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Releasing the A3 pulley and leaving flexor superficialis intact increases pinch force following the Zancolli lasso procedures to prevent claw deformity in the intrinsic palsied finger

Francisco J. Valero-Cuevas [a,b,*], Vincent R. Hentz [c,d]

[a] *Neuromuscular Biomechanics Laboratory, Sibley School of Mechanical and Aerospace Engineering, Cornell University, 222 Upson Hall, Ithaca, NY 14853-7501, USA*
[b] *Laboratory for Biomedical Mechanics and Materials, The Hospital for Special Surgery, New York, USA*
[c] *Rehabilitation Research and Development Center, Veterans Affairs Palo Alto Health Care System, Palo Alto, California, USA*
[d] *Department of Functional Restoration, Hand Surgery Division, Stanford University Stanford, California, USA*

Abstract

Objective estimates of fingertip force magnitude following surgery to prevent digital metacarpophalangeal (MCP) hyperextension (clawing) in cases of paralysis of the hand's intrinsic muscles will assist clinicians in setting realistic expectations for post-operative pinch strength. We used a cadaveric/optimization approach to predict and confirm the maximal biomechanically possible fingertip force in the intrinsic palsied hand before and after two popular tendon transfer methods to the volar plate of the MCP joint. Both surgeries were also evaluated after release of the A3 pulley—a modification predicted by our published computer model of the forefinger to increase fingertip force magnitude. We predicted maximal static fingertip force by mounting eight fresh cadaveric hands on a frame, placing their forefinger in a functional posture (neutral abduction, 45° of flexion at the MCP and proximal interphalangeal joints, and 10° at the distal interphalangeal joint) and pinning the distal phalanx to a 3D dynamometer. We pulled on individual tendons with tensions up to 25% of maximal isometric force of their associated muscle and measured fingertip force and torque output. Using these measurements, we predicted the optimal combination of tendon tensions that maximized palmar force (analogous to pinch force, directed perpendicularly from the midpoint of the distal phalanx, and in the plane of finger flexion-extension) for four cases: (i) the non-paretic case (all muscles available), (ii) intrinsic palsied hand (no intrinsic muscles functioning), (iii) transfer of flexor superficialis tendon to the volar plate of the MCP (Zancolli lasso) in the intrinsic palsied hand, and (iv) leaving flexor superficialis intact and transferring a tendon of comparable strength to the volar plate of the MCP in the intrinsic palsied hand. Lastly, we applied these optimal combinations of tension to the cadaveric tendons and measured fingertip output. With the A3 pulley intact, the maximal palmar force in cases (ii)–(iv) averaged $48 \pm 23\%$ SD (non-paretic = 100%; case (iv) ($61 \pm 25\%$) > cases (ii) and (iii) ($43 \pm 23\%$ and $39 \pm 19\%$, respectively), $p < 0.05$). Releasing the A3 pulley significantly increased the average palmar force in cases (ii)–(iv) ($73 \pm 42\%$, $p < 0.05$), with no significant differences among them. Thus, releasing the A3 pulley may improve palmar force magnitude when it is necessary to transfer the digit's own flexor superficialis tendon to the volar plate of the MCP to prevent clawing in the intrinsic palsied hand. © 2002 Orthopaedic Research Society. Published by Elsevier Science Ltd. All rights reserved.

Keywords: Hand; Finger; Cadaveric; Surgical planning; Muscle coordination; Intrinsic minus finger; Pinch

Introduction

Weakness and "claw deformity" of the fingers is an important clinical consequence of paralysis of the intrinsic muscles of the hand [4,20]. The *flexor digitorum superficialis* (FS) lasso active tendon transfer, described by Zancolli, or the intrinsic tenodesis passive transfer, described by House, are two of the many reconstructive procedures described to prevent the claw deformity [8,16] by creating a flexor effort at the metacarpopha-

* Corresponding author. Address: Neuromuscular Biomechanics Laboratory, Sibley School of Mechanical and Aerospace Engineering, Cornell University, 222 Upson Hall, Ithaca, NY 14853-7501, USA. Tel.: +1-607-255-3575/605-255-3575; fax: +1-602-255-1222/605-255-1222.
E-mail address: fv24@cornell.edu (F.J. Valero-Cuevas).
URL: http://www.mae.cornell.edu/valero.

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langeal (MCP) joint. The procedure described by Zancolli (referred to here as the "lasso procedure" (Fig. 1C)), is one of the most popular of its type in current clinical practice. Zancolli suggests using the FS as an intrinsic substitute by anchoring the tendon to the volar plate at the MCP joint of the affected digit. This prevents MCP joint hyperextension, or clawing of the digit [26]. These procedures, however, have not been shown to restore fingertip force and are of questionable value to the restoration of pinch function. Restoring even limited pinch function would substantially improve the functional independence of individuals with intrinsic palsied hands, especially those with spinal cord injuries.

