The Effect of Percutaneous Pin Fixation of the Interphalangeal Joint on the Thumb-Tip Force Produced by the Flexor Pollicis Longus: A Cadaver Study

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Purpose: Interphalangeal joint stabilization often is performed concomitantly with tendon transfers that restore key pinch (lateral pinch) to the paralyzed thumb. The goal of this study was to measure the effect of interphalangeal joint stabilization via percutaneous pin fixation on the thumb-tip force produced by the flexor pollicis longus (FPL).

Methods: We applied 10 N of force to the tendon of the FPL in 7 cadaveric specimens and measured the resulting thumb-tip force in the intact thumb and after stabilization of the interphalangeal joint.

Results: The nominal thumb-tip force was approximately 6 times less than the applied force and was directed primarily in the thumb's plane of flexion-extension at an oblique angle of 44° relative to the palmar direction (the direction that is perpendicular to the thumb tip in the plane). Joint stabilization increased significantly the nominal force and oriented the force more toward the palmar direction (ie, decreased the obliqueness of the force).

Conclusions: After paralysis and a tendon transfer to the paralyzed FPL the FPL is often the only muscle actuating the thumb. We conclude that the oblique nominal force direction is prone to cause the thumb to slip during pinch. Joint stabilization, however, has the capacity to reduce the tendency for slippage because it rotates the force toward the palmar direction. (J Hand Surg 2004;29A:1056–1062. Copyright © 2004 by the American Society for Surgery of the Hand.)

Key words: Flexor pollicis longus, joint stabilization, key pinch, percutaneous pin fixation, thumb-tip force.

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Key pinch (or lateral pinch) has been described as the primary hand function that should be restored to individuals with tetraplegia.[1] Key pinch involves the coordinated application of a force produced at the thumb tip to hold an object against the lateral aspect of the index finger. In tendon transfer designed to restore key pinch the donor muscle is attached commonly to the insertion tendon of flexor pollicis longus (FPL). The force produced at the thumb tip by the FPL is a critical determinant of clinical outcomes of the surgical restoration of key pinch.

During key pinch contact between the thumb and the object is maintained if the pinch force produced is large enough and if it is applied with sufficient directional accuracy. Different objects require different levels of force.[2] Friction between the skin and the object (which varies depending on the nature and exact conditions of the surfaces in contact) determines how precisely the force must be directed.[3] Optimally the applied force should be directed perpendicular to the surface of the object to eliminate the possibility of the object slipping out of the hand. Slip occurs if the angle at which the force is applied is too large, resulting in an unstable pinch.[4] For this reason force direction is an important consideration when evaluating the effectiveness of surgical interventions that restore thumb function.

Because the FPL is a thumb flexor it is likely that surgeons assume implicitly that the force it produces is directed suitably to facilitate acquiring and holding objects in the hand. The anatomic classification of a muscle, however, does not correlate perfectly with the direction of the force that it produces at the thumb tip. For example a recent study indicated that with the thumb in a key pinch posture the FPL's thumb-tip force is directed obliquely at an angle of 39° relative to the axis that passes through the thumbnail and is perpendicular to the thumb tip (ie, the dorsal–palmar axis).[5] In addition tendon transfer surgeries that restore pinch are complemented typically by stabilization of the interphalangeal (IP) joint to prevent hyperflexion.[1] Van Heest and colleagues[6] evaluated one approach to IP joint stabilization—the FPL split tendon transfer—and its effect on pinch force in cadaveric specimens. They concluded that split FPL transfer had no significant effect on pinch force magnitude. The study, however, does not address whether any other approach to IP joint stabilization influences pinch force and the researchers did not evaluate the effects of IP joint stabilization on force direction.

The goals of this study were to measure the force that the FPL produces at the thumb tip (ie, the tip-to-object force produced when force is applied to the insertion tendon of the FPL) and to measure the effects of percutaneous pin fixation of the IP joint on the FPL's thumb-tip force. We hypothesized that the surgical intervention would facilitate key pinch by increasing the magnitude of the FPL's thumb-tip force and shifting the direction of the thumb-tip force so that it was aligned more closely with the palmar direction.

