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published in
Journal of Biomechanics
2018

DOI (link to publisher)
10.1016/j.jbiomech.2017.11.023

Journal of Biomechanics 67 (2018) 62–68

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Tendon displacements during voluntary and involuntary finger movements

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A R T I C L E   I N F O

Article history:
Accepted 23 November 2017

Keywords:
Ultrasound
Tendon interconnections
Finger kinematics
Enslaving
Strain

A B S T R A C T

In the human hand, independent movement control of individual fingers is limited. One potential cause for this is mechanical connections between the tendons and muscle bellies corresponding to the different fingers. The aim of this study was to determine the tendon displacement of the flexor digitorum superficialis (FDS) of both the instructed and the neighboring, non-instructed fingers during single finger flexion movements. In nine healthy subjects (age 22–29 years), instructed and non-instructed FDS finger tendon displacement of the index, middle and ring finger was measured using 2D ultrasound analyzed with speckle tracking software in two conditions: active flexion of all finger joints with all fingers free to move and active flexion while the non-instructed fingers were restricted. Our results of the free movement protocol showed an average tendon displacement of 27 mm for index finger flexion, 21 mm for middle finger flexion and 17 mm for ring finger flexion. Displacements of the non-instructed finger tendons (≈12 mm) were higher than expected based of the amount of non-instructed finger movement. In the restricted protocol, we found that, despite minimal joint movements, substantial non-instructed finger tendon displacement (≈9 mm) was still observed, which was interpreted as a result of tendon strain. When this strain component was subtracted from the tendon displacement of the non-instructed fingers during the free movement condition, the relationship between finger movement and tendon displacement of the instructed and non-instructed finger became comparable. Thus, when studying non-instructed finger tendon displacement it is important to take tendon strain into consideration.

1. Introduction

The human hand has evolved to be able to perform complex hand actions and is essential in daily life to manipulate objects. Despite this capacity for dexterity, there are limitations to the independent movement of the digits (Hager-Ross and Schieber, 2000; van den Noort et al., 2016). These limitations have been attributed to both peripheral mechanical and central neural constraints (van Duinen and Gandevia, 2011). Because of these constraints, movement of one finger (instructed) may cause unintentional movements of the neighboring non-instructed finger(s), a phenomenon called enslaving (van Duinen and Gandevia, 2011; Zatsiorsky et al., 2000).

In previous work, we assessed the relationship between enslaved finger movements and activation patterns of finger specific flexor and extensor muscle regions (van Beek et al., 2017). We observed that the central nervous system is actively resisting movement of the non-instructed fingers by an increased activity of the antagonistic extensor digitorum (ED) muscle (van Beek et al., 2017). Such agonistic-antagonistic coactivation is expected to result in forces exerted at the tendons and, consequently, stretching of the tendons. Thus, tendon displacements in the non-instructed fingers will probably not only be the result of finger and tendon movement, but also of tendon stretch. However, tendon displacements have not been studied in the context of finger enslaving. Higher tendon displacements during active finger

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https://doi.org/10.1016/j.jbiomech.2017.11.023
0021-9290/

flexion compared to passive finger flexion, despite equal ranges of finger movement, have previously been reported (Korstanje et al., 2010). The presence of tendon stretch may explain this discrepancy between active and passive finger movements.

In various pathological conditions, the fingers and/or their tendons are affected, such as arthritis (Arauz et al., 2017), tenosynovitis and carpal tunnel syndrome (Bianchi et al., 2007; Kociolek and Keir, 2016; Korstanje et al., 2012; Singh et al., 2015; Tat et al., 2016). In patients with flexor tendon disorders, tendon displacements have been studied using ultrasound imaging (Korstanje et al., 2012). More insight into tendon behavior during finger movements is needed to more precisely evaluate finger movement pathologies and assess the effects of surgical interventions.

The aims of this study were (1) to investigate tendon displacement of the flexor digitorum superficialis (FDS) of both the finger which was instructed to move and of the non-instructed fingers during single finger flexion movements; and (2) to assess whether tendon stretching is present in the tendon of non-instructed fingers. We hypothesized that (1) the FDS tendons associated with the non-instructed fingers experience tendon stretching, and (2) if effects of tendon stretch are taken into account, there exists a one-on-one relationship between finger movement and tendon displacement.

