Ultrasonographic Assessment of Flexor Tendon Mobilization: Effect of Different Protocols on Tendon Excursion

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Background: Different mobilization protocols have been proposed for rehabilitation after hand flexor tendon repair to provide tendon excursion sufficient to prevent adhesions. Several cadaver studies have shown that the position of the neighboring fingers influences tendon excursions of the injured finger. We hypothesized that the positions of adjacent fingers influence the long finger flexor digitorum profundus tendon excursion, measured both absolutely and relative to the surrounding tissue of the tendon.

Methods: Long finger flexor digitorum profundus tendon excursions and surrounding tissue movement were measured in zone V in eleven healthy subjects during three different rehabilitation protocols and two experimental models: (1) an active four-finger mobilization protocol, (2) a passive four-finger mobilization protocol, (3) a modified Kleinert mobilization protocol, (4) an experimental modified Kleinert flexion mobilization model, and (5) an experimental modified Kleinert extension mobilization model. Tendon excursions were measured with use of a frame-to-frame analysis of high-resolution ultrasound images.

Results: The median absolute long finger flexor digitorum profundus tendon excursions were 23.4, 17.8, 10.0, 13.9, and 7.6 mm for the active four-finger mobilization protocol, the passive four-finger mobilization protocol, the modified Kleinert mobilization protocol, the experimental modified Kleinert flexion mobilization model, and the experimental modified Kleinert extension mobilization model, respectively, and these differences were all significant ($p \leq 0.041$). The corresponding relative flexor digitorum profundus tendon excursions were 11.2, 8.5, 7.2, 10.4, and 5.6 mm. Active four-finger mobilization protocol excursions were significantly ($p = 0.013$) greater than passive four-finger mobilization protocol excursions but were not significantly greater than experimental modified Kleinert flexion mobilization model excursions ($p = 0.213$).

Conclusions: The present study demonstrated large and significant differences among the different rehabilitation protocols and experimental models in terms of absolute and relative tendon displacement. More importantly, the present study clearly demonstrated the influence of the position of the adjacent fingers on the flexor tendon displacement of the finger that is mobilized.

Clinical Relevance: The positions of adjacent fingers in tendon mobilization protocols have a large influence on both absolute and relative tendon excursions. The most commonly used protocols after flexor tendon repair may not lead to optimal tendon excursions.

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A commentary by James H. Herndon, MD, is linked to the online version of this article at jbjs.org.

After flexor tendon reconstruction or repair, adhesions are common and contribute greatly to a poor hand function outcome. To prevent tendon adhesions, two types of rehabilitation protocols have been proposed: passive mobilization and active mobilization¹⁻³. Although active mobilization protocols are associated with larger tendon excursions than passive mobilization protocols and thereby decrease adhesion formation, active mobilization protocols also are associated with a higher prevalence of tendon repair reruptures^{1,4}. It is possible to increase the strength of the repair by using different suture techniques, enabling the use of an active mobilization protocol. However, increasing the number of sutures is likely to cause more damage to the tendon or to compromise its ability to heal¹. The ideal mobilization protocol would obtain the tendon excursion of the active mobilization protocol with the forces associated with a passive mobilization protocol.

Several passive mobilization protocols have been described, such as the modified Kleinert mobilization technique with palmar pulley and the four-finger mobilization protocol^{5,6}. These two protocols differ in that the modified Kleinert mobilization technique with palmar pulley involves the use of a rubber band that is attached to only the injured finger, whereas the four-finger mobilization protocol involves the use of rubber bands that are attached to all four fingers, including the injured finger, increasing tendon excursion and stress (Fig. 1, top and middle rows)⁷.

Neither of these mobilization protocols achieves excursions comparable with those achieved during active mobilization^{4,8}.

In vivo, the four-finger mobilization protocol achieves larger excursions than the modified Kleinert mobilization protocol⁷, indicating that the position of the adjacent fingers might influence the tendon excursion of the injured finger and might improve the tendon excursion achieved with the four-finger mobilization protocol as compared with that achieved with the modified Kleinert mobilization protocol. Therefore, it might be possible to increase tendon excursion with the modified Kleinert mobilization protocol by placing the adjacent fingers in different positions, such as full flexion or full extension. Although cadaver studies may not always represent in vivo tendon excursions⁴, several cadaver studies have compared tendon excursions during passive mobilization and active mobilization. In contrast, only a limited number of studies have assessed tendon excursions in vivo⁸⁻¹⁰. However, none of those studies have investigated the biomechanical influence of the adjacent fingers and surrounding structures on tendon excursions of the finger with the different mobilization protocols.

