—**Original**—

Ultrasound Evaluation of the Transverse Movement of the Flexor Pollicis Longus Tendon on the Distal Radius during Wrist and Finger Motion in Healthy Volunteers

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Purpose: This study aimed to evaluate the kinematics of the flexor pollicis longus tendon (FPL) at the wrist by examining the movement of the FPL on the distal radius during various wrist and finger motions using transverse ultrasound in healthy volunteers.

Methods: Forty-eight wrists of 24 asymptomatic volunteers were examined by transverse ultrasound to observe the location of the FPL on the distal radius at 5 wrist positions (neutral, 60° dorsal flexion, 60° palmar flexion, 40° ulnar deviation, and 10° radial deviation) with all 5 fingers in full extension and full flexion, and isolated thumb in full flexion, respectively.

Results: We found that the FPL was situated statistically significantly more ulnodorsally at the wrist dorsal and ulnar deviation positions, more ulnopalmarly at the wrist palmar flexion position, and more radiopalmarly at the wrist radial deviation-position than at the wrist neutral position with all 5 fingers at full extension. Especially, it moved statistically significantly most ulnodorsally at the wrist dorsal flexion position during finger motion. The FPL moved most statistically significantly ulnopalmarly at the wrist palmar flexion position with all 5 fingers in full extension among all wrist positions during finger motion. During finger motion, the wrist dorsal flexion position induced significant displacement of the FPL to the distal radius and compressed it between the flexor tendons and the distal radius. The average distance between the FPL and the volar surface of the distal radius in the palmar-dorsal direction at wrist dorsal flexion position in all fingers at full flexion was 1.9 mm, the smallest among all wrist positions during finger motion.

Conclusions: There is a significant relationship between the transverse movement of the FPL at the distal radius and wrist and finger motions. Our findings indicated that the irritation of the FPL caused by the movement of both the FPL itself and of the flexor digitorum superficialis and profundus is most induced with the wrist in dorsal flexion with all 5 fingers at full flexion compared to other wrist positions during finger motion. This wrist position might be the optimum one at which to evaluate the irritation of the FPL from volar locking plates in patients with distal radius fracture. We believe that our transverse ultrasound results can play a role in the gaining of a better understanding of the kinematics of the FPL. Moreover, they have potential to lead to improved diagnosis of and treatment for fractures of the distal radius and help to minimize the risk of FPL rupture related to volar locking plates.

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Key words: flexor pollicis longus, ultrasound, wrist position, finger motion, distal radius

Introduction

Distal radius fractures, which are the most common fractures of the upper extremity, are usually treated with volar locking plate fixation[1–5]. After this operation, a major

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complication[1–11], which occurs in 1.8% to 12% of cases[6,10,12], is rupture of the flexor pollicis longus tendon (FPL). These ruptures are reportedly caused by fracture malunion or plate prominence due to incomplete reduction or poor plate positioning[1,3–5,11,12]. However, even if efforts are made to prevent tendon irritation through the design, careful positioning, and application of low-profile anatomic volar locking plates, FPL tendon ruptures still occur[1,3,5,11].

To prevent the FPL tendon from rupturing, its movement on the distal radius has recently been evaluated. Several studies using longitudinal ultrasonography have found a relationship between the position of the volar plate and the movement of the FPL at the distal radius during thumb motion in patients who had undergone volar locking plate fixation of distal radius fractures[13,14]. Moreover, these studies have found that the FPL runs longitudinally and also shifts dorsally toward the volar plate in active isolated thumb flexion[13]. Ultrasonography is a useful for examining and elucidating the various tendon movements noninvasively and quantitatively at the wrist in vivo. Thus, ultrasonographic evaluation of FPL movement during wrist and finger motions is considered useful for providing detailed information about FPL kinematic changes in healthy subjects and in patients who have undergone volar locking plate fixation for distal radius fractures. However, with longitudinal ultrasonography, holding the transducer on the wrist, except at the wrist neutral or slightly dorsal flexion position, is difficult, and a transverse examination at varied wrist positions is necessary to further detail the kinematics of the FPL.

Few studies have evaluated the transverse ultrasonographic displacement of the FPL in relation to varied wrist and finger motions. If the location of the FPL could be evaluated as a coordinate on the transverse plane this would offer a more detailed understanding of the FPL orientation at the distal radius. Therefore, in the present study we performed a quantitative analysis with transverse ultrasonography of the displacement and location of the FPL as coordinates on the distal radius at varied wrist positions during finger motion in healthy volunteers.

We hope that this study could help further the knowledge of FPL kinematics, and moreover could help to provide precise diagnosis of and suggest the optimum treatments for distal radius fractures using volar locking plate fixation, while helping to prevent rupture of the FPL.

