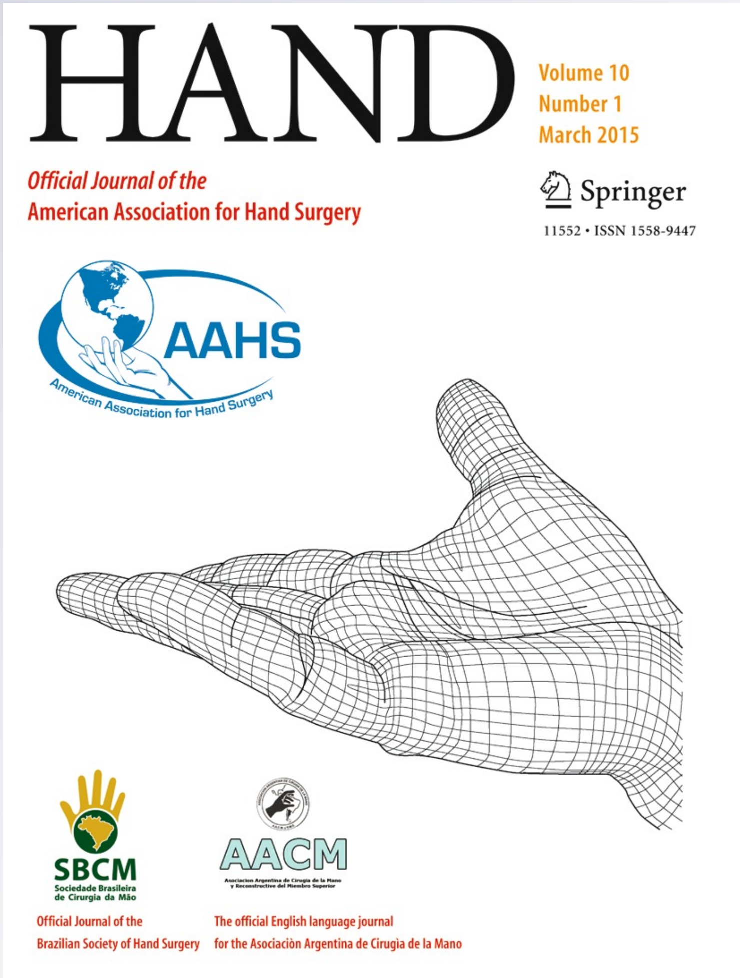
Implanted passive engineering mechanism improves hand function after tendon transfer surgery: a cadaver-based study

Katherine L. Mardula, Ravi Balasubramanian & Christopher H. Allan

HAND

ISSN 1558-9447
Volume 10
Number 1

HAND (2015) 10:116-122
DOI 10.1007/s11552-014-9676-0



Springer

HAND (2015) 10:116–122
DOI 10.1007/s11552-014-9676-0

Implanted passive engineering mechanism improves hand function after tendon transfer surgery: a cadaver-based study

Katherine L. Mardula · Ravi Balasubramanian · Christopher H. Allan

Published online: 11 September 2014

Abstract
Purpose The purpose of this study was to investigate if a new tendon transfer surgical procedure that uses an implanted passive engineering mechanism for attaching multiple tendons to a single donor muscle in place of directly suturing the tendons to the muscle improves hand function in physical interaction tasks such as grasping.
Methods The tendon transfer surgery for high median ulnar palsy was used as an exemplar, where all four flexor digitorum profundus (FDP) tendons are directly sutured to the extensor carpi radialis longus (ECRL) muscle to restore flexion. The new procedure used a passive hierarchical artificial pulley system to connect the muscle to the tendons. Both the suture-based and pulley-based procedures were conducted on $N=6$ cadaver hands. The fingers' ability to close around four objects when the ECRL tendon was pulled was tested. Post-surgery hand function was evaluated based on the actuation force required to create a grasp and the slip between the fingers and the object after the grasp was created.
Results When compared with the suture-based procedure, the pulley-based procedure (i) reduced the actuation force required to close all four fingers around the object by 45 % and (ii) improved the fingers' individual adaptation to the object's shape during the grasping process and reduced slip by 52 % after object contact (2.99°±0.28° versus 6.22°±0.66°).
Conclusions The cadaver study showed that the implanted engineering mechanism for attaching multiple tendons to one muscle significantly improved hand function in grasping tasks when compared with the current procedure.

