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Measurement of the Three-Dimensional Muscle Endpoint Forces in the Extended Thumb and Its Application to Determining Muscle Combinations that Enable Lateral Pinch Force Production Throughout the Plane of Flexion-Extension

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Abstract— **Functional outcomes of tendon transfer surgeries, designed to restore lateral pinch grasp to persons following cervical spinal cord injury, have been mixed. That is, pinch force magnitudes have varied by 10-fold and have been reported to be as low as low as tenths of a pound. We believe a novel tendon transfer approach in which the donor muscle actuates a small group of paralyzed thumb muscles, instead of just the flexor pollicis longus (FPL) muscle (the current approach), will enable endpoint forces that are better directed and therefore a consistently stronger pinch force following surgery. We further believe that such surgeries can be better designed to account for grasp force production throughout the entire plane of flexion-extension if muscle endpoint forces in the extended thumb are known. Consequently, we measured muscle endpoint forces in the extended thumb in 6 cadaveric specimens after a force of 10 N was applied to each muscle. Further, we simulated a tendon transfer surgery in which the donor muscle applied equal force to each muscle in 246 small groups of muscles, calculated the direction of the resulting endpoint force throughout the flexion-extension plane, and determined if those groups of muscles produced a better directed force than FPL's. While we found that 3 individual muscles and 52 muscle groups could produce desirably directed endpoint forces in *parts of* the flexion-extension plane, no muscle or muscle group could produce well-directed endpoint forces *throughout* the flexion-extension plane. We concluded that a group of muscles could likely be found if the donor muscle provided different levels of force to each of the muscles in a muscle group. This would be possible through intentional geometric manipulation of the donor-to-recipient muscle attachment to allow for unequal splitting of donor muscle force.**

***Clinical Relevance*—This work aims to determine whether the same combination of thumb muscles can produce well-directed endpoint forces throughout the flexion-extension plane. If so, then this work informs surgeons which muscle groups could be involved in a tendon transfer to restore lateral pinch grasp ability throughout the plane of flexion-extension in person with cervical spinal cord injury.**

I. Introduction

Grasp deficits following cervical spinal cord injury (SCI) substantially diminish the quality of life of up to 400,000 people in the US [1], representing approximately $80 million dollars annually in assistive care costs. Tendon transfer surgery—involving surgical transfer of the brachioradialis (Br, elbow flexor) to either the paralyzed extensor carpi radialis longus (ECRL, wrist extensor) or the paralyzed flexor pollicis longus (FPL, thumb flexor) [2]—is commonly performed to restore grasp between the thumb and side of the index finger in tetraplegic individuals who are surgical candidates. This type of grasp is called lateral or key pinch grasp [3]. Functional outcomes, however, have been mixed. That is, outcomes of such tendon transfer surgeries have varied greatly where maximum pinch forces in patients have differed by 10-fold and have been as low as tenths of a pound [3, 4]. The ability to perform activities of daily living (ADLs) remains quite limited for patients producing maximum forces in the lower range [5]. One possible cause for low pinch force production is the current single-insertion site approach, wherein Br is surgically attached to FPL to enable pinch function or attached to ECRL, which engages FPL through wrist extension, to enable pinch function. In either case, the endpoint force of FPL is poorly directed (95% CI: 46 deg to 55 deg relative to the palmar force direction, [line segment on the distal thumb in Fig. 3]) which contributes to weak pinch force and thumb-tip instability [6]. We hypothesized that novel multi-insertion site tendon transfers, i.e., transfers in which Br is directly attached to small groups of paralyzed thumb muscles (rather than a single muscle), enable thumb-tip forces that are better directed than that using the common approach and therefore produce more stable grasps.

Tendon transfer surgeries have been generally designed with one grasp posture in mind and that approach is functionally limiting for tendon transfer surgery recipients. For example, the Moberg Procedure and the Br-FPL tendon transfer have both been optimized to enable lateral pinch grasp of small objects, neglecting a focus on the grasp large objects as well [2]. This assertion logically follows from the way tendon transfers are evaluated during surgery. For example, a hand surgeon will manipulate the tendon of FPL, consider how the thumb pad contacts the index finger and consider the quality of the trajectory through which FPL moves the thumb from no contact to contact with the index finger. To the surgeon, both signify the quality of thumb contact and thumb-tip force production in the vicinity of the index finger.

