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Use of intrinsic thumb muscles may help to improve lateral pinch function restored by tendon transfer

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Abstract

Background. For surgical reconstruction of lateral pinch following tetraplegia, the function of the paralyzed flexor pollicis longus is commonly restored. The purpose of this study was to investigate if one of the intrinsic muscles could generate a more suitably directed thumb-tip force during lateral pinch than that of flexor pollicis longus.

Methods. Endpoint force resulting from 10 N applied to each thumb muscle was measured in eleven upper extremity cadaveric specimens. We utilized the Kruskal–Wallis test ($\alpha = 0.05$) to determine whether thumb-tip forces of intrinsic muscles were less directed toward the base of the thumb, i.e., proximally directed, than the thumb-tip force produced by flexor pollicis longus. Additionally, a biomechanical model was used to assess the effect of an increase in tendon force on intrinsic muscle endpoint forces.

Findings. All of the intrinsic muscles produced thumb-tip force vectors, ranging from 127° to 156°, that were significantly ($P < 0.009$) less proximally directed than that of flexor pollicis longus (66° (46°)). A biomechanical model predicted that intrinsic muscle thumb-tip forces would vary non-linearly with tendon force. A 2-fold increase in tendon force produced, on average, a 2.3-fold increase in force magnitude and an 8° shift in force direction across all intrinsic muscles.

Interpretation. This study suggests the possibility of using an intrinsic muscle, e.g., the flexor pollicis brevis (ulnar head), instead of flexor pollicis longus, to produce a more advantageously directed thumb-tip force during lateral pinch in the surgically-reconstructed tetraplegic thumb and thus potentially enhance function.

Keywords: Thumb-tip force; Thumb muscles; Lateral or key pinch; Tetraplegic hand; Upper extremity tendon transfer; Intrinsic thumb muscles

Introduction

Lateral pinch, also termed key pinch, is a simple grasp pattern in which the thumb applies force to an object to hold it against the lateral aspect of the index finger (Brand and Hollister, 1999a). A common objective of surgical reconstruction of the upper extremity in persons with tetraplegia is to restore active lateral pinch function, as it provides the ability to grasp objects (e.g., eating utensils) that are necessary for activities of daily living and self-care. Tendon transfer surgery is a commonly performed reconstructive surgical procedure that involves releasing the tendinous attachment of a muscle under voluntary control (the donor muscle) and typically re-attaching it to the tendon of a paralyzed muscle (the recipient muscle). For surgical reconstruction of lateral pinch, a forearm donor muscle is most often attached to the insertion tendon of the paralyzed flexor pollicis longus (FPL) (Cooney, 1988; House et al., 1976; Paul et al., 1994; Revol et al., 2002; Waters et al., 1985).

Despite the usual practice of surgically attaching a donor muscle to the paralyzed FPL, the direction of the

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thumb-tip force that FPL produces may be too proximally directly (i.e., directed too much toward the base of the thumb) (Towles et al., 2004). This characteristic of the muscle may contribute to slip in the proximal direction and loss of thumb contact during grasp (Buchholz et al., 1988). An FPL-actuated thumb also causes hyperflexion at the interphalangeal (IP) joint (Froment's Sign (Brand and Hollister, 1999b)), which can be another mechanism for slip during contact (Towles et al., 2004). To abate IP joint hyperflexion, the joint is sometimes stabilized through pin fixation (Goloborod'ko, 1998; Moberg, 1975); however such fixation diminishes the supple nature of the hand.

Given the potential differences in thumb-tip forces produced by FPL and intrinsic (flexor) muscles due to differences in musculoskeletal geometry (Smutz et al., 1998), it is reasonable to believe that at least one of the intrinsic muscles can produce a more suitably directed thumb-tip force for active lateral pinch function. Although it is more straightforward surgically to attach a forearm donor muscle to the tendon of a paralyzed extrinsic muscle because such muscles, unlike intrinsic muscles, originate in the forearm, interpositional tendon grafts can be utilized to lengthen the tendon of the donor muscle to enable attachment to an intrinsic muscle (e.g., the palmaris longus tendon is often sacrificed and subsequently used to lengthen the abductor pollicis longus tendon before it is transferred to the paralyzed first dorsal interosseus muscle (Neviaser et al., 1980)). *In this study, we hypothesized that an intrinsic muscle could produce a thumb-tip force that was less proximally directed than that of FPL.*

To accomplish this study, we used a similar experimental technique as Pearlman et al. (Pearlman et al., 2004) pertaining to their study of muscle thumb-tip force production during lateral pinch. Instead of reporting measurements of muscle thumb-tip force vectors that correspond to specific applied tendon forces, Pearlman and colleagues reported an average thumb-tip force vector for each muscle over a range of applied tendon forces. In this study, we wanted to assess whether other muscles produced less proximally directed thumb-tip forces than that of FPL. Their published data, measured during simulation of lateral pinch, preclude a careful assessment of that research question particularly because of the non-linear relation between muscle tendon force and the corresponding thump-tip force which they generally found. The non-linear relation means that, for a given muscle, thumb-tip force direction varies with tendon force and thumb-tip force magnitude varies non-proportionately with tendon force. They espoused that these variations were possibly due to alterations in thumb joint kinematics induced by tendon force-dependent carpal bone movement (Valero-Cuevas and Small, 1997). It has not been determined whether such non-linearity substantially affects thumb-tip force magnitude and direction for a given muscle/tendon force range. *In this study, the following questions were addressed*: (1) *Is there an intrinsic muscle whose thumb-tip force vector is less proximally directed than that of FPL; and* (2) *if so, does that muscle's thumb-tip force magnitude and direction substantially change due to the effect of tendon load-related carpal bone motion as predicted by a biomechanical model.*

Methods

In situ thumb-tip force measurements

Endpoint forces produced by the muscles of the thumb were measured in 11 upper extremity cadaveric specimens by adapting an experimental approach previously developed for studies of index fingertip (Valero-Cuevas et al., 2000) and thumb-tip (Towles et al., 2004) force production. For completeness, we measured thumb-tip forces produced by all thumb muscles, but focused our evaluation on FPL and the intrinsic muscles due to their clinical relevance.

