days Away from Work, 2011. Released: Novemeber 8, 2012. USDL-12-2204.

Appendix B: Pulley Design

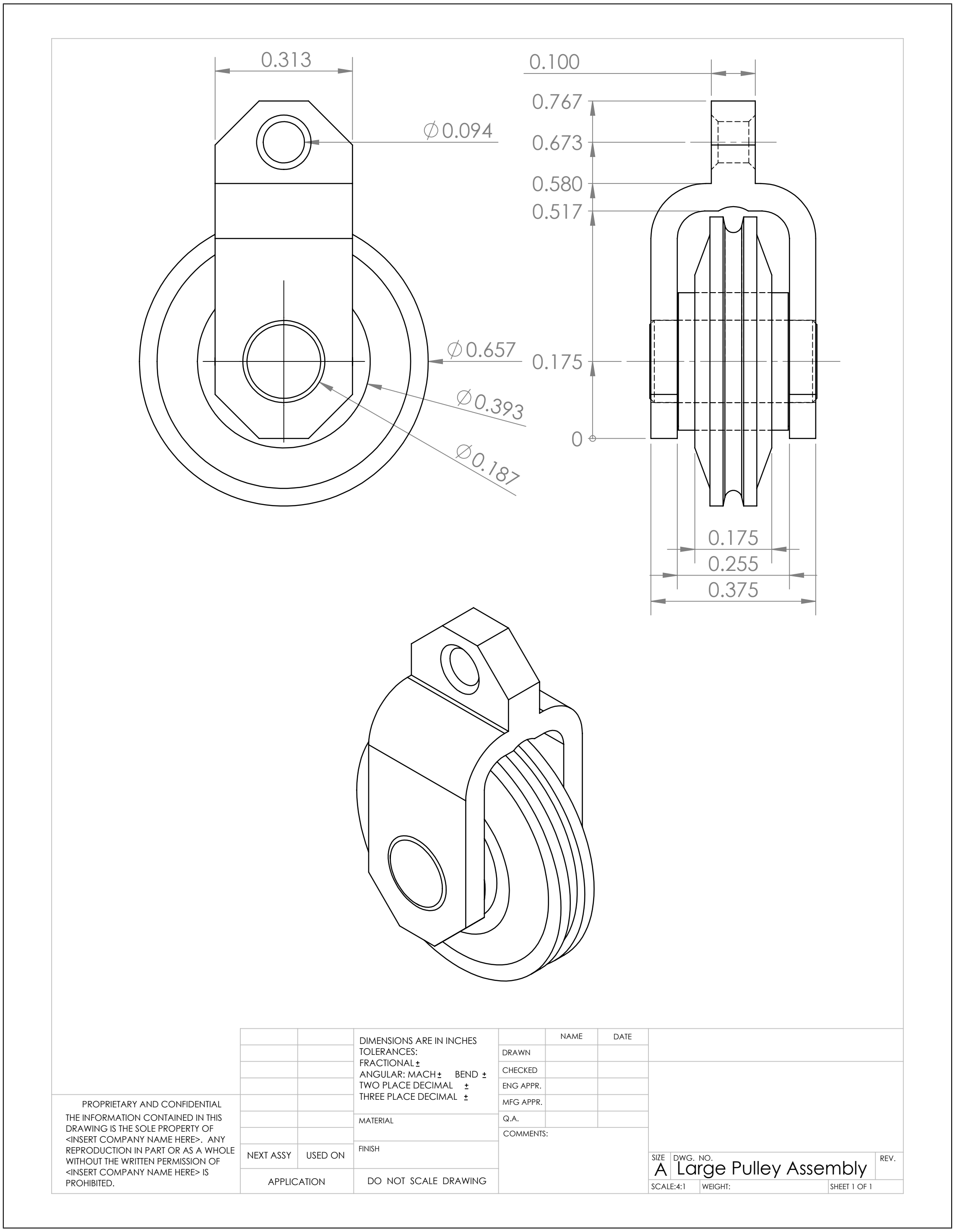

Figure B.1: Proximal pulley design used in cadaver experiments

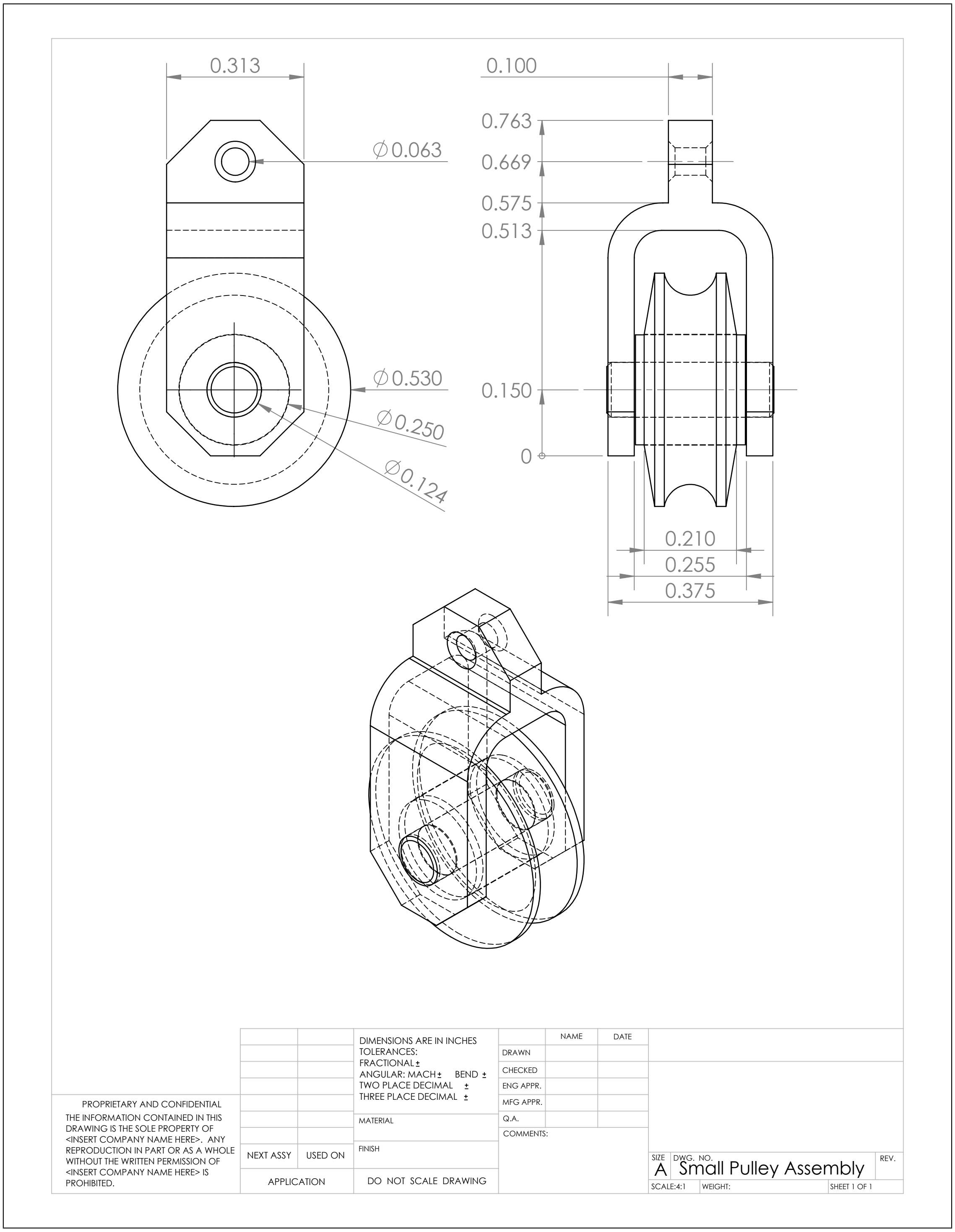

Figure B.2: Distal pulley design used in cadaver experiments

Appendix C: Experimental Set Up