Fig. 1 Transverse ultrasound examination setup

Materials and Methods

The subjects of this study were 24 healthy male volunteers (mean age, 35.8 years; age range, 24–56 years). Subjects were excluded if they had a history of traumatic injuries, such as fractures or tendon damage to the upper extremities, or had neurological deficit, hand pain, or numbness. Ultrasound examinations were performed for both wrists after signed consent forms were obtained from the subjects.

Subjects sat with the forearm in supination, the elbow at about 45° flexion, and the shoulder in neutral position. The subject's forearm was fixed to a custom-made table. An ultrasound scanner (Mylab Five, Hitachi Medical Corporation, Tokyo, Japan) equipped with an LA332 3.5/12-MHz hi-definition linear array transducer (LA332) was used. The study protocol was approved by our institutional review board.

All ultrasonographic examinations were performed by a single orthopedic surgeon (MN). The transducer was placed on the distal radius of the wrist (**Fig. 1**). A custom-made device fastened to the transducer was attached at the subjects's wrist to hold the transducer stable during all examinations, and the transducer was held at a 90° angle to the skin of the wrist proximal to the wrist crease to identify the ulnar edge of the most distal portion of the distal radius without applying extra pressure to the tissue above the distal radius. This bony landmark was easy to confirm by palpation and transverse ultrasonography in all wrists. The tendons of the FPL,

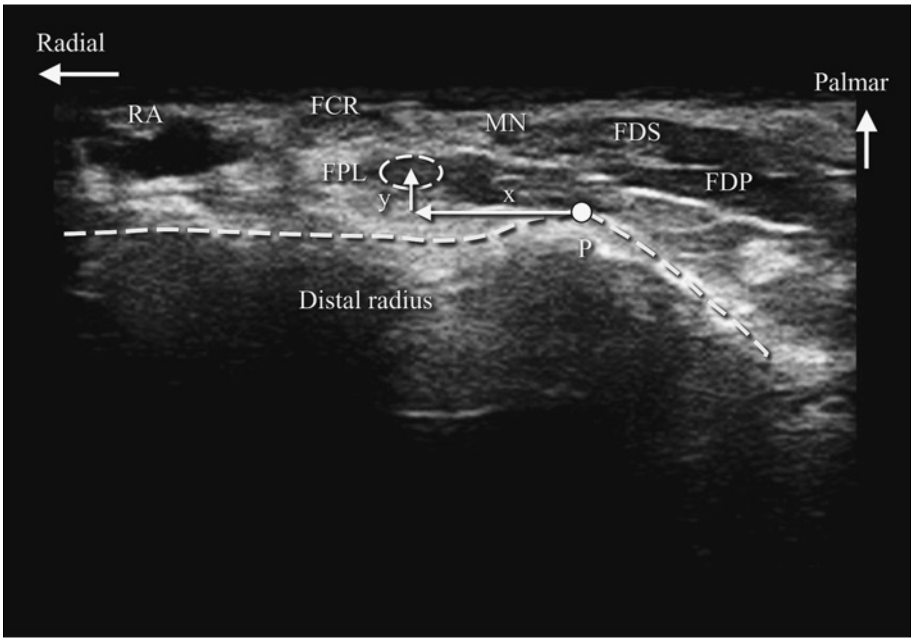

Fig. 2 Measuring the location of the flexor pollicis longus tendon on the distal radius as a coordinate
FPL: the flexor pollicis longus tendon, FCR: the flexor carpi radialis tendon, FDS: the flexor digitorumsuperficialis tendon, FDP: the flexor digiti profundus tendon, MN: the median nerve, RA: the radial artery
'P': the reference point defined as the vertex of the palmar bony prominence of the radiolunate fossa of the distal radius on the watershed line, Distance 'x': The distance between the 'P' and the centroid of FPL on the X-axis, Distance 'y': The distance between the 'P' and the centroid of FPL on the Y-axis

the flexor digitorum superficialis (FDS), and the flexor digitorum profundus (FDP) and the median nerve were identified with transverse ultrasonography during full flexion and full extension of all 5 fingers and full flexion of the isolated thumb. Transverse ultrasonographic images were obtained respectively at each of 5 wrist positions (neutral, 60° dorsal flexion, 60° palmar flexion, 40° ulnar deviation, and 10° radial deviation) during finger motion. Each wrist angle was measured with a goniometer (SD1-01, Suzukiiryo, Inc., Tokyo, Japan) positioned on the wrist. Subjects were asked to move from full extension to full flexion of all 5 fingers or from full extension of all 5 fingers to flexion of the thumb individually at each wrist position. The images of 2 cycles of the flexion-extension finger motion at each wrist position were examined.