Keywords Tendon transfer surgery · High median ulnar palsy · Implant · Engineering mechanism

K. L. Mardula · R. Balasubramanian (✉)
School of Mechanical, Industrial and Manufacturing Engineering, Oregon State University, 204 Rogers Hall, Corvallis, OR, USA
e-mail: ravi.balasubramanian@oregonstate.edu

C. H. Allan
School of Medicine, University of Washington, 4245 Roosevelt Way NE, Seattle, WA, USA

Introduction

Tendon transfer surgeries are performed to partially restore hand function for a variety of conditions such as stroke, paralysis, nerve, muscle, brain or spinal trauma, and congenital disorders [7, 15, 24, 25, 27]. The surgical procedure involves re-routing one or more tendons from an affected muscle and directly suturing it to (the tendon of) a functioning donor muscle.

In at least 15 types of hand tendon transfer surgeries, a single donor muscle is directly sutured to multiple recipient tendons [15, 25], for example, the tendon transfer surgery for high median ulnar palsy, a condition that paralyzes all four bellies of the flexor digitorum profundus (FDP) muscle, the flexor digitorum superficialis (FDS), and the intrinsic muscles. This devastating condition precludes the flexion of fingers, which in turn affects the performance of physical interaction tasks such as grasping. The current procedure to restore finger flexion for this condition sutures all four FDP tendons to the extensor carpi radialis longus (ECRL) muscle [7, 15, 25, 27] (see Fig. 1a, b; note that there are also procedures performed on the intrinsic muscles for this condition [26]; however, they are not the focus of this paper.). 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 object's shape during grasping tasks [11, 15, 19, 25]. Specifically, if one finger makes contact with an object during the grasping process while the other fingers are still closing in, further ECRL contraction to close the remaining fingers will force the finger that has already made contact to curl further and slip on the object. Furthermore, the muscle may have to stretch the tendon of the finger that has already made contact in order to flex the other fingers, increasing muscle force requirement. Overall, this affects grasping capability and limits activities of daily living [5, 6, 12, 14].

The tendon transfer surgery for median ulnar palsy is used to investigate a new surgical procedure that uses a passive hierarchical pulley system for attaching the donor muscle to the recipient tendons in place of the direct suture (see Fig. 1c, d). Inspiration for using these pulley mechanisms in hand surgery comes from their successful use in robotic hand design [4, 13]. This paper evaluates the use of this pulley mechanism in a cadaveric human hand. It is expected that the pulleys will enable the fingers to adapt individually during grasping tasks. Specifically, 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 and create a better grasp (see Fig. 1c; such mechanisms are termed "differential," due to their ability to transfer forces from one actuator to multiple joints while allowing each joint to find its own equilibrium [29].). The improved post-surgery hand function is tested using two hypotheses:

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 when compared with the suture-based procedure.

Materials and Methods

Both the suture-based and pulley-based tendon transfer procedures were conducted on six cadaver arms with mean age of 90.6±2 years. The cadavers were thawed for a minimum of 24 h and had reached a steady-state temperature before the first procedure was conducted on them. The arm was secured with bone screws to a horizontal test rig with the ulnar side along the table surface (see Fig. 2a). The fingers were set in their rest position. A 3.5-cm-diameter rigid sphere on top of a 2.5-cm-height rigid stem was attached to the table surface in front of the palm for grasping. Finger movement was created using a linear servomechanism (positioning motor) that pulled on the ECRL tendon. A single-axis load cell measured the actuation force applied. For each arm, the suture-based procedure was performed first and the grasping task was conducted. Then, the pulley-based procedure was performed and the grasping task again performed.

In the suture-based procedure, the ECRL tendon was routed in between the ulna and radial bones and directly sutured to the four FDP tendons with an "end-to-side" technique [7]. The ECRL tendon was cut from the muscle belly and attached to the linear servomechanism to produce tendon excursion. In the pulley-based procedure, the ECRL tendon was sutured to a cable attached to proximal pulley A (see Figs. 1c, d and 2b). The ring and small finger FDP tendons were sutured to a cable wrapped around distal pulley C, while the index and long finger tendons were sutured to a cable wrapped around distal pulley B. The heads of both pulleys were attached with a cable that was wrapped around pulley A. The proximal pulley had a diameter of 20 mm and was 10 mm thick, weighing 4.6 g. The distal pulleys were 15 mm in diameter and 10 mm thick, weighing 3.7 g. The cables were made of pre-strained 0.86-mm nylon-coated stainless steel. The forearms were sewn closed after the pulley mechanism was in place.