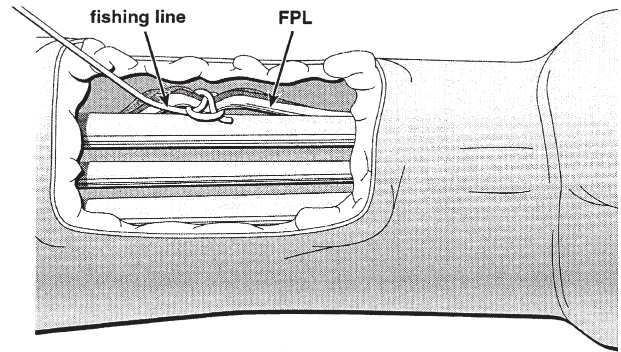

Figure 1. Dissection of the FPL tendon. The tendon was exposed and detached from the muscle belly. Extraneous muscle tissue was excised and fishing line was tied to the tendon.

Methods

Specimen Preparation

We measured the thumb-tip force produced by the FPL in 7 upper-extremity cadaveric specimens by adapting an experimental approach developed previously for the index finger.[7] Cadaveric upper-extremity specimens were obtained from the Division of Human Anatomy, Department of Surgery, Stanford University and were transected 13 cm above the wrist. To expose the tendon of the FPL an incision extending approximately 7 cm in length was made along the midline of the anterior forearm from the proximal border of the flexor retinaculum to a point approximately one third the length of the forearm. A second incision, approximately 3.5 cm in length, extended from the midline of the anterior forearm to the medial edge of the forearm. The tendon was freed at the muscle-tendon junction and fishing line (267-N test, braided, low-stretch trolling and bottom fishing line; Izorline, Gardena, CA) was attached to the tendon as a means to apply force (Fig. 1).

After the FPL's tendon was exposed each specimen was attached to a fixation device (Agee Wrist-Jack; Hand Biomechanics Laboratory, Inc, Sacramento, CA). The ring and small digits were

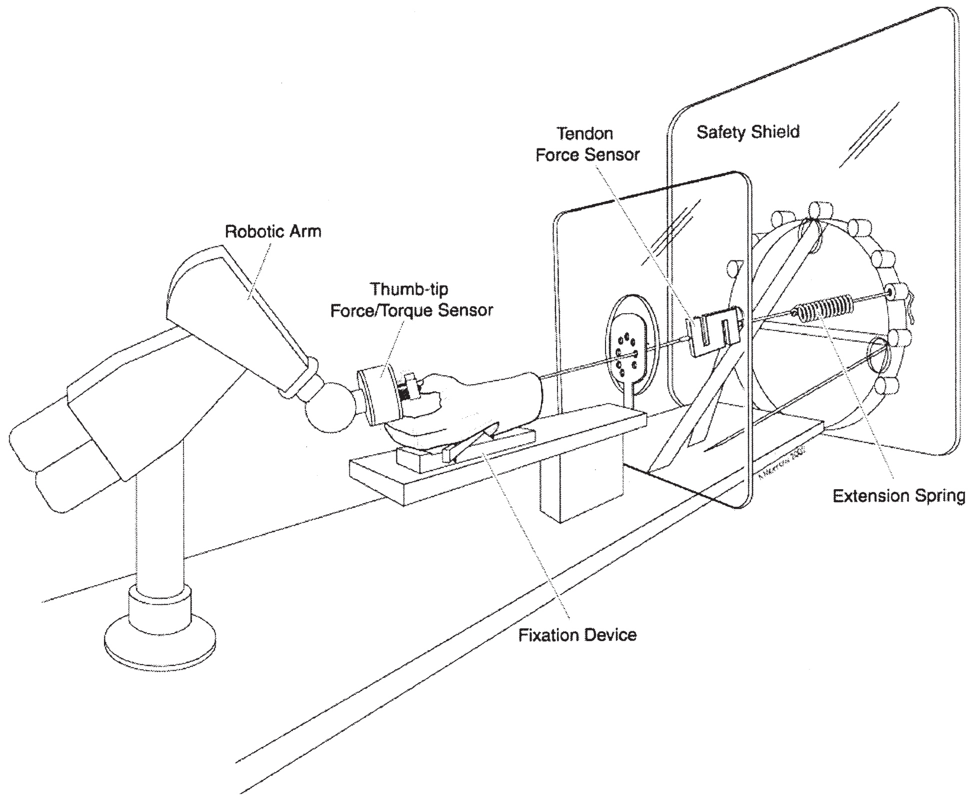

Figure 2. Experimental setup. To measure thumb-tip force each cadaveric specimen was fixed to the experimental jig with the thumb secured to a force sensor at the end of a robotic arm. Force was applied to the insertion tendon of the FPL by stretching an extension spring and the force was monitored using a tendon force sensor in line with the spring. The ensuing thumb-tip force was measured by the force sensor at the thumb tip.