All recorded images of the initial and final frames of each finger and wrist motion were also evaluated. Furthermore, the coordinates of the FPL were determined as follows (**Fig. 2**). The reference point (P) was defined as the vertex of the palmar bony prominence of the radiolunate fossa of the distal radius on the watershed line previously described as a transverse ridge bordering the pronator fossa distally[2]. The P can be easily identified with transverse ultrasonography or magnetic resonance imaging (**Fig. 3a and b**). The FPL has been previously reported to always be located on the radial side of point P[1]. We measured the distances between P and the centroid of the FPL on the X-axis (x) and on the Y-axis (y). The position of the FPL was shown as a coordinate point (x mm, Y mm). As the distance x or y increased, the location of the FPL was more deviated to the radial side or the palmar side. Thus, the FPL displacement in ulnar-radial and palmar-dorsal directions could be calculated with a comparison of the starting and ending coordinates of the FPL on the distal radius.

The results were calculated as the averages of 3 cycles. All data were analyzed with the software program IBM SPSS Statistics 21.0J (IBM Japan Ltd., Tokyo, Japan), and the FPL displacement from the neutral wrist position to the other 4 wrist positions in the extension of all 5 fingers and from the extension to the flexion of all 5 fingers and the isolated thumb at each of the 5 wrist positions were examined statistically with the paired t-test. A P-value of <0.05 was considered statistically significant.

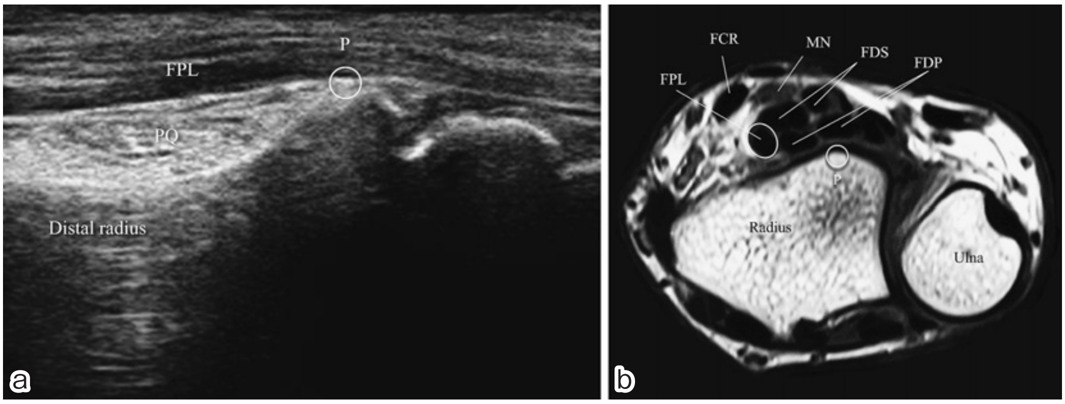

Fig. 3
a: Location of the 'P' on longitudinal sonographic image of the distal radius
○: 'P' (the reference point defined as the vertex of the palmar bony prominence of the radiolunate fossa of the distal radius on the watershed line), FPL: the flexor pollicis longus tendon, PQ: the pronator quadratus
b: Location of the 'P' on transverse magnetic resonance image of the distal radius
○: 'P' (the reference point defined as the vertex of the palmar bony prominence of the radiolunate fossa of the distal radius on the watershed line), FPL: the flexor pollicis longus tendon, FCR: the flexor carpi radialis tendon, MN: the median nerve, FDS: the flexor digitorum superficialis tendon, FDP: the flexor digitorum profundus tendon

Results

1) Movement of the FPL at Varied Wrist Positions with Full Extension of All Fingers

The average location of the FPL at the wrist neutral position in the extension of all fingers was 9.2±1.7 mm from the P in the radial-ulnar direction and 3.4±1.3 mm from the P in the palmar-dorsal direction (**Fig. 4, 5**).

In the radial-ulnar direction, the FPL was located significantly more ulnarly ($P<0.05$) at the wrist dorsal flexion, palmar flexion, or ulnar deviation position than at the wrist neutral position, and more radially at the wrist radial deviation position (**Fig. 4**). In the palmar-dorsal direction, the FPL was situated more palmarly at the wrist palmar flexion or radial deviation position than at the wrist neutral position, and more dorsally at the wrist dorsal flexion or ulnar deviation position (**Fig. 5**).

2) Movement of the FPL Comparing with Full Extension and Full Flexion of All Fingers

In the radial-ulnar direction, the FPL was positioned significantly ($P<0.05$) more ulnarly with the flexion of all fingers than with the extension of all fingers at all wrist positions (**Fig. 4**). In the palmar-dorsal direction position, the FPL was positioned significantly ($P<0.05$) more dorsally with the flexion of all fingers than with the extension of all fingers at all wrist positions at the wrist dorsal flexion or palmar flexion position (**Fig. 5**). Conversely, at the wrist neutral position, the FPL moved significantly ($P<0.05$) more palmarly with the full flexion of all fingers than with full extension.