There has been an increased interest in the tissue surrounding the tendon, reflected by the relatively large number of studies focusing on the repair of the tissue surrounding the tendon repair and its effect as a barrier to prevent the formation of extrinsic adhesions¹. The anatomy and nomenclature of this tissue are debated still. Traditionally, the tissue surrounding the

Fig. 1

Figs. 1-A through 1-E Overview of the active mobilization protocol, the two passive mobilization protocols, and the two experimental passive mobilization models used in the present study. The bottom row shows a typical example of absolute hand flexor tendon excursions, surrounding tissue motion, and relative tendon excursions obtained during the corresponding mobilization protocols and experimental models shown in the top and middle rows. **Fig. 1-A** The active four-finger mobilization protocol. **Fig. 1-B** The passive four-finger mobilization protocol. **Fig. 1-C** The modified Kleinert mobilization protocol. **Fig. 1-D** The experimental modified Kleinert flexion mobilization model. **Fig. 1-E** The experimental modified Kleinert extension mobilization model.

hand flexor tendons has been called a “paratenon” or “common carpal tunnel sheath.” Ettema et al. proposed an anatomical concept of the carpal tunnel focusing on surrounding tissues, hypothesizing that the tendon is surrounded with subsynovial connective tissue¹¹. Guimberteau proposed a similar anatomical concept, hypothesizing that the tendon is surrounded by a multimicrovacuolar collagenous dynamic absorbing system, which interconnects the tendon and the carpal retinaculum^{12,13}.

Recently, a small number of cadaver studies have investigated hand flexor tendon excursions and surrounding tissue movement, suggesting that the surrounding tissue moves in the same direction as the tendon, with excursions ranging from 3 to 13 mm¹⁴⁻¹⁹. Because this surrounding tissue moves in the same direction as the tendon, tendon movement relative to the surrounding tissue may be smaller than absolute tendon movement. Therefore, it may be misleading to study only tendon excursions measured with respect to a nonmoving reference such as a ruler or a bone. As a result, the 5 mm of excursion that has been suggested as necessary to overcome tendon adhesions may be more difficult to meet when considering this excursion relative to the surrounding area²⁰. However, results should be interpreted with caution as cadaver studies investigating tendon dynamics might not reflect the *in vivo* state well⁴.

In the present study, we hypothesized that the positions of adjacent fingers influence the long finger flexor digitorum profundus tendon excursion. Therefore, we measured the flexor digitorum profundus tendon excursions relative to both the stationary ultrasound scan head and the surrounding tissue of the tendon *in vivo* in healthy subjects with intact flexor tendons. To do so, we compared three different finger position protocols already used in a clinical setting: (1) the active four-finger mobilization protocol, (2) the passive four-finger mobilization protocol, and (3) the modified Kleinert mobilization protocol. In addition, we compared the protocols with two experimental models in which we positioned the other fingers in two extreme situations to evaluate the effect of the adjacent fingers on the tendon excursion: (1) an experimental model based on the modified Kleinert mobilization protocol, but with the adjacent fingers in full flexion (the experimental modified Kleinert flexion mobilization model), and (2) an experimental model based on the modified Kleinert mobilization protocol, but with the adjacent fingers in full extension (the experimental modified Kleinert extension mobilization model). We compared the absolute and relative excursions among the different protocols and experimental models as well as the minimal excursion of 5 mm needed to avoid adhesions as suggested by Duran and Houser²⁰.

Materials and Methods

Subjects and Measurements

Our institutional medical ethics committee approved the present study, and informed consent was obtained from each participant. Twelve healthy subjects (six male and six female) with a median age of twenty-four years (range, twenty-one to fifty-two years) and a median body mass index (BMI) of 23.7 kg/m² (range, 18.8 to 34.7 kg/m²) were enrolled in the present study. One subject was excluded because of failure to comply with the passive mobilization protocols.