2. Methods

Nine subjects participated in this study (5 male: 24–29 years, 4 female: 22–28 years). Anthropometric measurements of the digit lengths are shown in Table 1 and comparable with other studies (Buryanov and Kotiuk, 2010). All participants had no known neuromuscular disorders, did not play a musical instrument for more than two years over the course of the past five years and had no disability or surgery in the upper limb in the last two years. All subjects were right handed, which was confirmed by a laterality index of 94–100 as assessed by the Edinburgh Handedness Inventory (Oldfield, 1971). The Research Ethics Committee of the Arnhem-Nijmegen Region approved the study protocol and each subject signed a written consent before participating in the study.

Table 1
Anthropometric measurements of the digit lengths (cm) of the thumb, index, middle, ring and little finger (mean ± SD).

Finger lengths (cm)	
Thumb	6.9 ± 0.8
Index finger	9.4 ± 1.2
Middle finger	10.6 ± 1.2
Ring finger	10.0 ± 1.2
Little finger	8.0 ± 1.0

2.1. Measurement of finger kinematics

Finger movements were recorded with the PowerGlove (University of Twente, Enschede, Netherlands) (Kortier et al., 2014). This is a measurement system that consists of eighteen sensor units (magnetometers, accelerometers and gyroscopes), distributed over each finger joint (metacarpophalangeal (MCP), proximal (PIP) and distal (DIP) finger phalanges) and the dorsal side of the left hand.

2.2. Tendon displacement

Ultrasound video sequences of the FDS tendons inserting on the index, middle and ring fingers were acquired with a Philips Ie22 (Philips Medical systems, Best, Netherlands) in combination with an L11-3 ultrasound probe (frequency band from 3 to 11 MHz and a frame rate of 48 Hz) in B-mode placed longitudinally just proximal of the wrist flexion crease (Fig. 1A). Pressure of the ultrasound transducer on the underlying tissue was kept to a minimum by using large amounts of ultrasound gel and supplementing regularly. The FDS tendons corresponding to the fingers were localized by first identifying the FDP and FDS muscle bellies by palpation and ultrasound during corresponding finger movement both when the fingers are freely moved and when the neighboring fingers are restricted, and then using these muscle bellies as landmarks. The ultrasound probe was then gradually moved distally from the middle of the FDS muscle towards the tendon. To confirm that a FDS tendon was selected, the DIP joint of the finger was flexed and extended (Bianchi et al., 2007; Korstanje et al., 2012). Since the FDS tendon spans only the MCP and PIP joint, the tendon which showed the most displacement during DIP movement was identified as the FDP tendon. The distal end of the radius was taken as

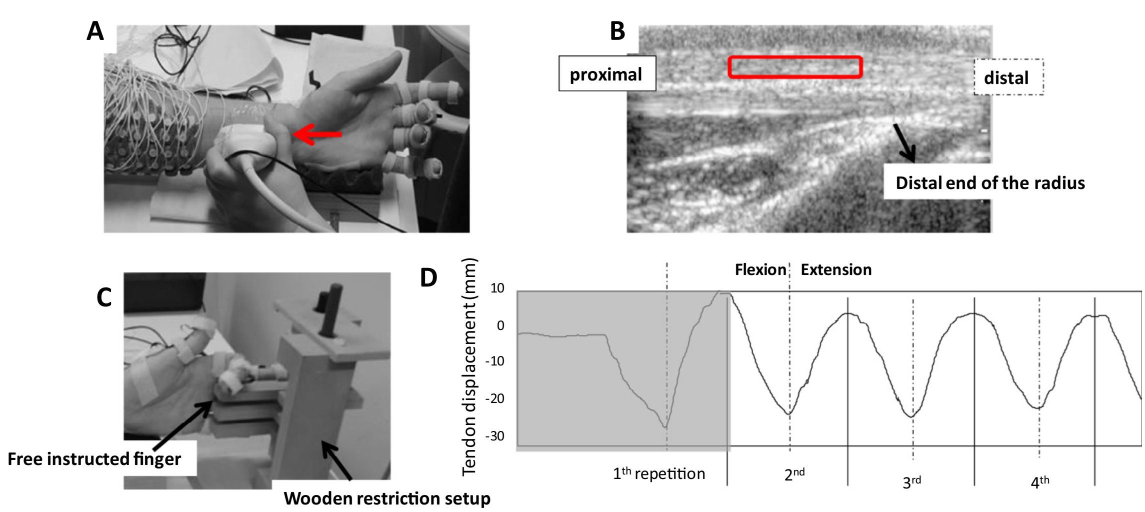

Fig. 1. (A) Placement of the ultrasound probe proximal of the wrist crease (red arrow). (B) Ultrasound B-mode showing in red the region of interest of the index FDS tendon and the styloid process of the radius used as landmark. (C) Set-up of the restricted protocol where non-instructed fingers were restrained in a fully extended position by wooden blocks on the palmer side of the finger. (D) Corresponding tendon displacement (mm) of the FDS tendon during four index flexion-extension movements. The first repetition (grey area) was omitted from the analysis. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