From the extension to the flexion of all fingers, the FPL tendons moved ulnodorsally or ulnarly, separately from the radiodorsal direction motion of the FDS and the FDP at the wrist dorsal flexion, palmar flexion, ulnar deviation, or radial deviation position, but not at the wrist neutral position. At the wrist neutral position, the FPL, the FDS, and the FDP all moved ulnopalmarly, and shifted away from the distal radius.

3) Movement of the FPL Comparing with All Fingers Flexion and Isolated Thumb Flexion

In the radial-ulnar direction, at the wrist neutral, dorsal, palmar, and ulnar deviation positions, there was no significant difference in the FPL displacement between all fingers flexion and isolated thumb flexion (**Fig. 4**). Conversely, at the wrist radial deviation position, the FPL moved statistically significantly ($P<0.05$) more radially in all fingers flexion than in isolated thumb flexion. In the palmar-dorsal direction, at the wrist neutral, dorsal or palmar flexion position, the FPL moved statistically significantly ($P<0.05$) more dorsally in all fingers flexion than in isolated thumb flexion (**Fig. 5**). There were no significant differences in the FPL displacement at the wrist ulnar or radial position between in all fingers flexion and in isolated thumb flexion.

Especially, the FPL moved the most statistically significantly ($p<0.05$) dorsally at the wrist dorsal flexion position in all fingers flexion among all wrist positions. In

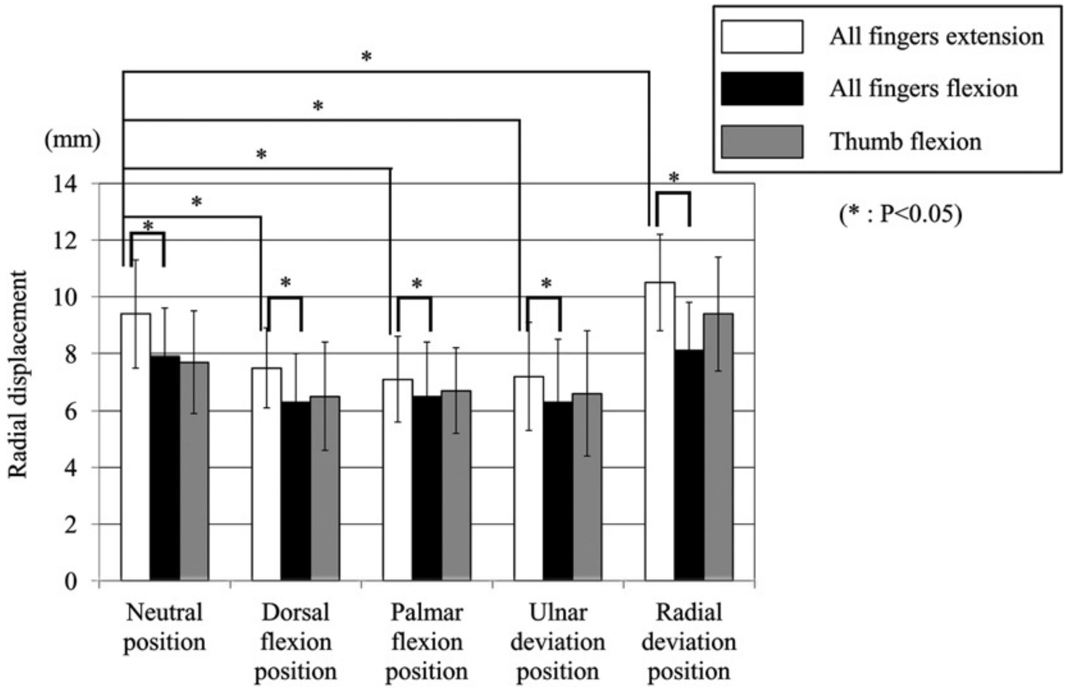

Fig. 4 Position of the FPL during wrist and finger motion (Radial displacement of the FPL from the 'P' in the radial-ulnar direction)

