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RESEARCH ARTICLE

Single finger movements in the aging hand: changes in finger independence, muscle activation patterns and tendon displacement in older adults

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Abstract

With aging, hand mobility and manual dexterity decline, even under healthy circumstances. To assess how aging affects finger movement control, we compared elderly and young subjects with respect to (1) finger movement independence, (2) neural control of extrinsic finger muscles and (3) finger tendon displacements during single finger flexion. In twelve healthy older (age 68–84) and nine young (age 22–29) subjects, finger kinematics were measured to assess finger movement enslaving and the range of independent finger movement. Muscle activation was assessed using a multi-channel electrode grid placed over the flexor digitorum superficialis (FDS) and the extensor digitorum (ED). FDS tendon displacements of the index, middle and ring fingers were measured using ultrasound. In older subjects compared to the younger subjects, we found: (1) increased enslaving of the middle finger during index finger flexion (young: 25.6 ± 12.4%, elderly: 47.0 ± 25.1%; $p = 0.018$), (2) a lower range of independent movement of the index finger ($\text{young}_{\text{middle}} = 74.0\%$, $\text{elderly}_{\text{middle}}$: 45.9%; $p < 0.001$), (3) a more evenly distributed muscle activation pattern over the finger-specific FDS and ED muscle regions and (4) a lower slope at the beginning of the finger movement to tendon displacement relationship, presenting a distinct period with little to no tendon displacement. Our study indicates that primarily the movement independence of the index finger is affected by aging. This can partly be attributed to a muscle activation pattern that is more evenly distributed over the finger-specific FDS and ED muscle regions in the elderly.

Keywords Finger enslaving · Tendon interconnections · Motor control · Muscle coactivation · Multi-channel EMG · Ultrasound

Introduction

Aging eventually limits the quality of all daily activities, including the mobility and dexterity of the hand, an important determinant of human autonomy. The human hand has evolved to be able to perform complex hand actions such as prehension, gripping and pinching and its function is necessary in daily life for both fine and gross motor tasks. A gradual decline in such functions is observed in elderly persons especially from about the age of 65 years onwards, which eventually hampers everyday tasks such as tying shoelaces, writing, holding a cup and keyboard typing (Shiffman 1992). An important feature for the object manipulation implicated by the age-dependent motor deteriorations

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is finger independence (Carmeli et al. 2003; Shinohara et al. 2003b; Cole et al. 2010). Both young and elderly are not fully capable of independent force and movement control of the individual fingers (Kilbreath and Gandevia 1994; Zatsiorsky et al. 2000; Lang and Schieber 2004; van Duinen and Gandevia 2011). Some studies have reported an increased finger force independence with aging during static finger pressing tasks, as indicated by a decreased force exerted by the non-instructed fingers (Li et al. 2000; Shinohara et al. 2003a; Oliveira et al. 2008; Kapur et al. 2010). In contrast, a decreased force independence in elderly has recently been found for a dynamic finger force task (Mirakhorlo et al. 2018). However, changes in finger movement independence with aging have only been studied for restricted finger movements and not free finger flexion movements, which might better resemble the finger movements in daily life.

Changes in finger independence with aging may have different underlying causes. One cause may be changes in skeletal muscle properties. With aging muscle mass is lost (Keller and Engelhardt 2013) and the relative amount of non-contractile tissue within the muscle belly (Power et al. 2013) and muscle stiffness increases (Tseng et al. 1995; Carmeli et al. 2003; Short et al. 2005; Demontis et al. 2013). In addition, changes in the properties of the connective tissues within the muscle have been reported. The muscle belly also becomes less compliant due to an increase in the quantity and stiffness of the intramuscular connective tissue (Alnaqeeb et al. 1984). Furthermore, changes in muscle activation have been reported. The number of motor units (MU) decreases with age, which first results in an increase in the average MU size and an alteration in MU activation and synchronization (Kawamura et al. 1977; Kamen et al. 1995; Johnson and Duberley 1998; Roos et al. 1999). Also often seen in elderly is an enhanced agonist–antagonist muscle co-activation and an increase in the co-activation of muscle synergists (Spiegel et al. 1996; Tang and Woollacott 1998; Klein et al. 2001; Macaluso et al. 2002; Hortobagyi and Devita 2006). The above-mentioned neuromuscular changes with aging have been found predominantly in the lower limbs, but changes in neural control of the regions corresponding to the different fingers of the extrinsic finger muscles have not been assessed. All these changes may have an impact on the control of the hand and could contribute to impaired hand versatility in elderly.