a landmark for the final position of the ultrasound transducer over the wrist (Fig. 1B). Because the FDS tendon of the little finger was difficult to find in most of our subjects and tended to move out of the image plane during finger movement, it was not included in this study.

Finger movement and ultrasound data were synchronized using a custom-made trigger input. A 5 MHz signal was sent to a sonomicrometry crystal (1mm; Sonometrics Ltd, Ontario, Canada), which was attached to the end of the ultrasound probe. This resulted in a white signal (synchronization spike) on the edge of the ultrasound image. Simultaneously, the 5 MHz signal was sent to a custom made PowerGlove triggerbox where a 3 sine waves signal (20 Hz) was generated, which was picked up by the magnetometers in the PowerGlove.

2.3. Experimental protocol

The left forearm was placed on a custom-made armrest that supported elbow and wrist. The task consisted of a single finger flexion over the full range of motion of all the finger joints of the index, middle and ring finger until the tip of the finger touched the palm of the hand. The hand was held palmside up in a 45° pronation angle relative to the anatomical position with the fingers held straight and in line with the metacarpals (i.e., MCP, PIP and DIP joints at 0°). Subjects were asked to flex one finger (=instructed finger) during one second until the tip of the finger touched the palm of the hand and then to extend the finger back towards its starting position in the following second. A metronome (60 bpm) was used to help the subjects to follow the prescribed timing of the finger movements and several practice trials were performed prior to the actual measurements.

Single finger flexion was performed in two conditions. In the first condition fingers were free to move and tendon displacement of both instructed and non-instructed fingers were measured (free protocol). Subjects were asked not to actively resist involuntary movements of the non-instructed fingers. In the second condition only the instructed finger was free to move and non-instructed fingers were restrained in a fully extended position (restricted protocol; Fig. 1C). Tendon displacement of the instructed finger and the neighboring restricted finger was measured. Tendon displacement measured in the restricted non-instructed finger was interpreted as the result of mainly a tendon length change because of strain.

FDS tendon displacements of the instructed finger, as well as those of the neighboring non-instructed finger(s) were assessed. First, the ultrasound transducer was placed on the FDS tendon of the instructed finger. The task was repeated with the transducer positioned on the tendon of the neighboring finger(s). During index and ring finger flexion, the non-instructed middle finger tendon was thus also measured, while during the middle finger flexion task both the non-instructed index and the non-instructed ring finger FDS tendon were measured. In total, seven free and restricted finger movements were performed (Table 2). For each FDS finger tendon, placement of the ultrasound transducer was adjusted.

Table 2
Table showing the order of finger tasks with corresponding placement of the ultrasound transducer on the FDS tendon of the instructed or neighboring non-instructed finger during free and restricted finger protocol.

Free and restricted finger movement	
Finger flexion	FDS tendon measurement
Index	Index
Index	Middle
Middle	Middle
Middle	Index
Middle	Ring
Ring	Ring
Ring	Middle

2.4. Data analysis

PowerGlove data were analyzed with a custom-made algorithm applying an anatomical segment calibration and information from the sensor units (Kortier et al., 2014). Because the FDS spans only the MCP and PIP joints, the angles of these two joints were summed ($\sum\theta$) to represent the movement of the finger that can be the result of FDS activity. All kinematic data were low-pass filtered using a second order, zero-lag Butterworth filter (5Hz) before angular velocity was derived. Zero-crossings of the angular velocity signals of the fingers were used to determine the end of the flexion and extension phases (for details see (van Beek et al., 2017)). All data were averaged over the last three repetitions because finger movement and tendon displacement in the very first repetition frequently differed from the other repetitions (Fig. 1D).