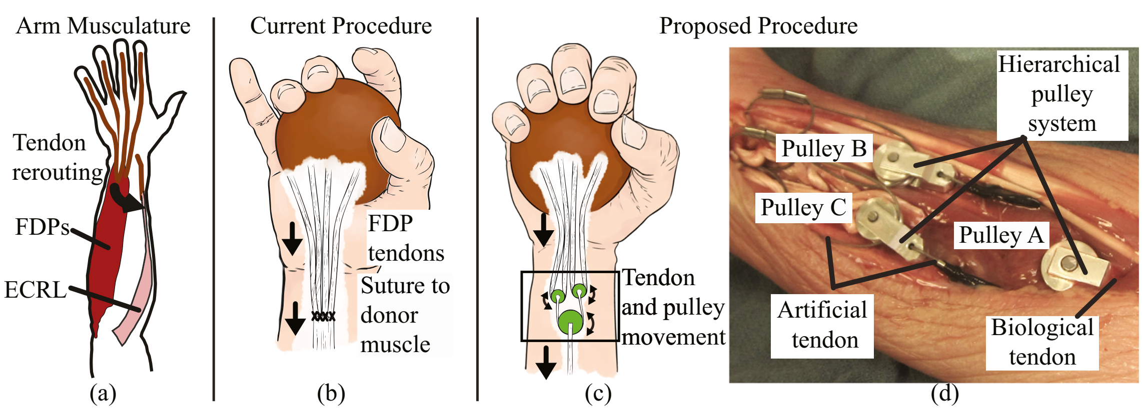


Fig. 1 **a** Hand musculature and tendons and tendon transfer surgery for high median ulnar nerve palsy, where tendons are transferred from the FDP to the extensor carpi radialis longus (ECRL) muscle. **b** Current tendon transfer procedure using sutures. **c** The proposed procedure using a pulley mechanism. **d** Prototype pulley mechanism implanted in cadaver forearm for the study

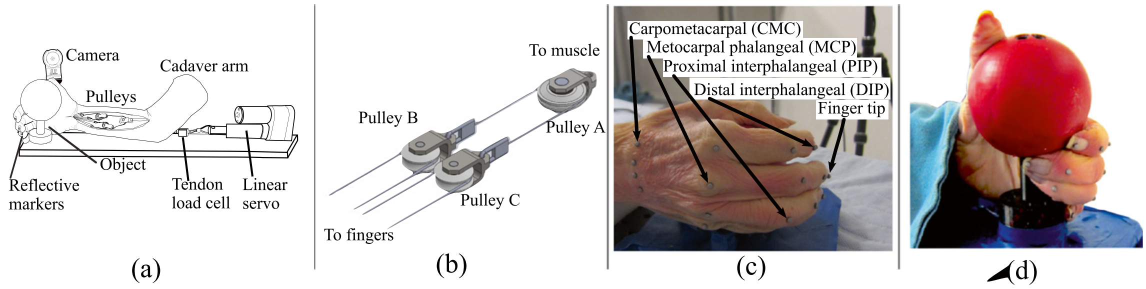


Fig. 2 **a** Experimental setup for evaluating post-surgery grasp capability. **b** Initial pulley design for concept test. **c** Marker placement on the fingers. **d** Cadaver hand grasping the stemmed ball after the pulley-based procedure

Synchronized data streams from the single-axis load cell, motion capture system, and linear servomechanism were collected using National Instruments LabVIEW [18] software. The experimenter commanded the servomechanism's excursion in steps of 1.8 mm. The total servomechanism travel never surpassed the ECRL's optimal fiber excursion length of 8.1 cm [16]. The servomechanism actuation was continued until all the fingers made contact with the ball or a maximum of 150 N in actuation force was reached. The actuation force used was thus less than the ECRL's maximum force of 304 N [16, 22].