Cadaveric specimens of the forearm and hand were dissected, exposing the tendons of the extrinsic muscles – FPL, extensor pollicis longus (EPL), extensor pollicis brevis (EPB) and abductor pollicis longus (APL) – and then exposing the aponeuroses of the intrinsic muscles, including the radial and ulnar heads of the flexor pollicis brevis (FPBr, FPBu), abductor pollicis brevis (APB), adductor pollicis (ADP), and opponens pollicis (OPP). Medium grade fishing line (60-lb/247-N test, braided, low-stretch trolling and bottom fishing line; Izorline; Gardena, CA, USA) was tied or sutured to either the tendon or the aponeurosis of each muscle. For the intrinsic muscles, the line was routed around a metal pin inserted into the carpal bones to best approximate the anatomical path and the direction of pull of that muscle.

As described previously (Towles et al., 2004), thumb-tip forces were measured using a six-axis force/torque sensor (F/T Gamma 130, ATI Industrial Automation; Apex, NC, USA) after applying a known force to the tendon or aponeurosis. Specimens were first mounted onto a frame and the wrist was positioned in neutral using a fixation device (Agee WristJack; Hand Biomechanics Laboratory, Inc.; Sacramento, CA, USA). As in a previous study (Towles et al., 2004), the thumb-tip was rigidly coupled to the six-axis force/torque transducer, which served as the end-effector of a robotic arm (Staubli-Unimate Puma 260 programmable robot, Staubli Corporation; Duncan, SC, USA). The robotic arm enabled reproducible positioning of the thumb (Fig. 1).

Each thumb was positioned to simulate lateral pinch, broadly characterized by neutral adduction of the thumb, and contact between the thumb and the lateral aspect of the index finger (Brand and Hollister, 1999a). In our specimens, we simulated contact between the mid-distal thumb pulp and the middle phalanx of the index finger by placing the TMC joint in extension (median: $-28°$; interquartile range: $-36°$ to $-27°$), the MP joint in flexion ($31°$ ($24°, 36°$)), and the IP joint in flexion ($37°$ ($34°, 50°$)). Joint angles were quantified using a digital picture of each specimen in the plane of flexion–extension. As described previously (Towles et al., 2004), joint angles were defined with

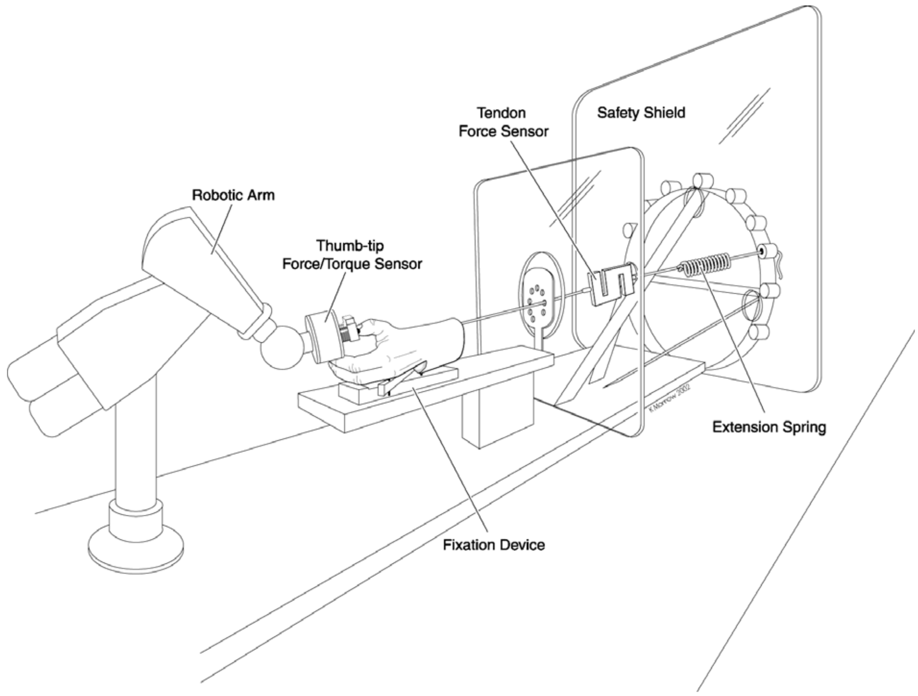


Fig. 1. Experimental setup. The distal upper extremity of each specimen was mounted on a frame to a fixation device, and the thumb to the end of a robotic arm. Force was applied to the muscle's insertion by stretching the attached extension spring. The in-series tendon force sensor measured the applied force. The resulting thumb-tip force was measured by the six-axis force/torque sensor rigidly attached to the thumb-tip.

respect to adjacent bone segments and bone lengths were measured manually as the distance between palpable joint spaces in the thumb. The median lengths of the metacarpal, and the proximal and distal phalanges were 54 (49, 60) mm, 32 (28, 34) mm, and 19 (16, 24) mm, respectively.