Ultrasound images were exported as uncompressed audio-video interleave (AVI) files using OsiriX (version 3.7.0; Pixmeo, Geneva, Switzerland). These files were then analyzed with in-house-developed tracking software (Lopata et al., 2009b). For this application, tracking was not performed on the raw ultrasound data (rf-data), but on the envelope as present in the AVI files. The software uses a 2D cross-correlation algorithm to calculate the tissue displacements in the proximo-distal direction, which corresponds with the lateral direction (perpendicular to the ultrasound beam). Tissue displacement was calculated from one ultrasound frame to the next by an iterative cross-correlation based search algorithm (Lopata et al., 2009a). A region of interest (ROI) was selected for calculating tissue displacement between frames (Fig. 1B) to determine the tendon displacement using the previously calculated interframe displacements. The ROI was adjusted to the size of the tendon and chosen so that only the respective tendon and no surrounding tissues were measured. The length of the tendon was fixed to the maximum length of the image (i.e. 34 mm), but the width of the tendon differed between finger tendons and subjects (i.e. approximately 3 mm). For each subject the ROI remains constant for the respective tendon in all tests. Tendon displacement was low-pass filtered using a second order, zero-lag Butterworth filter (5 Hz). Both tendon displacement and finger movement data were divided into a flexion and extension component. Each component was resampled to 100 data points and averaged over three repetitions.

Tendon displacement (*Td*) detected by the applied image analysis can be the result of tendon movement (*Tm*) and/or tendon stretch (*Ts*) over its whole length [Eq. (1)].

$$Td = Tm + Ts \tag{1}$$

Tendon displacement of the non-instructed finger, while restricted, will be considered as an estimate of Ts. To confirm that tendon displacement related to finger movement can be described by Eq. (1), we subtracted stretch-related tendon displacement as assessed during the restricted finger protocol from the tendon displacement measured during non-instructed finger movement (=corrected tendon displacement). Equal tendon stretch of the non-instructed finger tendon between these two conditions was assumed (Fig. 2).

To compare tendon displacement during instructed movement with that during non-instructed movement, a Ratio was calculated for the instructed (*i*), non-instructed (*ni*) and corrected (*c*) finger tendons as a change in tendon displacement (ΔTd) expressed relative to the change in summed joint angle ($\Delta\sum\Theta$) between 0° and 10° [Eq. (2)] (Fig. 2). The maximum value of 10° finger angle was selected as this was the highest common non-instructed finger angle found over all finger movement tasks.

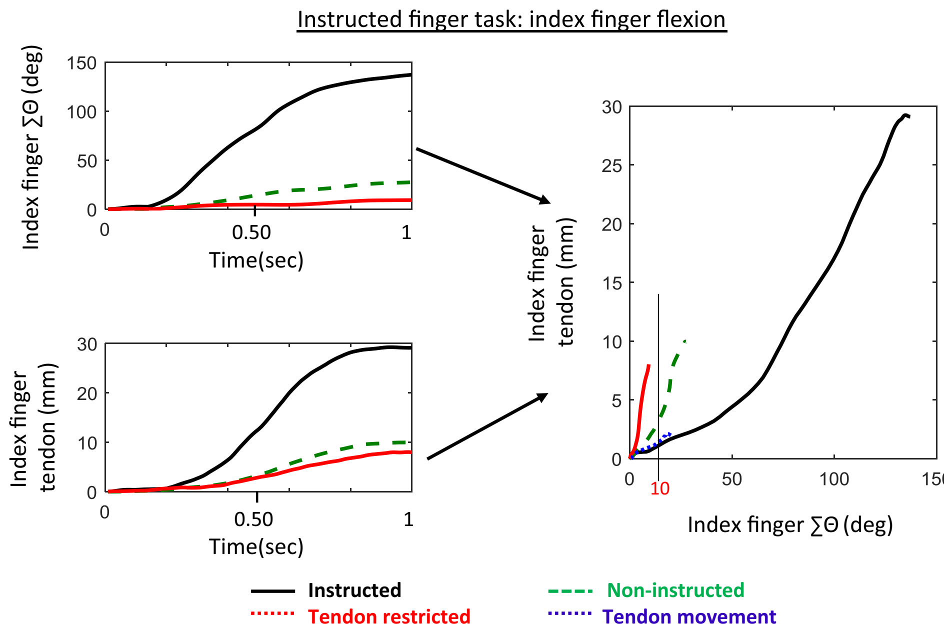

Fig. 2. Left: $\sum\Theta$ (deg.) and tendon displacement (mm) shown as a function of time for instructed (i.e., during index finger flexion), non-instructed and restricted index finger conditions (i.e., the latter two conditions being during middle finger flexion). Right: Tendon displacement (mm) as a function of $\sum\Theta$ (deg) for the index. The corrected tendon displacement (non-instructed tendon displacement minus tendon strain) during non-instructed finger movement is shown by the dotted blue line. The vertical line at 10° finger angle indicates up to which angle the estimated slope of these curves were calculated [Eq. (2)] ($\Delta Td/\Delta\sum\Theta$). Data of a representative subject are shown. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