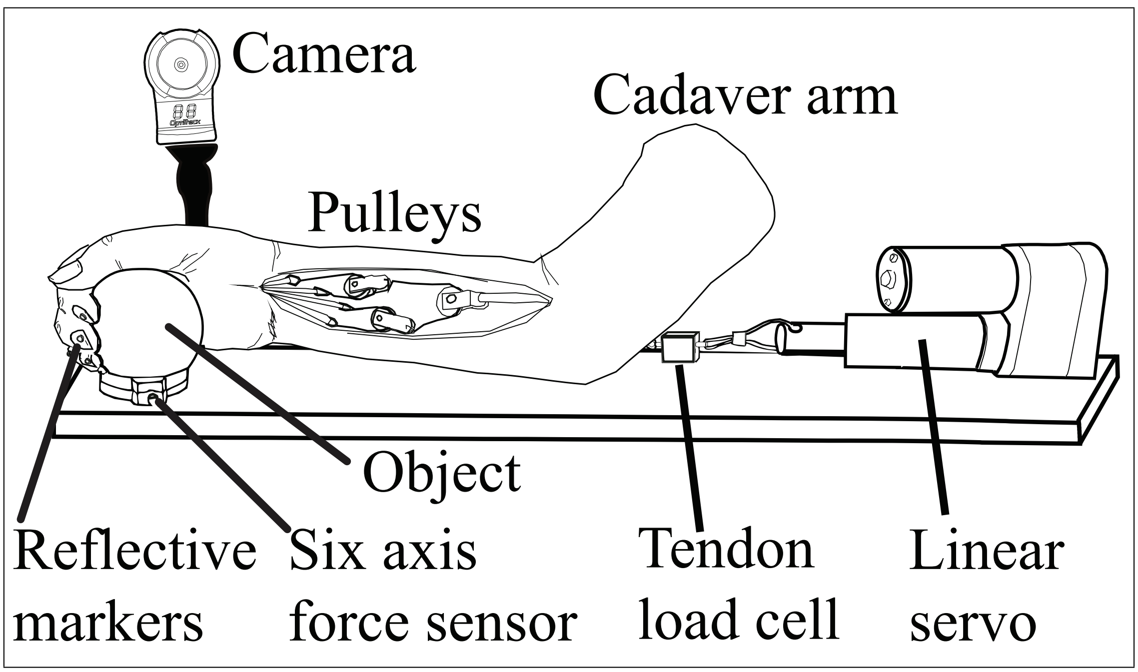

Figure C.1: Wireframe drawing of experimental set up for April 2013 cadaver experiments.

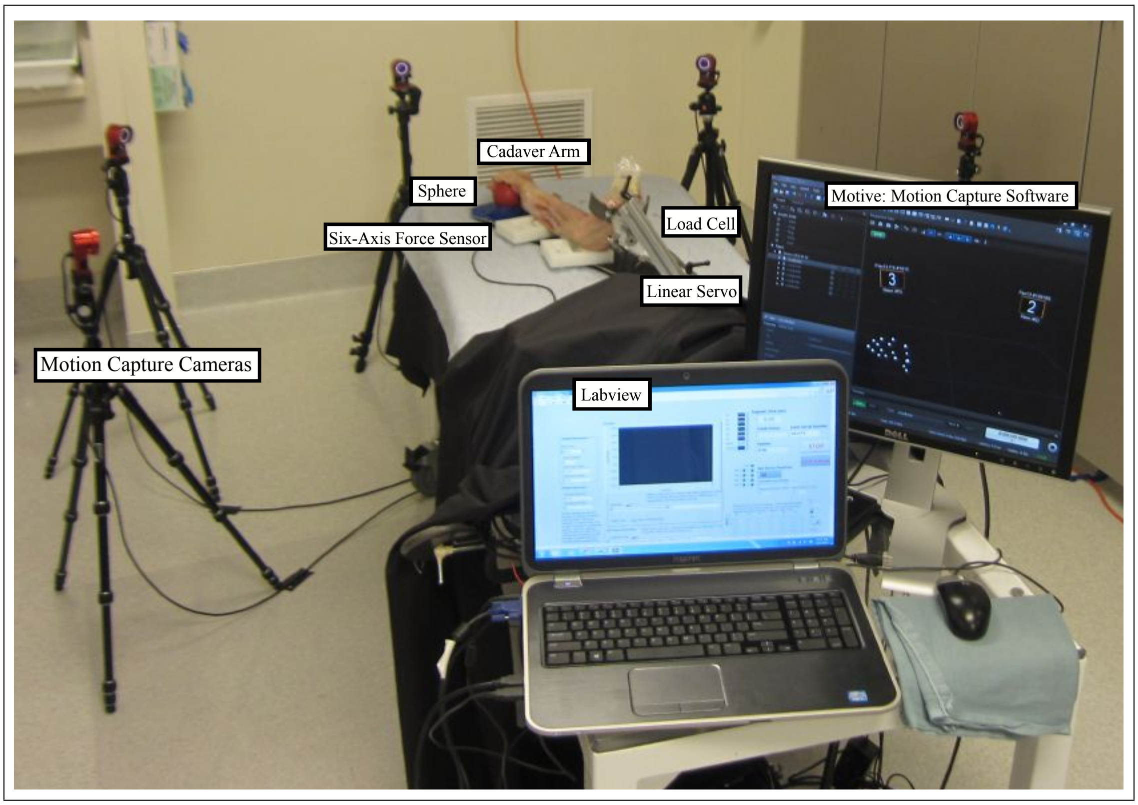

Figure C.2: Photo with labels of experimental set up for April 2013 cadaver experiments. Linear servo and load cell are not visible in photo.