disarticulated through the carpometacarpal joints and 3-mm–diameter, 10-cm–long fixation pins were drilled into the radius, ulna, and the index and middle finger metacarpals. The wrist was placed in neutral and the thumb was placed in a flexed posture to simulate key pinch. The thumb tip was secured rigidly to a 6-axis force/torque sensor (F/T Gamma 130; ATI Industrial Automation, Apex, NC) with a screw-plate assembly positioned on the dorsal and palmar sides of the thumb tip. The sensor was fixed to the end of a robotic arm (Fig. 2) to facilitate positioning of the thumb.

In each specimen thumb posture was quantified using a digital picture to characterize the joint angles of the thumb after completion of data collection. The trapeziometacarpal joint angle was defined as the angle between the medial edge of the forearm and the metacarpal bone. The angle between the metacarpal and the proximal phalanx defined the metacarpophalangeal joint angle. The IP joint angle was the angle between the proximal and the distal phalanges. Each specimen was maintained in the same thumb posture for both experimental conditions (the nominal and pinned conditions as described below). The posture for each specimen was intended to simulate key pinch; that is, contact between the thumb pulp and the middle phalanx of the index finger resulting in extension of the trapeziometacarpal joint and flexion of the metacarpophalangeal and IP joints (see Table 1 for specific joint angles for each specimen).

Thumb-Tip Force Measurement

To quantify the thumb-tip force produced by the FPL a force of 10 N was applied to the insertion tendon of the FPL using an extension spring. The level of force applied to the tendon was monitored using a uni-axis force sensor (NS-25 Nikkei S-type uni-axis load cell; Transducer Techniques, Temecula, CA) connected to the fishing line. The resulting output of the 6-axis force/torque sensor was sampled at 100 Hz over a period of 1 second and was recorded on a personal computer (Macintosh, Apple Computers, Cupertino, CA) to allow for further analysis (see below).

Because the thumb tip was coupled rigidly to the force sensor they shared the same reference frame (Fig. 3). The screw-plate assembly, oriented along the first axis of the force sensor, was used to align the distal phalanx's ulnar-radial axis with the sensor's

Table 1. Bone Lengths and Joint Angles of Specimens

Specimen	Side	Bone Lengths (mm)			Joint Angles (degrees)		
		MC	PP	DP	TMC	MP	IP
A	L	53	35	16	–35	36	36
B	R	60	36	13	–28	24	54
C	L	57	33	20	–28	27	34
D	L	61	36	20	–30	31	37
E	L	53	30	19	–31	23	60
F	R	48	35	24	–29	28	50
G	L	58	39	21	–26	20	52
Median		57	35	20	–29	27	50
IQR		(53, 60)	(34, 36)	(17, 21)	(–31, –28)	(23, 30)	(36, 54)

Note. Bone lengths were measured manually as the distance between the palpable joint spaces in the thumb (eg, metacarpal length is the distance between the trapeziometacarpal and the metacarpophalangeal joint spaces). As described in the text joint angles were estimated based on a digital picture of the experimental set-up for each specimen. Positive angles indicate flexion; negative angles indicate extension. DP, distal phalanx; MC, metacarpal; PP, proximal phalanx; TMC, trapeziometacarpal.

first axis. By virtue of how the assembly fixed the thumb to the sensor the proximal–distal axis of the distal phalanx was aligned with the second axis of the force sensor. The distal phalanx's dorsal-palmar axis and the sensor's third axis coincided necessarily and were perpendicular to the other axes.

Data are reported for 2 experimental conditions: (1) the nominal condition (all joints unpinned) and (2) with the IP joint stabilized. In the second condition the joint was pinned percutaneously using 1.5-mm–diameter K-wires. Statistical analysis performed on 12 repeated measurements of condition 1 in 1 specimen and an error propagation technique[8] were used to determine the minimal change in thumb-tip force that could be detected between the 2 experimental conditions in 1 specimen. These analyses indicated that force magnitude changes greater than 0.3 N and thumb-tip force direction changes greater than 2° represented measurable differences in thumb-tip force.