In a recent study, we used mathematical optimization and cadaver specimens to quantify the reduction of fingertip force in the palmar direction (analogous to tip pinch force, directed perpendicularly from the midpoint of the distal phalanx, and in the plane of finger flexion-extension) in the simulated paralysis of intrinsic muscles (see Fig. 4A) [23]. In this study, we report the portion of that study where we quantified the maximal biomechanically possible palmar force magnitude following the execution of two modalities of the lasso procedure: (i) utilizing the finger's own FS to perform the lasso, and (ii) utilizing another motor of comparable strength to FS, preserving the action of the digit's FS (e.g., an extradigital muscle-tendon unit as the active transfer). Our previous biomechanical modeling work predicts that the magnitude of palmar force is most sensitive to the moment arms of FS and *flexor digitorum profundus* (FP) at the proximal interphalangeal (PIP) joint [24]. Thus we also evaluated if releasing the A3 pulley increases palmar force magnitude of the lasso procedures.

Our first hypothesis was that performing an active lasso tendon transfer that preserves the action of FS of the finger results in greater palmar force magnitude than when the FS of the finger is harvested for the procedure. Our second hypothesis was that releasing the A3 pulley would lead to greater palmar force magnitude for both procedures. We tested these hypotheses by applying mechanically optimal tension combinations to the appropriate tendons of cadaveric fingers before and after execution of the tendon transfers, and measuring 3D fingertip force.

Methods

We utilized a technique previously described in detail [23]. We began by thawing eight adult cadaveric arms (4 right, 4 left) at the mid-forearm and dissected the forefinger tendon origins (see Figs. 1 and 2) of FP, FS and *extensor digitorum communis* (EC), as well as *extensor indicis proprius* (EI). These were tied and glued (Vetbond Tissue Adhesive, 3M Inc., St. Paul, MN) to nylon cords. The distal aponeuroses of *first lumbrical* (LUM) and *first palmar interosseous* (PI) were similarly attached to nylon cords without dissecting their origins. To accommodate the short insertion tendon of *first dorsal interosseous* (DI) into the proximal phalanx of the forefinger [3,4,11,20], a nylon cord

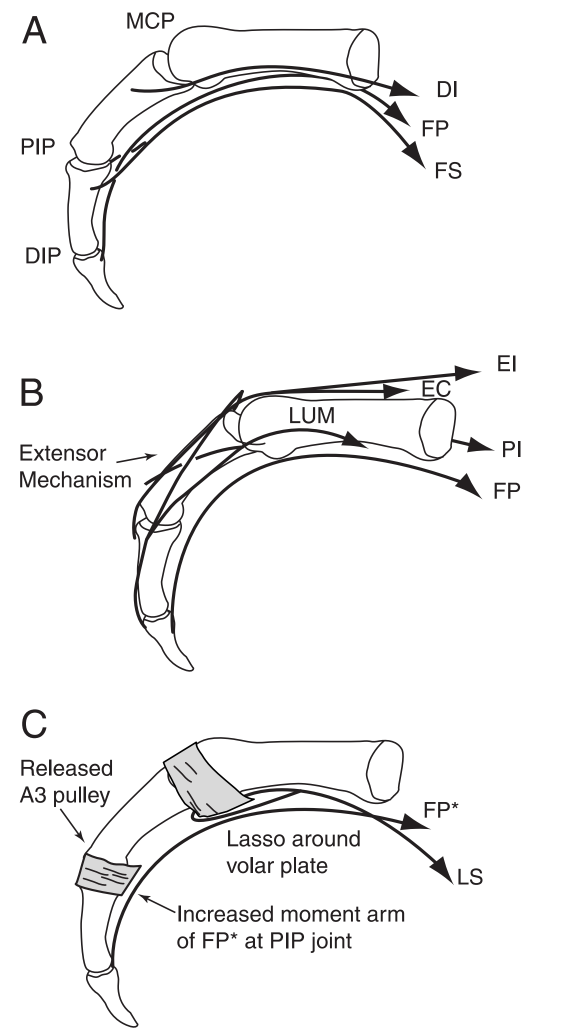

Fig. 1. Forefinger anatomy and surgical modifications. A: The MCP, PIP and DIP joints, and the schematic paths of the FP, FS and DI muscle-tendon units, B: schematic representation of the extensor mechanism (after Winslow), the EC, EI, PI and LUM muscle-tendon units, C: FP muscle-tendon unit after A3 pulley release (FP*) and lasso tendon (LS, tied around the volar plate of the MCP joint).

was anchored to a 3-mm flathead screw placed at the insertion of DI into the proximal phalanx. In addition, a nylon cord was wrapped around the volar plate of the finger, simulating the lasso procedure. This "tendon" was labeled LS. Two 1.6 mm diameter K-wires were inserted into the distal phalanx parallel to its longitudinal axis and were potted with polymethylmethacrylate (leaving the DIP joint and the insertions of the extensor mechanism and FP tendon intact). The cadaver material was donated to the Division of Human Anatomy, Department of Surgery, Stanford University School of Medicine. Universal safety precautions were adhered to throughout.