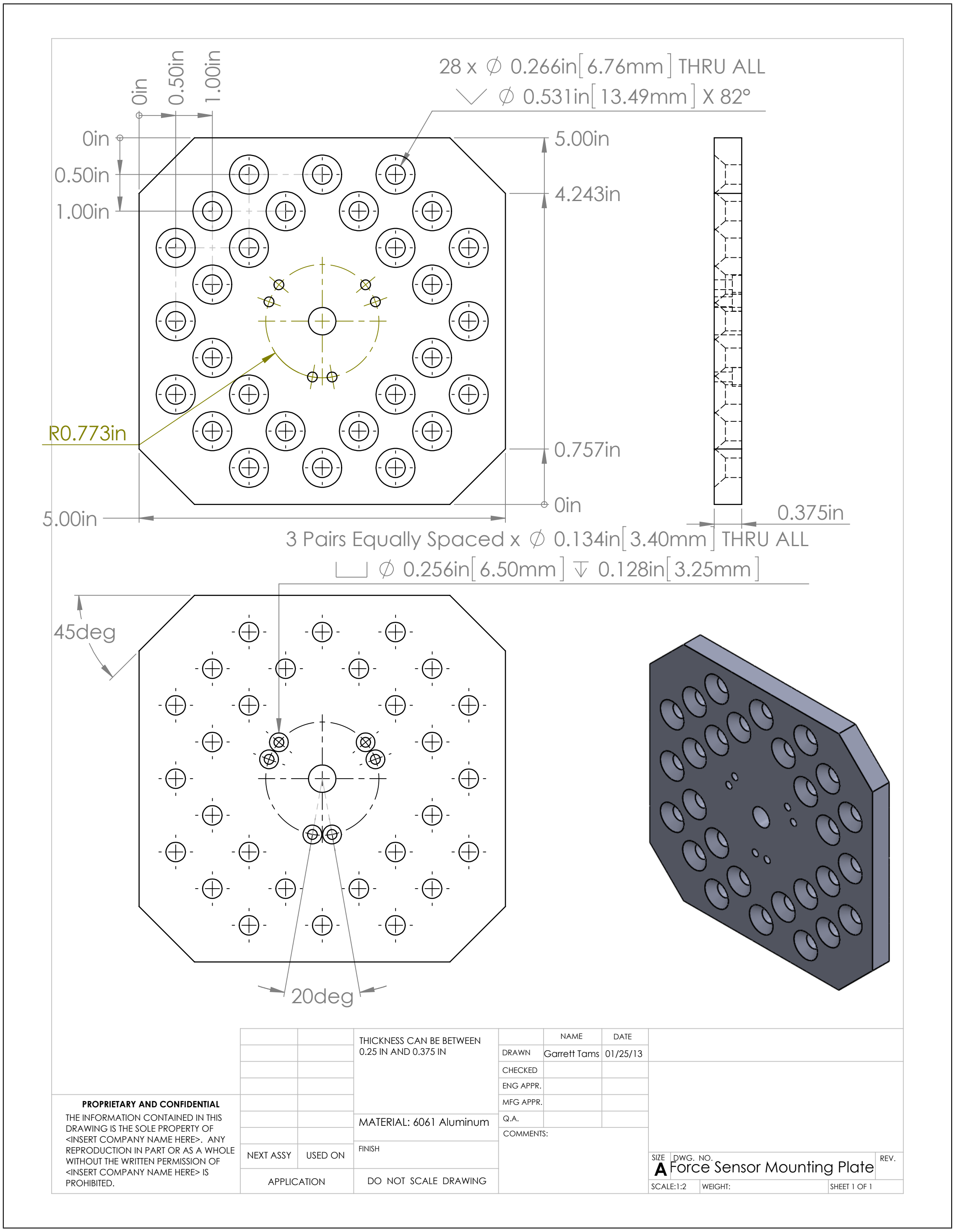

Figure C.3: Drawing of fixture to secure six-axis force sensor for test set up.