Four-millimeter reflective markers were placed on the fingertips, distal interphalangeal (DIP) joints, proximal interphalangeal (PIP) joints, metacarpal phalangeal (MCP) joints, and carpometacarpal (CMC) joints (see Fig. 2c, d) to track finger movement using a five-camera OptiTrack motion capture system [23] at 30 Hz. A separate video camera was also used to record each trial. After each trial, the servomechanism 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 procedure pair.

Analysis

Actuation Force

To analyze the force required by the ECRL to grasp the sphere, the actuation force applied by the servomechanism 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 was averaged across the trials, such that F_{si} represented the mean actuator force for subject i for the suture-based procedure, and F_{pi} the mean actuator force for the subject i for the pulley-based procedure. In order to test if the pulley-based procedure enabled grasp creation at lower actuation forces (hypothesis I), statistical significance of the force data for each subject was tested with a one-sided paired *t* test between the procedures.

In addition, the ratio $R_{fi} = \frac{F_{pi}}{F_{si}}$ of the mean actuation forces between the two procedures was also computed for each subject i. The ratio of forces $R_{f\ i}$ was averaged across all subjects to compute R_F.

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 finger's movement during the grasping process was quantified as the sum of movement of all the joints ($\Sigma\theta_i = \theta_{MCP} + \theta_{PIP} + \theta_{DI\ P}$). The digital videos were analyzed to visually determine the time that each finger contacted the ball, which defined the stages of the grasping process.

This paper quantifies the adaptability in finger movement during grasping as the relative movement of fingers that have contacted the object with respect to the movement of fingers that have not contacted the object [8]. The goal was to show the improvement in grasping capability through the entire grasping process and not just the final grasping state. This is because the grasping process involves a staggered interaction between the fingers and the object and the grasp can fail at any point. With this goal, the grasping process during each trial was split into four phases based on the sequence of fingers making contact: phase 1, movement beginning to first finger contact; phase 2, period between first finger contact and second finger contact; phase 3, period between second contact and third contact; and phase 4, period between third finger contact and fourth finger contact (full contact). Each phase of the grasping process is shown for subject 6 in Fig. 3. Note that in some trials, some fingers made 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 change in joint angles, $\Sigma\Delta\theta_c$, for the fingers that established contact and the fingers that had not established contact, $\Sigma\Delta\theta_{nc}$, was computed for each phase. It was expected that (i) the sum of the change in joint angles after contact $\Sigma\Delta\theta_c$ would be lower for the pulley-based procedure when compared with the suture-based procedure and (ii) the sum of the change in joint angles after contact $\Sigma\Delta\theta_c$ would be less than the sum of the change in joint angles $\Sigma\Delta\theta_{nc}$ for the pulley-