In addition to the effects of aging on muscle properties and neuromuscular control, the mechanical properties of tendon tissue have been shown to alter with age as well (Nordin et al. 1989; O'Brien 1992; Best et al. 1994). However, there are large discrepancies in the results of different studies. Some studies have shown that aging can result in stiffer tendons (Shadwick 1990; Wood et al. 2011), while other studies have shown the opposite (Narici and Maganaris 2006; Kubo et al. 2007; Couppe et al. 2008) or reported no changes (Carroll et al. 2008; Couppe et al. 2009). These inconsistencies can be explained by the use of different species, different tendon types [positional or energy storing; (Screen et al. 2013)] and a wide range in subjects' age in studies. The effects of aging on the tendons of the extrinsic finger muscles have not been studied. As tendons transmit muscle forces to produce finger movements, the changes in mechanical properties with age may also affect finger movement control and, possibly, finger independence.

The aim of this study was to investigate how aging affects finger movement control. For this purpose, we compared a group of healthy elderly with previously measured younger subjects (van den Noort et al. 2016; van Beek et al. 2018b). The following features were assessed during single finger flexion: (1) finger independence, (2) neural control of the extrinsic finger flexor and extensor muscles and (3) displacements of the tendons of the flexor digitorum superficialis (FDS) muscle that insert on the index, middle and ring fingers.

We present the first study where the effects of aging on three aspects of finger movement control, namely finger independency, muscle activation and tendon displacement, are studied in elderly during free, single finger flexion tasks and compare these results with young subjects. Although all these systems have often been studied separately, an integrative approach as can be found in this article, i.e., studying both the finger movement mechanics and the hand motor drive, could clarify their effects on independent finger movement and the possible changes that may occur with aging.

Methods

Subjects

Twelve elderly (age 68–84 years) and nine young (age 22–29 years) right-handed subjects participated. Data of the young subjects have been published previously (van den Noort et al. 2016; van Beek et al. 2017b). Part of the already published results was used in this study for comparison purposes. Subject exclusion criteria were (i) any known neuromuscular disorder, (ii) experience with playing musical instruments for more than 2 years over the course of the past 5 years and (iii) disability or surgery in the upper limb in the last 2 years. Musicians were excluded due to the fact that their musical training might have influenced finger independence. Each subject filled out the Edinburgh Handedness Inventory (Oldfield 1971) and a mini-mental state examination test (MMSE) was performed for all elderly subjects to determine possible cognitive impairment. A score greater than or equal to 24 points (out of 30) indicates a normal cognition (Mungas 1991). In our elderly subjects, MMSE values between 28 and 30 were found. The Research Ethics Committee of the Arnhem-Nijmegen Region approved the study protocol. Each subject signed an informed consent before participating in the study. The following anthropometric measurements were taken: the length of fingers and arm, the width of the wrist and the circumference of the arm at different arm lengths.

Data acquisition

Finger kinematics

Finger movements were recorded with a measurement system called the PowerGlove (University of Twente, Enschede, Netherlands), which measures hand and finger kinematics in three dimensions (Kortier et al. 2014). It consists of eighteen sensor units (each containing a 3D magnetometer, an accelerometer and a gyroscope) that are placed on each finger segment (i.e., proximal, intermediate and distal phalanges) of the index, ring, middle and little fingers and the dorsal side of the left hand (Fig. 1). The PowerGlove was calibrated prior to each measurement for each subject individually using a standard set of hand and finger postures (Kortier et al. 2014). Kinematic data from the PowerGlove were recorded with a sample frequency of 100 samples/s.

Electromyographic signals

Muscle activation was assessed using a surface electromyography (sEMG) electrode grid placed over a large area estimated to cover the FDS and extensor digitorum (ED) muscle groups [for details see van Beek et al. 2018b] (Fig. 1). For positioning the grid over the extensor muscles, a reference line from the lateral epicondyle to the ulnar styloid was drawn. For the grid over the flexor muscles, a line from the