It is challenging to design tendon transfers optimized for a

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single thumb position. It is even more challenging to do so for multiple thumb positions of lateral pinch grasp, one position being when the thumb is flexed near the index finger to grasp small or thin objects, and another position being when the thumb is extended far away from the index finger to grasp large or thick objects. However, to plan and implement tendon transfers that are functional at multiple postures in the plane of flexion-extension, the endpoint forces that thumb muscles produce at multiple postures must be known. Currently, only the thumb-tip forces that muscles produce in the flexed thumb are known [7-9]. Toward this end, the goals of this study were: (1) to measure endpoint forces of muscles in the extended thumb; and (2) to determine, through simulation, whether alternative multi-insertion site tendon transfer surgeries can generate better-directed thumb-tip forces than standard approaches throughout the plane of flexion-extension. This work builds on prior work [7].

II. Methods

A. Cadaver Preparation and Measurement of Muscle Endpoint Forces

The endpoint forces of the muscles of the thumb were measured and analyzed to investigate the feasibility of finding sets of muscles with desirable endpoint force production characteristics for lateral pinch grasp throughout the plane of thumb flexion-extension. Muscle endpoint forces in the extended thumb were measured in cadaveric specimens using a protocol described in our previous studies [7, 8]. Specifically, cadaveric specimens of the forearm and hand were dissected (Fig. 1) to expose the tendons/aponeuroses of the nine muscles of the thumb. Four of the muscles are extrinsic, meaning their muscle bellies are in the forearm. They are flexor pollicis longus (FPL), extensor pollicis longus (EPL), extensor pollicis brevis (EPB), and abductor pollicis longus (APL). The remaining five muscles are intrinsic, meaning their muscle bellies are in the hand. They are the radial and ulnar heads of flexor pollicis brevis (FPBr, FPBu), abductor pollicis brevis (APB), adductor pollicis (ADP), and the opponens pollicis (OPP). Nylon thread was tied or sutured to each muscle's tendon/aponeurosis in such a way to best approximate the line of action of its musculotendon force.

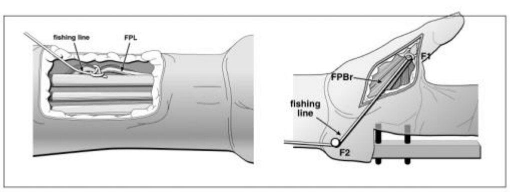

Figure 1: Cadaveric Dissection. Cadaveric specimens were dissected in the distal forearm and on the anterior and posterior aspects of the thumb to expose all nine thumb muscles. Nylon cord was tied or sutured to each muscle's insertion tendon or aponeurosis for the purpose of approximating the line of action of force that each muscle would apply to the thumb.

The distal upper extremity of each specimen was mounted on a frame (Fig. 2) to facilitate data collection. The thumb was neutrally adducted and maximally extended such that joint extension at the trapeziometacarpal (TMC) ranged from 35 deg to 50 deg relative to the line of action of the radius. Additionally, the metacarpophalangeal (MP) and interphalangeal (IP) joints were nearly neutrally extended. A force of 10 N was applied to the muscle's insertion point. The resulting endpoint force was measured by the six-axis force/torque sensor rigidly attached to the thumb-tip. Data for each muscle was recorded at 100 Hz for 1 s. Three-dimensional endpoint force magnitude and direction were compared among all muscles using a one-way ANOVA ($\alpha = 0.05$) and a post-hoc Tukey test ($\alpha = 0.05$) if significance resulted.

Functionally, we defined endpoint force production throughout the plane of thumb flexion-extension as forces being produced when the thumb is flexed, mid-flexed and extended (Fig. 3). Muscle endpoint force production during lateral pinch grasp, when the thumb is flexed, was presented in a previous study [7]. Muscle endpoint force production in the extended thumb were measured in this study. Lastly, muscle endpoint force production, associated with a mid-flexed thumb posture, was approximated as the mean of the

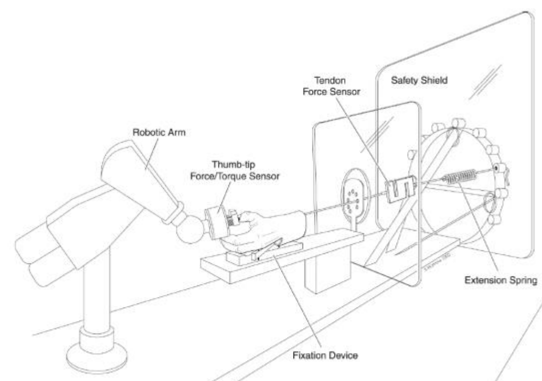

Figure 2: Experimental Setup. Each cadaveric specimen was mounted onto an experiment frame in a posture that simulated lateral pinch. A force of 10 N was applied to each thumb muscle's insertion tendon/aponeurosis using a uni-axial spring-force system and the resulting thumb-tip force was measured using a six-axis load cell. The load cell was positioned in 3D space by a robotic arm.