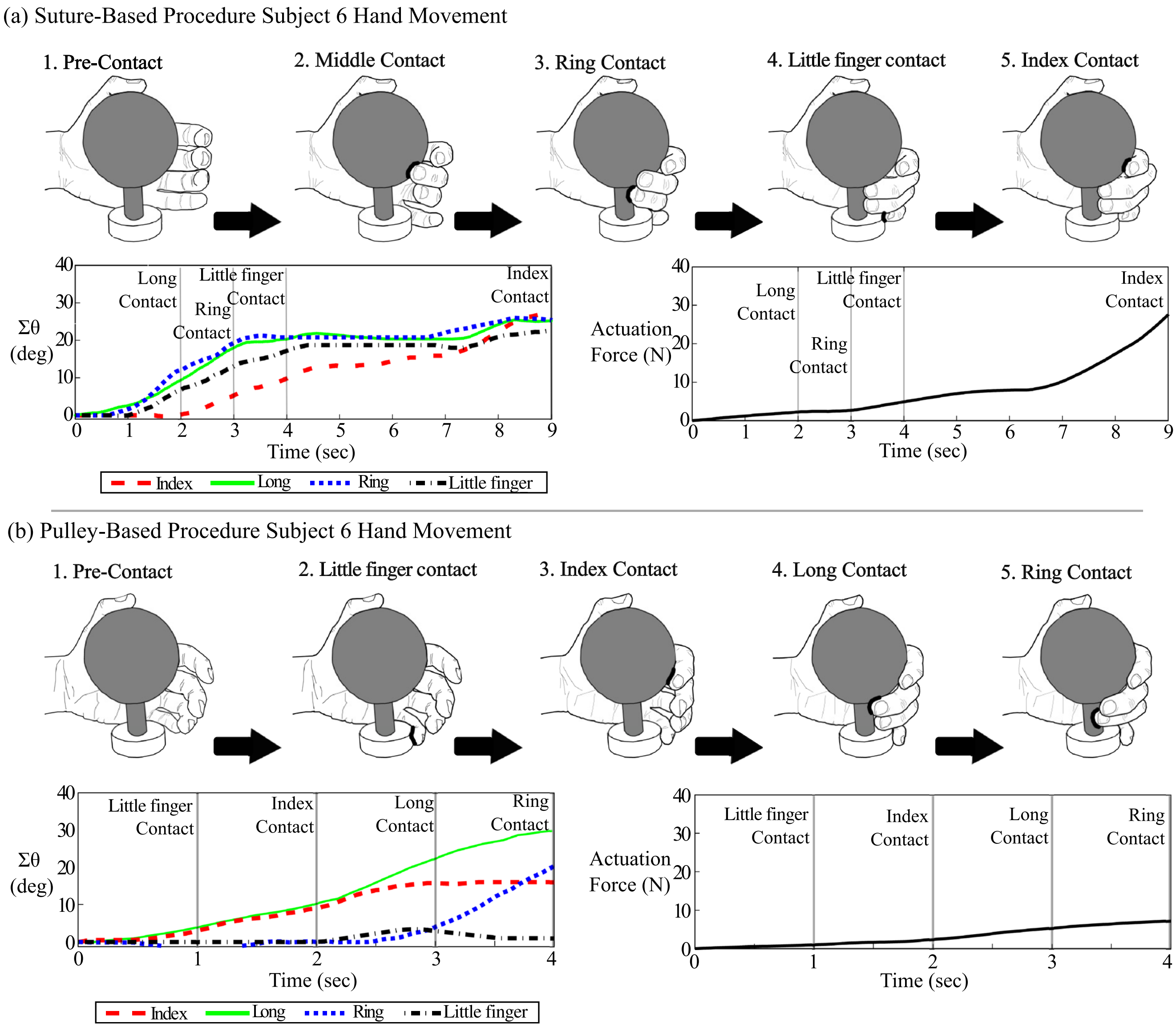


Fig. 3 An example of the phases of the grasping process, the actuation force used, the finger movement, and the contact sequence for the **a** suture-based procedure and **b** pulley-based procedure for subject 6. Finger contact is identified with a *darker line* in the line drawings, which were created from a trial video

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 during the grasping process. For the suture-based procedure, $\Sigma\Delta\theta_c$ is expected to be equal to $\Sigma\Delta\theta_{nc}$, showing coupled finger movement through the grasping process. The movement of the fingers that have not yet contacted the ball $\Sigma\Delta\theta_{nc}$ was also compared for the suture-based procedure and pulley-based procedures, in order to verify if the pulleys hindered finger movement. Statistical significance was determined with an independent sample *t* test based on the mean of the joint angle changes computed across all the trials and subjects.

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 the markers could not be individually distinguished. This is because the markers placed on the fingers can come very close to each other during the grasping process. Figure 3 shows the time history of finger movement and actuation force in order to create the grasps following the suture-based and pulley-based procedures. Figure 3a shows an example of the coupled movement after the suture-based procedure, where the long finger continues to move even after making contact because the other fingers are closing in. In contrast, Fig. 3b shows the adaptive movement after the pulley-based procedure, where the little finger moves negligibly after making contact while the other fingers close in. Also, the force required to create a full grasp is much greater for the suture-based procedure when compared with the pulley-based procedure.

Hypothesis I: Pulley-Based Procedure Reduces Actuation Force Requirement when Compared with the Suture-Based Procedure

Figure 4 shows the mean actuation force required for establishing full contact between the fingers and the object for the pulley-based and the suture-based procedures. A paired *t* test across all the subjects showed that the mean actuation force required following the pulley-based procedure was significantly lower than the force required for the suture-based procedure (*p* value 0.03). Furthermore, the mean of the ratio of forces across the subjects was $R_F=0.55\pm0.12$, indicating that the pulley-based procedure decreased force requirement by 45 % on average across the subjects. Note that the intersubject variability in actuation force required is likely because of different innate properties of each cadaver such as tendon or joint stiffness, finger lengths, finger rest position, and slippage.