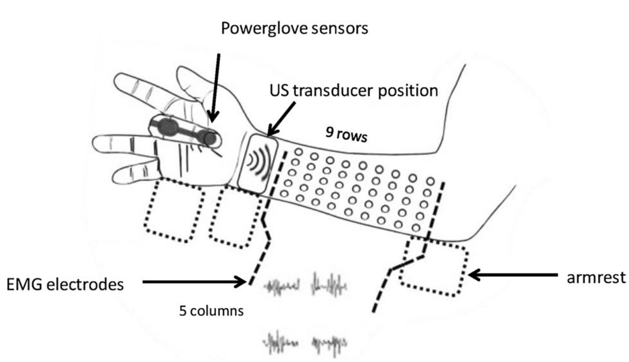

Fig. 1 Schematic illustration of the experimental setup with the motion capture system, PowerGlove (see "Methods"), attached to the fingers (dorsal side), the ultrasound transducer placed parallel on the wrist flexion crease and a grid of surface EMG electrodes (9 × 5) placed over the flexor digitorum superficialis (FDS) and extensor digitorum (ED) muscles (the latter being not visible in this illustration)

medial epicondyle to the middle of the wrist was drawn. Muscle position was checked using palpation during voluntary flexion movements of the instructed fingers. Cloth electrodes (KendallTM H69P Cloth Electrodes, Medtronic, Eindhoven, The Netherlands) were reduced in size to obtain an interelectrode distance of approximately 1.7 cm over the proximal–distal axis and 1.3 cm over the medial–lateral axis. Two grids of 45 surface electrodes (5 rows of 9 distal to proximal columns) were placed over both the flexor and extensor muscles with the middle row aligned with above-described reference lines. sEMG signals were collected in a monopolar montage with the technical ground electrode placed on the olecranon and the common reference electrode placed on the ulnar styloid, amplified with a 128-channel amplifier and sampled at 2048 samples/s (Refa-136; TMSi, Oldenzaal, The Netherlands).

Tendon displacements

Ultrasound video sequences of the FDS tendons inserting on the index, middle and ring finger were acquired with a Philips IU22 (Philips Medical systems, Best, Netherlands) using an L11-3 ultrasound probe, with a frequency band ranging from 3 to 11 MHz and a frame rate of 48 frames per second in B-mode. The probe was longitudinally placed just proximal to the wrist flexion crease (for details see van Beek et al. 2018a) (Fig. 1). The FDS tendons corresponding to the fingers were localized by first identifying the FDP and FDS muscle bellies by palpation and movements of individual fingers, 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 an FDS tendon was selected, the distal interphalangeal joint (DIP) of the finger was flexed and extended (Bianchi et al. 2007; Korstanje et al. 2012). Since the FDS tendon spans the metacarpophalangeal (MCP) and proximal interphalangeal (PIP) joint, but not the DIP joint, the tendon which showed a considerable tendon displacement (Td) during DIP movement was identified as a FDP tendon. Because the FDS tendon of the little finger was difficult to locate in most of our subjects and tended to move out of image plane during finger movement, the FDS tendon corresponding to the little finger was not included.

Experimental protocol

Subjects were seated in a chair with their left forearm on a custom-made armrest, which supported the elbow and wrist, with a palmar position of the hand of 45°. The main task tested was full range single finger flexion until the tip of the finger touched the palm of the hand (Fig. 1) immediately followed by extension towards its starting position. The initial position of all the fingers prior to the movement was a zero degree joint angle in all finger joints (i.e., MCP, PIP, DIP joints at 0°). A metronome (2 s interval) was used to help the subjects with the timing of flexion (in 1 s) and extension (in 1 s) movements. Single finger flexion was performed in two conditions. In the first condition, fingers were free to move and tendon displacement of both the instructed and the 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) (for details see van den Noort 2016; van Beek et al. 2018a, b). Tendon displacement of the instructed finger and the neighboring restricted finger was measured. In addition, a single finger hyperextension was performed. This extension was solely used to localize the sEMG extensor muscle regions and to normalize the sEMG amplitude. No tendon displacements or finger kinematics were measured during this condition. For the finger hyperextension task, the hand was placed horizontally on a flat surface with the wrist and elbow supported by the armrest. Subjects were instructed to maximally extend their fingers one by one, hold this position for five seconds and then return to the starting position. In both conditions, five repetitions of each finger were performed.

Finger kinematics, sEMG recordings and ultrasound data were measured simultaneously and synchronized using a custom-made trigger input. The ultrasound transducer was adjusted so that the respective finger tendon was kept in view during each finger task. A 5 MHz signal was sent to a sonomicrometry crystal (1 mm; Sonometrics Ltd, Ontario, Canada), which was attached to the end of the ultrasound probe, inducing a synchronization spike on the edge of the ultrasound image. Simultaneously, the 5 MHz signal was sent to a custom-made PowerGlove triggerbox, where a signal consisting of three sine waves (20 Hz) was generated which was picked up by the magnetometers in the PowerGlove, and by the trigger input channel of the EMG amplifier.