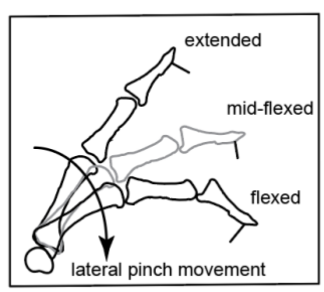

Figure 3: Thumb Postures. These are the postures associated with muscle endpoint force production during lateral pinch throughout the plane of flexion-extension. The line segment normal to the thumb pad is the palmer force direction, the most desirable direction in which to produce force.

forces produced in the flexed and extended thumb postures.

B. Creation of Muscle Groups and Simulation of Multi-Insertion Site Tendon Transfers

In this study, a desirable endpoint force was defined as having an endpoint force direction that is more closely aligned with the palmar force direction than FPL's direction. That is, a force direction that is within 45 deg of the palmar force direction.

To simulate multi-insertion site tendon transfer surgeries with hopefully desirable pinch force characteristics throughout the plane of thumb flexion-extension, muscle endpoint forces were considered individually and in small groups in the three postures. Pertaining to muscles groups, muscles were grouped to form 36 groups of two muscles, 84 groups of three muscles and 126 of groups of four muscles. Thirty-six, 84, and 126 were the maximum number of muscle combinations when muscles were chosen 2, 3, and 4 at a time. Group sizes were chosen based on the small number of thumb muscles that hand surgeons have typically manipulated during surgery [2]. To simulate the force produced by a particular tendon transfer in which the donor muscle applied equal force to each paralyzed muscle, individual muscle endpoint forces were added vectorially to find the resultant endpoint force or lateral pinch force vector in all three postures. The angle of the resultant endpoint force direction, relative to the palmar force direction (Fig. 3), was calculated for each muscle/muscle group. From the resultant vector solutions, we determined which individual muscles and muscle groups produced endpoint forces that were better directed than FPL's (if any) and the muscle(s) common to the solutions for individual postures and across all postures.

III. RESULTS

A. Individual Muscle Endpoint Force Production

The three-dimensional endpoint force magnitudes that muscles produced was on average 50% of the force applied to the insertion tendons (10 N) or 5.0 N and ranged from 26% (OPP) to 90% (FPL) or 2.6 N and 9.0 N, respectively (Fig. 4; force magnitudes were computed from force components in Table 1). The magnitude of the endpoint force that FPL produced (9.0 N) was significantly greater ($p \leq 0.05$) than that produced by FPBr (5.1 N), OPP (2.6 N), FPBu (3.0 N) and ADP (3.5 N). Muscles produced force either primarily in the proximal force direction or primarily in the combined proximal-palmar force direction in the plane of flexion-extension (Fig. 4A). In the proximal force production case, the muscles were EPL, EPB, APL, FPL, and APB. The mean unit vector component among these muscles and all specimens tested was 0.96 in the proximal direction. In the combined proximal-palmar force production case, the muscles were FPBr, OPP, FPB and ADP. The mean unit vector components among these muscles and all specimens tested in the proximal and palmar directions were 0.53 and 0.57, in that order (unit vector directions and unit vector directional components were computed from force components in Table 1). Despite the limited endpoint force directions spanned by all nine muscles, their directions were significantly different ($p \leq 0.05$) from each other.

MUSCLE	FORCE COMPONENTS [N]		
	Ulnar	Proximal	Dorsal
EPL	0.35 (0.01, 0.96)	5.90 (4.71, 7.44)	0.02 (-0.92, 0.22)
EPB	-0.23 (-0.71, 0.25)	6.30 (4.36, 8.93)	0.66 (-0.71, 0.94)
APL	-0.11 (-0.37, 0.06)	2.65 (1.72, 7.33)	0.41 (-0.51, 0.44)
FPL	-0.29 (-0.84, 0.11)	7.98 (6.91, 9.20)	-1.88 (-2.35, -1.56)
FPBr	-0.51 (-0.91, -0.18)	2.22 (-0.47, 3.99)	-1.43 (-2.09, -0.89)
APB	-1.30 (-1.57, -0.81)	4.69 (3.10, 6.04)	-1.06 (-1.79, -0.91)
OPP	-0.44 (-0.61, -0.36)	1.54 (-0.10, 4.08)	-1.01 (-1.36, -0.58)
FPBu	0.31 (0.08, 0.65)	2.08 (0.77, 3.73)	-1.34 (-2.02, -1.23)
ADP	0.75 (0.62, 0.86)	2.50 (0.71, 4.35)	-1.87 (-2.68, -1.32)