Force was applied to the tendon (or aponeurosis) of each muscle to yield thumb-tip force for that muscle. A moderate level of force (10 N) was applied to each tendon and monitored using a single axis force sensor (NS-25 Nikkei S-type uni-axis load cell, Transducer Techniques; Temecula, CA, USA). The output of the six-axis force/torque sensor, to which the thumb-tip was attached, was sampled at 100 Hz. In each trial, data was collected over a time period of 1 s and was recorded on a Macintosh computer (Apple Computer, Inc.; Cupertino, CA, USA).

Data analysis

After cadaveric testing was completed, the components of the measured force vectors for each muscle and each specimen were expressed in spherical coordinates, ζ (elevation angle) and β (azimuth angle) (see Table 2 for graphic representation for force production by generic muscle M). To examine the extent to which thumb-tip force vectors were proximally directed, the smallest angle between the proximal direction and the thumb-tip force vector, projected to the flexion-extension plane, was calculated for each intrinsic muscle per specimen

$$\theta = \cos^{-1}(\sin \varsigma \sin \beta) \tag{1}$$

where $0^o \leqslant \theta \leqslant 180°$ (see Table 2 for graphic representation for generic muscle force). We utilized the Kruskal-Wallis test ($\alpha = 0.05$; SPSS, Inc.; Chicago, IL, USA), and if necessary, a post-hoc Wilcoxon signed-rank test ($\alpha = 0.05$), to determine whether thumb-tip forces of intrinsic muscles were less proximally directed (i.e., have a greater θ) than the thumb-tip force produced by FPL.

Model development

A two-dimensional, kinematic model was developed to estimate how thumb-tip force, produced by a given thumb muscle, varied with carpal bone motion. The model consisted of four bones (the trapezium, the metacarpal (MC) and the proximal (PP) and distal phalanges (DP)), three hinge joints (the trapeziometacarpal (TMC), the metacarpophalangeal (MP) and the interphalangeal (IP) joints), and the nine thumb muscles. The model was fully constrained at the thumb-tip to replicate the experimental condition under which muscle-produced thumb-tip force vectors were measured *in situ*. A force f_t was applied to the insertion tendon of a thumb muscle, and the resulting thumb-tip force and torque vector *f*, expressed in the thumb-tip's reference frame, was computed using Eq. (2):

$$\underset{(3x1)}{f} = \underset{(3x3)}{J^{-T}} \underset{(3x1)}{r} \underset{(1x1)}{f_t} \tag{2}$$

r is a vector of muscle moment arms at the TMC, MP and IP joints. The product rf_t is a vector of joint torques which J^{-T} transforms into the thumb-tip force and torque vector *f*. $f = [f_f\, f_\tau]^T$ where $f_f \in \Re^{2x1}$ and $f_\tau \in \Re^{1x1}$. Bone lengths and joint angles were defined to be the median lengths and angles, respectively, measured in the cadaveric specimens tested above. Muscle moment arms were set to the mean estimates derived from Smutz et al. (1998) (Table 1).

A force of 10 N was applied to the tendon of each muscle and the thumb-tip force was computed according to Eq. (2). Computed thumb-tip force components, i.e., components of f_f, of a muscle were compared to the extreme values of the interquartile ranges (IQR's) of the muscle thumb-tip force components measured in the cadaveric specimens to evaluate how effectively the model represented muscle force production at the thumb-tip. If the computed thumb-tip force components exceeded the extremes values for a given muscle, muscle moment arms were varied within three standard deviations (SD's) of published mean values to improve the model's prediction (Valero-Cuevas et al., 1998) (Table 1).

To simulate carpal bone movement, the base of the metacarpal bone was allowed to translate horizontally along the length of the radius as a function of muscle tendon force (Fig. 2). Pearlman et al. (2004) provided experimental data from two cadaveric specimens that described the maximal displacement of the metacarpal base with maximal FPL tendon force. They found that ~30 N of FPL tendon force produced ~2 mm of metacarpal base movement along the length of the radius (toward the elbow). Interestingly, that data provides a good or worst-case estimate of the amount of metacarpal base displacement had 30 N been applied to any of the other muscles because FPL, unlike most thumb muscles, exerts force along almost the entire length of the thumb. That condition arguably produces the greatest displacement of the metacarpal base. The model was used to predict variations in muscle thumb-tip force vectors when muscle tendon forces varied from 10 to 30 N as the metacarpal base was displaced from 0 to 2 mm. Mechanical modeling simulation software (Working Model, Knowledge Revolution; San Mateo, CA, USA) was used to determine the change in thumb posture corresponding to the 2-mm metacarpal base displacement.