Data analysis

Finger kinematics

The angles of the PIP, DIP and MCP joints of each finger were calculated by analyzing the PowerGlove data with a custom-made algorithm applying the anatomical segment calibration and information from the sensor units (Kortier et al. 2014). Because the FDS muscle only spans the MCP and PIP joints, the angles of these joints were summed ($\sum\Theta$) to represent the movement of the finger. All kinematic data were low-pass filtered using a second-order, zero-lag Butterworth filter (5 Hz) before angular velocity was derived. Zero crossings of the angular velocity signal of the instructed finger were used to determine the end of the flexion and extension phases (for details see van Beek et al. 2017b).

For comparison with the literature, the enslaving effect (based on Zatsiorsky et al. 2000) was calculated for each of the non-instructed fingers by calculating $\sum\Theta$ of the non-instructed finger relative to the $\sum\Theta$ of the instructed finger and represented in percentages (1),

$$\text{Enslaving effect}_{\text{non-instructed}} = \frac{\left(\sum \boldsymbol{\Theta}\right)_{\text{non-instructed finger}}}{\left(\sum \boldsymbol{\Theta}\right)_{\text{instructed finger}}} \times 100\%. \quad (1)$$

The range of independent movement of the instructed finger (for details see van den Noort et al. 2016) with respect to the $\sum\Theta$ was determined for each finger movement. The start of the non-instructed finger movement was defined as a change in $\sum\Theta$ of more than 3 degrees, based on reported thresholds to detect finger movements (Wycherley et al. 2005). Finger kinematics data were divided into a flexion and extension component. Each component was resampled to 100 data points and averaged over 3 repetitions.

Surface EMG

sEMG signals were band-pass filtered using a fifth-order, zero-lag Butterworth filter (10–500 Hz). The signals were rectified using the Hilbert transformation followed by a low-pass Butterworth filter at 5 Hz to extract the movement-related EMG envelope (Myers et al. 2003). To focus on the changes in amplitude, the baseline level (i.e., the minimum in the 30 ms before the start of flexion) was subtracted from the EMG envelope. The average rectified values were calculated for the respective finger muscle belly. The sEMG signals were normalized to the maximum sEMG amplitude for that specific finger over all finger movements. The mean envelopes of the cyclic sEMG signal of which the baseline was subtracted (Δ EMG) of the flexor and extensor EMG clusters were calculated for each finger.

To localize finger-specific muscle regions with the sEMG electrode grid, a zero-cross covariance was applied between the EMG envelopes and the finger angle during finger flexion (for the flexor muscles) and extension (for the extensor muscles). Three, unique channels with the highest covariance were determined as a finger-specific cluster. Each subject had a total of eight channel clusters (four flexor and extensor clusters, one cluster for each finger). As expected, the maximum sEMG amplitude for the flexor clusters was found during flexion phase of the full range flexion movement and for the extensor clusters during the extension phase of the hyperextension movement.

One of the main challenges of using multi-electrode surface sEMG to assess activity in FDS and ED compartments was to identify the regions that correspond to the FDS muscle regions of the different fingers. Cluster positions generally corresponded to the underlying anatomy as described in the literature (Frohse and Frankel 1908) and were consistent with electrode placement reported in previous studies (Bickerton et al. 1997; Leijnse et al. 2008; Henzel et al. 2010; Gallina and Botter 2013; Gazzoni et al. 2014; Hu et al. 2015).

Tendon displacement (Td)

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 speckle tracking software (van Slochteren et al. 2014). Tissue displacement was calculated from one ultrasound frame to the next by an iterative cross-correlation-based search algorithm (Lopata et al. 2009). Td data was low-pass filtered using a second-order, zero-lag Butterworth filter (5 Hz). Tendon displacement data were divided into a flexion and extension component. Each component was resampled to 100 data points and averaged over 3 repetitions. To determine the relationship between $\sum\Theta$ and Td during the instructed movement with that during the non-instructed movement, a ratio was calculated as a change in tendon displacement (ΔTd) expressed relative to the change in summed joint angle ($\Delta\sum\Theta$) over the first 10° $\sum\Theta$ (Eq. 2).

$$\text{Ratio}_{\text{ilnilc}} = \frac{\Delta\ Td}{\Delta\ \sum\Theta}. \quad (2)$$

Statistics

All the statistical analyses were performed using R [version 3.1.0; R Foundation for Statistical Computing (Team 2013)]. Prior to analyses, a Shapiro–Wilk test was used to test whether the data were normally distributed. Some statistical tests were solely performed for the elderly as a subset of the analyses for the young subjects which were reported in previous articles from our groups(van den Noort et al. 2016; van Beek et al. 2017a, b).

