

Ultrasonographic Assessment of Long Finger Tendon Excursion in Zone V During Passive and Active Tendon Gliding Exercises

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Purpose Cadaver and *in vivo* studies report variable results for tendon excursion during active and passive hand movements. The purpose of this study was to measure long finger flexor digitorum profundus (FDP) tendon excursion during active and passive movement using high-resolution ultrasound images.

Methods The FDP tendon excursion was measured at the wrist level in 10 healthy subjects during full tip-to-palm active and passive flexion of the fingers. Passive movement was performed 2 ways: (1) straight to full fist: passive flexion starting at the metacarpophalangeal joint, followed by proximal interphalangeal and distal interphalangeal joint flexion; and (2) hook to full fist: passive flexion starting at the distal interphalangeal joint, followed by proximal interphalangeal and metacarpophalangeal joint flexion. Tendon excursion was measured using an in-house-developed, frame-to-frame analysis of high-resolution ultrasound images.

Results Median FDP excursion was 24.3 mm, 14.0 mm, and 13.6 mm for active fist, straight to full fist, and hook to full fist movements, respectively. Tendon excursions during active movements was significantly larger than excursions during passive movements ($p = .005$). The adjusted median tendon excursion was $12.7 \text{ mm}/100^\circ$, $7.5 \text{ mm}/100^\circ$, and $7.4 \text{ mm}/100^\circ$ for active fist, straight to full fist, and hook to full fist movements, respectively. Adjusted tendon excursions during active movement were significantly larger than those achieved during passive straight to full fist movement). Adjusted tendon excursions during straight to full fist movements were significantly larger than those achieved during passive hook to full fist movement.

Conclusions Active motion produced 74% and 79% increases in excursions compared to both passive motions in healthy controls. The study results can serve as a reference for evaluating excursions in patients with tendon pathology, including those who have had tendon repair and reconstruction. (*J Hand Surg* 2010;35A:559–565. Copyright © 2010 by the American Society for Surgery of the Hand. All rights reserved.)

Key words Early active mobilization, early controlled mobilization, rehabilitation, tendon excursion, ultrasound.

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ADHESION FORMATION IS a major problem following hand tendon surgery. Historically, 3 rehabilitation protocols have been used after flexor tendon repair: (1) immobilization; (2) early, controlled mobilization or passive mobilization; and (3) early, active mobilization.¹⁻³ Because immobilization is thought to contribute to tendon adhesion formation,⁴ Duran and Houser (Duran et al., presented at the AAOS Symposium on Tendon Surgery in the Hand, 1975) introduced early, controlled mobilization or passive mobilization protocols to minimize tendon adhesion formation. However, Manske⁵ suggested that there might not be sufficient tendon movement at the repair site during passive motion protocols and active motion was necessary. Strickland et al.¹ reported that early active mobilization can generate larger tendon excursions but is associated with an increased risk of tendon rupture at the repair site.⁶

Although it is generally accepted that tendon excursion is needed to avoid adhesion, the amount of excursion needed is unknown. Duran and Houser (Duran et al., presented at the AAOS Symposium on Tendon Surgery in the Hand, 1975) suggested that 5 mm of tendon gliding should prevent firm tendon adhesions; however, this has not been experimentally supported. In addition, the amount of excursion attained during different rehabilitation protocols is unknown.

Current knowledge of flexor and extensor tendon excursion is based primarily on cadaver studies. Although cadaver studies are generally well-controlled, reported tendon excursions vary widely between studies. Excursions range from 10 mm to 33 mm for active movement⁷⁻¹⁰ and from 1 mm to 21 mm for passive movement excursions.^{9,10} This suggests that cadaver studies are unreliable in establishing tendon excursion and reference values, especially for passive joint movements.

Much of the variation in cadaver and perioperative investigations might be due to disrupted physiology of the tendon and surrounding tissues. Therefore, *in vivo* tendon movement measurements should provide more reliable and valid excursion data. Thus far, studies of *in vivo* FDP tendon gliding have been limited. Using color Doppler imaging, Soeters et al.¹¹ also found that tendon excursion was larger in active versus passive protocols; however, differences in tendon excursion between passive and active movements were not statistically significant and color Doppler imaging measurement errors were approximately 10%.