We mounted each cadaveric hand to a tabletop fixture and fixed the distal phalanx to a 3D dynamometer, taking the midpoint of the distal phalanx as the origin for force and torque measurement (Fig. 2). An external fixation device (Agee-WristJack, Hand Biomechanics Lab, Inc., Sacramento, CA) held the hand and forearm in neutral wrist extension and ulnar deviation. We placed the finger in a standardized posture of neutral abduction, 45° flexion at the MCP and PIP joints, and 10° flexion at the distal interphalangeal (DIP) joint. A robotic arm (Stäubli-Unimate Puma 260) allowed us to accurately move, then rigidly hold, a 3D force and torque dynamometer (F/T Gamma130, ATI Industrial Automation, Garner, NC) against the fingertip. The K-

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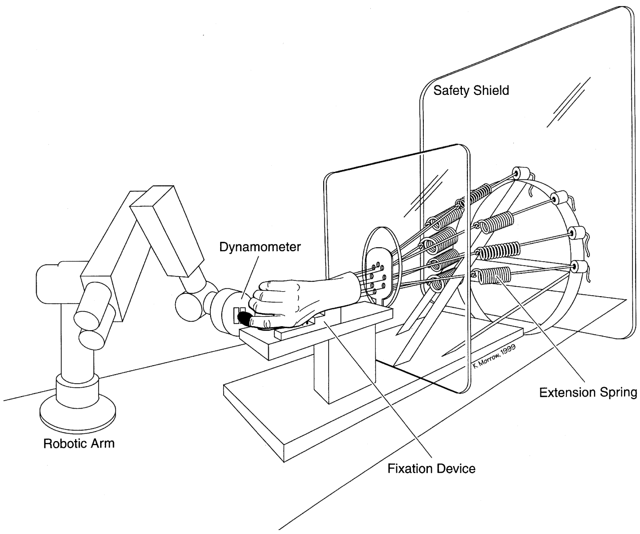


Fig. 2. Experimental apparatus. Fresh cadaveric hands were resected at the mid-forearm, rigidly mounted on a frame using an external fixation device and the insertion tendons of all forefinger muscles exposed. Nylon strings were glued to each insertion tendon, and proximal end of each Nylon cord was fed proximally through radius-countersunk holes in a low-friction acetal resin (Delrin®, DuPont) plate before radiating out and attaching to the distal end of an extension spring. Hole locations set anatomically correct lines of action for the strings. Pulling on and anchoring a thin rope (Kevlar®, DuPont) tied to the proximal end of the spring was what stretched the spring and produced a constant tension at the tendon (read on a calibrated scale mounted with the spring, ±10%). Springs were chosen such that 0.20 m of extension produced 25% of the maximal isometric force. Preliminary tests established that tying and gluing string to tendon withstood up to 60 N, hence the highest tension applied at the tendon of the strongest muscle (FS) was limited to 60 N (i.e., 25% of it maximal force [20]). Because dorsal interosseous has a very short insertion tendon, its nylon string was tied to a 3-mm flathead screw placed at the insertion point of DI into the proximal phalanx. Two K-wires were potted into the distal phalanx with polymethylmethacrylate and rigidly clamped to a six-axis dynamometer rigidly held by a robotic arm. Known tensions could then be applied to individual tendons, and simultaneously to several tendons, and the fingertip force/torque output measured.

wires protruding from the distal phalanx were clamped to the dynamometer. As illustrated, each spring could be individually loaded by pulling on and anchoring a thin rope tied to the proximal end of a spring (Fig. 2). The springs were more compliant than the tendons, and stretching the springs provided a constant tension within 10% of the calibrated value. The springs applied tensions up to 25% of the estimated maximal strength of the muscle associated with each tendon. We applied the same maximal tensions, which were derived from physiological cross-sectional areas [12,14] and a biomechanical model [24], to all hands [23]. Because the finger was immobilized proximally and distally, the applied tendon tensions did not affect finger posture.