Table 1: Muscle Endpoint Force Components. Medians and extreme values of interquartile ranges are presented for muscle endpoint force components

B. Endpoint Forces of Muscle Combinations

Throughout the plane of flexion-extension, no single thumb muscle, of the nine in total, could produce a desirably directed endpoint force, i.e., a force that was directed 45 deg or less relative to the palmar force direction. However, three muscles--FPBr (25 deg), FPBu (29 deg) and ADP (32 deg)--produced well-directed forced in the mid-flexed posture. Like individual muscle endpoint force production, none of the 246 muscle groups tested could produce endpoint forces in the desired directional range across all postures considered. However, 52 of 246 (21%) muscle groups tested produced well-directed endpoint forces in one posture (Fig. 5). The 52 muscle groups consisted of eleven from the 36 muscle pairs, 19 from the 84 muscle triplets and 22 from the 126 muscle quadruples. In the group of muscle pairs, 4 produced desired forces in the flexed thumb and 7 in the mid-flexed thumb. In the group of muscle triplets, 10 produced well-directed forces in the flexed thumb and 9 in the mid-flexed thumb. In the remaining group, there were 13 muscle combinations and 9 muscle combinations that produced well-directed forces in the flexed and mid-flexed thumbs, respectively. In no instance did a muscle combination produce a desirably directed force in the extended posture. The most common muscle used among the muscle pairs was FPBu (5 times), among the muscle triplets, FPL (10 times), and among the muscle quadruples, FPL (14 times).

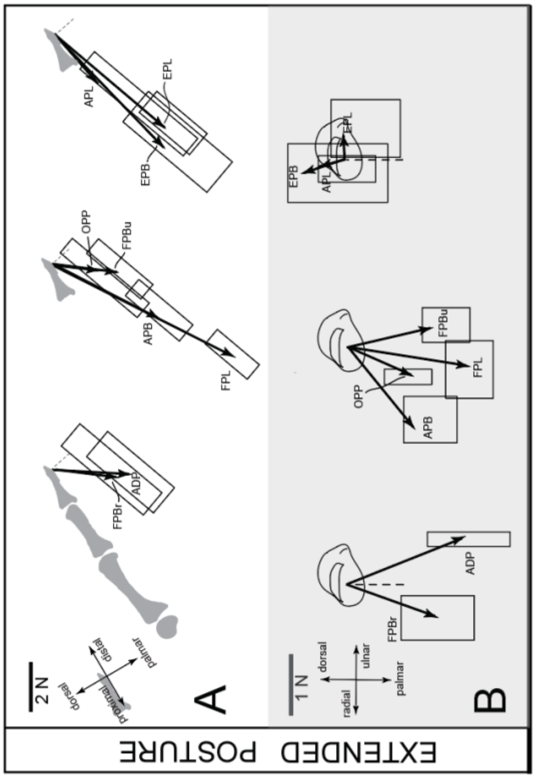

Figure 4: Muscle Endpoint Force Vectors Measured During Thumb Extension. The arrows represent median endpoint force vectors and the boxes the interquartile ranges associated with force components following 10 N of force applied to tendons/aponeuroses of the nine thumb muscles. Forces are presented both in the proximal-dorsal (A) and ulnar-dorsal (B) planes.

Muscle Pairs	
Flexed	
2	4
2	5
2	7
5	8
Midflexed	
4	5
4	7
4	9
5	7
5	9
6	7
7	9
Extended (none)	

Muscle Triplets		
Flexed		
1	2	4
1	2	6
2	3	7
2	4	5
2	4	8
2	5	6
2	5	7
2	5	8
2	5	9
2	7	8
Midflexed		
4	5	6
4	5	7
4	5	9
4	6	7
4	7	9
5	6	7
5	6	9
5	7	9
6	7	9
Extended (none)		

Muscle Quadruples			
Flexed			
1	2	4	5
1	2	4	8
1	2	5	6
1	2	7	8
2	3	4	5
2	3	5	6
2	4	5	6
2	4	5	8
2	4	7	8
2	5	6	8
2	5	7	8
2	5	8	9
2	6	7	8
Midflexed			
2	4	5	7
4	5	6	7
4	5	6	9
4	5	7	8
4	5	7	9
4	6	7	9
4	7	8	9
5	6	7	9
5	7	8	9
Extended (none)			

Figure 5: Muscle Combinations that Can Produce Well-Directed Forces. Each number in a group represents a muscle. The muscle order is as follows: EPL (1), FPL (2), EPB (3), FPBr (4), FPBu (5), APB (6), ADP (7), APL (8), OPP (9). Eleven muscle pairs, 19 muscle triplets and 22 muscle quadruples produced desirably directed forces across two thumb postures. No muscle combination could produce a well-directed endpoint force in the extended thumb.