Table 1
Muscle moment arm values for nominal and adjusted models

Muscle	Nominal (mm)			Adjusted (mm)		
	TMC	MP	IP	TMC	MP	IP
EPL	−8.1 (2.6)	−9.9 (1.2)	−5.0 (0.6)	−9.7	−8.8	7
FPL	14.3 (4.0)	8.7 (1.2)	7.2 (1.4)	10.9	10.5	7
EPB	−13.0 (2.5)	−8.8 (0.8)		−13.2	−5.5	
FPBr	13.4 (7.5)	3.9 (2.1)		15.8	5.2	
FPBu	27.0(10.5)	3.0 (3.4)		15	6.1	
APB	3.9 (3.1)	0.3 (2.2)		9.8	2.7	
ADP	36.9 (5.8)	4.4 (4.5)		22.5	7	
APL	−7.1 (3.4)			–		
OPP	12.9 (3.8)			–		

Values are expressed as mean (standard deviation). Flexion moment arms are positive; extension moment arms are negative.
"–" means nominal value was unchanged.
Abbreviations: extensor pollicis longus/brevis (EPL/EPB); flexor pollicis longus (FPL); radial and ulnar heads of flexor pollicis brevis (FPBr, FPBu); abductor pollicis longus/brevis (APL/APB); adductor pollicis (ADP); opponens pollicis (OPP); trapeziometacarpal (TMC); metacarpophalangeal (MCP); interphalangeal (IP).

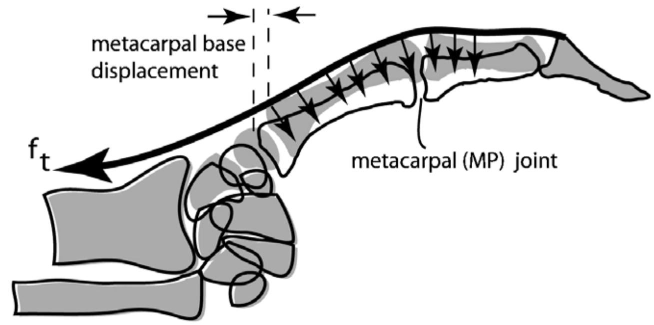


Fig. 2. Effect of tendon force on thumb posture. The pull of the tendon pushes the MP joint into less flexion as base of the metacarpal moves into the wrist due to the mobility of the carpal bones. A flexor tendon would produce a similar result through the action of tendon pulleys.

Results

Individual thumb-tip force production by intrinsic muscles

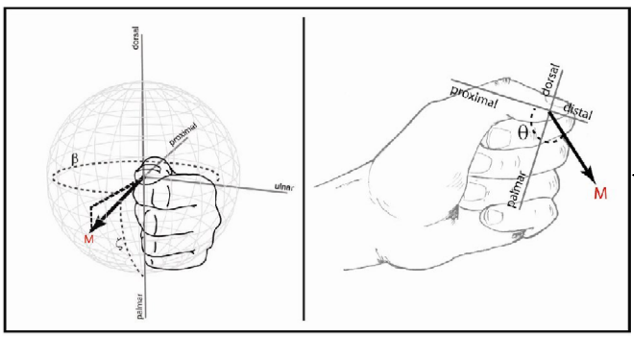
We found that all of the intrinsic muscles (OPP, APB, ADD, FPBu, FPBr) produced thumb-tip force vectors that were less proximally directed than that of FPL (Table 2, Fig. 3B) when the thumb was positioned in a lateral pinch posture (28° of TMC extension, 31° of MP flexion, 37° of IP flexion) and when 10 N of force was applied to each muscle's tendon. The thumb-tip force produced by FPL was oriented 66° (46°) relative to the proximal direction, while, as a group, the orientation of the intrinsic muscles ranged from 127° to 156°. Specifically, FPBu was oriented at 127° (15°); APB, 130° (26°); ADP, 142° (27°); OPP, 152°(29°); and FPBr, 156° (15°). While all of these muscles produced thumb-tip force vectors that were less proximally directed than FPL's, only ADP and FPBu produced thumb-tip forces with desirable characteristics, i.e., some combination of palmar and distal and/or ulnar force components. The palmar force component is necessary to accomplish grasp and, while the other two components can cause slip of the thumb-tip if contact friction is minimal, potential slip is limited by musculoskeletal structures that prevent large distally-directed thumb movements and ulnarly-directed thumb movement beyond the first webspace.

Model predictions

A biomechanical model of the thumb showed that thumb-tip forces of intrinsic muscles varied non-linearly with tendon force-dependent, carpal bone displacement. Two millimeters of carpal bone displacement was simulated by altering joint angles in the model. Trapeziometacarpal joint extension was decreased from 28° to 24°. Metacarpo-

Table 2
Magnitude, direction, and force components of measured muscle thumb-tip forces

Muscle	Magnitude (N) and Force Angles (deg)				Force Components (N)		
	Magnitude	ζ	β	θ	Ulnar	Proximal	Dorsal
EPL	1.7 (0.4)	116 (15)	354 (35)	93 (33)	1.2 (1.1, 1.4)	−0.5 (−0.6, 0.4)	0.7 (0.5, 0.8)
FPL	2.8 (1.2)	50 (21)	101 (57)	66 (46)	−0.1 (−0.3, 0.1)	2.1 (0.7, 2.7)	−1.6 (−2.1,−1.2)
EPB	1.8 (0.3)	137 (24)	118 (79)	73 (33)	−0.1 (−0.6, 0.0)	0.6 (−0.1, 1.0)	1.5 (0.9, 1.5)
FPBr	2.4 (0.8)	75 (18)	259 (12)	156 (15)*	−0.3 (−0.8, 0.1)	−2.2 (−2.5,−1.5)	−0.5 (−0.9, 0.0)
FPBu	2.4 (0.7)	55 (19)	307 (19)	127 (15)*	1.0 (0.5, 1.4)	−1.3 (−1.8, −0.9)	−1.3 (−1.5,−1.2)
APB	2.2 (0.5)	87 (18)	223 (26)	130 (26)*	−1.3 (−1.6, −1.2)	−1.5 (−1.9, −1.2)	0.1 (−0.1, 0.3)
ADP	3.3 (1.2)	74 (22)	298 (35)	142 (27)*	0.8 (0.7, 1.8)	−3.1 (−3.4, −1.7)	−0.7 (−1.3, 0.1)
APL	1.9 (0.9)	85 (15)	109 (15)	24 (15)	−0.5 (−0.7, −0.2)	1.5 (1.2, 1.8)	0.0 (−0.4, 0.1)
OPP	3.1 (1.1)	100 (25)	258 (33)	152 (29)*	−0.4 (−0.6, −0.1)	−2.8 (−3.5, −2.1)	0.8 (0.0, 1.6)