Hypothesis II: Adaptive Finger Movement in the Pulley-Based 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 touched at separate times). The 29 trials for the suture-based procedure had 55 phases during the grasping process

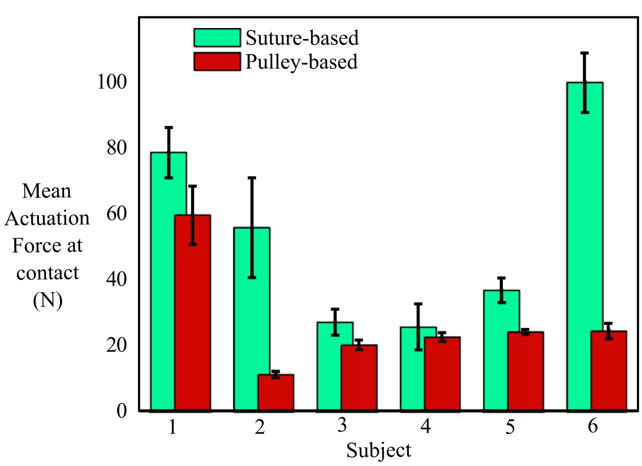


Fig. 4 Mean actuation force across all trials for each procedure and each subject used to create full contact between the object and the fingers

Table 1 A comparison of finger movement between the two surgical procedures

Procedure	Mean joint angle change for fingers that have made contact $\Sigma\Delta\theta_c$ (deg±standard error)	Mean joint angle change for fingers that have not made contact $\Sigma\Delta\theta_{nc}$ (deg±standard error)
Pulley-based	2.99°±0.28°	6.42°±0.57°
Suture-based	6.22°±0.66°	6.14°±0.75°

N=6 subjects

(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 1.

For the pulley-based procedure, the mean joint angle change for fingers that made contact ($\Sigma\Delta\theta_c=2.99°\pm0.28°$) was significantly different (*p* value <0.001) from the mean joint angle change for fingers that did not make contact ($\Sigma\Delta\theta_{nc}=6.42°\pm0.57°$). The suture-based procedure mean joint angle changes, $\Sigma\Delta\theta_c=6.22°\pm0.66°$ and $\Sigma\Delta\theta_{nc}=6.14°\pm0.75°$, were not significantly different from each other (*p* value 0.9). The mean values of $\Sigma\Delta\theta_c$ across all six subjects for the pulley-based procedure were significantly less (*p* value <0.001) than the corresponding values for the suture-based procedure.

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 [2, 25] or quantitatively for finger and wrist movement in free space without external contact [11, 16]. The experiments in this paper begin to address this issue by quantitatively testing through cadaver studies the hypotheses that the pulley-based procedure leads to a better grasping capability when compared with the suture-based procedure.

A key aspect of the grasping process is that it is difficult to predict 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 a patient with impairments, since she may not have individual control of finger flexion and proper tactile or proprioceptive feedback. Furthermore, the patient may be re-learning to use her musculature after a tendon transfer surgery. Specifically, patients who undergo the suture-based procedure for restoring finger flexion following high median ulnar palsy have coupled finger movement. Thus, the fingers do not adapt individually to the object's shape during grasping, forcing the patient to perform awkward wrist and arm movements to create a secure grasp. This effect will be most prominent when grasping objects of irregular shape.

The implanted pulleys in the new procedure address this problem by enabling the fingers to individually adapt to the object shape and close in on the object using 45 % less actuation force than the force required following the suture-based procedure (hypothesis I; see "Introduction"). The unused muscle force may be used to increase grip strength after the fingers close in on the object. For example, for the suture-based procedure, if the fingers make contact with the object in a staggered fashion (either due to the object shape or tendon tensioning error [1, 19]), then the muscle 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. This would require greater actuation force than normal finger flexion which would only work against the much lower joint stiffnesses [3, 10]. Two benefits of the reduced force requirement after the pulley-based procedure are that (i) it could increase the number of candidate donor muscles for the surgery and (ii) it will mitigate the effects of losing muscle strength that is typical in tendon transfer surgery [7]. Finally, the cause for intersubject variability in actuation force required should be evaluated in a larger study, either cadaveric or simulation-based.