$$Ratio_{i|ni|c} = \frac{\Delta Td}{\Delta \Sigma \Theta} \quad (2)$$

2.5. Statistics

All the statistical analyses were performed using R (version 3.1.0; R Foundation for Statistical Computing; (Team, 2013). One- and two-way ANOVAs were performed to test if the $\sum\theta$ and tendon displacement differed between instructed and non-instructed fingers and if the instructed, non-instructed and the corrected tendon Ratio differed significantly. To test for differences between each finger, a post-hoc analysis was performed with TukeyHSD. Significance level was set at a p-value of .05.

3. Results

3.1. Joint movement and tendon displacement

As expected, the instructed finger had a higher joint movement and tendon displacement (index = 27 mm, middle = 21 mm, ring = 17 mm) compared to the non-instructed finger(s) (average of ≈12 mm) in all tasks (Fig. 3). During index finger flexion in the free movement condition, the middle finger moved significantly more than the ring finger. During middle finger flexion, tendon displacements of the non-instructed index and instructed middle finger did not differ significantly.

During the restricted movement protocol, joint movement and tendon displacement of the instructed fingers were similar to those during the free movement. Despite minimal joint movements ($\sum\theta\leq5°$) of the restricted non-instructed fingers, substantial tendon displacements (≈9mm) were observed (Fig. 3D–F). The extent of tendon displacement during the restricted protocol was significantly less than during free movement, except for the non-instructed middle finger during index finger flexion (Fig. 3D). These results indicate length changes caused by stretching in the tendons of the restricted fingers.

The relationship between $\Delta\sum\Theta$ and tendon displacement is rather linear (Fig. 4). Only when tendon stretch is taken into account, corrected tendon displacement as a function of $\sum\Theta$ of the non-instructed fingers closely resembles the instructed finger pattern (Fig. 4).

3.2. Tendon Ratio

Differences between instructed, non-instructed and corrected tendon Ratio were found for the index finger ($p < .001$) and middle fingers ($p < .02$). For the middle finger, a higher non-instructed tendon Ratio was found compared to the instructed tendon Ratio during index ($p = .022$) and ring finger flexion ($p = .044$). For the index finger, the non-instructed tendon Ratio was significantly higher than the instructed ($p = .018$) and corrected tendon Ratio ($p = .045$) (Table 3). For the ring finger, we found no significant differences between tendon Ratio's. No differences between the corrected and the instructed tendon Ratio were found for both index, middle and ring finger flexion tasks. These results indicate that for the index and middle finger, during non-instructed finger movement, a substantial part of the tendon displacement was the result of tendon stretch.

4. Discussion

We found that in the restricted protocol, non-instructed fingers showed substantial tendon displacement even though minimal finger movement was observed. These results indicate tendon stretch in the restricted finger tendons. This tendon stretch was taken into consideration when studying non-instructed index and middle finger tendon displacements. When the additional stretch component was subtracted from the non-instructed tendon displacement, the relationship between flexion angle and tendon displacement of the instructed and non-instructed finger was similar. These results fully support our first hypothesis and partly our second hypothesis, as will be discussed below.