Experimental Conditions

Ultrasound video sequences of the long finger flexor digitorum profundus tendons were acquired with use of a Philips iE33 ultrasound system (Koninklijke Philips Electronics, Eindhoven, the Netherlands) with a 7-MHz linear array at 100 frames per second. The image resolution was 0.0166 mm/pixel.

The experimental conditions are shown in Fig. 1. The dominant forearm was immobilized in the supine position with use of Velcro straps. The forearm was fixed to the brace at the midpoint of the forearm, just proximal to the wrist, and just proximal to the metacarpophalangeal joints. The wrist was positioned in 30° of flexion, with the metacarpophalangeal joints in 60° of flexion and the interphalangeal joints fully extended. Rubber bands were attached to the tips of all four fingers at the start of the experiments.

To localize the long finger flexor digitorum profundus and flexor digitorum superficialis tendons with ultrasound, we first identified a landmark close to these tendons. In this case, we palpated the flexor digitorum profundus and flexor digitorum superficialis muscles, but another landmark such as the flexor carpi radialis is also suitable as a starting point to identify the flexor digitorum profundus and flexor digitorum superficialis tendons with ultrasound. After localizing the flexor digitorum profundus and flexor digitorum superficialis muscles, we moved the probe along the muscles toward the flexor digitorum profundus and flexor digitorum superficialis tendons. When both the flexor digitorum profundus and flexor digitorum superficialis tendons were visualized, the distal interphalangeal joint of each finger was flexed and extended separately by the investigator to identify the two tendons. The flexor digitorum profundus tendon was identified if there was more flexor digitorum profundus excursion than flexor digitorum superficialis excursion during the distal interphalangeal movement. Moreover, the identification of the flexor digitorum profundus tendon was confirmed by its position and orientation as the flexor digitorum profundus tendon commonly passes through the carpal tunnel at an angle whereas the flexor digitorum superficialis tendon passes through the carpal tunnel more horizontally.

Motion Protocols and Finger Positions

In the present study we compared one active protocol (which served as the reference), two passive protocols already used in a clinical setting, and two experimental passive models. The protocols and experimental models are depicted in Fig. 1, and the order of execution was randomized to minimize possible learning effects.

In the active four-finger mobilization protocol, the subject was asked to make a fist starting from full extension, which was limited by the splint, and to move to full flexion without squeezing at the end point. In the passive four-finger mobilization protocol, the rubber bands for all four fingers were guided through a guiding system that was placed in the palm of the subject and attached to the splint⁶⁰. The subject was asked to fully extend the fingers followed by full relaxation, which resulted in passive flexion due to the attached rubber bands. The subject was specifically instructed not to actively flex any of the fingers.

In the modified Kleinert mobilization protocol, the rubber band for the long finger was attached proximally on the splint and all other rubber bands were detached²¹. Again, the subject was asked to fully extend the long finger followed by full relaxation, which resulted in passive flexion due to the attached rubber band. The subject was specifically instructed not to actively flex any of the fingers, but passive movement of all fingers was allowed.

In the experimental modified Kleinert flexion mobilization model, the three fingers were positioned in full flexion and were fixed to the splint with Velcro straps. The subsequent steps were the same as for the modified Kleinert mobilization protocol.

In the experimental modified Kleinert extension mobilization model, the three fingers were positioned in full extension and were fixed to the splint with Velcro straps. Again, the subsequent steps were the same as for the modified Kleinert mobilization protocol.

Ultrasound Imaging Analyses

Ultrasound images were exported as uncompressed Audio Video Interleave files with use of OsiriX (version 3.7.0; Pixmeo, Geneva, Switzerland). The uncompressed Audio Video Interleave files then were imported into MATLAB 7.5 (R2007a; The MathWorks, Natick, Massachusetts) and were analyzed with in-house-developed tracking software with use of a dedicated two-dimensional multikernel block-matching scheme with normalized cross-correlation, which has