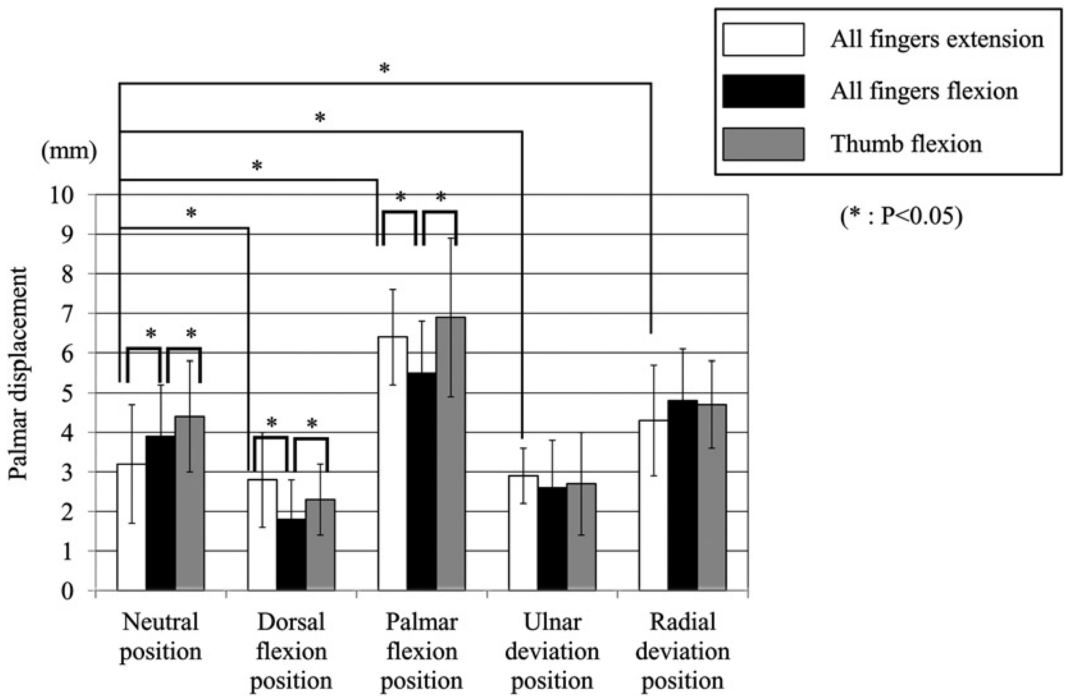

Fig. 5 Position of the FPL during wrist and finger motion (Palmarl displacement of the FPL from the 'P' in the palmar-dorsal direction)

addition, at wrist dorsal flexion position, the distance between the FPL and the distal radius in the palmar-dorsal direction was 1.9 mm±0.7 mm, and statistically significantly smallest among all wrist positions (P<0.05).

Discussion

The volar locking plate is commonly used for the treatment of unstable distal radius fractures because it provides stable fixation and allows for an early return to daily activity[1–4]. Recently, several studies have reported that FPL tendon rupture is sometimes caused by poor plate positioning, prominent distal edge of the plate, prominent screw heads, inadequate fracture reduction, or fracture collapse[1,3–7,9–11]. Particularly, a number of authors mentioned that plate prominence and placement on or distal to the watershed line, defined as the distal rim of the pronator fossa could potentially impinge on flexor tendons and ultimately cause tendon ruptures[1,3–5,7–10], as the flexor tendons run closest to the bone and the plate at the watershed line[2,8]. Several authors have recommended that the plate be positioned proximal to the watershed line to minimize the prominent distal edge of the plate in an attempt to reduce the risk of FPL rupture. However, the plate positioning proximal to the watershed line for fixation of the distal fracture fragment according to the fracture pattern may not always be possible[9]. In some cases it may be necessary to position the plate beyond the watershed line to support a subchondral buttress to the volar aspect of the articular surface and to fix fractures with very small distal fragments or their comminuted intra-articular fractures for stability. There are limitations in preventing tendon irritation only by the plate position for all distal radius fractures types. While plate prominence and distal plate positioning are known risk factors for tendon ruptures, the relationship between the plate position and FPL kinematics is not yet known. Therefore, to detail this association, it is necessary to examine the movement of the FPL on the watershed line of the distal radius. We believe that a better understanding of the kinematics of the FPL on the distal radius can help in reducing these complications. Moreover, this study might serve as beneficial basic information for future studies in patients with distal radius fractures with volar locking plates.

Recently, toward the prevention of tendon irritation, some studies on the movement of the FPL on the distal radius during finger and wrist motion using longitudinal ultrasound have been reported[13,14]. Kameyama et al reported the displacement patterns of the FPL at the distal radius during isolated thumb motion at the wrist in slightly dorsal flexion position to detect tendon irritation early in the volar plate fixation of distal radius fractures[13]. Moreover, they mentioned that longitudinal ultrasound revealed that the FPL shifted toward the watershed line of the distal radius[14]. Doi et al also described that the average distance between the volar rim of the watershed line and the FPL by longitudinal ultrasound was 1.9 mm in 30 healthy subjects, similar to our study[13]. However, they had not evaluated the FPL displacement with various wrist and finger motions, except for the wrist at slightly dorsal flexion position in isolated thumb flexion[13,14].