The pulley-based procedure also leads to significantly better finger movement in terms of enabling the fingers to individually wrap around the object even when actuated by just one muscle (hypothesis II; see "Introduction"). This is quantified through four major comparisons between the pulley-based and suture-based procedures based on the movement of fingers before and after making contact with the object (see Table 1). First, for the pulley-based procedure, the mean joint angle change $\Sigma\Delta\theta_c$ for those fingers that make contact is significantly smaller than the mean joint angle change $\Sigma\Delta\theta_{nc}$ for the fingers that have not contacted the object. This comparison shows that following the pulley-based procedure, the fingers that made contact move much less than the fingers that have not yet made contact and that the grasp changes minimally after each stage of the grasping process. Second, the mean joint angle change before and after contact for the suture-based procedure is similar, showing that the fingers have coupled movement even after contact has been made. This implies that the fingers that have made contact slip on the object's surface at the same rate that the fingers that have not made contact close in on the object.

Third, the mean joint angle change for those fingers that have made contact, $\Sigma\Delta\theta_c$, across all six subjects is significantly less for the pulley-based procedure when compared with the suture-based procedure. This indicates 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. Specifically, the suture-based procedure would lead to more than 18° joint angle change in the first finger to make contact at the end of a three-stage grasping process (see Table 1; $3\times6.22°$), 12° for the second finger to make contact, and 6° for the second finger that makes contact. This would result in a significant difference between the initial and final grasps. In contrast, the pulley-based procedure would only lead to half of the joint angle change between the initial and final grasps. Fourth, finger movement before making contact with the object was similar for both the pulley-based and suture-based procedures. This indicates that the pulleys do not hinder finger movement.

These promising results from cadaver studies show that the pulley-based tendon transfer surgery improves hand function when compared with the suture-based procedure. However, some challenges must be overcome before this procedure can be used clinically. First, in addition to fabricating the device using biocompatible materials such as titanium or ultra high molecular weight polyethylene (UHMWPE), the mechanism may have to be chemically coated to reduce fibrosis when implanted in vivo long-term [30]. Second, the pulley-based procedure also depends on technology to make attachments between the biological tendon and the mechanism's artificial components [17, 21, 28]. Third, the mechanism may have to be enclosed in a sheath of biocompatible material in order to reduce injury to surrounding tissue while the mechanism moves inside the forearm [9, 20]. Finally, note that the pulley mechanism shown in this paper is only a prototype of one embodiment of an engineering mechanism to create the differential movement between the fingers when they are actuated by one muscle. Smaller, thinner, and smoother embodiments of this fundamental mechanism should be investigated. Immediate 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.

Acknowledgments A special thanks to the Institute for Simulation and Interprofessional Studies at UW Medicine for their support during the cadaver experiments, Sarani Chatterjee for aiding in the data processing, and Dr. Cliff Pereira for the statistical guidance. Drs. Joseph McGuire, Brian Bay, and Buddy Ratner also provided advice for the project.

Conflict of Interest Katherine L. Mardula states that she has no conflict of interest in conducting this research. Christopher H. Allan states that he received a grant from the army and money from Oregon State University for conducting this research (please see complete COI statement). Ravi Balasubramanian states that he has no conflict of interest in conducting this research.

Statement of Human and Animal Rights This article does not contain any studies with human or animal subjects.

Statement of Informed Consent This is to state that no human subjects were used in the conduct of the experiment described in the paper titled "Implanted Passive Engineering Mechanism Improves Hand Function After Tendon-Transfer Surgery: A Cadaver-Based Study."