See Table 1 for muscle abbreviations. Mean values and standard deviations, in parentheses, are presented for force magnitudes and angles. Medians and extreme values of interquartile ranges, in parentheses, are reported for force components.
ζ is the angular deviation (0–180°) with respect to the palmar portion of the distal-palmar axis. β is the angular deviation (0–360°) in the plane of the thumb pad relative to the ulnar portion of the ulnar-radial axis. θ is angular deviation (0–180°) relative to the proximal portion of the proximal-distal axis.
* Significantly less proximally directed muscle thumb-tip force vector than FPL's ($P < 0.009$).

phalangeal joint flexion was decreased from 31° to 21° and IP joint flexion was increased from 37° to 43°. Following a 2-fold increase in applied tendon force and 2 mm of carpal bone displacement, median variations in thumb-tip force magnitude and direction across all intrinsic muscles were 2.3 fold (interquartile range extremes, IQRE: 2.1 to 2.8 fold) and 8° (IQRE: 6°, 12°), respectively (Fig. 3D, Table 3). The model predicted that thumb-tip force vectors produced by FPBu and ADP would change in magnitude by a factor of 2.1 and 2.3, respectively, and in direction by 6° toward the palmar direction and 11° away from the palmar direction, respectively. These model predictions intimate that FPBu may be more suited than ADP to replace FPL as a recipient muscle in a tendon transfer surgical procedure aimed at restoring lateral pinch following spinal cord injury.

Nominal vs. adjusted model

The biomechanical model used to simulate the effect of tendon force-dependent carpal bone displacement on intrinsic muscle thumb-tip force was not derived from average parameter values from the literature and median data from the cadaveric specimens used (Tables 1 and 2). With the exception of FPBr, the thumb-tip forces predicted by the *nominal* model did not fall within the extremes of the IQR's of the thumb-tip force components measured for each muscle (dotted lines in Fig. 3B). In 6 of 9 cases (EPL, EPB, APL, OPP, FPBu, ADP), computed thumb-tip forces were larger in magnitude and, in 5 of 9 cases (APL, FPL, FPBu, ADP, APB), oriented counter-clockwise with respect to the measured thumb-tip forces. These results were probably reflective of the differences between cadaveric specimens used in each of the studies that provided parameters for the nominal model. To improve the nominal model's thumb-tip force predictions, muscle moment arms were adjusted heuristically using the columns of J^{-T} as a guide. The columns vectors of J^{-T} indicate the influence of a muscle moment arm at a joint on that muscle's endpoint force (Yoshikawa, 1990). The *adjusted* biomechanical model (Table 1) replicated the thumb-tip forces of all muscles except those of APL and OPP (solid lines in Fig. 3B).

Individual thumb-tip force production by all muscles

While the goal of this work was to find an intrinsic muscle that could be used in a tendon transfer surgery that restores pinch function in the tetraplegic hand, the first step in accomplishing this goal was to measure the thumb-tip force vectors that individual muscles produced. As has been reported previously (Pearlman et al., 2004), such force vectors varied in both direction and magnitude. Muscles produced thumb-tip force vectors in a myriad of directions that spanned a large portion of the space around the thumb-tip (Fig. 3). The three-dimensional force magnitudes produced at the thumb-tip ranged from 17% (EPL) to 33%