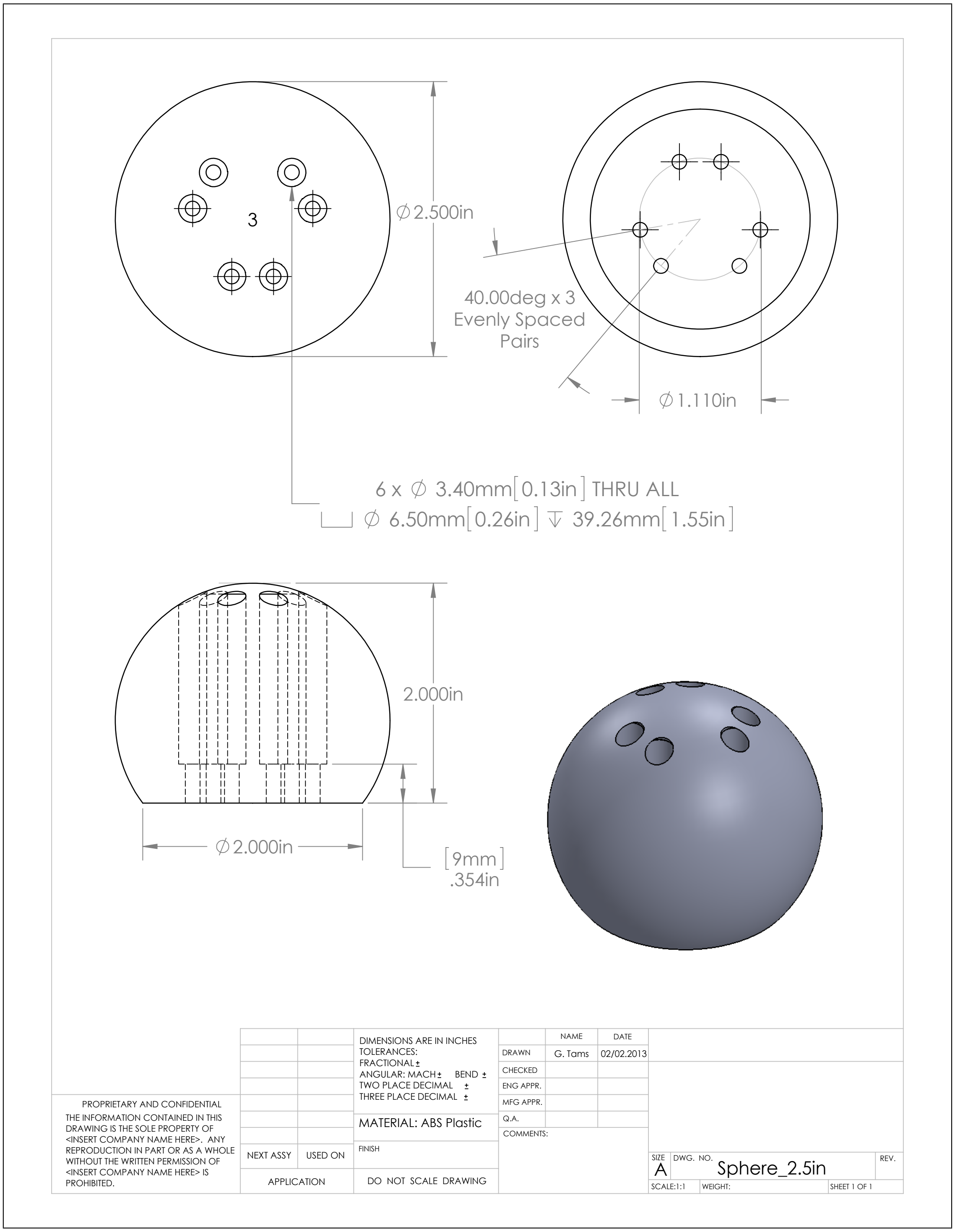

Figure C.4: Drawing of Ball 1

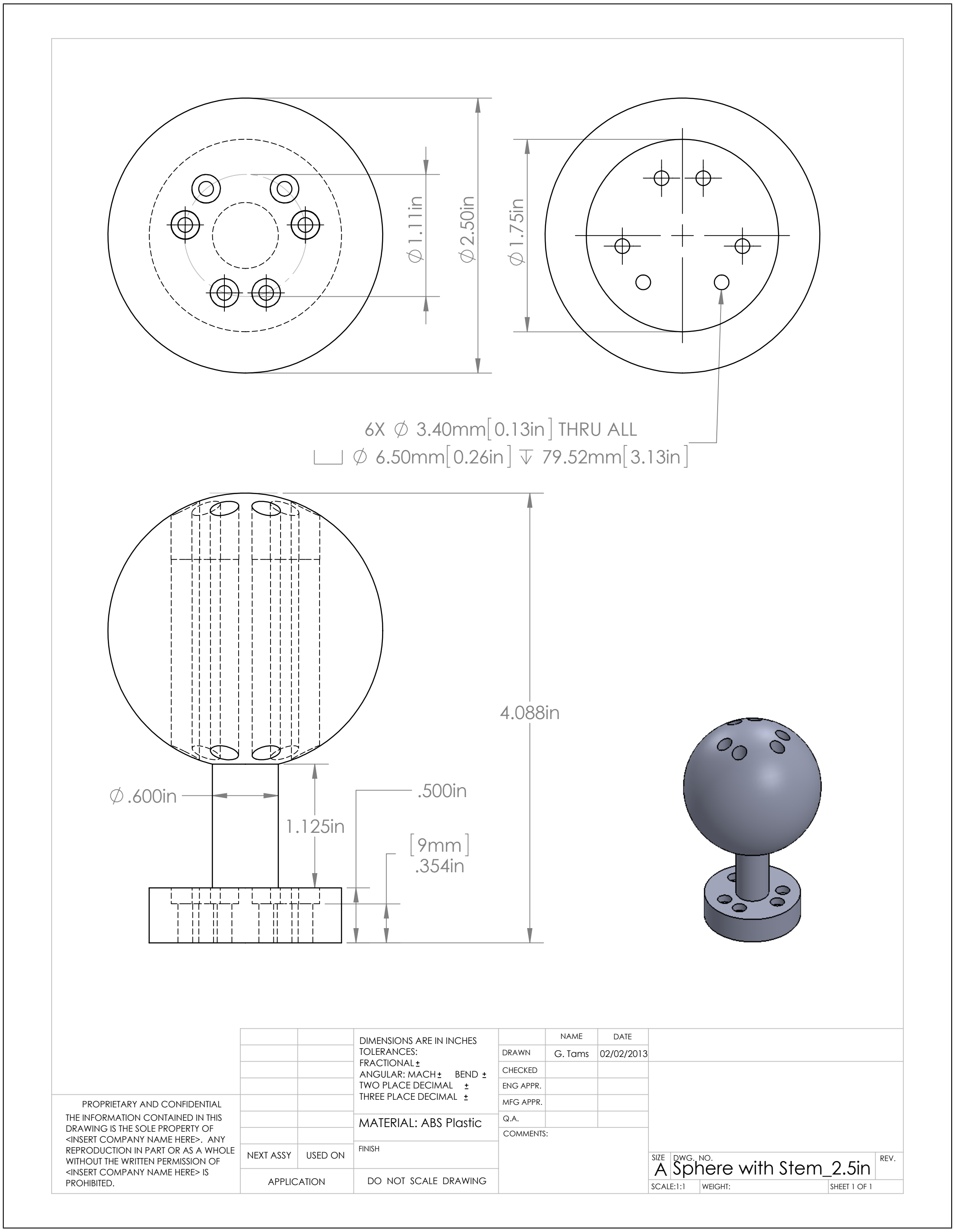

Figure C.5: Drawing of Ball 2

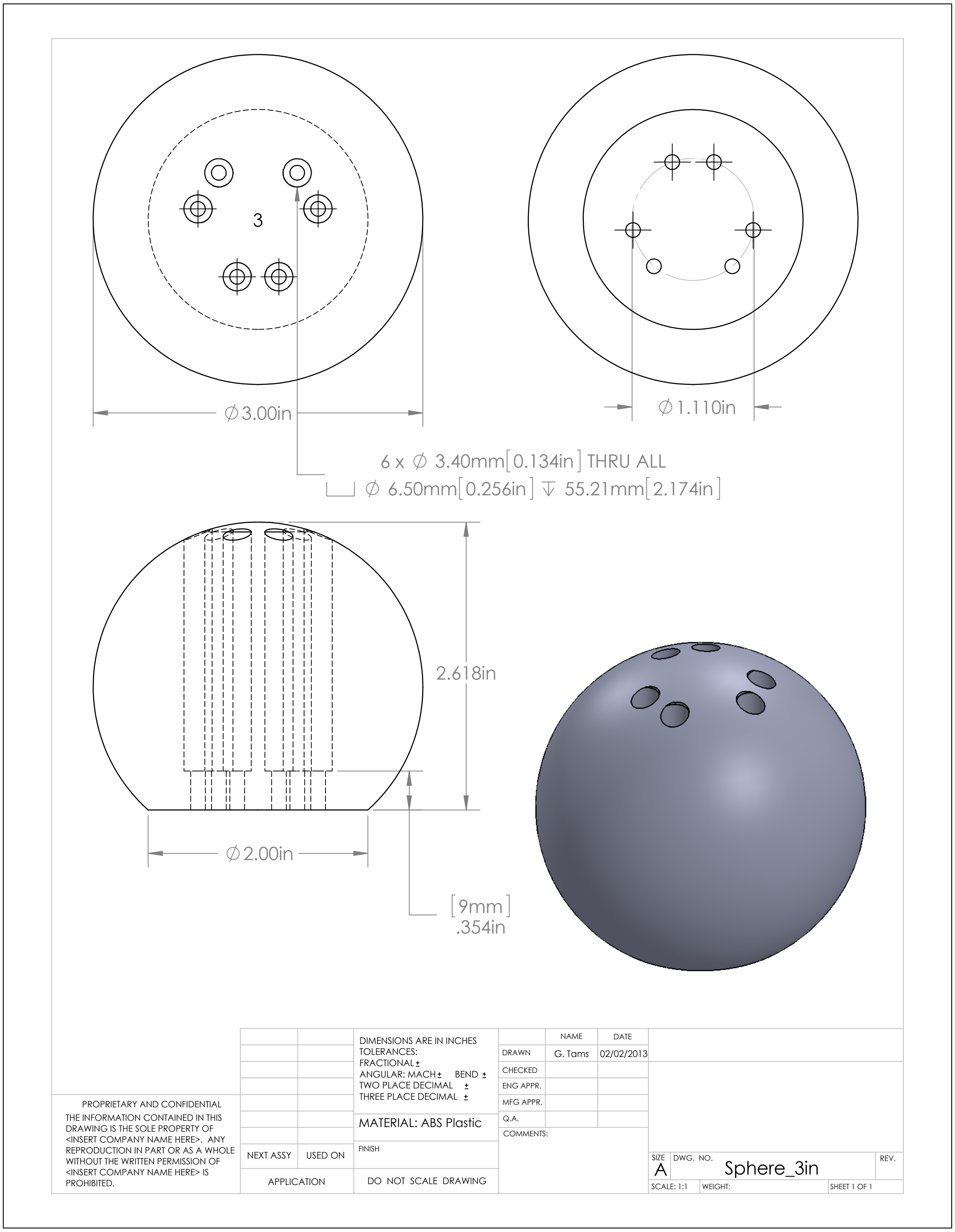

Figure C.6: Drawing of Ball 3

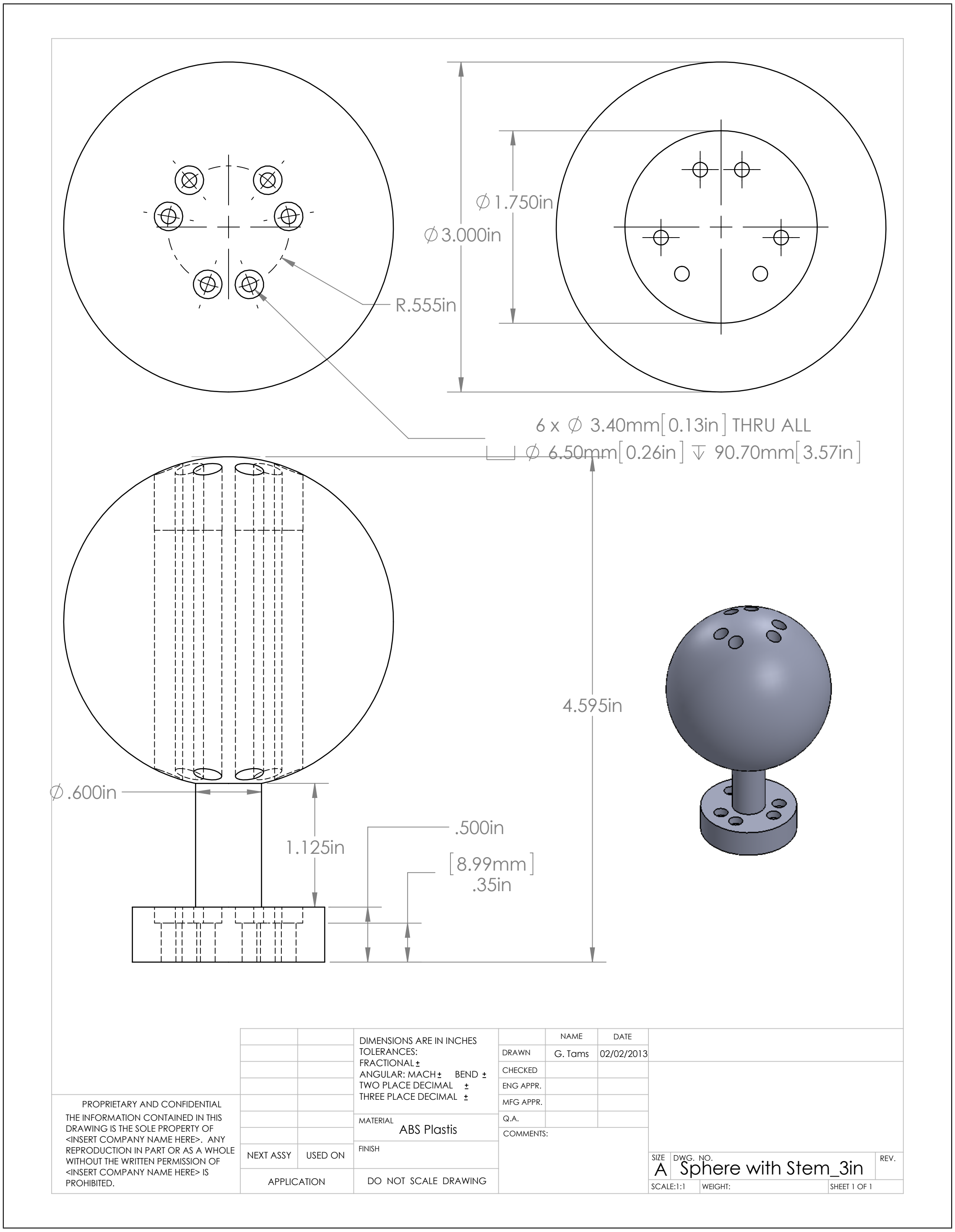

Figure C.7: Drawing of Ball 4

Appendix D: All Design Concepts