For the $\sum\Theta$, a two-way ANOVA was performed (factors: finger and age) for each finger movement task (index flexion, middle flexion, ring flexion, little flexion) separately. Enslaving effect and range of independent movement were compared between young and elderly with a two-way ANOVA (factors: finger and age) and tested for each finger movement task separately.

A two-way ANOVA compared the muscle activation between young and elderly (factors: age, finger) for each finger movement task and muscle type (flexors, extensors).

A two-way ANOVA compared the tendon displacements between young and elderly (factors: finger and age) for each finger movement task and protocol separately. A one-way ANOVA was performed to test for differences in the slope of the $\sum\Theta$–Td relationship for each finger movement task between young and elderly.

If ANOVA indicated significance, a post hoc analysis was performed using Tukey HSD correction. A p value of <0.05 was considered significant. Effect sizes were calculated with eta-squared (η^2). A value of <0.01 equals a small effect, >0.06 equals a medium effect and >0.14 equals a large effect size (Cohen 1992; Maher et al. 2013).

Results

The description of results focuses predominantly on the comparison between elderly and young subjects. For the anthropometric measurements (Table 1), a significant but small difference between the two age groups was found for the width of the wrist (young = 6.1 ± 0.6 vs elderly = 7.0 ± 0.6).

Finger kinematics, enslaving and range of independent movement

For the $\sum\Theta$ of the instructed fingers, no significant differences between young and elderly subjects were found (Table 2). For the non-instructed middle finger during index ($p = 0.002$, $\eta^2 = 0.85$) and ring finger flexion ($p = 0.018$, $\eta^2 = 0.66$) and the non-instructed ring finger during little finger flexion ($p = 0.042$, $\eta^2 = 0.59$), more angular movement was found in the elderly (Table 2).

Enslaving patterns were similar in elderly compared to young subjects, i.e., the highest enslaving effect was seen in the adjacent non-instructed finger and lower degrees of enslaving for the non-adjacent fingers (Fig. 2). The enslaving effects were generally higher in the elderly than in the young subjects, but this was only significant

Table 1 Arm and hand measurements (mean ± SD) of both young and elderly subjects. The laterality index refers to the right hand preference percentage of full 100%

	Young subjects	Elderly subjects
Laterality index	97 ± 6	95 ± 10
Arm and finger lengths		
Arm length (cm)	25.3 ± 2.0	25.5 ± 3.0
Length thumb (cm)	90. ± 1.6	9.3 ± 1.2
Length index finger (cm)	9.4 ± 1.2	9.7 ± 0.7
Length middle finger (cm)	10.6 ± 1.2	10.2 ± 1.8
Length ring finger (cm)	10.0 ± 1.2	9.4 ± 1.8
Length little finger (cm)	8.0 ± 1.0	7.5 ± 0.8
Width wrist (cm)	6.1 ± 0.6*	7.0 ± 0.6*

The asterisk indicates a significant difference ($p < 0.05$) between young and elderly

Table 2 Mean and standard deviation $\sum\Theta$ (°) for elderly ($n=12$) and young ($n=9$) subjects during all finger tasks (index, middle, ring and little finger flexion)

	Elderly	Young
	Index fixation (°)	
Index finger	124.2 ± 43.6	120.1 ± 9.3
Middle finger	70.9 ± 57.1*	32.4 ± 7.1*
Ring finger	23.9 ± 22.2	3.4 ± 4.2
Little finger	13.1 ± 11.6	3.2 ± 2.9
	Middle fixation (°)	
Index finger	44.9 ± 28.6	25.7 ± 7.8
Middle finger	143.3 ± 73.8	140.1 ± 11.3
Ring finger	59.3 ± 33.7	46.4 ± 10.2
Little finger	20.3 ± 15.2	12.4 ± 7.35
	Ring finger (°)	
Index finger	13.0 ± 4.7	10.5 ± 7.8
Middle finger	64.8 ± 16.4*	27.4 ± 6.1*
Ring finger	137.6 ± 42.4	115.9 ± 18.1
Little finger	67.9 ± 30.0	61.8 ± 40.8
	Little finger (°)	
Index finger	18.9 ± 16.2	9.98 ± 10.2
Middle finger	35.6 ± 29.9	14.3 ± 8.55
Ring finger	90.1 ± 44.3*	45.3 ± 28.7*
Little finger	119.1 ± 64.4	97.7 ± 23.9

The asterisk indicates a significant difference ($p<0.05$) between young and elderly

during index finger flexion ($p=0.009$). Post hoc analysis revealed that this was significant for the middle finger (young = 25.6 ± 12.4%, elderly: 47.0 ± 25.1%; $p=0.018$, $\eta^2=0.46$).