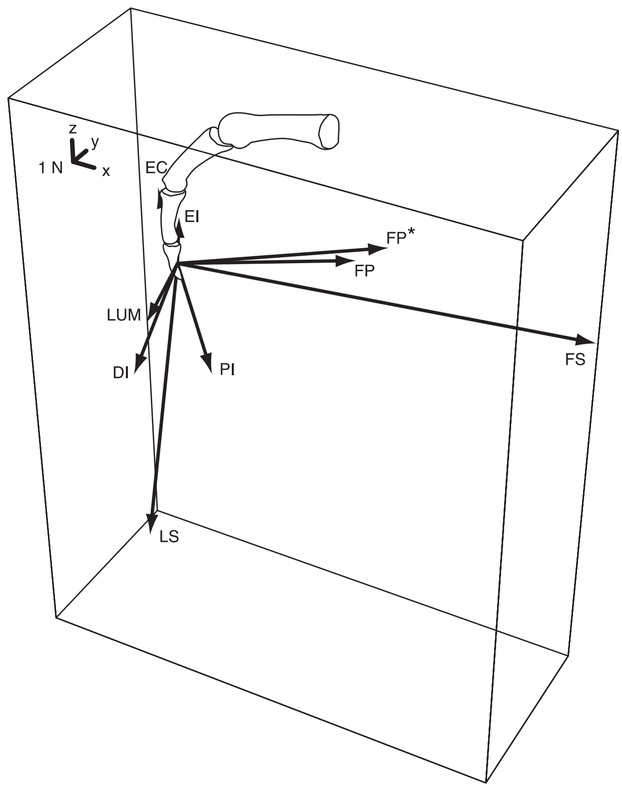
We applied discrete levels of tension to each tendon individually (up to 25% of the maximal force of the muscle associated with each tendon) and recorded the 6D fingertip output vector for each tendon tension level [23]. Our preliminary work indicated that the tendon-string connection failed at 60 N. Because this maximal experimental tension represented 25% of maximal estimated in vivo force of the strongest muscle (FS), we scaled the maximal tension applied to each tension to 25% of the estimated in vivo values. To ensure that only one tendon was loaded at a time, the nylon strings of the tendons receiving no load were disconnected from their associated springs. The output force and torque components were measured with a resolution of 0.1 N and 0.01 N m, respectively. At each tendon tension level, a computer (PowerMacintosh 7200, Apple Computer, Inc., Cupertino, CA) with data acquisition hardware/software (NB-MIO-16 card and LabView, National Instruments, Austin, TX) recorded the output from the dynamometer for 2 s at 1000 samples/s and stored the *average* fingertip output vector produced by each tendon (output forces are in units of N, torques in N m). Based on the measurements of the input tension at each tendon and the corresponding fingertip output vector, we used linear programming [5] to predict the optimal combination of tendon tensions that would produce the maximal magnitude of a desired *resultant* fingertip output vector [23]. The goal of linear programming was to maximize force in the "palmar" direction (i.e., in the x direction, perpendicular to the midpoint of the distal phalanx in the plane of finger flexion-extension, analogous to that used in pad-to-pad pinch, Fig. 3). In our previously described work [23], we showed that maximal biomechanically possible palmar force in the simulated intrinsic palsied condition (where the action of LUM, DI and PI was removed) was on the average 57% of the non-paretic case (where all forefinger muscles were active [23]). In this study, we predict the biomechanically maximal palmar force for two procedures which create the lasso (LS) tendon in the simulated intrinsic palsied finger: (i) where the finger's own FS is harvested to create the lasso (LS) tendon to act in concert with FP, EI, and EC and (ii) where the lasso (LS) tendon is created with a supernumerary to act in concert with FP, FS, EI, EC (see Fig. 1). By supernumerary, we mean any other musculo-tendon from other fingers or the wrist that could be used to create the lasso. For each specimen, we predicted and applied optimal combinations of tendon tensions for each case, and measured the resultant fingertip output vector.

Lastly, the skin was reflected from the volar aspect of the PIP joint and the A3 pulley was released by cutting a 4-mm incision along the volar midline of the PIP joint with surgical scissors. We calculated the change in FP moment arm at the PIP joint by comparing the antero-posterior girth of the PIP measured with digital calipers with a resolution of 0.1 mm while applying 30 N to the FP tendon before and after release of the A3 pulley. The symbol FP* represents the action of FP after A3 pulley release, for which a new set of fingertip force data was collected by individually pulling on the FP tendon. We again predicted and implemented the biomechanically maximal palmar force where only FP*, EI, EC and LS were available (simulating the lasso that harvests FS with A3 release) and when FP*, FS, EI, EC and LS were active (simulating the lasso procedure with a supernumerary that leaves the finger's own FS intact).

Results

The fingertip force output vector produced by the transferred lasso tendon (LS) was nearly collinear with the distal phalanx direction and perpendicular to the palmar direction. LS behaved much like a PI muscle as it had a dominant negative z component (Fig. 3). The fingertip force output vector produced by FP* was, on average, larger in magnitude than FP, and was oriented closer to the x direction (compare f_x components in the table in Fig. 3). Average fingertip force vectors for 25% of maximal tension at each tendon are plotted in Fig. 3. Because 3D vectors are difficult to convey on the printed page, we have created a web site (www.mae.cornell.edu/valero/JOR) where the reader can interactively visualize and explore all 3D data presented in Figs. 3 and 4.

The fingertip forces of the individual tendons superimposed linearly. When tension was applied to multiple tendons simultaneously, the measured fingertip output was equivalent to the vector sum of the outputs produced by individual tendons. Palmar force magnitudes measured in the cadaveric fingers were not significantly different from those predicted by linear programming