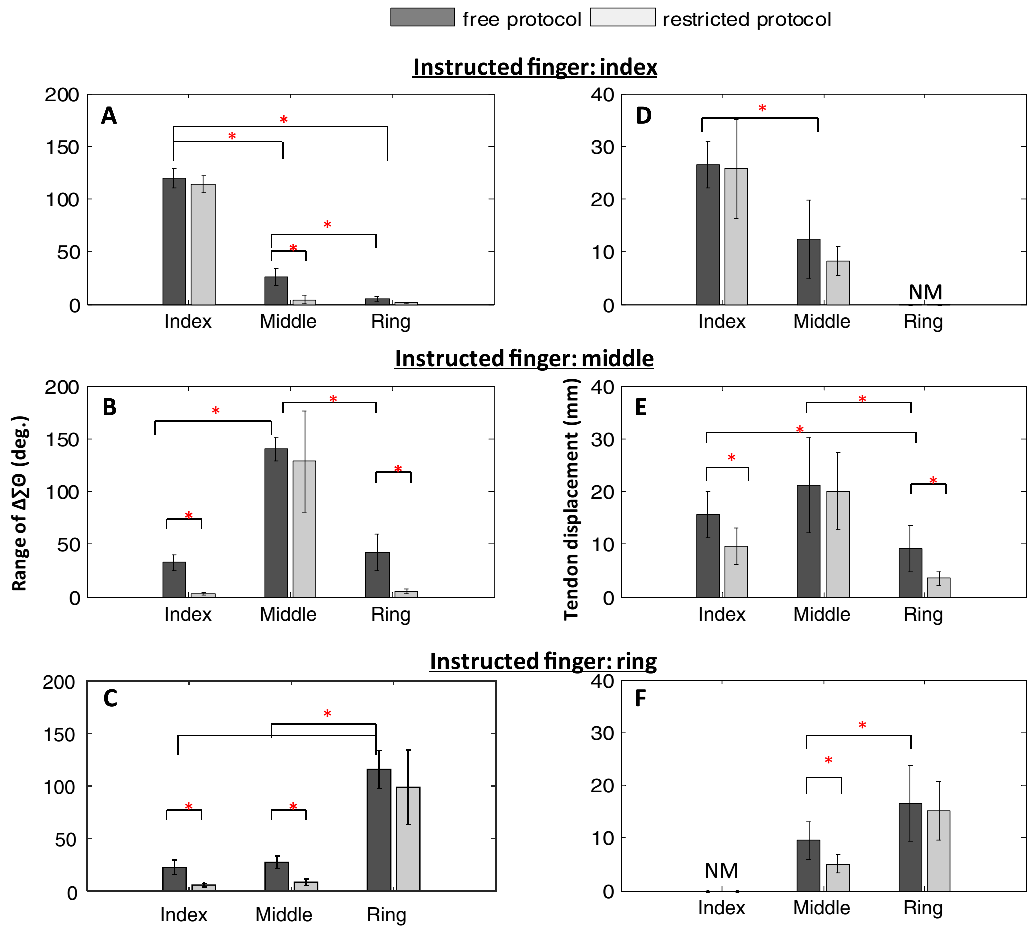

Fig. 3. $\Delta\sum\Theta$ (deg.) and the maximal tendon displacement (mm) of the instructed and non-instructed finger(s) during free (dark grey bars) and restricted (light grey bars) condition (index, middle and ring finger flexion). Values are shown as mean ± SD (n = 9). The horizontal lines with asterisks indicate significant differences between fingers or protocols ($p < .05$). Ring finger tendon displacement during index finger flexion and index finger tendon displacement during ring finger flexion was not measured (=NM).

While no other studies have measured FDS tendon displacements of non-instructed fingers, previous studies have reported a maximum FDS tendon displacement of the middle finger during full middle finger flexion of 20–30 mm (Ettema et al., 2008; Kociolek and Keir, 2015, 2016; Tat et al., 2016; Yamaguchi et al., 2008). This is similar to our results (21 ± 9 mm) during full middle finger flexion. Index FDS tendon displacement has been studied in cadavers exclusively, where a maximum tendon displacement of 20 mm was found for 90° MCP flexion of (An et al., 1983). When more finger joints are free to move, tendon displacement will increase. Thus, our maximum index tendon displacement of 27 ± 4 mm for an average 120° finger joint angle is a logical extrapolation from cadaver data (Kociolek and Keir, 2016; Lopes et al., 2011). Ring finger FDS tendon displacement has not been studied before.

Our results show that for the middle and index finger our first hypothesis was correct: when tendon stretch as measured during restricted protocol is taken into account, the tendon displacement of the non-instructed fingers closely resemble the instructed finger tendon displacement pattern. We have previously shown an increased activation of the extensor digitorum muscle during single finger flexion tasks (van Beek et al., 2017). So, the additional stretch that non-instructed fingers endure is likely caused by forces exerted by this antagonist. Possible reasons for these antagonistic muscle activations can be either the coactivation of neighboring non-instructed synergistic finger muscles (Kilbreath and Gandevia, 1994; Schieber and Hibbard, 1993) or the presence of mechanical linkages, such as tendon interconnections (Keen and Fuglevand, 2003), subsynovial connective tissue (Festen-Schrier and Amadio, 2017) or myofascial linkages (Maas et al., 2003), that cause involuntary movement of the non-instructed fingers. Activation of antagonists may counteract this. Consequently, tendon stretch will occur in the non-instructed finger tendons, as we observed in the present study. Further research is still needed to make a distinction between the mechanical and neural causes of antagonistic muscle activation, as our tendon ultrasonography is unable to make this distinction.