The range of independent movement was significantly lower in elderly during index finger flexion (Fig. 3a). Start of movement of the non-instructed middle (young: 74.0%, elderly: 45.9%; $p=0.049$, $\eta^2=0.17$) and ring finger (young = 100%, elderly = 92.4%, $p=0.037$, $\eta^2=0.20$) was found at a smaller $\sum\Theta$ of the index finger. This indicates that the index finger of the elderly can only move slightly without moving the non-instructed fingers.

Muscle activations from sEMG

For the elderly, no differences were found between instructed and non-instructed flexor and extensor finger muscle activations (Fig. 4 a–h). In contrast, younger subjects showed a higher flexor muscle activation and lower instructed extensor muscle activation for the instructed index and middle finger flexion, comparable to results previously shown in (van Beek et al. 2018b). Thus, the elderly show an activation pattern that is more evenly distributed over the finger-specific FDS and ED muscle regions.

Some significant differences in finger-specific muscle activations were found between young and elderly during index and middle finger flexion (Fig. 4 a, b, e, f). During index finger flexion, elderly have a higher non-instructed middle (young = 25.3 ± 17.6, elderly = 38.2 ± 14.7 ΔEMG amplitude, $p=0.049$, $\eta^2=0.25$) and little finger flexor muscle activation (young = 25.8 ± 11.2, elderly = 55.7 ± 29.8 ΔEMG amplitude, $p=0.018$, $\eta^2=0.32$) (Fig. 4a) as well as a higher ring finger extensor muscle activation (young = 36.9 ± 15.8, elderly = 60.4 ± 23.6 ΔEMG amplitude, $p=0.037$, $\eta^2=0.26$) (Fig. 4e). During middle finger flexion, the elderly have a lower extensor muscle activation for the index (young = 79.

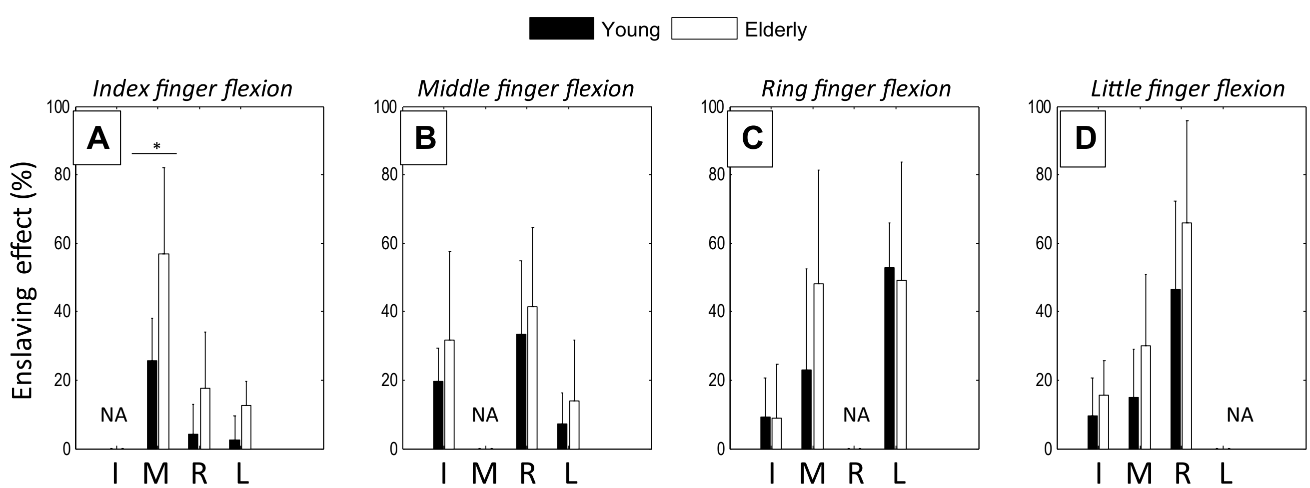

Fig. 2 Mean and standard deviation of the enslaving effect (%) of the $\sum\Theta$ of non-instructed fingers during the index (I), middle (M), ring (R) and little (L) finger flexion tasks for young (black bars, $n=9$) and elderly subjects (white bars, $n=12$). The asterisk (*) indicates a significant difference ($p<0.05$) between young and elderly. The enslaving effect can be assessed only for the non-instructed fingers, hence the NA (non-applicable) is shown for the instructed finger