These design concepts are preliminary ideas established for evaluation. Images provided are estimates of how the device would work or what it could look like, but are not intended to be a final design.

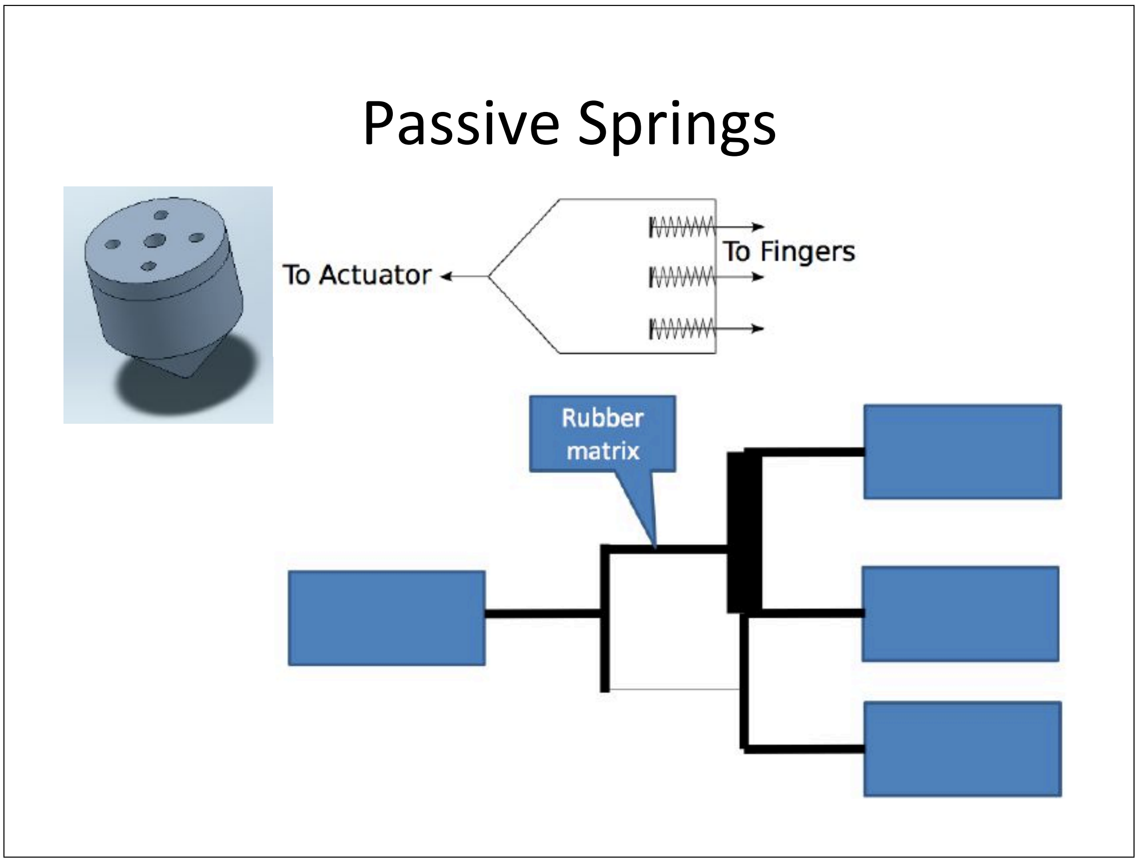

Figure D.1: Passive Springs: Allows compliance within the tendons when the donor muscle contracts and a finger makes contact, the springs compress allowing all fingers to make contact.