Fig. 2

Flowchart showing the speckle-tracking algorithm to calculate excursions of the tendon and the subsynovial connective tissue/multimicrovacuolar collagenous dynamic absorbing system. The upper part of the figure shows Frame 1 of the ultrasound recording of the flexor digitorum profundus tendon and its surrounding tissue, mostly referred to as either subsynovial connective tissue or multimicrovacuolar collagenous dynamic absorbing system. The two manually placed white rectangles are the regions of interest, which depict where the tendon and the subsynovial connective tissue are located. The user places both regions of interest in Frame 1; in the consecutive frames, the regions of interest are automatically updated. The second step in the algorithm is the automated placement of six kernels covering both regions of interest. The size of the kernels for the tendon and subsynovial connective tissue/multimicrovacuolar collagenous dynamic absorbing system is optimized on the basis of the properties of the speckle pattern. The third step is to define a search region for both regions of interest in Frame 2. Within this search region, the algorithm tries to find the pattern that best matches the pattern from the kernel. Matching is performed separately for all kernels for both regions of interest. When displacements have been calculated for all kernels, the displacement vector of each kernel is multiplied by its corresponding normalization coefficient, and all weighted displacement vectors are averaged, resulting in a single displacement vector for both the tendon and the subsynovial connective tissue. For all consecutive frames the algorithm repeats itself, starting with the automated placement of both regions of interest in Frame 2. SSCT/MCDAS = subsynovial connective tissue/multimicrovacuolar collagenous dynamic absorbing system, FDP = flexor digitorum profundus, ROI = region of interest.

been described extensively and validated elsewhere^{22,23}. This algorithm can track tendons with a mean measurement error of 50 μm over physiological tendon excursions and velocities. The algorithm is based on the general concept of block-matching schemes, which are frequently used to track cardiac wall movements²⁴⁻²⁶.

Figure 2 shows the general concept of our software. The user first identifies a region of interest in the first frame of the Audio Video Interleave files. This region of interest is a rectangle that describes the location of the tendon and therefore is placed on the tendon without capturing any other

TABLE I Overview of Studies Measuring Absolute Tendon Excursions and Surrounding Tissue Excursions

Study	Surrounding Tissue: Tendon Excursion Ratio*		Active or Passive	Flexor Digitorum Superficialis or Flexor Digitorum Profundus
	Single-Digit	Full-Fist		
Ettema et al. ¹⁴ †‡	0.16	0.30	Active	Flexor digitorum superficialis
Yamaguchi et al. ¹⁵ †	0.10	0.25	Active	Flexor digitorum superficialis
Horibe et al. ¹⁷ †	0.44	NA§	Active	Flexor digitorum profundus
Yoshii et al. ¹⁹ ‡	0.18	0.30	Active	Flexor digitorum superficialis
Present study‡				
Active four-finger mobilization protocol	NA§	0.45	Active	Flexor digitorum profundus
Passive four-finger mobilization protocol	NA§	0.53	Passive	Flexor digitorum profundus
Modified Kleinert mobilization protocol	0.22	NA§	Passive	Flexor digitorum profundus
Experimental modified Kleinert flexion mobilization model	0.23	NA§	Passive	Flexor digitorum profundus
Experimental modified Kleinert extension mobilization model	0.32	NA§	Passive	Flexor digitorum profundus

*The ratio is defined as the surrounding tissue excursion divided by the tendon excursion. A higher ratio indicates relatively more surrounding tissue excursion. †Cadaver study. ‡In vivo study. §NA = not applicable.

structure. Then the user identifies a second region of interest in the first frame of the Audio Video Interleave files, which is placed on the surrounding tissue instead of the tendon. The algorithm automatically places several overlapping kernels in the region of interest. Kernels are small, rectangular-shaped blocks that capture a part of the speckle pattern of the structure. In our application, the kernel is a small part of the tendon with sufficient speckle patterns so that the algorithm can find a good match in the next frame. The algorithm searches for a best-matching speckle pattern in the next frame in an automatically defined search region. We avoid searching the entire image to reduce computational load. In the algorithm, each block in a particular frame is matched with a block in the next frame; hence the term “block-matching.” The goodness of the match is defined by the normalized cross-correlation measure, which ranges from 0 (meaning that there was no match at all between a kernel and the speckle pattern captured within the search region) to 1 (meaning that there was a full match). We use multiple kernels to increase accuracy as more kernels allow for weighting the tendon excursions with the normalized cross-correlation outcome, thereby minimizing the contribution of possible outliers. Only matches with a normalized cross-correlation of ≥ 0.7 were considered good matches. This lower bound was adopted from the report by Farron et al.²⁷.