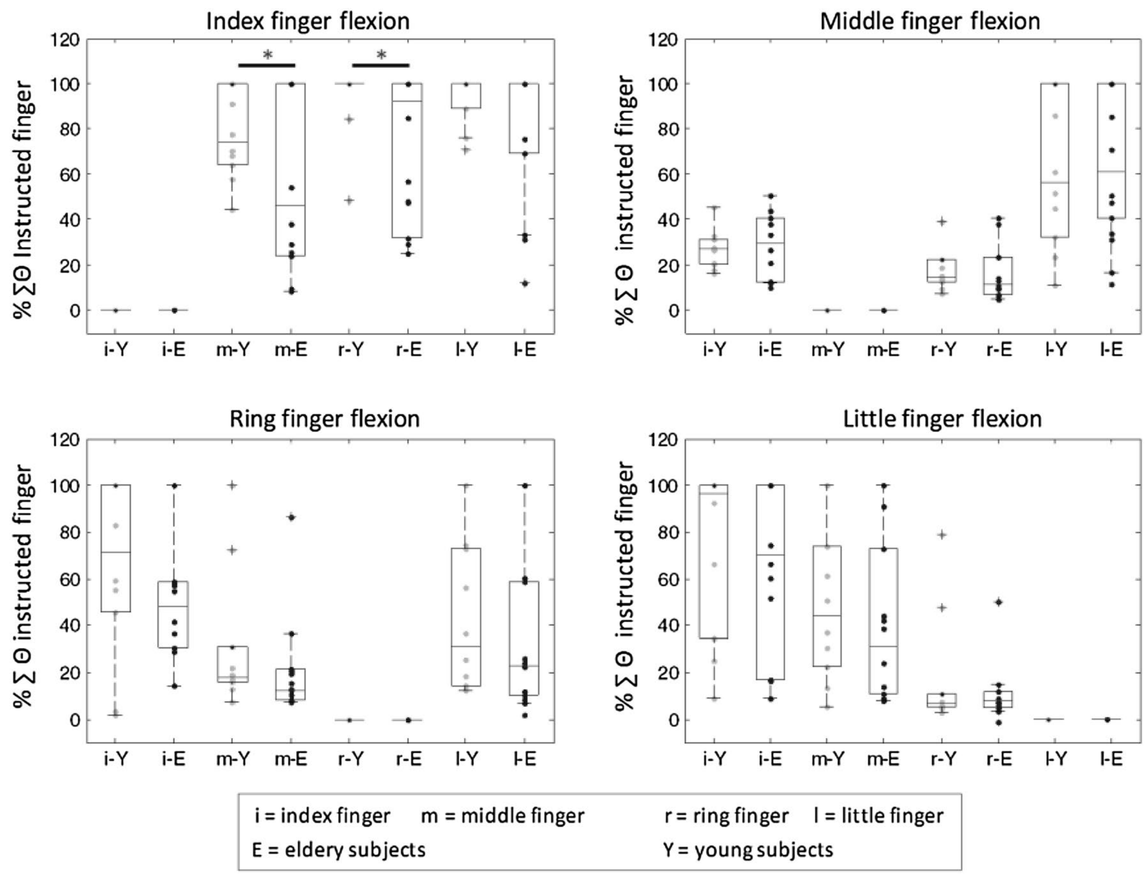

Fig. 3 Box plots showing the range of independent movement of the instructed finger(s) (%∑Θ) of all young (Y, $n=9$) and elderly (E, $n=12$) subjects. This was defined as follows: where in the ΣΘ (%) of the instructed finger(s) (vertical axes), the non-instructed finger(s) start(s) to move (horizontal axes). Data are presented for all finger movement tasks (*i* index, *m* middle, *r* ring, *l* little). Individual results (mean over trials) per subject are presented in the light gray (young) and black (elderly) dots

2 ± 23.0, elderly = 61.9 ± 26.1 ΔEMG amplitude, $p=0.038$, $\eta^2=0.27$), middle (young = 51.5 ± 17.1, elderly = 35.2 ± 16.3 ΔEMG amplitude, $p=0.037$, $\eta^2=0.27$) and ring fingers (young = 76.7 ± 29.9, elderly = 42.5 ± 19.5 ΔEMG amplitude, $p=0.020$, $\eta^2=0.31$) (Fig. 4f) and a lower instructed middle finger flexor muscle activation (young = 62.5 ± 28.7, elderly = 41.0 ± 16.4 ΔEMG amplitude, $p=0.039$, $\eta^2=0.27$) (Fig. 4b). No differences in activation patterns were found for ring and little finger flexion.