References

1. Balasubramanian R, Montgomery J, Mardula KL, et al. Implanted miniature engineering mechanisms in tendon-transfer surgery improve robustness of post-surgery hand function. Hamlyn Symp Med Robot. 2013.
2. Beaton DE, Davis AM, Hudak P, et al. The DASH (disabilities of the arm, shoulder, and hand) outcome measure: what do we know about it now? Br J Hand Ther. 2001;6(4):109–18.
3. Bennett DJ, Hollerbach JM, Xu Y, et al. Time-varying stiffness of human elbow joint during cyclic voluntary movement. 1992; 88: 433–442.
4. Birglen L, Lalibert'e T, Gosselin C. Underactuated robotic hands. Springer, 2008.
5. Bookman A, Harrington M, Pass L, et al. Family caregiver handbook. Cambridge: MIT Press; 2007.
6. Bosse M, Ficke JR. Extremity war injuries V: barriers to return of function and duty. J Am Acad Orthop Surg. 2011.
7. Brand PW, Hollister A. Clinical mechanics of the hand. 2nd ed. Mosby Year Book Inc.; 1993.
8. Bullock IM, Dollar AM. Classifying human manipulation behavior. In: 2011 I.E. international conference on rehabilitation robotics (ICORR). Switzerland, EHT Surich Science City; 2011.
9. Cater DR, Belenman PR, Beaupr GS. Correlations between mechanical stress history and tissue differentiation in initial fracture healing. J Orthop Res. 1988;6(5):736–48.
10. Chen S, Kao I. Conservative congruence transformation for joint and Cartesian stiffness matrices of robotic hands and fingers. Int J Robot Res. 2000;19(9):835–47.
11. Cooney WP, Linscheid RL, An KN. Opposition of the thumb: an anatomic and biomechanical study of tendon transfers. J Hand Surg. 1984;9A(6):777–86.
12. Cross J, Ficke J, Hsu J, et al. Battlefield orthopedic injuries cause the majority of long-term disabilities. J Am Acad Orthop Surg. 2011;19 suppl 1:S1–7.
13. Dollar AM, Howe RD. The highly adaptive SDM hand: design and performance evaluation. Int J Robot Res. 2010;29(5):585–97.
14. Friden J, Lieber R. Tendon transfer surgery: clinical implications of experimental studies. Clin Orthop Relat Res. 2002; 403S(S163-S170).
15. Green DP, Hotchkiss RN, Pederson WC, et al. Green's operative hand surgery, volume 1. 2. fifth ed. Elsevier Churchill Livingstone; 2005.
16. Holzbaur KRS, Murray WM, Delp SL. A model of the upper extremity for simulating musculoskeletal surgery and analyzing neuromuscular control. Ann Biomed Eng. 2005;33(6):829–40.
17. Hunter Implants. Ortotech. http://www.ortotech.c.
18. Labview. National Instruments. http://www.ni.com/labvie.
19. Lieber RL. Biology and mechanics of skeletal muscle: what hand surgeons need to know when tensioning a tendon transfer. J Hand Surg. 2008. doi:10.1016/j.jhsa.2008.08.010.
20. Lilla JA, Vistnes LM. Long-term study of reactions to various silicone breast implants in rabbits. Plast Reconstr Surg. 1976;57(5):637–49.
21. Melvin AJ, Litsky AS, Mayerson JL, et al. Extended healing validation of an artificial tendon to connect the quadriceps muscle to the tibia: 180-day study. J Orthop Res. 2012;30(7):1112–7.
22. Murray WM, Buchanan TS, Delp SL. The isometric functional capacity of muscles that cross the elbow. J Biomech. 2000;30:943–52.
23. OptiTrack. Natural point. http://www.naturalpoint.com/optitrac.
24. Riordan DC. Tendon transfers for median, ulnar or radial nerve palsy. Hand. 1969;1:42–6.
25. Sammer DM, Chung KC. Tendon transfers: part I. Principles of transfer and transfers for radial nerve palsy. Plast Reconstr Surg. 2009;123(5):169e–77.
26. Sepienza A, Green S. Correction of the claw hand. Hand Clin. 2012; 28(1).
27. Strickland JW, Graham TJ. The hand: master techniques in orthopedic surgery. Lippincott Williams & Wilkins; 2005.
28. Su BW, Solomans M, Barrow A, et al. A device for zone II flexor tendon repair. J BoneJoint Surg [AM]. 2006;88-A(Supplement 1): 37–49.
29. Wikipedia. Differential mechanisms. http://en.wikipedia.org/wiki/Differential.
30. Zhang L, Cao Z, Bai T, et al. Zwitterionic hydrogels implanted in mice resist the foreign-body reaction. Nat Biotechnol. 2013;31:553–6.