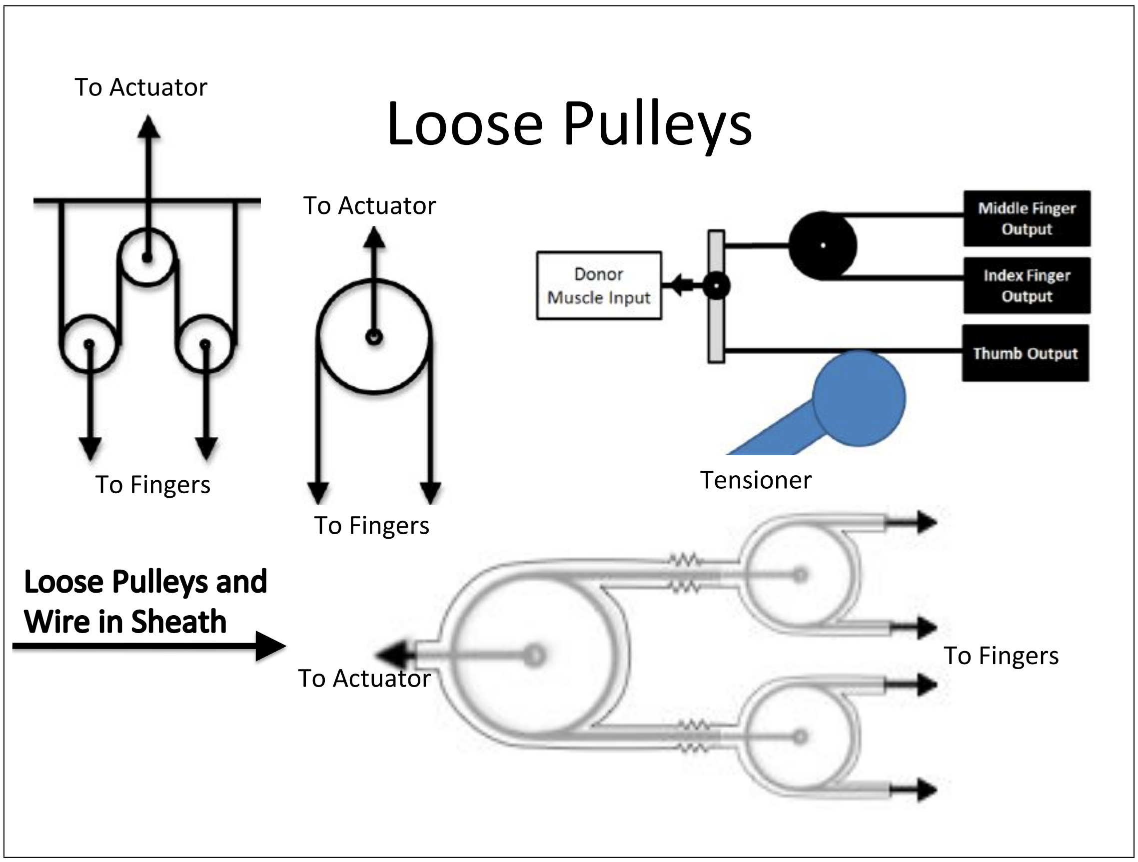

Figure D.2: Loose Pulleys: A similar design to hierarchical pulley system with different ideas on pulley placement.

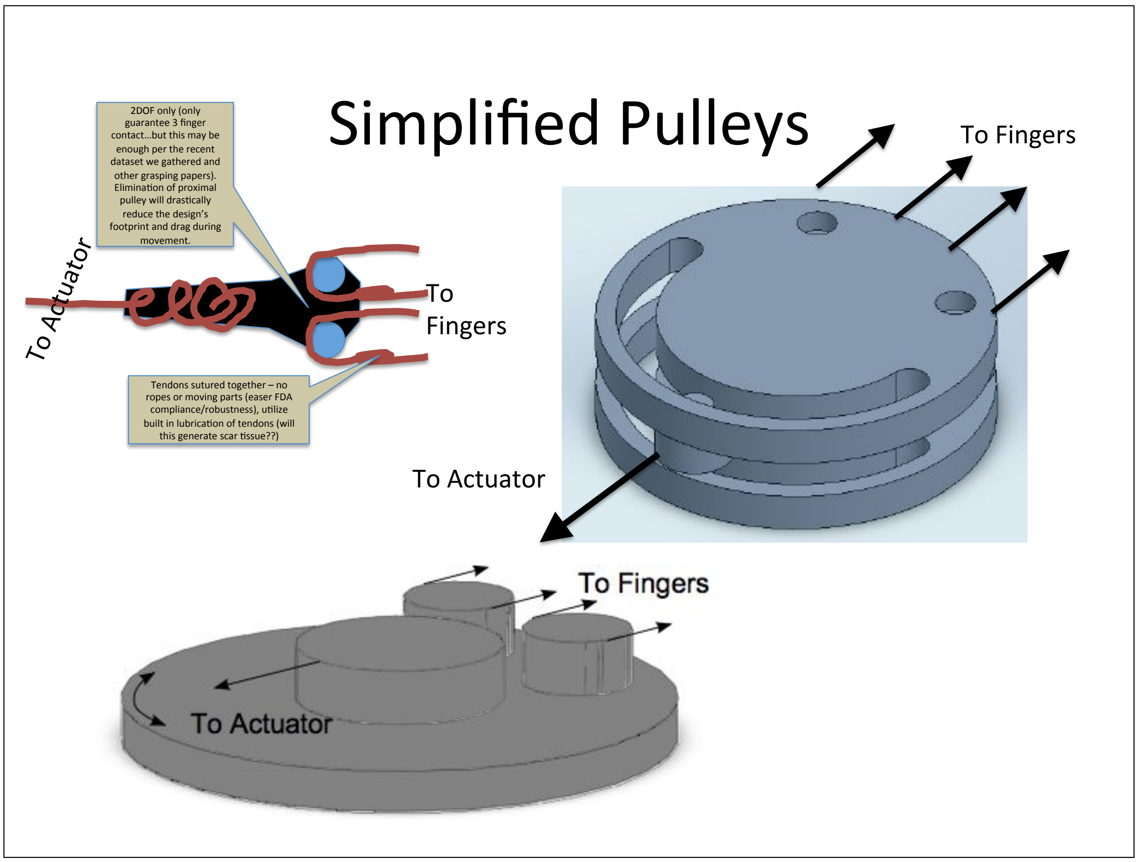

Figure D.3: Simplified Pulleys: A passive pulley system with view moving parts that are more integrated.