The purpose of this study was to quantify *in vivo* long finger FDP tendon excursion during 3 rehabilita-

TABLE 1. Participant Characteristics (5 Male, 5 Female Subjects)

Characteristics	Median	Range
Age (y)	26	17–52
Height (cm)	183	171–203
Hand length (mm)	193	187–220
MCP joint thickness (mm)*	25.5	22.2–28.5
PIP joint thickness (mm)*	16.3	15.0–18.1
DIP joint thickness (mm)*	12.7	11.3–21.3

*Thickness was measured in the palmo-dorsal plane

tion protocols used after flexor tendon repair, using a validated, tendon-tracking ultrasound algorithm.

MATERIALS AND METHODS

Subjects and measurements

The medical ethics committee approved this study, and informed consent was obtained from each participant. Ten healthy volunteers with a median age of 25.5 years (range, 17 to 52), including 5 male and 5 female subjects, were enrolled in this study. Height and hand length, as well as wrist, metacarpophalangeal (MCP), proximal interphalangeal (PIP), and distal interphalangeal (DIP) joint thicknesses were measured (Table 1).

Experimental conditions

Ultrasound video sequences of long finger FDP tendons were acquired using an iE33 ultrasound system (Philips Electronics, Eindhoven, The Netherlands), which used a 7 MHz linear array probe at 100 frames per second. The image resolution was 0.021 mm/pixel.

The experimental conditions are illustrated in Figure 1. Subjects were positioned on an examination bench and asked to wear a standard medical examination glove (Ansell NitraTex, Ansell health care LLC, Red Bank, NJ). To relate tendon excursion to joint range of motion (ROM), 5-mm, spherical, reflective markers were placed on the glove on the radial side of the MCP, PIP, and DIP joints of the long finger. The glove was used to ensure high contrast between markers and background. The index and long fingers were taped (Leukotape Classic, 2 cm, BSN Medical GmbH, Hamburg, Germany) together at the PIP joint level to ensure minimal discrepancy between measured index finger joint angles and actual long finger joint angles. A digital camera captured finger ROM during flexion at 25 frames/s. Video and ultrasound synchronization was conducted using the audio start signal of the iE33 as the starting point for video analysis.



FIGURE 1: Experimental conditions with the subject's arm positioned in the custom-made brace. Four markers on the index finger were used to automatically track the joint angle.

A custom thermoplastic splint was used to minimize arm and wrist movement without limiting finger ROM. Subjects' right hands were splinted and immobilized in the supine position using hook and loop straps. Forearms were fixed to the brace at forearm midpoint, wrist, and just proximal to the MCP joint. The lateral thumb was taped to the brace to prevent it from obscuring the marker view of the camera. The splint was fixed to an x-y-z-table containing a 3-dimensional micro-manipulator, using double-sided adhesive tape. The scanhead of the ultrasound scanner was placed in the 3-dimensional micro-manipulator by using a custom-made plastic holder and was used to position and fix the scanhead to the wrist. The FDP and flexor digitorum superficialis (FDS) muscle locations of the long finger were identified by palpation and marked on the wrist as the starting point to localize the long finger FDP using ultrasound. After localizing the FDP tendon and the FDS tendon, the DIP joint was flexed and extended to distinguish between the FDP tendon and FDS tendon, based on more FDP excursion during DIP movement. Moreover, the FDP tendon commonly passes through the carpal tunnel at an angle, and the FDS tendon does not; this additional feature also distinguished the FDP tendon from the FDS tendon. After analysis, the DIP joint angle was compared to the FDP tendon excursion; if a change in DIP joint angle did not result in FDP tendon excursion, it was likely that not the FDP tendon but the FDS tendon was scanned. However, this was not the case in any of the measurements.

An EMG was used to verify that passive movements were performed without muscle activity. Two electrodes were placed longitudinally at the midpoint of a line between the medial epicondyle and the ulnar

styloid. The ground electrode was positioned to create an equilateral triangle.¹² Although surface EMG cannot discriminate single muscle activity, all increases in activity were considered as possible FDP activity. Therefore, trials were repeated until fully passive movement was achieved. The EMG threshold for passive movement was set at twice the baseline measured during relaxation.