For the ring finger tendon displacement, no significant differences were found between non-instructed and instructed ring finger tendon displacement with or without taking the additional stretch component into consideration. This suggest that the non-instructed ring finger does not experience the same amount of stretch when restricted and appears to not be held back as much as the non-instructed index and middle finger by antagonistic muscle activations.

Our second hypothesis was proven to be partly correct, as it is shown in our results that after tendon stretch subtraction non-instructed finger tendon displacement follows the same pattern as instructed finger tendon displacement for the index and middle finger. However, since this assumption does not seem to hold for the ring finger, we have to take into consideration that the stretching a restricted finger endures is not always equal to the stretch a non-instructed finger may endure. If the amount of stretch a restricted finger endures is much higher than the stretch a free, non-instructed finger experiences, other factors besides antagonis-

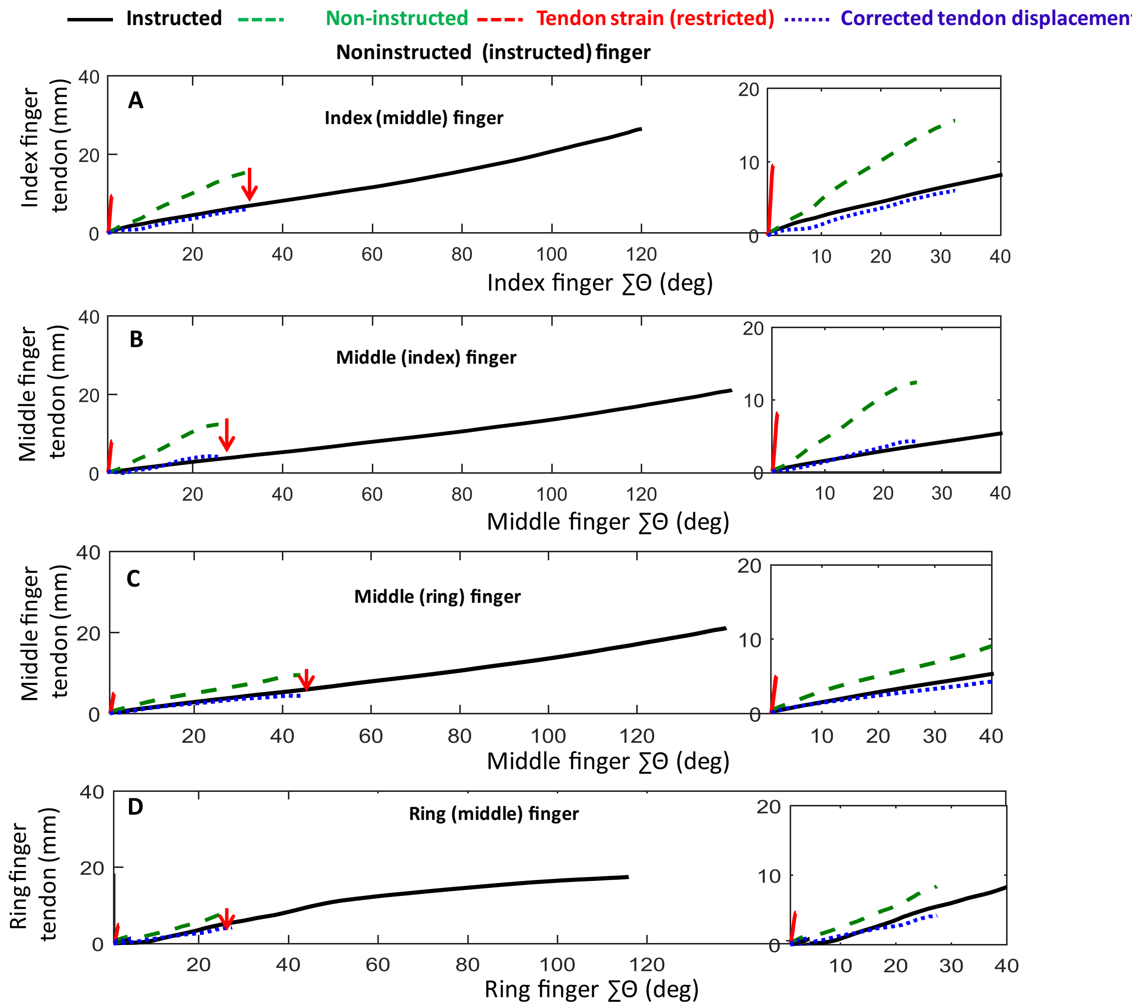

Fig. 4. Finger tendon displacement (mm) shown as a function of $\sum\theta$ (deg.) for the index, middle and ring finger. The imbedded panels to the right show a close-up of the respective graph in the range of 0–40° finger angle. Tendon displacement of a finger is shown for three conditions: free instructed movement (black line), non-instructed movement (dashed green line) and restriction (vertical red line at ±0 deg.). In addition, the corrected tendon displacement during non-instructed finger movement was shown (dotted blue line). The effect of taking tendon strain into account for the slope of the curve is shown by the red arrow. Data shows the mean of 9 subjects. The task during which the non-instructed finger tendon displacement was measured, is given between brackets in the legend embedded in each graph. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 3
Average tendon Ratio (tendon displacement (mm) per 10° $\sum\Theta$ (deg) (2)) for the index, middle and ring finger when the finger was instructed ($Ratio_i$) and non-instructed ($Ratio_{ni}$). Tendon strain was measured during the restricted task and subtracted from the non-instructed finger tendon displacement to form the corrected tendon Ratio of the non-instructed finger ($Ratio_c$), shown in the last column.

Finger	$Ratio_i$	Non-instructed (instructed) finger	$Ratio_{ni}$	$Ratio_c$
Index finger	0.25 ± 0.14	Index (middle) finger	0.62 ± 0.33^	0.24 ± 0.34
Middle finger	0.18 ± 0.15	Middle (index) finger	0.68 ± 0.63#	0.15 ± 0.42