Data Analysis

The effect of joint stabilization on thumb-tip force magnitude was expressed as a percent change from

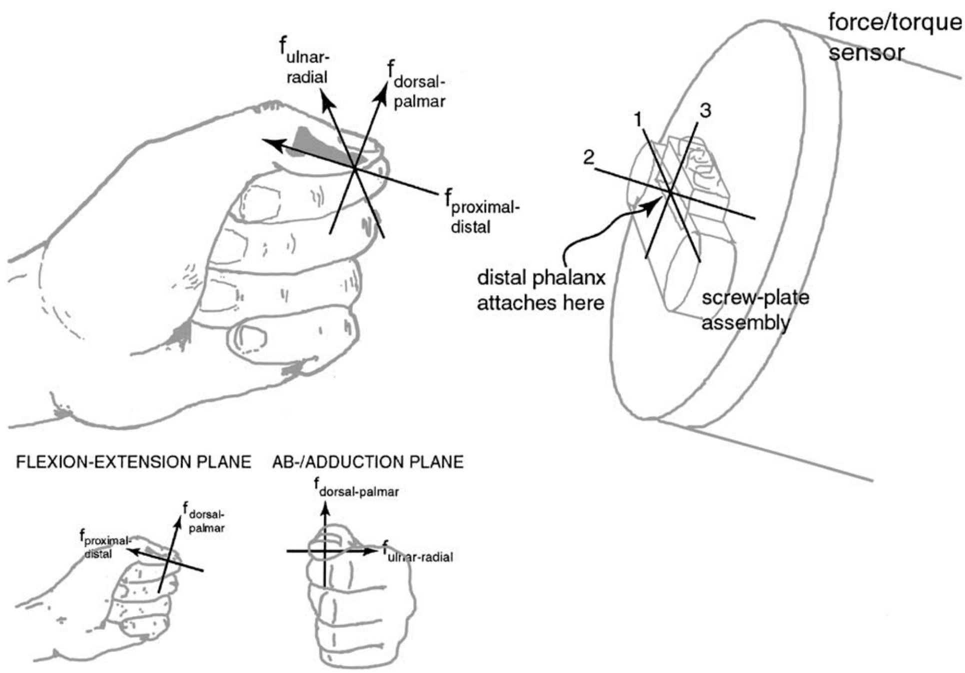

Figure 3. Thumb-tip and force sensor reference frames. The ulnar, proximal, and dorsal directions are positive.

Table 2. FPL Force Magnitude and Direction

	FPL Nominal Force			After IP Joint Stabilization		
Specimen	Mag (N)	FE Dir* (degrees)	AA Dir* (degrees)	Mag (N)	FE Dir* (degrees)	AA Dir* (degrees)
A	4.0	44	2	4.9	38	5
B	1.5	45	31	3.8	39	23
C	1.5	32	–23	3.1	32	–9
D	4.1	57	–8	4.2	57	–7
E	1.7	–10	32	2.5	3	9
F	3.5	40	0	3.3	27	12
G	1.2	45	50	3.3	31	8
Median	1.7	44	2	3.3	32	8
IQR	(1.5, 3.9)	(34, 45)	(–6, 32)	(3.1, 4.1)	(28, 39)	(–4, 11)

Note. Specimens with forces directed in the proximal-palmar and the radial-palmar quadrants have positive angles. Forces that are directed in the distal-palmar and the ulnar-palmar quadrants have negative angles.

AA, abduction-adduction; dir, direction; FE, flexion-extension; mag, magnitude.

*Force directions are described relative to the palmar axis in both the FE and AA planes (Fig. 3). The data are presented with respect to the left thumb-tip.

the nominal magnitude for each specimen as seen in equation 1:

$$\% \text{ change} = \frac{100(f_{alt} - f_{nom})}{f_{nom}}$$

where f_{nom} represents the magnitude of the thumb-tip force in the nominal case and f_{alt} is the force magnitude after joint stabilization. Direct comparisons of the direction of the nominal force and the force measured after stabilization were used to evaluate whether the force was aligned more closely with the palmar direction of the thumb when the IP joint was pinned. The direction of the force relative to the palmar direction was evaluated in 2 planes, the flexion–extension plane (defined by the proximal–distal and dorsal–palmar axes) (Fig. 3) and the abduction–adduction plane (defined by the ulnar–radial and dorsal–palmar axes).