From the displacement estimates, we calculated absolute flexor digitorum profundus tendon excursion, absolute surrounding tissue excursion, and flexor digitorum profundus tendon excursion relative to its surrounding tissue. We also calculated the excursion ratios, defined as the absolute surrounding tissue excursion divided by the absolute tendon excursion, categorized in terms of single-digit movement or full-fist movement.

Statistical Analyses

To perform a power analysis, we extracted excursion data from the study by Silfverskiöld et al.²⁸, who reported a mean excursion (and standard deviation) of 11.9 ± 4.1 mm for the passive four-finger mobilization protocol and 5.6 ± 3.5 mm for the modified Kleinert mobilization protocol. On the basis of an effect size of 1.23, an α of 0.05, and a power ($1 - \beta$) of 0.80, six subjects were needed, so we decided to include twelve subjects in the present study.

We used the Wilcoxon signed rank test to evaluate differences in tendon excursions, surrounding tissue movement, and relative tendon excursions among the different protocols and experimental models. The level of significance was set at $p < 0.05$. All results were expressed as the median and the range.

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Results

Table I shows the excursion ratios during full-fist movement (that is, during the active four-finger mobilization protocol and the passive four-finger mobilization protocol) and single-digit movement (that is, during the modified Kleinert mobilization protocol, the experimental modified Kleinert flexion mobilization model, and the experimental modified Kleinert extension mobilization model) in the present study and compares these findings with those from in the literature.

The top and middle rows of Figure 1 depict the extreme positions for the different mobilization protocols and experimental models, and the bottom row depicts the corresponding typical plots of absolute long finger flexor digitorum profundus excursion, surrounding tissue excursion, and relative flexor digitorum profundus excursion. The absolute excursions of long finger flexor digitorum profundus tendon for different mobilization protocols and experimental models for all subjects are summarized in Figure 3. The median absolute long finger flexor digitorum profundus tendon excursions were 23.4, 17.8, 10.0, 13.9, and 7.6 mm for the active four-finger mobilization protocol, the passive four-finger mobilization protocol, the modified Kleinert mobilization protocol, the experimental modified Kleinert flexion mobilization model, and the experimental modified Kleinert extension mobilization model, respectively. All comparisons among protocols and experimental models showed significant differences in long finger flexor digitorum profundus excursions ($p \leq 0.041$). Excursions were largest during the active

Fig. 3

Box plot showing the absolute flexor digitorum profundus (FDP) tendon excursions for the three different mobilization protocols and the two experimental mobilization models, which are visually separated by the dashed vertical line. The values are given as medians, interquartile ranges, and ranges. Differences in excursions among all protocols were significant. The solid horizontal lines and the p values above each solid horizontal line refer to comparisons between two protocols, two models, or a protocol and a model.

four-finger mobilization protocol, followed by the passive four-finger mobilization protocol. The excursions obtained during the experimental modified Kleinert flexion mobilization model were significantly greater than those obtained during the modified Kleinert mobilization protocol ($p = 0.013$) and the experimental modified Kleinert extension mobilization model ($p = 0.041$).

The movements of the tissue surrounding the long finger flexor digitorum profundus tendon are depicted in Figure 4. Surrounding tissue excursions obtained during the active four-finger mobilization protocol were significantly greater than those obtained during the modified Kleinert mobilization protocol ($p = 0.003$), the experimental modified Kleinert flexion mobilization model ($p = 0.016$), and the experimental modified Kleinert extension mobilization model ($p = 0.003$). Excursions obtained during the passive four-finger mobilization protocol were significantly greater than those obtained during the modified Kleinert mobilization protocol ($p = 0.003$), the experimental modified Kleinert flexion mobilization model ($p = 0.010$), and the experimental modified Kleinert extension mobilization model ($p = 0.004$).

The long finger flexor digitorum profundus tendon excursions relative to the surrounding tissue are depicted in Figure 5. The median relative flexor digitorum profundus tendon ex-

cursions were 11.2, 8.5, 7.2, 10.4, and 5.6 mm for the active four-finger mobilization protocol, the passive four-finger mobilization protocol, the modified Kleinert mobilization protocol, the experimental modified Kleinert flexion mobilization model, and the experimental modified Kleinert extension mobilization model, respectively. The relative excursions obtained during the experimental modified Kleinert flexion mobilization model did not differ significantly from those obtained during the active four-finger mobilization protocol ($p = 0.213$). Similarly, the relative excursions obtained during the passive four-finger mobilization protocol did not differ significantly from those obtained during the experimental modified Kleinert flexion mobilization model ($p = 0.374$). However, the excursions obtained during the active four-finger mobilization protocol were significantly greater than those obtained during the passive four-finger mobilization protocol ($p = 0.013$).