To date, there has been almost no research about the transverse movement of the FPL on the distal radius during various wrist and finger motions by ultrasound. We examined the transverse displacement of the FPL on the distal radius at 5 wrist positions, namely the neutral, dorsal flexion, palmar flexion, radial deviation and ulnar deviation positions, in both fist and isolated thumb motions. Subsequently, we showed that certain wrist and finger motions ended significantly in the displacement of the FPL at the distal radius on the transverse ultrasound images in normal subjects. Concretely, the FPL moved statistically significantly ($P<0.05$) ulnodorsally at the wrist dorsal and ulnar deviation positions, ulnopalmarly at the wrist palmar flexion position, and radiopalmarly at the wrist radial deviation position, respectively, compared to at the wrist neutral position (**Fig. 6**). Especially, we observed that the FPL was situated most ulnodorsally on the distal radius at the wrist dorsal flexion position. Tanaka et al reported that at the 60° or 30° wrist dorsal flexion position, contact pressure between the FPL and the volar plate significantly increased compared with at the other wrist positions[4]. Conversely, the FPL at the wrist palmar flexion position was located the most ulnopalmarly on the distal radius among all wrist positions during finger motion. From this report, it is speculated that the irritation of the FPL would be stronger in the wrist dorsal flexion position compared to other wrist positions.

Besides, we have observed that the transverse displacement of the FPL on the distal radius is affected not only by wrist motion, but also by finger motion (**Fig. 7**). And, we found that the FPL moved ulnodorsally at the wrist dorsal and palmar flexion positions, and ulnarly at the wrist ulnar and radial deviation positions during fist motion. In all finger flexion, the FPL separately moved ulnodorsally or ulnarly, while both the FDS and the FDP moved radiopalmarly. Consequently, the space in which the FDS and the FDP had been positioned became empty after their movements. Thus, the FPL shifted into that space, that is, in an ulnodorsal or ulnar direction, and it was pushed further to the ulnodorsal side by both the FDS and the FDP. Lastly, the FPL shifted into that space, that is, in an ulnodorsal or ulnar direction, and was pushed and might have been compressed between the FDS and the FDP and the volar surface of the distal radius. In particular, we have demonstrated that at the

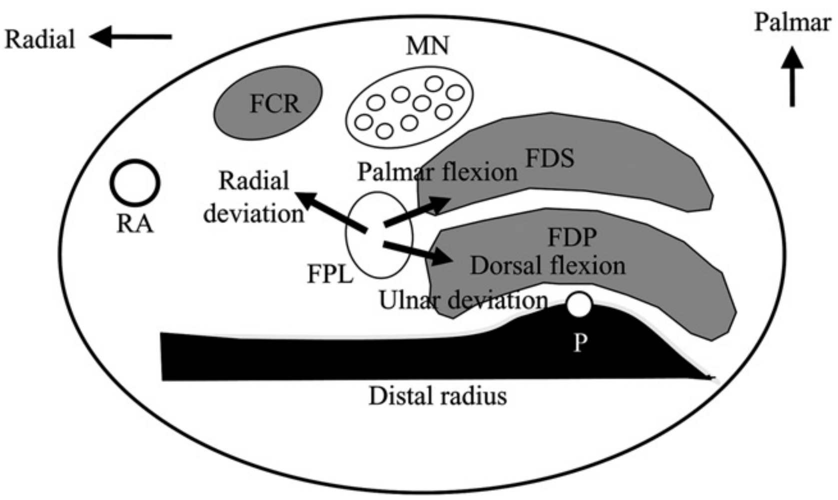

Fig. 6 Illustration of the movement of the FPL during the wrist motion with all fingers in extension
(The FPL position on the distal radius at the wrist neutral position is fixed as a starting point)
FPL: the flexor pollicis longus tendon, FDS: the flexor digitorum superficialistendon, FDP: the flexor digitorum profundus tendon, FCR: the flexor carpi radialis tendon, MN: the median nerve, RA: the radial artery, Point 'P': the reference point defined as the vertex of the palmar bony prominence of the radiolunate fossa of the distal radius on the watershed line
Radial deviation: the wrist radial deviation, Palmar flex: the wrist palmar flexion, Dorsiflex: the wrist dorsal flexion, Ulnar deviation: the wrist ulnar deviation