Muscle	f_x mean	sd	f_y mean	sd	f_z mean	sd	τ_y mean	sd
FP	6.7	(1.1)	2.3	(1.5)	0.88	(1.2)	-0.039	(0.056)
FS	17.0	(4.2)	4.4	(2.4)	-1.1	(3.3)	0.18	(0.13)
EI	-0.27	(0.68)	0.61	(0.45)	1.1	(0.31)	0.004	(0.023)
EC	-0.76	(1.2)	0.16	(1.2)	2.7	(1.2)	0.018	(0.04)
LUM	-1.2	(0.94)	-0.19	(0.71)	-2.6	(0.72)	-0.019	(0.016)
DI	0.4	(1.4)	-3.9	(1.6)	-2.5	(1.8)	0.014	(0.025)
PI	-1.7	(2.2)	4.9	(2.3)	-8.6	(3.0)	0.015	(0.038)
LS	-4.58	(4.09)	3.76	(3.34)	-18.71	(5.49)	-0.05	(0.066)
FP*	8.16	(1.98)	2.45	(1.45)	1.83	(2.22)	0.005	(0.057)

Fig. 3. Average maximal fingertip force output vector for 25% of maximal tension applied at each tendon (for clarity, output fingertip torque is not shown). Forces in N, output fingertip torque in N m, mean (SD). FP, FS, EI, EC, LUM, DI and PI vectors were obtained in a previous study, $n = 11$ [19]. LS and FP* vectors $n = 8$. Data from left forefingers was appropriately rotated to a right forefinger orientation.

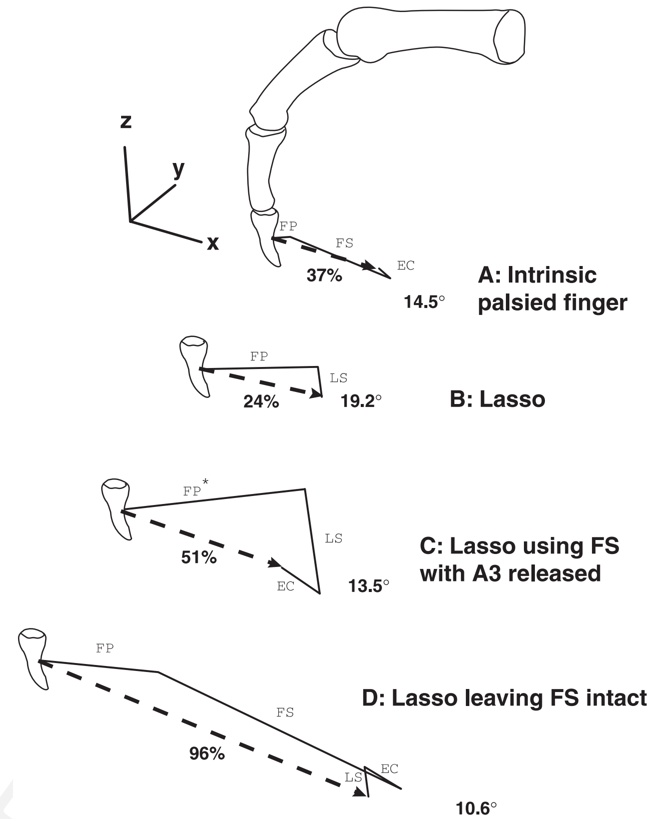


Fig. 4. 3D plot of the optimal vector addition of tendon actions that maximize palmar force in one specimen for A: intrinsic palsied finger, B: harvesting the forefinger's own FS tendon to perform the lasso procedure, C: harvesting the forefinger's own FS tendon to perform the lasso procedure and releasing the A3 pulley, and D: performing the lasso procedure leaving the FS tendon and A3 pulley intact. Percentages indicate palmar force magnitude relative to the maximal non-paretic case for that specimen. The angle indicates deviation from desired palmar force direction along the x-axis. For clarity, fingertip output torque is not shown.

(average difference of 3.9 ± 12% (mean ± SD)), but the measured forces were directed significantly further from the desired x direction by an average of 3.6 ± 7.4°.

Performing the lasso procedure leaving the FS tendon intact achieved significantly larger palmar force magnitude than harvesting the forefinger's own FS tendon to perform the lasso procedure (60% vs. 39%, comparing rows in Table 1). Harvesting the forefinger's own FS tendon to perform the lasso procedure resulted in statistically similar palmar force magnitude as compared to the intrinsic palsied condition for this number of specimens (39% vs. 43%, Table 1). All three conditions had statistically similar directional accuracy of palmar force of about 20° (Table 1).

Releasing the A3 pulley increased the PIP moment arm of the FP tendon by an average 1.5 ± 1.0 mm and resulted in a significant increase in palmar force magnitude of 74% for low ulnar palsy case, and 64% when harvesting the forefinger's own FS tendon to perform the lasso procedure (comparing columns in Table 1). The pulley release did not affect the maximal palmar force when leaving the FS tendon intact to perform the lasso procedure, or the directional accuracy of any of the cases (Table 1). Fig. 4 shows the optimal vector addition of muscle actions for one representative specimen for all four cases studied (visit www.mae.cornell.edu/valero/JOR to interactively visualize and explore the data in Fig. 4).