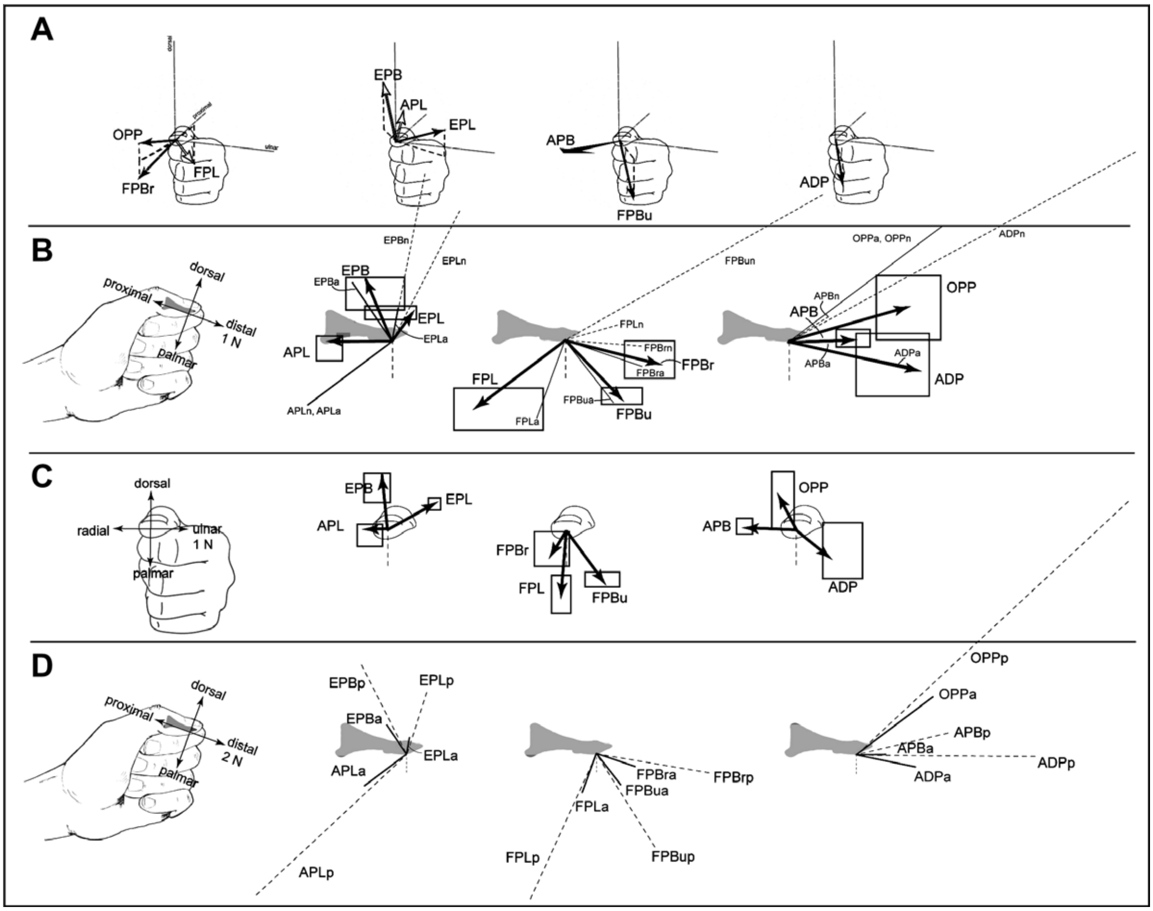


Fig. 3. Measured and model-predicted thumb-tip force vectors from the nine thumb muscles. A. Each arrow represents the unit thumb-tip force vector for a muscle averaged across the 11 specimens tested. Vectors with solid arrow heads have distal force components (i.e., point away from the thumb nail or base of the thumb) and vectors with un-filled arrow heads have proximal force components (i.e., point toward the thumb nail or base of the thumb). Mean and circular standard deviation (SD) in unit vector directions are presented numerically as mean (SD) in Table 2. B–C. Each arrow represents median thumb-tip force and the box the extreme values of interquartile range (IQREV) in thumb-tip force components for a muscle after 10 N of force was applied to the muscle's insertion tendon/aponeurosis. The median and IQREV are presented numerically as median (IQREV) in Table 2. In B, the dotted and solid lines (no arrows) represent muscle thumb-tip force predictions by the nominal and adjusted models, respectively (e.g., "FPLn" vs. "FPLa"). The proximal-distal and dorsal-palmar axes form a basis for the thumb's flexion-extension plane in B while the ulnar-radial and dorsal-palmar axes form a basis for the supination-pronation plane in C. D. The solid and dotted lines represent muscle thumb-tip force predictions by the adjusted and perturbed models, respectively (e.g., "FPLa" vs. "FPLp"). See Table 3 for nominal, adjusted and perturbed model-computed values.

(ADP) of the force applied to the insertion tendons (Table 2). The low gain in force from tendon to thumb-tip was most likely due to the relatively small muscle moment arms (i.e., their size is on the order of millimeters) (Smutz et al., 1998).

Discussion

Flexor pollicis brevis and adductor pollicis muscles

Two questions were addressed in this study: (1) is there an intrinsic muscle whose thumb-tip force vector is less proximally directed than that of FPL; and (2) if so, does that muscle's thumb-tip force direction substantially change due to the effect of tendon load-related carpal bone motion as predicted by a biomechanical model. We found that all intrinsic muscles produced thumb-tip force vectors that were less proximally directed than that of FPL (Fig. 3B, θ in Table 2) when 10 N of force was applied to each muscle's tendon. We also found that intrinsic muscle thumb-tip force directions were altered by, at most, 12° due to a 2-fold increase in applied tendon force and the concomitant 2-mm shift in carpal bones (Table 3). Specifically for the two intrinsic muscles, FPBu and ADP, that were found to have the most desirable force production characteristics when 10 N of force was applied to each muscle's tendon, the model predicted that their thumb-tip force vectors would change non-linearly in response to a 2-fold increase in tendon force and 2-mm of translation of the metacarpal base along the radius. Thumb-tip force produced by FPBu and ADP would change in magnitude by a factor of 2.1 and 2.3, respectively, and in direction by 6° toward the palmar direction and 11° away from the palmar direction respectively. The predicted changes in thumb-tip force direction suggest that FPBu may be better suited than ADP to replace FPL as a recipient muscle in a tendon transfer sur-