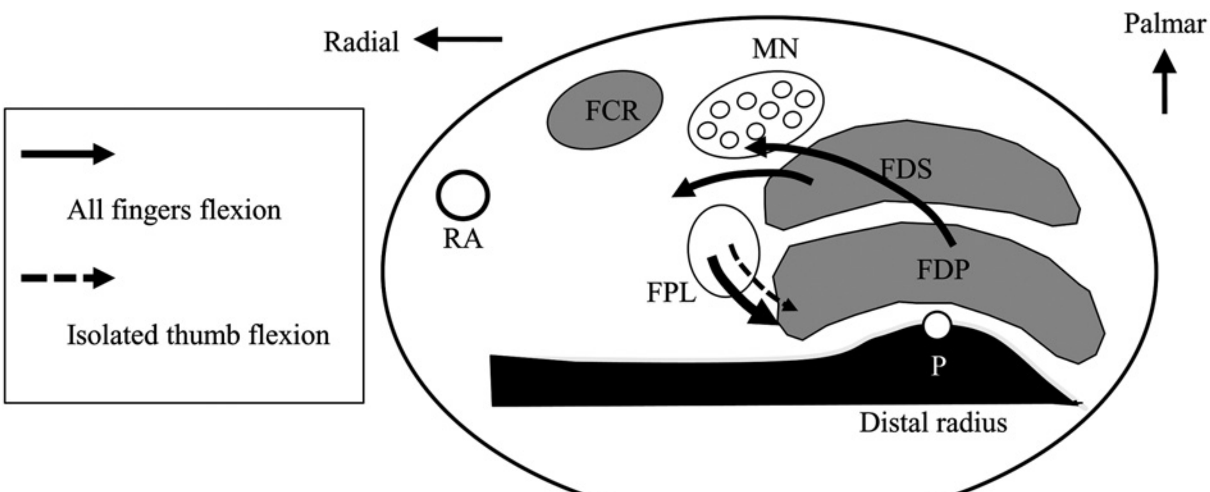

Fig. 7 Illustration of the movement of the FPL, the FDS and the FDP during all 5 finger flexion and isolated thumb flexion at the wrist dorsal or ulnar deviation position
MN: the median nerve, FPL: the flexor pollicis longus tendon, FDS: the flexor digitorum superficialis tendon, FDP: the flexor digitorum profundus tendon

wrist dorsal flexion position with all finger flexion, the FPL moved the most ulnodorsally and got the most friction at the rim of the watershed line of the distal radius among all the wrist positions. On the other hand, at the wrist palmar flexion position with all finger flexion, the FPL was displaced more ulnopalmarly and shifted away from the distal radius more than at other wrist positions.

Additionally, we compared the FPL displacement between fist motion and isolated thumb motion. Almost all studies by longitudinal ultrasound have only described

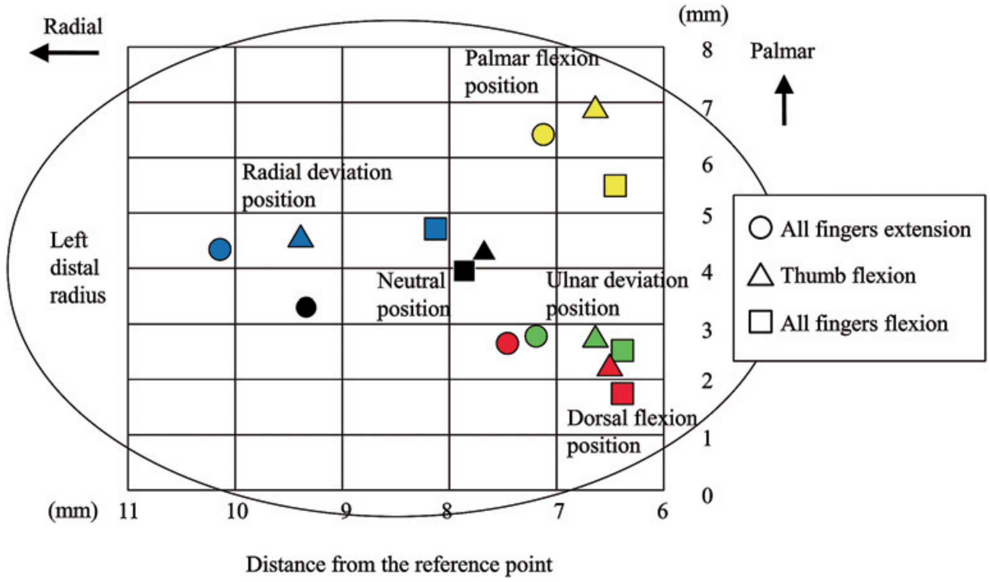

Fig. 8 Location of the FPL during wrist and finger motion on the distal radius (Average value)
○: All fingers extension, △: Isolated thumb flexion, □: All fingers extension
Black: Wrist neutral position, Red: Wrist dorsal flexion position, Yellow: Wrist palmar flexion position, Green: Wrist ulnar deviation position, Blue: Wrist radial deviation position