When the relative flexor digitorum profundus tendon excursion was compared with the suggested 5-mm minimum excursion needed to prevent tendon adhesions, only the active four-finger mobilization protocol ($p = 0.003$), the passive four-finger mobilization protocol ($p = 0.021$), and the experimental modified Kleinert flexion mobilization model ($p = 0.010$) showed

Fig. 4

Box plot showing the excursion of the tissue surrounding the flexor digitorum profundus tendon for the three different mobilization protocols and the two experimental mobilization models, which are visually separated by the dashed vertical line. The values are given as medians, interquartile ranges, and ranges. Both the active four-finger protocol and the passive four-finger protocol differed significantly from the experimental modified Kleinert flexion mobilization model, the modified Kleinert mobilization protocol, and the experimental modified Kleinert extension mobilization model. The solid horizontal lines and the p values above each solid horizontal line refer to comparisons between two protocols, two models, or a protocol and a model.

Fig. 5

Box plot showing the relative long finger flexor digitorum profundus (FDP) tendon excursions for the three different mobilization protocols and the two experimental mobilization models, which are visually separated by the dashed vertical line. The values are given as medians, interquartile ranges, and ranges. The relative excursion is defined as the long finger flexor digitorum profundus excursion relative to its surrounding tissue. The horizontal dashed line is the minimum tendon excursion of 5 mm, suggested by Duran and Houser²⁰ to prevent tendon adhesions. The solid horizontal lines and the p values above each solid horizontal line refer to comparisons between two protocols, two models, or a protocol and a model.

significantly greater excursions than this threshold. The excursions obtained during the modified Kleinert mobilization protocol ($p = 0.050$) and the experimental modified Kleinert extension model ($p = 0.859$) were not significantly greater than this threshold.

Discussion

In the present study, we investigated, *in vivo*, the influence of adjacent finger positions on the absolute tendon excursions, surrounding tissue excursions, and relative tendon excursions in eleven healthy subjects with intact flexor tendons. We found that different adjacent finger positions in the different mobilization protocols and experimental models had a large influence on the absolute and relative long finger tendon excursions. The absolute tendon excursion of the long finger flexor digitorum profundus was greater for the active four-finger mobilization protocol in comparison with the passive four-finger mobilization protocol, which, in turn, was greater in comparison with the modified Kleinert mobilization protocol and the two experimental models. With regard to the movement of surrounding tissue, two groups can be distinguished: (1) the active and passive four-finger mobilization protocols had relatively large surrounding tissue movements, and (2) the modified Kleinert mobilization protocol and the two experimental models had relatively small surrounding tissue movements. Consequently, the largest relative flexor tendon excursions (with respect to the surrounding tissue) were measured during the active four-finger mobilization protocol, and potentially similar relative tendon excursions were measured during the experimental modified Kleinert flexion mobilization model. The latter finding may be surprising, as the Kleinert protocol commonly is thought to be inferior in terms of excursions. Furthermore, we found that excursions of >5 mm were measured only during the active four-finger mobilization protocol, the passive four-finger mobilization protocol, and the experimental modified Kleinert flexion mobilization model.

Only a few studies have shown tendon excursions relative to the surrounding tissue expressed as a ratio, and these were mostly measured in cadavers (Table I). The ratios ranged from 0.10 to 0.44 during active movement, meaning that the surrounding tissue excursion was 10% to 44% of the tendon excursion. In the present study, we found ratios ranging from 0.22 to 0.53, which are comparable with, although somewhat larger than, those reported in previous studies.