Motion protocols

Active fist, passive straight to full fist, and passive hook to full fist protocols were used.^{13,14} For the active protocol, subjects were asked to make a fist, starting from full extension, without using excessive force at the endpoint. To control for possible squeezing forces at the full fist position, we evaluated tendon excursion only to the point at which the total joint angle stopped changing. For passive straight to full fist movements, all fingers were moved from full extension to full flexion, from MCP joint flexion, through PIP joint flexion, and finally to DIP joint flexion. Passive hook to full fist movements started with DIP joint flexion, followed by PIP joint flexion, and concluded with MCP joint flexion. Each movement was executed twice. When the arm moved with respect to the scanhead, measurements were discarded and repeated. A visual check ensured that subjects moved toward the same end position of full extension against the brace.

Ultrasound imaging analyses

Ultrasound images were exported as uncompressed audio-video interleave (.avi) files using Qlab 7 (Philips, Best, The Netherlands). A dedicated 2-dimensional multi-kernel block-matching scheme using normalized cross-correlation was used to measure tendon excursion. This algorithm has been extensively tested and described elsewhere, and it has a mean measurement error of 1.6% (Korstanje et al., presented at the SPIE Medical Imaging conference, 2009).¹⁵ The algorithm is based on the general concept of block-matching schemes, which are frequently used to track cardiac wall movements (Korstanje et al., presented at the SPIE Medical Imaging conference, 2009; Revell et al., presented at the 8th Medical Image Understanding and Analysis conference, 2004).¹⁵⁻²⁰ Uncompressed audio-video interleave (.avi) files were imported into Matlab (7.5, R2007b; The MathWorks, Inc., Natick, MA), and a region of interest was manually assigned to the first frame.

Frame-to-frame displacement was estimated by using multiple overlapping small kernels. Each kernel was compared with a search region in a subsequent frame

using normalized cross-correlation as a similarity measure. A correlation of one indicated a perfect match and a correlation of 0 indicated no match. We considered all correlations greater than 0.7 to be good matches. The total 2-dimensional region of interest displacement was calculated from all kernel displacements within the region of interest that had good correlations. We used a correlation-weighted displacement vector average, so that unreliable estimates were discarded and best estimates were given more weight to the average.

Video recordings of joint movements were imported using Pinnacle Studio 9 (Pinnacle Systems Inc, Mountain View, CA). Simi-motion 7.5 (SIMI Reality Motion Systems, Unterschleissheim, Germany) was used to analyze exported audio-video interleave (.avi) files to identify individual joint ROM. The 3 phalanges of the fingers were identified using the spherical markers. Angular rotation of the MCP joint was calculated as the angle between the proximal phalanx and the horizontal baseline. Angular rotation of the PIP joint was calculated as the angle between the middle phalanx and the proximal phalanx. DIP joint rotation was calculated as the angle between the distal phalanx and middle phalanx.

Excursions for the 3 protocols were adjusted for total joint angle by using video tracking. The total excursion was divided by the total ROM and normalized to 100°. Displacements are reported as median excursions and ranges, unless otherwise noted.

Statistical analyses

We used Kendall's W test to evaluate the ROM and joint angles for all 3 protocols. For all significant differences, we subsequently used the Wilcoxon signed rank test to evaluate differences between protocols. We also used the Wilcoxon signed rank to compare excursions between active and passive protocols, for both adjusted and unadjusted excursions. In addition, the straight to full fist and hook to full fist protocols were compared. Statistical significance was set at $p = .05$.

RESULTS

Figure 2 illustrates the mean, summed joint angles (MCP joint + PIP joint + DIP joint) versus mean tendon excursions. Total tendon excursions were larger during active movement compared to both passive movements. This difference was more pronounced closer to the full fist position. Differences in tendon excursion between active fist movement and passive straight to full fist movement became statistically significant at 130° ($p = .047$). Differences in tendon excursion between active fist movement and passive hook

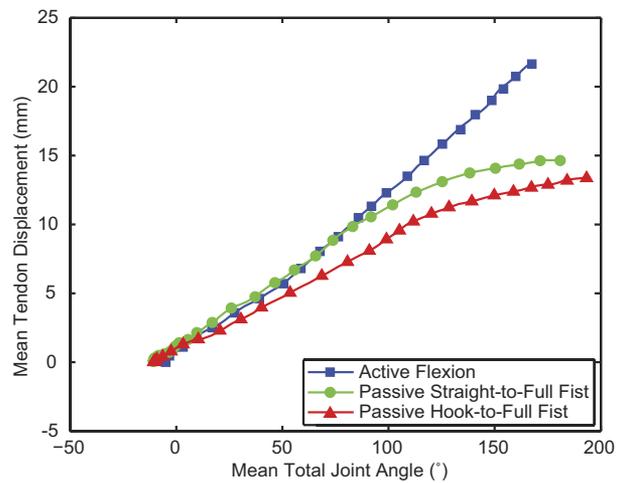


FIGURE 2: Mean tendon excursion during active and passive protocols as a function of mean total joint angle. During passive hand movement, tendon excursion diminished compared to active hand movement. The cut-off point for the passive straight to full fist movement was 130° ($p = .047$) and the cut-off point for passive hook to full fist was at 90° ($p = .037$).