the FPL displacement during the isolated thumb motion[13,14]. However, we also added the examination of the FPL displacement during fist motion which is common to many daily hand activities. As a result, we have shown that there was a significant difference in the FPL displacement comparing between all 5 finger motion and isolated thumb motion. Particularly, at the wrist neutral, dorsal and palmar flexion positions, the FPL moved significantly more dorsally in all 5 full finger flexion than in the isolated thumb flexion (**Fig. 8**). In the isolated thumb flexion, the FPL shifted slightly to the volar surface of the distal radius. However, the FPL movement was blocked by the FDS and the FDP, thus it shifted very little. Meanwhile, in all 5 finger full flexion, the FDS and the FDP moved together radiodorsally, so the FPL was pushed into the ulnodorsal space by them, as we mentioned before. These results suggest that the FPL might get friction at the rim of the watershed line of the distal radius more strongly in all 5 finger flexion than in isolated thumb flexion at the wrist dorsal flexion position.

Some authors have reported that longitudinal ultrasound has an advantage to be able to detect easily the FPL irritation after volar plating of distal radius fractures[13]. Conversely, the advantages of using the transverse ultrasound in this study compared to the longitudinal technique are thought to be as follows: 1) The FPL movement can be shown not only in the palmar-dorsal direction, but also in the radial-ulnar direction, while longitudinal ultrasound only gets images of the FPL movement in the palmar-dorsal direction. 2) In the current study, the transducer was always fixed at the wrist with a custom-made transducer-fixing device, so measurement error using the transverse ultrasound technique would be reduced compared with that by the longitudinal ultrasound. Because the FPL travels both longitudinally and transversely during finger motion, the examiner needs to slide the transducer in the radioulnar direction in order to obtain the best image of the FPL when using the longitudinal ultrasound technique. 3) By the longitudinal ultrasound technique, it is quite difficult to position the transducer at the level of the distal radius not only at the wrist palmar flexion position, but also at the wrist full dorsal flexion position, while the FPL movement at all wrist positions can be demonstrated by transverse ultrasound. Accordingly, we chose to use the transverse ultrasound technique to evaluate the detailed movement of the FPL on the distal radius at the varied wrist positions during finger motion in this study.

In addition, to our knowledge, no other studies have described the detailed location of the FPL as a coordinate on the distal radius. We believe that showing the location of the FPL as a coordinate can provide more precise knowledge of the FPL orientation on the distal radius, that is, from the initial point to the final one of the FPL during wrist and finger motions. In this study, we examined and calculated the specific precise location and the displacement of the FPL as a coordinate on the distal radius quantitatively during wrist and finger motions using transverse ultrasound in healthy volunteers (**Fig. 8**). Our results indicate that the irritation of the FPL against the volar rim of the distal radius in response to FPL's movement itself could be reduced at the wrist palmar flexion position compared to other wrist positions. Conversely, at the wrist dorsal flexion position, the FPL moved the most dorsally among all wrist positions during finger motion. The average distance between the FPL and the volar rim of the watershed line at the wrist dorsal flexion position was 1.9 mm and the smallest among all the wrist positions. From these findings, it is speculated that the risk for FPL attrition after volar plating of distal radius fractures may increase due to higher contact pressures between the FPL and the plate at the wrist dorsal flexion position, assuming a volar locking plate thickness of 2 mm. This wrist dorsal flexion position may be the most appropriate one in which to examine the FPL irritation at the rim of the watershed line. Kitay et al examined the association between flexor tendon ruptures and Soong grade[3], which is a visual estimation of plate position relative to the volar rim of the distal radius[11]. They also described that plates positioned more than 2.0 mm prominent to the volar rim had high risk of the tendon rupture after volar plating of the distal radius fractures[11].

In conclusion, these results from transverse ultrasound could assist in a better understanding of the kinematics of the FPL. They could also help to provide precise diagnosis of and suggest the optimum treatments for distal radius fractures using volar locking plate fixation, while helping to prevent rupture of the FPL.

This study has some limitations. First, our study had a relatively small sample size. A large sample size may provide more detailed conclusions to our findings. Second, even though it is known that ultrasound measurement is a highly examiner- and experience-dependent tool, we did not calculate inter-observer reliability. In addition, the transducer was held with a custom-made fixing device and table, however motion of the patient' wrist and fingers may have influenced the results. This remains for future studies. Finally, in this study we evaluated the FPL kinematics of only normal subjects. We consider that this would be a useful first step towards using transverse ultrasound for diagnosing and preventing the FPL irritation after volar plate fixation of distal radius fractures.

Conflict of Interest: The authors declare no conflict of interest.

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