		Middle (ring) finger	0.44 ± 0.18#	0.11 ± 0.38
Ring finger	0.31 ± 0.29	Ring (middle) finger	0.37 ± 0.20	0.18 ± 0.11

^ Significant differences ($p < .05$) between $Ratio_{ni}$ and $Ratio_i$ and between $Ratio_{ni}$ and $Ratio_c$.
# Significant differences ($p < .05$) between $Ratio_{ni}$ and $Ratio_i$.

tic muscle activations could also play a role, such as mechanical constraints (Kilbreath and Gandevia, 1994; Leijnse, 1997; Maas et al., 2003).

In this study, the ultrasound probe was placed on the wrist crease. Thus, only tendon displacement close to the connection of the muscle belly with the tendon was measured. Tendon behavior further away from the muscle belly may differ and could possibly give further information about non-instructed finger tendon dynamics. A second methodological consideration is the restriction of the speckle tracking software. Displacement measurements in the lateral direction of the ultrasound data have been shown to have larger irregularities and drift compared to radial measurements (Gijsbertse et al., 2017; Lopata et al., 2009a). This could have caused larger mismeasurement of the finger tendon displacement. However, as our results of tendon displacement are in line with studies that do not use ultrasound (An et al., 1983; Ugbolue et al., 2005; Yoshii et al., 2008), this effect appears to be small. In addition, direct assessment of stretch applying current speckle tracking methods still yield inaccurate results (Gijsbertse et al., 2017). Finally, it should be noted that our results are applicable only to free voluntary finger movements. Tendon displacements, as well as tendon stretch, during static or dynamic force pressing tasks will probably differ.

5. Conclusions

Our results indicate that, even during conditions involving minimal loads, tendon displacements, as assessed with ultrasonography, can be the result of tendon movement and tendon stretching. In particular when studying tendon displacements of non-instructed fingers, it is important to consider tendon length changes.

Acknowledgements

The authors thank the subjects for participating in the study, Thomas van der Kraan and Barry Hes for assisting in the measurements, the department of Medical Ultrasound Imaging Center (MUSIC) and Rik Hansen for their help with the ultrasound software and Henk Kortier, Ed Droog and the technical division of the department of Human Movement Sciences for technical assistance. This research is funded by the European Commission through MOVE-AGE, an Erasmus Mundus Joint Doctorate program (2011-0015).

Conflict of interest

The authors declare that they have no conflict of interest.

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