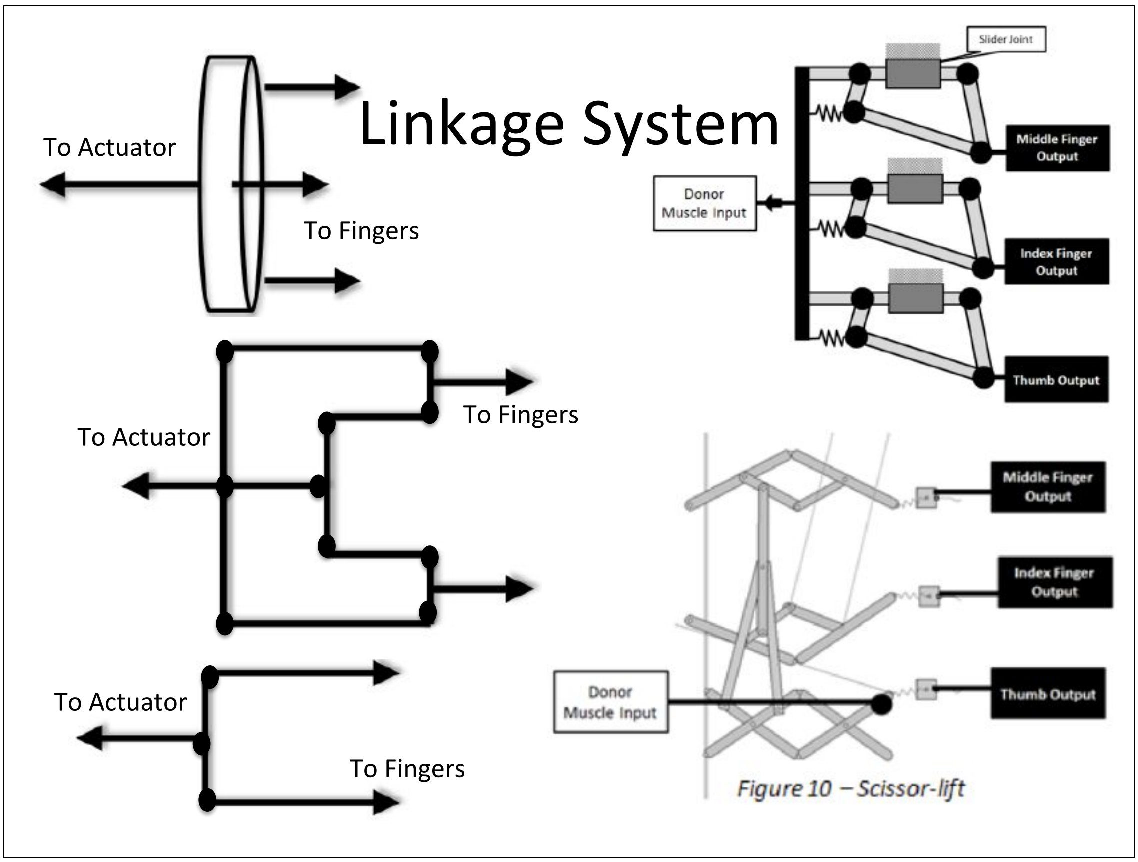

Figure D.4: Linkage Systems: Similar to a see-saw design, the linkages can rotate around a fixed point for adaptive movement.

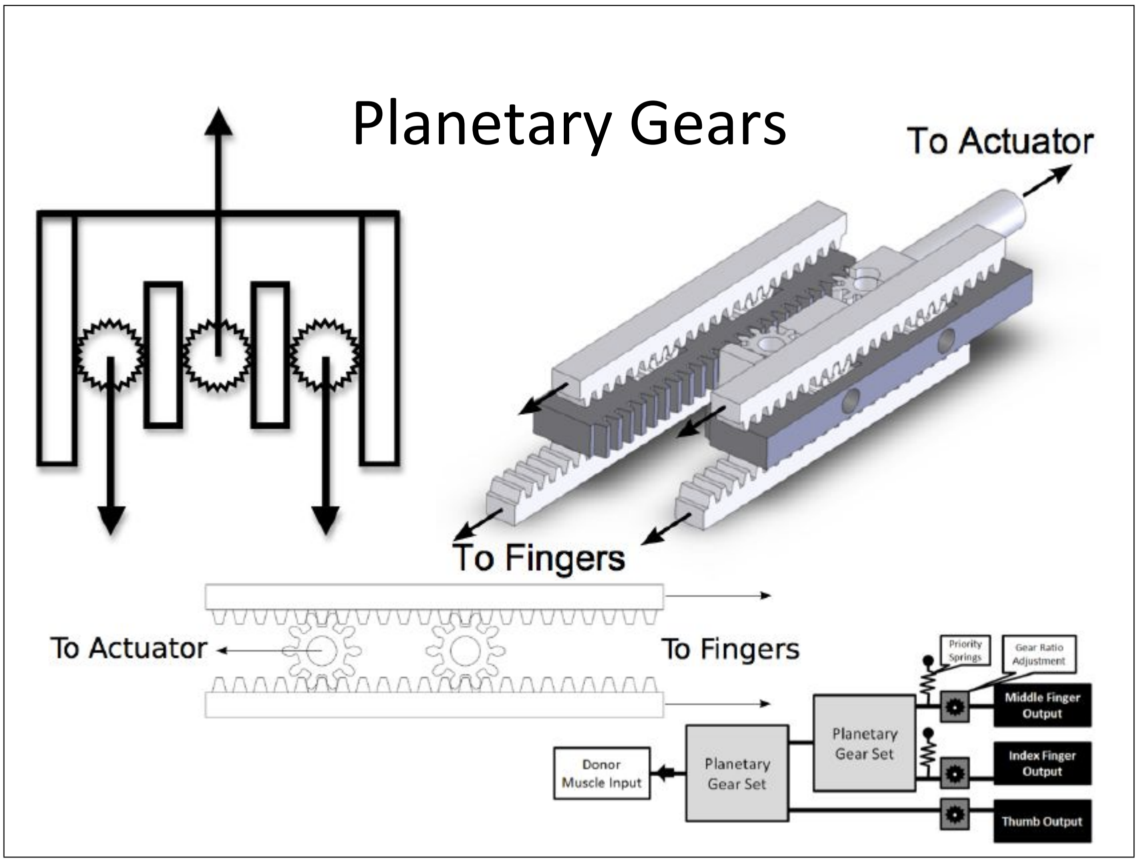

Figure D.5: Planetary Gears: Gears rotate allowing translation movement.

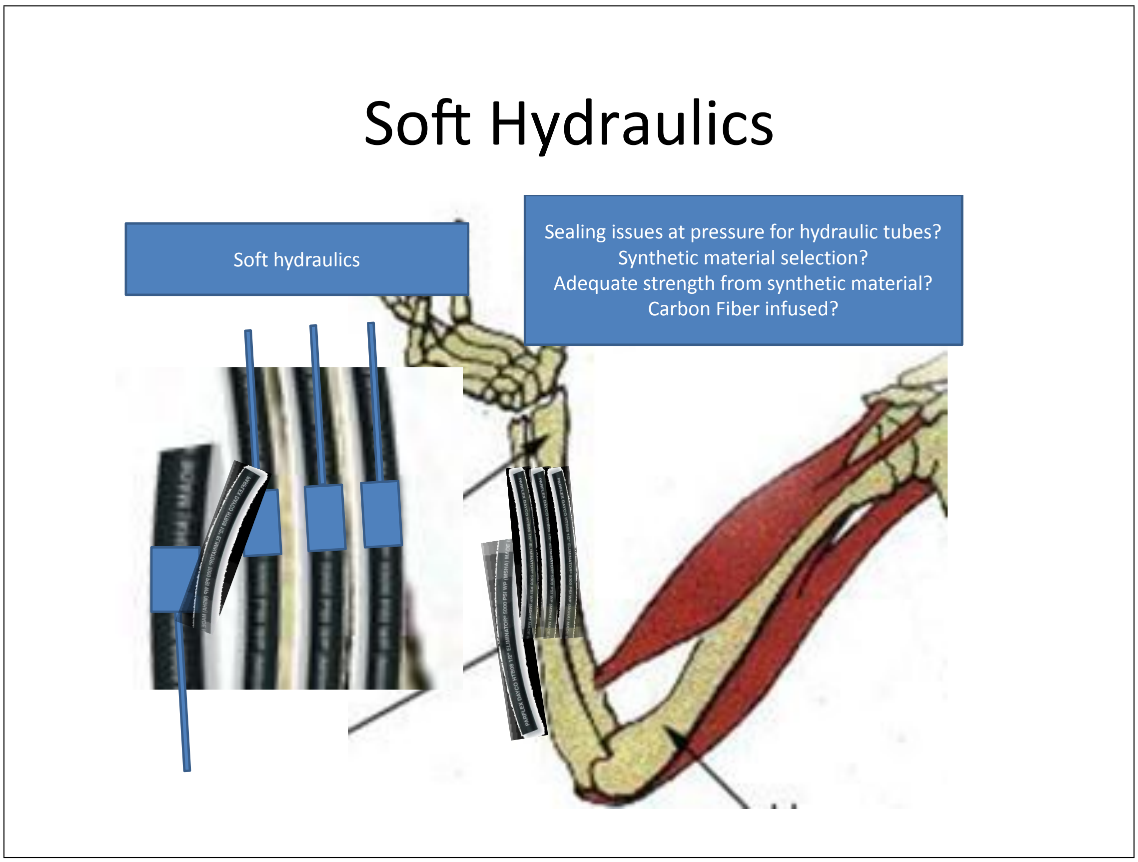

Figure D.6: Soft Hydraulics: Maleable tubes with hydraulics to produce tendon force.