to full fist movement became statistically significant at 90° ($p = .037$).

Table 2 shows angular displacements and joint angular velocities for each protocol. Although the total joint angle did not differ significantly between the 3 protocols ($p = .905$), the MCP joint ROM was significantly smaller for active fist movements compared to passive straight to full fist movements ($p = .007$). The MCP joint ROM was significantly smaller for passive straight to full fist movements compared to hook to full fist movements ($p = .007$). The joint angular velocity did not differ between the 3 protocols ($p = .130$).

The median absolute tendon excursion for the long finger FDP was 24.3 mm, 14.0 mm, and 13.6 mm for active fist, straight to full fist, and hook to full fist movements, respectively. Tendon excursion was increased 74% and 79% in active versus both passive protocols ($p = .005$) (Fig. 3). There were no significant differences between passive protocols ($p = .059$).

Adjusted tendon excursions for total joint angular displacements were 12.7 mm/100°, 7.5 mm/100°, and 7.4 mm/100° for active fist, straight to full fist, and hook to full fist movements, respectively. All adjusted tendon excursions differed significantly: (1) active to straight to full fist (approximately 69% increase in tendon excursion for active fist movement compared to straight to full fist, $p = .013$); (2) active fist to hook to full fist protocol (72% increase in tendon excursion for active movement compared to hook to full fist, $p = .017$); and

TABLE 2. Median and Ranges for Long Finger Joint Angles and Angular Velocity

	Active	Straight to Full Fist	Hook to Full Fist
MCP joint (°)*	64.9 (36.1–97.3) [†]	77.1 (61.6–98.0) [‡]	67.7 (55.9–89.2) [§]
PIP joint (°)	53.1 (9.3–63.6)	49.8 (5.5–72.4)	41.4 (34.7–87.4)
DIP joint (°) [¶]	71.6 (46.9–81.1)	60.6 (47.2–81.0)	68.5 (49.7–78.9)
ROM (°) [#]	176.0 (134.3–231.9)	191.9 (148.0–226.6)	183.3 (157.6–225.1)
Angular velocity (°/s)**	41.5 (31.2–52.3)	39.9 (31.2–49.3)	38.4 (34.1–62.6)

*p = .008 (Kendall's W test).

[†]p = .007, tested between the active and straight to full fist protocols (Wilcoxon's signed rank test).

[‡]p = .007, tested between the straight to full fist and hook to full fist protocols (Wilcoxon's signed rank test).

[§]p = .508, tested between the active and hook to full fist protocols (Wilcoxon's signed rank test).

^{||}p = .905 (Kendall's W test).

[¶]p = .150 (Kendall's W test).

[#]p = .905 (Kendall's W test).

**p = .130 (Kendall's W test).

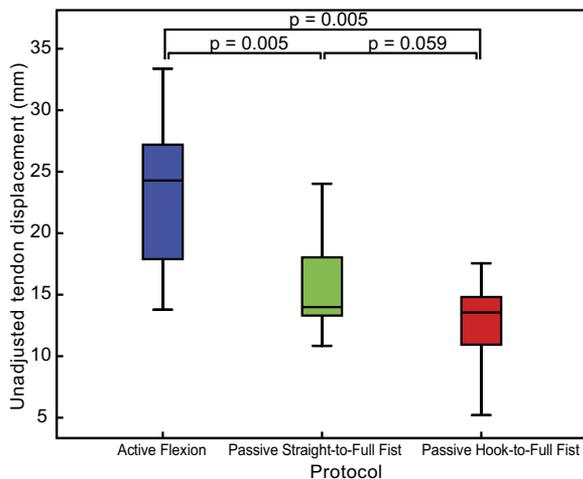


FIGURE 3: Box plot of the absolute tendon excursion (mm) for the 3 movement protocols. Excursion in the active protocol was significantly larger than excursion in the passive straight to full fist ($p = .005$) and hook to full fist ($p = .005$) protocols.