Importantly, releasing the A3 pulley significantly changed the tensions in FP, FS, EC and LS tendons necessary to achieve maximal biomechanically possible palmar force. The low ulnar palsy cases saw a significant increase in FP, and a decrease in FS and EC tendon

Table 1
Effect of A3 pulley release on the direction and magnitude of maximal palmar force, and the tendon tensions that produce it, mean (SD)

	A3 Intact	A3 Released
Palmar force		
Direction (deg from *x*-axis)		
Ulnar palsy	19.5 (9.9)	20.4 (6.7)
Lasso using FS tendon	22.2 (10.7)	17.3 (8.8)
Lasso leaving FS intact	20.8 (11.1)	19.4 (8.3)
Magnitude (% of non-paretic)		
Ulnar palsy	43.0 (22.0)	74.0 (33.0)*
Lasso using FS tendon	39.0 (19.0)	64.0 (43.0)*
Lasso leaving FS intact	60.0 (23.0)	64.0 (38.0)
Ratio of tendon tension to palmar force		
FP		
Ulnar palsy	1.65 (1.14)	1.74 (1.20)*
Lasso using FS tendon	4.80 (1.18)	3.81 (0.77)*
Lasso leaving FS intact	1.71 (1.22)	1.80 (1.37)
FS		
Ulnar palsy	1.99 (1.31)	1.70 (1.32)*
Lasso leaving FS intact	2.18 (1.21)	2.06 (1.36)
EI		
Ulnar palsy	0.12 (0.58)	0.08 (0.18)
Lasso using FS tendon	0.02 (0.04)	0.00 (0.00)
Lasso leaving FS intact	0.17 (0.68)	0.42 (1.08)
EC		
Ulnar palsy	0.41 (0.69)	0.26 (0.61)*
Lasso using FS tendon	0.73 (1.15)	0.50 (1.06)
Lasso leaving FS intact	0.56 (0.76)	0.74 (0.89)
LS		
Lasso using FS tendon	0.42 (0.66)	1.05 (1.13)*
Lasso leaving FS intact	0.14 (0.25)	0.30 (0.53)*

* Represents $p < 0.05$.

tensions (Table 1). When harvesting the forefinger's own FS to perform the lasso procedure, releasing the A3 pulley decreased FP and increased LS tendon tensions. Releasing the A3 pulley when performing the lasso procedure leaving the FS tendon intact increased tension in the LS tendon.

Discussion

This study involves a novel combination of mathematical parameter optimization with experimentally controlled fingertip force production in cadaveric fingers to study differences in maximal palmar force as a result of alternative surgical procedures. This work demonstrates the clinical usefulness of combining mathematical rigor with cadaver studies to measure the biomechanical consequences of surgical procedures, and to augment the armamentarium to optimize outcomes. Our results show that performing the lasso tendon transfer while preserving the action of FS of the finger results in 50% greater palmar force magnitude than when the FS of the finger is harvested for the procedure. Harvesting the FS of the finger for the lasso procedure does not improve palmar force magnitude compared to the pre-operative finger, and may even reduce it as per the trend seen in these specimens. In addition, this study confirms the prediction of a biomechanical computer model of the finger that PIP flexion moment arms strongly influence palmar force production [24]. Our results show that the finger can produce almost twice as much palmar force when the A3 pulley is released in the pre-operative intrinsic palsied finger, and in the finger with a lasso procedure that harvests the digit's own FS. However, if the lasso procedure is performed leaving the finger's own FS intact (a condition not considered in previous simulations) we find there is no significant advantage to releasing the A3 pulley. We propose the following algorithm for the choice of lasso procedure to maximize palmar force in intrinsic palsied fingers that should apply to all fingers: If a supernumerary is available, use it to perform the lasso. Otherwise use the digit's own FS and release the A3 pulley.

Our work is motivated by the need to objectively evaluate the biomechanical consequences of the numerous procedures described in the surgical literature to mitigate the deleterious functional consequences of injuries or conditions that paralyze the intrinsic muscles of the hand. Typically, these procedures may be categorized as static or passive procedures such as a tenodesis, or a dynamic procedure such as a tendon transfer. Tendon transfers are often preferred if sufficient numbers of donor muscle-tendon units are available. Performing the lasso procedure with the digit's own FS must have consequences for the force production capabilities of the digit. These consequences, and how to counteract their deleterious nature, are the subject of this study. Our data clearly indicate that when the digit's own FS is re-deployed to act at the MCP joint only, the consequence is a significant reduction in the digit's potential for palmar force production.