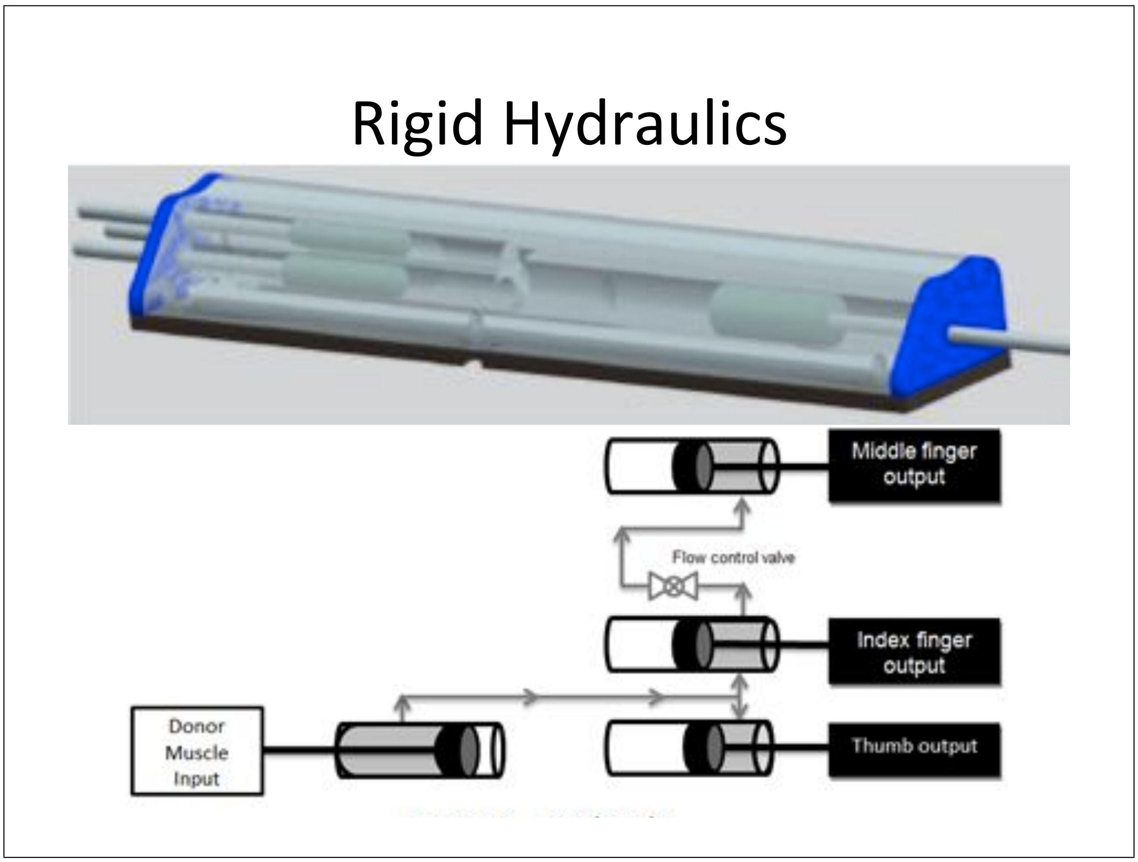

Figure D.7: Rigid Hydraulics: A rigid hydraulic system translates forces through internal pressure.

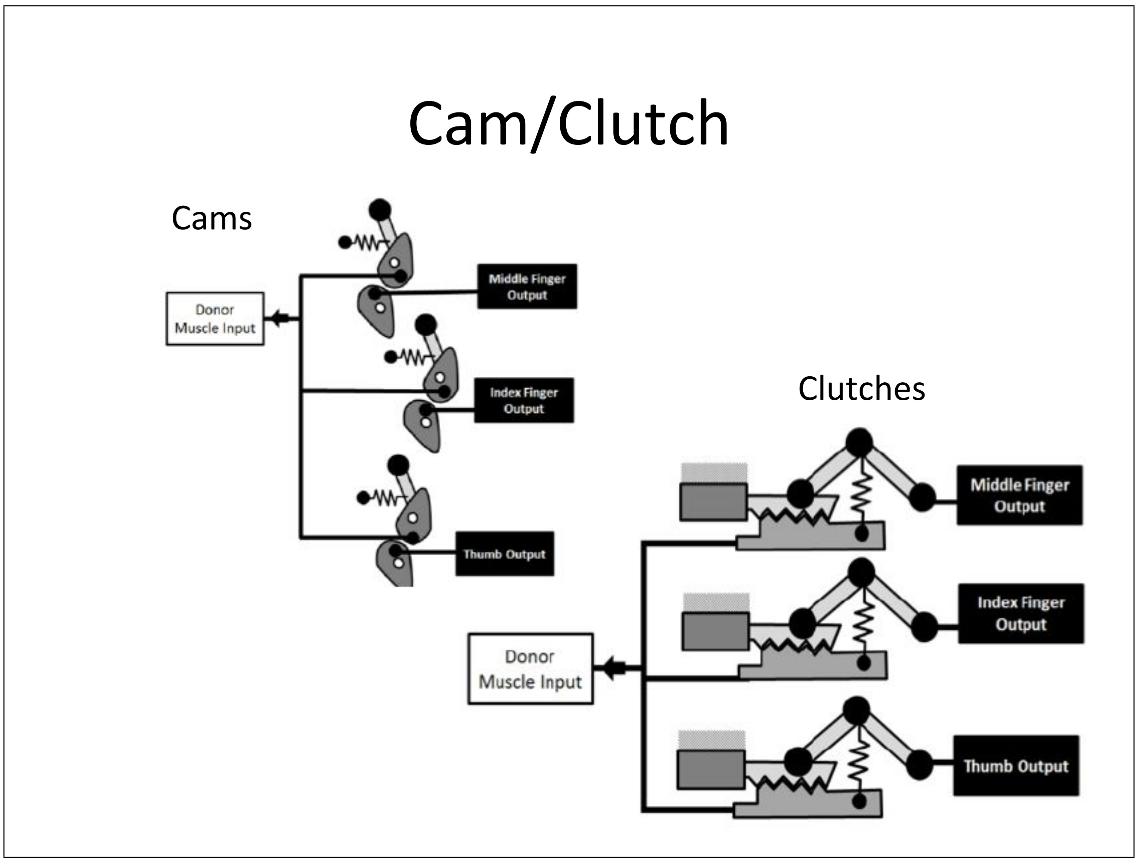

Figure D.8: Cams/ Clutch: Forces amplified or absorbed with moving cams as fingers make contact with object.