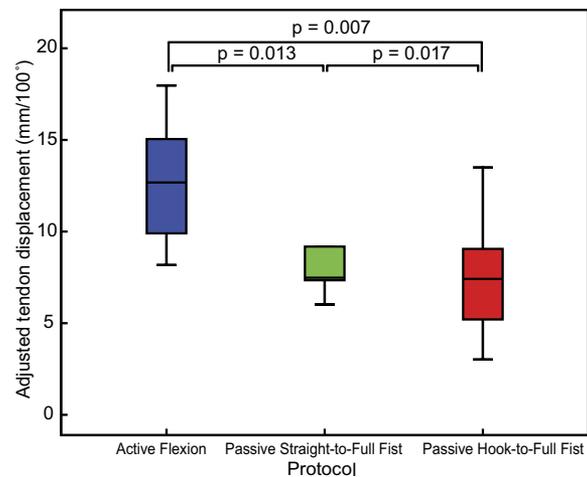


FIGURE 4: Box plot of the tendon excursion, adjusted for the total summed joint angle for the 3 different protocols. Excursion was significantly larger for active than for straight to full fist ($p = .013$) and the hook to full fist ($p = .007$) protocols.

(3) straight to full fist to hook to full fist (6% increase in tendon excursion for straight to full fist compared to hook to full fist, $p = .007$, Fig. 4).

DISCUSSION

Only 2 studies to date have noninvasively quantified *in vivo* tendon excursion during rehabilitation.^{10,11} In the present study, we investigated *in vivo* tendon excursion by using 3 rehabilitation protocols in 10 healthy subjects. Both unadjusted and adjusted tendon excursions were significantly larger during active compared to passive movements. This difference might result from tendon buckling, as suggested by Horii et al.²¹ Whereas

tendons are continuously loaded during active movements, passive flexion shortens the FDS muscle to the point of no passive tension. After that, the tendon might buckle as it is forced through its surrounding sheath without loading.

In comparing passive protocols, we observed a small but significantly larger adjusted tendon excursion during straight to full fist compared to hook to full fist movement. This difference is likely caused by differences in joint angles at the end of the flexion movement. The MCP and PIP joint ranges were larger and the DIP joint range smaller during straight to full fist compared to hook to full fist protocols. Because the tendon moment arm is largest at the MCP joint, a similar angular

TABLE 3. Long Finger Flexor Digitorum Profundus Tendon Excursions and Tendon Excursions Normalized to 100° Total Joint Angle in Published Studies

Study	Cadaver or <i>In Vivo</i>	Excursion (mm)	Range of Motion (°)	Adjusted Excursion (mm/100°)
Active				
McGrouther ⁷	Cadaver	18	150	12.0*
Horibe et al. ⁸	Cadaver	30	152	19.7 [†]
Panchal et al. ¹⁰	Cadaver	10	110	9.1 [‡]
Panchal et al. ¹⁰	<i>In vivo</i>	33	160	20.6 [§]
Soeters et al. ¹¹	<i>In vivo</i>	13	120	10.8
This study	<i>In vivo</i>	24	176	12.7 [¶]
Passive				
Tanaka et al. ⁹	Cadaver	21	210	10.0 [#]
Panchal et al. ¹⁰	Cadaver	1	110	0.9 [†]
Panchal et al. ¹⁰	<i>In vivo</i>	7	160	4.4 ^{**}
Soeters et al. ¹¹	<i>In vivo</i>	11	120	9.2
This study	<i>In vivo</i>	14	188	7.4 ^{††}

*90° PIP joint and 60° DIP joint flexion.

[†]105° MCP joint, 32° PIP joint, and 15° DIP joint flexion.

[‡]90° PIP joint and 40° DIP joint flexion.

[§]Assuming at least 90° PIP joint and 70° DIP joint flexion.

^{||}Assuming 60° PIP joint and 60° DIP joint flexion.

[¶]65° MCP joint, 53° PIP joint, and 72° DIP joint flexion.

[#]Assuming 90° MCP joint, 60° PIP joint, and 60° DIP joint flexion.

^{**}90° PIP joint and 70° DIP joint flexion.