We used nonparametric statistical analyses to evaluate the data because the measured changes in thumb-tip force magnitude due to joint stabilization were not distributed normally.[9] As such we report the median and interquartile range (IQR)—that is, median (IQR)—to describe the central tendency and the spread in the data, respectively. A 1-tailed Wilcoxon's matched-pair signed-ranks test was performed to test the hypothesis that the surgical intervention would increase the magnitude of the FPL's nominal thumb-tip force. A 1-tailed sign test was performed to test the hypothesis that IP joint stabilization would cause the direction of the nominal force to be closer to the palmar direction than without stabilization. Results were considered significant for $p \leq .05$.

Results

When the FPL tendon was loaded with 10 N of force the median (IQR) magnitude of the tip-to-object force produced by the FPL was 1.7 N (range, 1.5 N–3.9 N). In the abduction–adduction plane the median (IQR) direction of the force relative to the palmar axis was 2° (range, –6° to 32°) (Table 2). The minimal misdirection in the abduction–adduction plane indicates that the FPL's thumb-tip force acts primarily in the plane of flexion-extension. In the flexion-extension plane the median (IQR) force was directed obliquely 44° (range, 34°–45°) relative to the palmar direction (Fig. 4).

Stabilization of the IP joint increased significantly the magnitude of the nominal thumb-tip force ($p = .03$) (Table 3). The median force increased 51% (IQR, 8%–137%). Interphalangeal joint stabilization also produced a significant shift ($p = .03$) in the orientation of the thumb-tip force in the flexion–extension plane so that the force was aligned more closely with the palmar direction (Table 3, Fig. 5). The median shift was 6° (IQR, 2°–12°).

Discussion

Most surgical procedures that restore key pinch in persons with tetraplegia include either tenodesis of or tendon transfer to the tendon of the FPL. These procedures are intended to improve the patient's ability to grip objects and therefore to aid functional independence. Mechanically it is necessary to in-

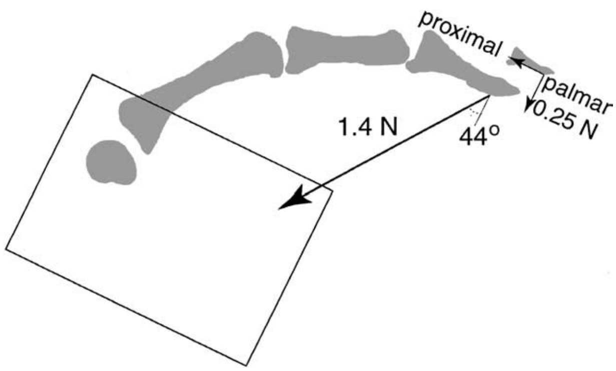

Figure 4. Projection of the median thumb-tip force of the FPL in the flexion-extension plane, nominal condition. The arrow indicates the median force direction in the plane for the 7 specimens tested in this study. The box represents the IQRs of the thumb-tip force components. The projection of the median force in the abduction-adduction plane is not shown because it was aligned essentially with the palmar axis in this plane (ie, misdirection of only 2°) (Table 2).

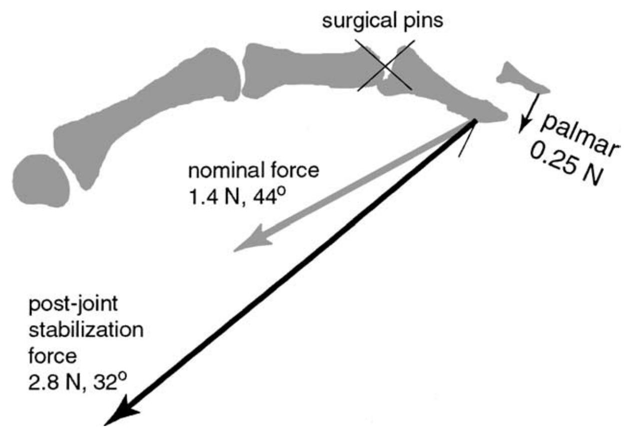

Figure 5. Projection of the median thumb-tip force of the FPL in the flexion-extension plane, nominal condition and after joint stabilization. The gray arrow is the projection of the force in the plane under the nominal condition. The black arrow is the projection of the force in the plane after IP joint stabilization. Note that the difference in median force directions (12°) does not represent the statistical difference (6°) reported in Table 3.