Our results also allow us to describe the general 3D force production capabilities of the fingers. Fig. 5 shows a large wire-frame cage representing the average 3D feasible force set (FFS) of the non-paretic forefinger calculated using the output vectors shown in Fig. 3. The distance between the fingertip and any point on the surface of the FFS represents the maximal possible biomechanical force that can be produced in that direction [22]. This average FFS was calculated by finding all possible positive combinations of the maximal fingertip force output of each tendon seen in Fig. 3 [6,13]. Fig. 5A shows, in gray, a narrow solid polyhedron that is a sub-region of the FFS for the forefinger without active intrinsic musculature. The difference between this narrow sub-region and the wire-frame cage represents the force production deficiencies of the paretic finger as the fingertip is no longer able to produce force of even

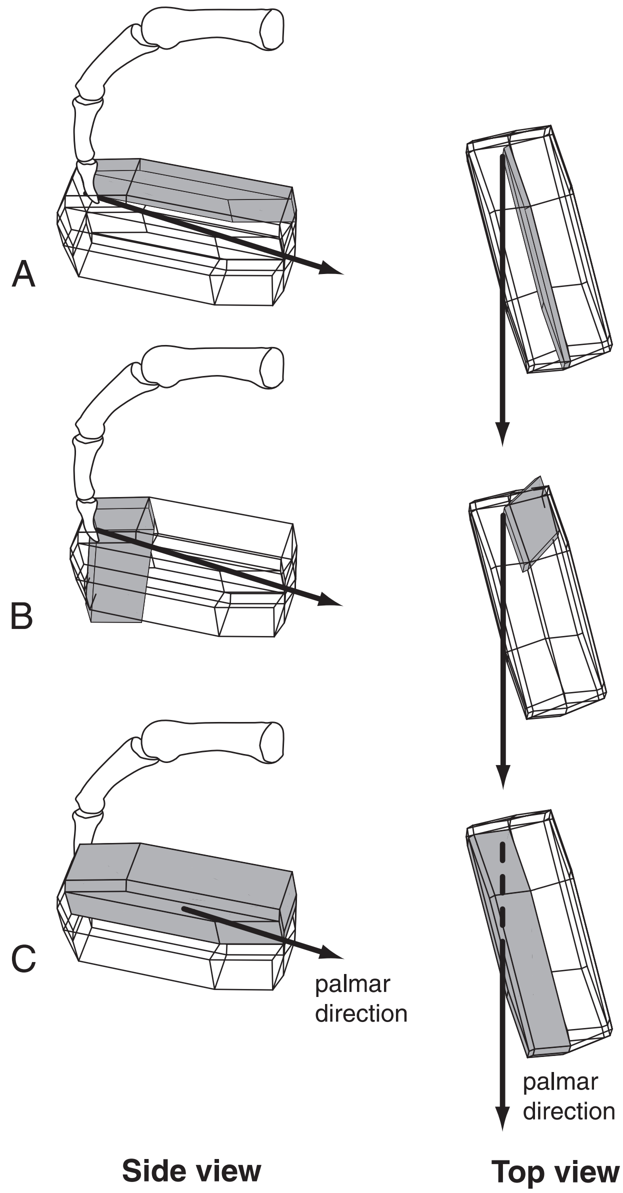


Fig. 5. Predicted 3D fingertip force production of a forefinger for the non-paretic and three post-surgical conditions. The wire-frame cage represents the average 3D FFS of the non-paretic forefinger. The distance between the fingertip and any point on the surface of a FFS represents the maximal biomechanically possible force that can be produced in that direction. The bold line indicates the desired palmar force direction towards the thumb (i.e., the x-axis). A: the solid polyhedron represents the FFS for the intrinsic palsied forefinger, which does not include the palmar force direction, B: the FFS set when the lasso is performed harvesting the digit's own FS, where large fingertip forces can be produced parallel to the distal phalanx, but not towards the thumb, C: the FFS when the FS is re-deployed to the insertion of first DI on the radial aspect of the proximal phalanx, where palmar force magnitude is comparable to the non-paretic finger.

moderate magnitude in most every direction. The fact that this narrow sub-region does not include the palmar force direction towards the thumb (i.e., the x-axis, shown as a bold arrow) means that a forefinger without intrinsic musculature cannot direct force towards the thumb, and an ulnarly deviated resultant force is unavoidable (see Table 1). The FFS set for the Zancolli lasso performed harvesting the digit's own FS (Fig. 5B, solid polyhedron) shows that large fingertip forces can now be produced parallel to the distal phalanx, but does not improve the ability to produce palmar force towards the thumb to produce pinch. Lastly, Fig. 5C shows that the FFS can be made to include the palmar direction (i.e., fingertip force can be directed towards the thumb with maximal magnitude) if the FS is re-deployed to the insertion of first DI on the radial aspect of the proximal phalanx. This analysis suggests that the forefinger can produce palmar force of magnitude comparable to the non-paretic finger, while clawing is prevented by the flexion action of the DI at the MCP joint. This novel procedure is supported by our previous modeling and EMG studies [22,24] showing that maximizing palmar force in unimpaired individuals requires activity in the flexors, extensors, and first DI, while first PI remains silent. We are now designing clinical trials to investigate the outcomes achieved with this novel transfer in the forefinger.