IV. Discussion

A major goal of this work was to find individual thumb muscles and groups of thumb muscles that could produce well-directed endpoint forces throughout the plane of flexion-extension (Fig. 3) as approximated by force production at different thumb postures in the plane. This goal was motivated by the need to find surgical alternatives to the standard treatment approach to restore lateral pinch grasp in persons with cervical spinal cord injury (tetraplegia). The standard approach entails actuating the paralyzed FPL which has less than ideal endpoint force production characteristics [7, 8]. The surgical alternatives that we considered were a reimagining of tendon transfer surgery. Typically, in a tendon transfer surgery, one donor muscle is attached to one paralyzed (recipient) muscle. In this study, we put forward the idea that if a donor muscle could drive a small group of paralyzed thumb muscles, then the combined musculoskeletal mechanics of the muscle group could produce better directed endpoint forces throughout the plane of flexion-extension than FPL could. This idea is based on the understanding that the musculoskeletal mechanics of multiple muscles are coordinated to produce well-directed forces [10]. In this study, we found that certain muscle groups (Fig. 5) produced endpoint forces with desirable directions, but for a single posture—either the flexed thumb posture or the mid-flexed thumb posture and never the extended posture. While we could not find a set of muscles that produced desirably directed force vectors throughout the flexion-extension plane, we did show that one could theoretically improve endpoint force production during lateral pinch grasp in a single functional posture if multiple recipient muscles were involved and equal donor muscle force was applied to each muscle. Improvement levels, however, may vary from the mean improvement levels presented given variability in individual muscle endpoint force production (e.g., consider the interquartile ranges in muscle endpoint force production in Fig. 4). The possibility that improvement levels may vary, still, does not change the main finding that simultaneous actuation of small groups of muscles is predicted to improve grasp force direction as compared to the standard of care. As for finding a set of muscles that could produce desirable lateral pinch force throughout the plane of flexion-extension, such a set could likely be found if the donor muscle provided different levels of force to each of the muscles in a muscle group. This would be possible through intentional geometric manipulation of the donor-to-recipient muscle attachment to allow for unequal splitting of donor muscle force. For example, one could alter angles *a* and *b* in the figure below to modulate the distribution of donor muscle force to each of two paralyzed muscles (Fig. 6).

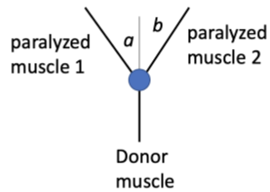

Figure 6: Donor Muscle Contributions to Paralyzed Muscles in the Thumb. Angles *a* and *b* describe the lines of action of each paralyzed muscle and determine the contribution of donor force each paralyzed muscle receives. If *a* and *b* are equal, the paralyzed muscles receive equal force contributions from the donor muscle. As angle *b* decreases, the donor muscle contributes more force to *b* and less force to *a*.

In this study, it seemed especially difficult to find muscle combinations in the extended thumb posture that could meet the desired grasp force directional characteristic. This may have been the case because many muscles' endpoint forces were primarily directed in the proximal force direction (Fig. 4). This result was not that unexpected when considering concepts in robotics. The theoretical map between joint torque, τ, and endpoint force, f_{ep} [6]

$$f_{ep} = J^{-T}\tau \qquad (1)$$

is an accepted robotics-based model of the thumb [7, 11]. The force manipulability ellipsoid, a graphical representation of the preferred endpoint force directions of the model, is nearly oriented along the proximal and distal directions [6]. This theoretical finding from robotics combined with results from the work of others on the movement of carpal bones at the base of the thumb [12, 13] supports the idea that the dominant endpoint force production direction would be the proximal direction.

V. Conclusion

To our knowledge, this study was the first to investigate whether small groups of thumb muscles could be used to generate suitable lateral pinch force production throughout the flexion-extension plane. This work has application to improving current tendon transfer procedures that restore lateral pinch grasp following cervical spinal cord injury. As we alluded to earlier, future studies will consider ways to vary the force that the donor muscle contributes to each paralyzed recipient muscle. Future studies will also explore whether muscle combinations with favorable endpoint force production characteristics are also suitable for moving the thumb throughout the plane of flexion-extension.

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