Table 3
Magnitude and direction of computed thumb-tip forces produced by muscles

Muscle	Model-computed force magnitudes and directions			
	Nominal	Adjusted	Perturbed	Δ
	(mag_n, θ_n) [N, deg]	(mag_a, θ_a) [N, deg]	(mag_p, θ_p) [N, deg]	$\left(\frac{mag_p - mag_a}{mag_a}, \lvert\theta_p - \theta_a\rvert\right)$ [--, deg]
EPL	(3.5, 117)	(0.8, 100)	(3.4, 108)	(3.2, 8)
FPL	(1.3, 164)	(2.0, 70)	(8.6, 65)	(3.3, 5)
EPB	(4.1, 101)	(1.7, 56)	(5.4, 63)	(2.2, 7)
FPBr	(1.8, 176)	(2.0, 162)	(6.1, 170)	(2.0, 8)
FPBu	(7.1, 119)	(1.9, 128)	(5.8, 122)	(2.1, 6)
APB	(1.1, 148)	(1.4, 179)	(5.1, 167)	(2.6, 12)
ADP	(9.5, 151)	(2.9, 169)	(9.5, 180)	(2.3, 11)
APL	(2.5, 37)	(2.6, 37)	(11, 43)	(3.2, 6)
OPP	(4.6, 143)	(4.6, 143)	(20, 137)	(3.3, 6)
Median (IQREV) for intrinsic muscles only				Δmag: 2.3 (2.1, 2.8) Δθ: 8°(6°,11°)
Median (IQREV) for all muscles				Δmag: 2.6 (2.2, 3.2) Δθ: 7° (6°, 9°)

θ_i is with respect to proximal axis as in Table 2. $0° \leqslant \theta_i \leqslant 180°$.
Nominal: model-produced quantities in which model consisted of median/average parameters; applied tendon force was 10 N; thumb posture was 28° TMC extension, 31° MP flexion, 40° IP flexion.
Adjusted:model-produced quantities in which model parameters were adjusted to replicate experimental thumb-tip force data; applied tendon force was 10 N; thumb posture was 28° TMC extension, 31° MP flexion, 40° IP flexion.
Perturbed:model-produced quantities in which model parameters were same as "Adjusted"; applied tendon force was 30 N; thumb posture was 24° TMC extension, 21° MP flexion, 43° IP flexion.

gery aimed at restoring lateral pinch force production in the tetraplegic hand.

Implications of model findings

In addition to the results of the model suggesting that FPBu may be the best one-muscle choice to replace FPL, the modeling results also suggest that the variation in muscle-produced thumb-tip force vectors with tendon force is nearly linear over the tendon force range considered (e.g., (Valero-Cuevas et al., 2000)). The *perturbed* model predicted a 2.6 median fold increase in thumb-tip force magnitude and a 7° median rotation in thumb-tip force direction for all muscles following a 2-fold increase in force applied to the tendons and 2 mm of movement in the carpal bones (Fig. 3B, Table 3). These findings suggest that two or more muscles, e.g., FPL and FPBu, may be combined and actuated by a single donor muscle to produce a well-directed thumb-tip force. In summary, the endpoint action of a single intrinsic muscle and the combined action (superimposition) of multiple paralyzed hand muscles may be *new* viable surgical designs for surgical reconstruction of lateral pinch in the tetraplegic hand over the tendon force considered in this study.

The thumb-tip force data collected in this study compares well with previously published data. Good qualitative agreement between our data, collected at one tendon force level (10 N), and that of Pearlman and colleagues (Pearlman et al., 2004), averaged over various ranges of tendon force levels between 0 and 30 N, lends some support to the modeling result that directions of muscle-produced thumb-tip force vectors do not change appreciably up to 30 N of tendon force. The most notable exception between our data and that of Pearlman and colleagues is the thumb-tip force vector produced by APB. We found that APB produced force primarily in the distal and radial directions. They found, however, that it produced force in the palmar, proximal and radial directions. Differences in determining APB's line of action *in situ* could explain this discrepancy. Magnitudinal variations in thumb-tip forces of muscles were largely comparable in both studies and likely due to anatomic (e.g., bone lengths, muscle moment arms) and/or postural (e.g., joint angles) differences among the cadaveric specimens used. Comparable variations in muscle endpoint force components were also reported in *in situ* measurements of muscle fingertip force vectors (Valero-Cuevas et al., 2000). It is worth noting that Pearlman and colleagues utilized a special thumb-tip-to-load cell fixation that attempted to preserve the compliance of the thumb pulp to improve thumb-tip force measurements. We believed that such an approach was unnecessary because endpoint compliance in theory does not affect endpoint force measurements under static conditions (Beer and Johnston, 1992; Hibbeler, 1992). Thus we rigidly coupled the distal phalanx to the load cell as was done previously (Towles et al., 2004; Valero-Cuevas et al., 2000). Agreement between our thumb-tip force data set and that of Pearlman et al. helps to confirm the lack of influence of endpoint compliance on static endpoint force measurements.

The goals of this work were to assess whether an intrinsic muscle could produce a less proximally directed thumb-tip force than that of FPL, and to assess whether that muscle's thumb-tip force would be substantially affected by tendon load-related carpal bone motion in the wrist. With regard to the latter goal, Pearlman and colleagues identified two other potential sources for the non-linear mapping of tendon force into thumb-tip force: load-dependent viscoelastic tendon paths and joint seating. Although this study did not explore those, it did explore the one that is arguably the greatest source for the non-linear map. The results of this study are limited to the tendon force range, up to 30 N, for which there was experimental data. Additional experiments are needed to describe both carpal bone displacement at tendon force levels greater than 30 N and how the end-point actions of multiple thumb muscles combine over a broad range of tendon forces. Finally, this study is also limited in that it does not address the properties of potential donor muscles. Briefly, for restoration of lateral pinch following spinal cord injury, muscle architectural properties (e.g., excursion, speed and force production capacities) of a potential donor muscle need to be comparable to that of the recipient muscle(s) (Lieber et al., 1992; Zajac, 1992).