^{††}72° MCP joint, 46° PIP joint, and 65° DIP joint flexion.

change in this joint contributes more to tendon excursion than in the other joints. Although clinicians should consider that different flexion patterns result in different tendon excursions, the small differences between the excursions might have little impact on adhesion formation after tendon repair.

Previous investigations of tendon excursion in cadaver hands produced widely varying tendon excursion results (see Table 3). McGrouther and Ahmed⁷ reported a mean long finger tendon excursion of 17.6 mm during active movement simulated by full extension to 90° PIP joint flexion and 60° DIP joint flexion. Horibe et al.⁸ reported larger tendon excursions, but these were mean tendon excursions with no distinction between index and long finger FDP tendon excursions. In that study, mean tendon excursion was 30.4 mm during active movement (full extension to 105° MCP joint flexion plus 32° PIP joint flexion plus 15° DIP joint flexion). Tanaka et al.⁹ reported a mean tendon excursion of 20.9 mm for the index finger FDP in zone II during passive movement from full extension to full flexion. Panchal et al.¹⁰ investigated active and passive tendon excursion in cadavers, showing larger tendon excursions during simulated active movement (10 mm) compared to passive movement (1 mm). The ROM was 90° at the PIP joint

TABLE 4. Measurement Devices and Cadaver Conditions

Study	Type	Measurement Device	Cadaver Conditions
McGrouther ⁷	Cadaver	Suture/ruler	Complete removal of tissue
Tanaka ⁹	Cadaver	Marker*	Open incision Open sheath No pretension
Panchal ¹⁰	Cadaver	Marker/ruler	Removal of subcutaneous fat Removal of skin No pretension
Horibe ⁸	Cadaver	X-rays	Digit separated from hand
Panchal ¹⁰	<i>In vivo</i>	Marker/ruler	NA
Soeters ¹¹	<i>In vivo</i>	Doppler	NA
This study	<i>In vivo</i>	Ultrasound tracking	NA

*Assumed ruler, not otherwise specified.

and 70° at the DIP joint with the MCP joint splinted at 90° flexion. Panchal et al.¹⁰ observed similar tendon excursions during *in vivo* studies, with a mean tendon excursion of 11 mm during simulated active movement and 4 mm during passive movement. Soeters et al.¹¹ reported mean tendon excursions of 13.3 mm during active movement and 11.4 mm during passive movement (PIP joints and DIP joints moved from full extension to full flexion).

Variations in tendon excursion in these earlier studies are much larger than can be expected based on individual differences; the differences more likely relate to experimental conditions, such as measurement techniques, tissue changes in cadaver tendons, or surgery-induced changes to tendons (see Table 4). Our *in vivo* study yielded larger active and passive tendon excursions than those reported in the literature.

The present study has some limitations. We limited FDP tendon excursion measurement to zone V. Because proximal to this point, FDP tendons are oriented longitudinally during flexion and extension, measurement biases due to out-of-plane tracking errors are minimized. Another limitation is that the sample was limited to 10 healthy subjects. Despite the small size, we found statistically significant differences by using conservative, nonparametric, Wilcoxon signed rank tests. Future studies will determine whether our findings in healthy controls are applicable to patients who have had flexor tendon reconstruction. Also, motion was not

device-controlled, so motion patterns differed slightly between conditions. Consequently, ROMs differed for MCP, PIP, and DIP joints across protocols. This motion variation might explain differences in tendon excursion between passive protocols. In addition, joint angular velocities might differ between protocols, although Fukunaga et al.²² showed that this velocity does not influence tendon displacement in their studies of the lower leg. A potential limitation is the possibility that examination glove pressure increased tendon friction. However, examination gloves were chosen to closely fit subjects' hands. Another potential limitation is that angle measurements might be less accurate because we taped the index and long fingers together. However, the relationship between active tendon excursion and total joint angle was nearly linear, as predicted by biomechanical models and experimental data, indicating that the angle measurements were accurate.²³ Finally, our subjects were young and tall, with long hands.^{24,25}

This study demonstrates large and statistically significant differences in tendon excursion during active and passive movements. These baseline data can be used to develop FDP tendon mobilization protocols, and the experimental method that we applied might help surgeons and therapists to quantify early tendon gliding after tendon repair. The method can be used to assess sufficiency of tendon gliding and modify post-surgical exercises to avoid tendon adhesion.

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