crease the thumb-tip force that can be produced and to orient the force appropriately to achieve the functional aims of these procedures. With the thumb in a key pinch posture we found that the FPL's nominal thumb-tip force is oriented primarily in the flexion-extension plane and that within the plane the force is oriented 44° relative to the palmar direction (Fig. 4). These results are consistent with the data reported by Pearlman et al.[5] In our cadaveric study stabilization of the IP joint via percutaneous pin fixation achieved the mechanical goals of increasing thumb-tip force magnitude and orienting the thumb-tip force toward the palmar direction (Table 3, Fig. 5).

To evaluate the functional consequences of the orientation of the FPL's thumb-tip force we performed a mechanical analysis to estimate the angular deviation with which a force can be applied to an object before it begins to slip out of the hand. The theoretical analysis is based on published empirical data describing the coefficients of friction between

Table 3. Effect of IP Joint Stabilization on FPL Force

		Change in Direction		
		Flexion-Extension Plane		Abduction-Adduction Plane
Specimen	Change in Magnitude (%)	Is direction closer to palmar?	How much closer? (degrees)	Is direction closer to palmar?
A	20	Yes	6	No
B	148	Yes	6	Yes
C	106	No difference	0	Yes
D	0*	No difference	0	Yes
E	51	Yes	7	No difference
F	0*	Yes	11	No
G	182	Yes	14	Yes
Median	51†	Yes‡	6	§
IQR	(8, 137)		(2, 12)	

NOTE. Positive percent change in force magnitude indicates percent increase; negative change indicates decrease.
*The magnitude changes due to joint stabilization in specimens D and F were assumed to be zero because only differences greater than 0.3 N were measurable with our system (see Methods).
†$p = .03$, Wilcoxon matched-pair signed-rank test
‡$p = .03$, sign test
§No significant change in force direction was observed in the abduction-adduction plane for these 7 specimens.

the skin and objects of different materials.[10] The coefficient of friction is determined primarily by the nature of the surfaces in contact and does not depend on the area in contact.[3] We calculate that thumb-tip forces may need to be oriented as accurately as 15° relative to the palmar direction to prevent paper objects (with a reported coefficient of friction of 0.27) from slipping. Less slippery materials such as vinyl and sand paper have larger coefficients of friction (0.55 and 0.65, respectively), are more resistant to slippage, and therefore require less directional accuracy (29° and 33°, respectively, relative to the palmar direction). Notably the orientation of the median thumb-tip force in the abduction-adduction plane was substantially less than 15° both before and after IP joint stabilization (Table 2), suggesting that the FPL's nominal force direction reduces inherently the chance of slippage in this plane. In contrast the misdirection observed in the flexion-extension plane implies that individuals who use a surgically reconstructed key pinch may be prone to slip in the flexion-extension plane. This could cause loss of contact with the object being grasped or hyperflexion of the IP joint. Hyperflexion of the IP joint during pinch (Froment's sign) affects thumb positioning, causes a loss of pulp pinch, and subjects the distal thumb to large contact stresses.[11]

Clinically stabilization of the IP joint is performed frequently to prevent the development of Froment's sign.[12] Our finding that percutaneous pin fixation of the IP joint results in both an increase in the FPL's nominal thumb-tip force magnitude and rotation of the force toward the palmar direction in the flexion-extension plane provides mechanical evidence that this procedure has the capacity to improve pinch function in tetraplegic individuals who have surgical reconstruction of the FPL.

In contrast to this study's result Van Heest et al[6] found no change in force magnitude due to IP joint stabilization via split FPL tendon transfer,[13] another common procedure to reduce hyperflexion at the IP joint. The mechanical differences between these 2 procedures (ie, FPL split tendon transfer preserves some movement of the joint whereas percutaneous pin fixation simulates fusion of the distal and proximal phalanges) may explain the different findings regarding pinch force magnitude. Van Heest and colleagues reported that the IP joint angle chosen for stabilization did not influence their results. Future research should investigate whether there is an optimal joint angle for IP joint stabilization via percutaneous pin fixation (fusion) and whether FPL split tendon transfer has an effect on FPL force direction.

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