In sum, this work investigates a new surgical design to restore pinch function in the tetraplegic hand. Typically, intrinsic muscles are not considered for restoration of lateral pinch in the paralyzed thumb. This work, however, suggests that one or more intrinsic muscles may have the potential to improve thumb-tip force production following surgical reconstruction of lateral pinch in the tetraplegic hand.

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References

Beer, F.P., Johnston, E.R., 1992. Mechanics of Materials, second ed. McGraw-Hill Inc., New York, NY.

Brand, P.W., Hollister, A.M., 1999a. Operations to Restore Muscle Balance to the Hand. Clinical Mechanics of the Hand. Mosby, Inc., St. Louis, Missouri, pp. 274–321.

Brand, P.W., Hollister, A.M., 1999b. Transmission. Clinical Mechanics of the Hand. Mosby, Inc., St. Louis, Missouri, pp. 61–99.

Buchholz, B., Frederick, L.J., Armstrong, T.J., 1988. An investigation of human palmar skin friction and the effects of material, pinch force, and moisture. Ergonomics 31, 317–325.

Cooney, W.P., 1988. Tendon transfer for median nerve palsy. Hand Clinics 4, 155–165.

Goloborod'ko, S.A., 1998. Treatment of interphalangeal hyperflexion and metacarpophalangeal hyperextension of the thumb in combined low median-ulnar nerve palsy. Journal of Hand Surgery [Am] 23, 1059–1062.

Hibbeler, R.C., 1992. Engineering Mechanics: Statics, sixth ed. Macmillan Publishing Company, New York, NY.

House, J., Gwathmey, F., Lundsgaard, D., 1976. Restoration of strong grasp and lateral pinch in tetraplegia due to cervical spinal cord injury. Journal of Hand Surgery [Am] 1, 152–159.

Lieber, R.L., Jacobson, M.D., Fazeli, B.M., Abrams, R.A., Botte, M.J., 1992. Architecture of selected muscles of the arm and forearm: anatomy and implications for tendon transfer. Journal of Hand Surgery [Am] 17, 787–798.

Moberg, E., 1975. Surgical treatment for absent single-hand grip and elbow extension in quadriplegia: principles and preliminary experience. Journal of Bone and Joint Surgery 57A, 196–206.

Neviaser, R.J., Wilson, J.N., Gardner, M.M., 1980. Abductor pollicis longus transfer for replacement of first dorsal interosseous. Journal of Hand Surgery 5A, 53–57.

Paul, S.D., Gellman, H., Waters, R., Willstein, G., Tognella, M., 1994. Single-stage reconstruction of key pinch and extension of the elbow in tetraplegic patients. Journal of Bone and Joint Surgery 76A, 1451–1456.

Pearlman, J.L., Roach, S.S., Valero-Cuevas, F.J., 2004. The fundamental thumb-tip force vectors produced by the muscles of the thumb. Journal of Orthopedic Research 22, 306–312.

Revol, M., Cormerais, A., Laffont, I., Pedelucq, J.P., Dizien, O., Servant, J.M., 2002. Tendon transfers as applied to tetraplegia. Hand Clinics 18, 423–439.

Smutz, W.P., Kongsayreepong, A., Hughes, R.E., Niebur, G., Cooney, W.P., An, K.N., 1998. Mechanical advantage of the thumb muscles. Journal of Biomechanics 31, 565–570.

Towles, J.D., Murray, W.M., Hentz, V.R., 2004. The effect of percutaneous pin fixation of the interphalangeal joint on the thumb-tip force produced by flexor pollicis longus during key pinch: a cadaver study. Journal of Hand Surgery 29A, 1056–1062.

Valero-Cuevas, F.J., Small, C.F., 1997. Load dependence in carpal kinematics during wrist flexion in vivo. Clinical Biomechanics 12, 154–159.

Valero-Cuevas, F.J., Zajac, F.E., Burgar, C.G., 1998. Large index-fingertip forces are produced by subject-independent patterns of muscle excitation. Journal of Biomechanics 31, 693–703.

Valero-Cuevas, F.J., Towles, J.D., Hentz, V.R., 2000. Quantification of fingertip force reduction in the forefinger following simulated paralysis of extensor and intrinsic muscle. Journal of Biomechanics 33, 1601–1609.

Waters, R., Moore, K.R., Graboff, S.R., Paris, K., 1985. Brachioradialis to flexor pollicis longus tendon transfer for active lateral pinch in the tetraplegic. Journal of Hand Surgery [Am] 10A, 385–391.

Yoshikawa, T., 1990. Kinematics. Foundations of Robotics: Analysis and Control. MIT Press, Cambridge, MA, pp. 13–80.

Zajac, F.E., 1992. How musculotendon architecture and joint geometry affect the capacity of muscles to move and exert force on objects: a review with application to arm and forearm tendon transfer design. Journal of Hand Surgery [Am] 17, 799–804.