We also compared the ratios measured during single-digit motion and full-fist motion in the present study with those in the literature. In the literature, the ratios during single-digit motion (ranging from 0.10 to 0.18) consistently have been smaller than those during full-fist motion (ranging from 0.25 to 0.30). In the present study, we also found smaller ratios during single-digit motion (ranging from 0.22 to 0.32) than during full-fist motion (ranging from 0.45 to 0.53). In the present study, we excluded the results reported by Horibe et al.¹⁷ as they fully dissected the finger, thereby removing any interaction with the adjacent fingers. The somewhat higher ratios in the present study may result from different experimental conditions, most notably the *in vivo* nature of our experiment as compared with the cadaver measurements in previous studies. Furthermore, the somewhat higher

ratios may also be due to the fact that we investigated the long finger flexor digitorum profundus, whereas the previous studies also investigated the flexor digitorum superficialis tendon.

The present study had a number of limitations. An important limitation is that we measured flexor digitorum profundus tendon excursion in zone V as at that point the flexor digitorum profundus tendon runs almost completely longitudinally, minimizing measurement errors such as out-of-plane motion. For flexor tendon rehabilitation, it would be very valuable to obtain similar data from zone II because zone-II tendon repairs are associated with a high prevalence of adhesion formation²⁹. Because the tendons were very stiff in the low loading levels applied in the present study and because the joints between zone II and zone V were fixed, absolute tendon excursion in zone II is likely to be similar to that in zone V. However, this will not apply to the surrounding tissue. For example, Horibe et al.¹⁷ showed larger tendon sheath excursions more proximally around the tendon as compared with distally in cadavers. The results of the relative excursion from zone V therefore cannot be generalized to apply to zone II.

Another limitation is that we evaluated only healthy control subjects. The tissue surrounding a flexor tendon repair site is unavoidably damaged during tendon repair. However, during rehabilitation, the majority of patients have a range of motion that is good to excellent according to the Strickland and Buck-Gramcko classification systems³⁰; therefore, we are assuming that the tendon and the anastomosis are able to exhibit excursions far beyond the damaged area of the surrounding tissue and thereby move through the intact surrounding tissue. It can be argued that sutures can negatively influence tendon excursions, and it is reasonable to assume that the sutures will affect excursions for all mobilization protocols. Nevertheless, several studies have shown that, even with sutures in place, excursions are well within the physiological range and are therefore likely to move far beyond the repair site and mostly through the normal surrounding tissue^{7,9}.

A third limitation is the small sample size of eleven subjects. Although the present study was small, the results convincingly showed significant differences among the three rehabilitation protocols and the two experimental models according to the most conservative nonparametric statistical tests. These significant differences in a very small study size resulted from very consistent effects of the different protocols and experimental models in the different subjects. In addition to enlarging the study population, we believe that it is important for future studies to evaluate if there are similar findings in patients with flexor tendon injury in which tendon gliding may be reduced and if there are similar findings in different zones of the hand.

A more technical limitation is that the accuracy of the speckle tracking approach depends on the kernel size. For the surrounding tissue, we used very thin and elongated kernels. Although the total area of the kernel for the surrounding tissue was smaller than that for the tendon, we found similarly high normalized cross-correlations, indicating that the surrounding tissue was tracked successfully^{22,23}.

It should be noted that the two extensions of the modified Kleinert mobilization protocol were designed primarily to

study the influence of the positions of the adjacent fingers on tendon excursion. Therefore, the most important clinical message is to focus not only on the injured finger but also on the adjacent fingers to optimize tendon excursion during rehabilitation. The experimental modified Kleinert flexion model seems especially promising because of the high tendon excursion rates. Although it may be uncomfortable for patients to maintain the flexed position of the other fingers in a clinical situation, this model may serve as a basis for more short-term mobilization exercises to increase tendon excursion.

In addition, our findings indicated that tendon excursion is reduced when an adjacent finger is immobilized in extension for fracture fixation, wound-healing, or central slip repair. This may necessitate additional mobilization exercises. In addition, for these patients, it may be especially worthwhile to perform exercises with the other adjacent fingers in a flexed position.

In conclusion, the present study demonstrated large and significant differences among the different rehabilitation protocols and experimental models in terms of absolute flexor tendon displacement, movement of surrounding tissue, and relative tendon displacement in healthy subjects with intact flexor tendons. The present study clearly demonstrated the influence of the position of

the adjacent fingers on the flexor tendon displacement of the finger that is mobilized. Therefore, clinicians need to focus not only on the injured finger but also on the adjacent fingers to optimize tendon excursion during rehabilitation after tendon repair. ■

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