The limitations of this cadaveric/optimization method have been discussed in the literature [23] and include the exclusion of physiological secondary effects of paralysis (such as sensory deficit, and muscle atrophy and re-education), and the inability to predict the consequences of modifying a specific anatomical feature mathematically (as parameter-based computer models can [1,19,24]). The passive forces produced in vivo by paralyzed muscles were not considered because we do not have reliable estimates of what they would be. Also, while the passive transfer of force between LUM and FP was not investigated explicitly, our leaving of LUM intact did consider the passive transfer of FP force in the paralyzed LUM, if any, Fig. 1B. Recognizing that the innervation of LUM could vary [4], we chose not to apply force to it in the palsied condition to obtain a worst-case estimate of force reduction. Clinical pinch force reduction may be less severe in cases of incomplete nerve injury, partial recovery of nerve function, or variable muscle innervation. In addition, we have not yet considered force deficits due to physiological consequences of surgery and rehabilitation because the effect of the release of the A3 pulley on force–length properties and range of motion has not been studied clinically. We are not aware of measurements of FP muscle fiber length at the posture studied. The expected and unpredictable post-surgical response of tissue such as healing, scarring, muscle atrophy, joint stiffness and tendon adhesions is beyond the scope of this work, but will be studied in the future. Another potential clinical consequence of the increased FP moment arm at the PIP joint following A3 pulley release in the intrinsic minus digit is the increased resistance to active PIP extension via the innervated extrinsic extensors. For example, releasing the A3 pulley might lead to increased risk of flexion contracture at the PIP joint. Lastly, the method of this study, in its current form, is applicable only to the study of *active* tendon transfers, and not intrinsic tenodesis passive transfers such as the procedure described by House and associates [9]. Nevertheless, this work does establish biomechanically rigorous expectations of the best-case recovery of post-surgical palmar force production, which is a useful objective reference against which clinical functional outcomes can be compared.

The linearity (i.e., scaling and superimposition) of tendon interactions after simulated tendon transfers corroborates the findings in the intact digit [23] and has important clinical implications. Our results suggest the complex tendon interconnections [20,27] and elastic material properties of the tendon paths and pulleys [7,10] do not introduce important non-linearities into the transmission of tendon tension in the finger posture studied. This linearity also validates using linear optimization to produce clinically meaningful predictions. These results do not rule out non-linear changes in transmission of tendon tension with the known changes in the geometric arrangement of the extensor mechanism at different finger postures [7], or changes in finger posture itself [21].

Figs. 3 and 4 show, geometrically, the biomechanical interactions among muscle tensions necessary to maximize palmar force. Please visit www.mae.cornell.edu/valero/JOR for an interactive 3D exploration of these fingertip force vectors. The FS produces a fingertip force vector with the largest component in the desired palmar direction (x-axis), thus its presence is conducive to a greater magnitude of palmarly directed force (Fig. 4D). Harvesting the FS to create the lasso (LS) then leaves the FP as the only muscle with an important fingertip force vector component along the desired x direction (Figs. 3 and 5B). Releasing the A3 pulley has the biomechanical consequence of increasing the x-component of the FP* force, leading to a greater magnitude of palmarly directed force (Fig. 3). Lastly, the positive z component of the extensor muscles is necessary to counteract the negative z tendency of the FS and LS (Fig. 4A, C and D), making extensor muscle activity critical to the proper direction of the resultant fingertip force.

The changes in relative tendon tensions necessary to maximize palmar force following the tendon transfers are evidence of the neurological and biomechanical adaptations necessary to maximize static palmar force in the surgically modified digit (Table 1). This study is the first to describe the pre- and post-operative tensions at all finger tendons during production of a functional static force. When the lasso procedure is executed with the finger's own FS tendon, the FP must carry roughly twice the relative tension than in any other condition studied here, which may increase the likelihood of pathological responses to biomechanical overloading such as tendonitis [17,18]. The significant changes in tendon tension after release of the A3 pulley also reveal what specific muscle re-training is necessary to exploit the biomechanical capabilities of the post-operative digit. While there is evidence of gross muscle re-training following tendon transfers [4,15], it is not known if refined retraining is indeed achievable. Importantly, the post-operative force demands on the LS (i.e., the transferred FS) to maximize palmar force are quite low (Table 1), which opens the possibility of transferring muscles weaker than FS and still maximize palmar force. We anticipate that further modeling will demonstrate the potential for using muscles that are currently considered too weak for transfer (Grade 3 muscles), and will suggest other counterintuitive solutions to clinically important problems.

Lastly, this novel cadaveric/optimization method also has the potential to allow the design of patient-specific surgical procedures, or control strategies for functional electrical stimulation of digits. This method is, in essence, a means to quantify the biomechanical input/output relationship of a digit without making any assumptions about finger anatomy (e.g., moment arms, bone lengths), as computer biomechanical models often must [1,2,24]. For example, characterizing the biomechanical input/output relationship of a digit can be done intra-operatively by applying known stimulation trains to individual muscles and measuring 3D-fingertip force or motion output. The tendon force-to-fingertip force (or tendon excursion-to-finger motion) input/output relationship thus found can be combined with mathematical optimization to find patient-specific functional electrical stimulation patterns to optimize specific finger forces (or movements). Similarly, performing this input/output characterization before committing to a surgical procedure can reveal idiosyncratic muscular, tendinous or articular characteristics, and lead to the real-time design and validation of patient-specific surgical modifications to optimize outcomes.

Uncited reference

[25].

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