Tendon displacement

In general, elderly subjects showed the same pattern of tendon displacements as the younger subjects (previously reported in van Beek et al. 2018a) (Fig. 5). Instructed finger tendon displacement was found to be around ± 20–30 mm and the non-instructed finger tendon displacement was around ± 10–15 mm. We found that in the restricted protocol, non-instructed fingers showed substantial tendon displacement even though minimal finger movement was observed. There were no significant differences in the amount of tendon displacement between younger and elderly subjects, neither in the free nor in the restricted condition (Fig. 5).

In contrast to the total amplitude results, we observed differences between young and elderly in the shape of the ∑Θ–tendon displacement curves of instructed and non-instructed fingers. During the instructed finger movement, the slope is substantially lower for the elderly compared to the young subjects particularly in the first phase of finger flexion (Fig. 6). In other words, initially the finger moves with little or no tendon displacement. Statistical analysis revealed a significantly lower slope only for the instructed ring finger tendon during ring finger flexion ($p<0.001$, $\eta^2=0.25$) (Table 3, Fig. 6d).

Besides the instructed finger movements, a disparity in the tendon displacements between young and elderly was also found for the non-instructed finger movements. During the non-instructed finger movement, a significantly lower slope was found for the index ($p<0.001$, $\eta^2=0.35$) and middle ($p<0.001$, $\eta^2=0.49$) fingers in the elderly (Table 3, Fig. 6a, b). Note that the difference in slope between

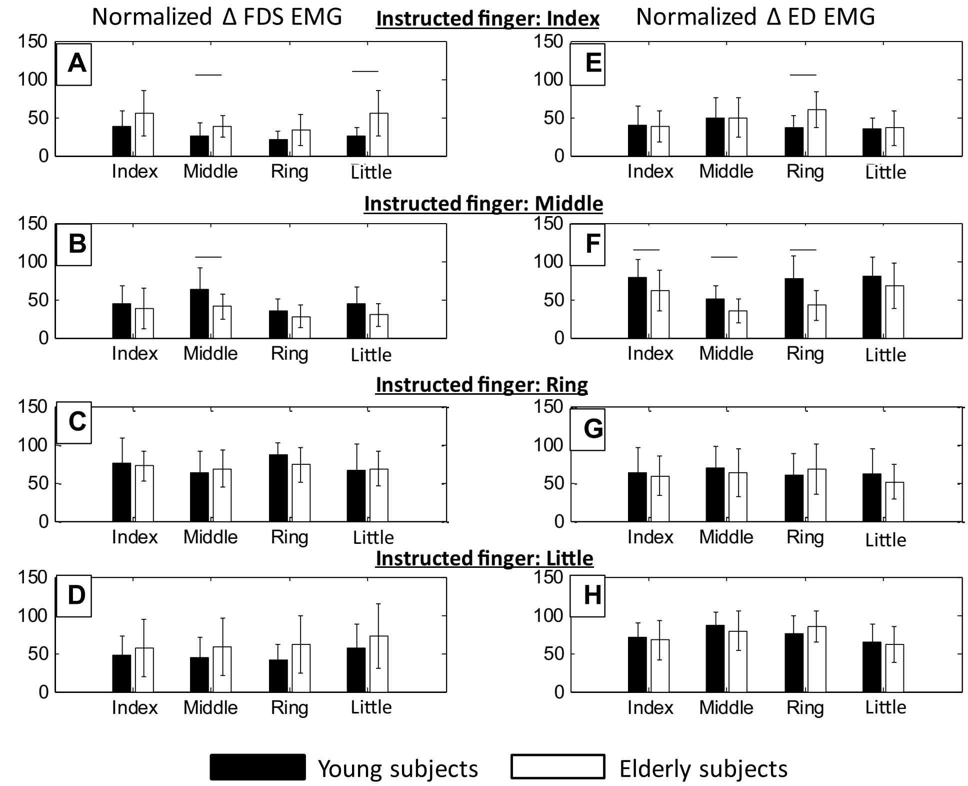

Fig. 4 Mean normalized flexor (FDS) and extensor (ED) muscle activation (normalized to the maximum sEMG amplitude found for each finger over all tasks) for young (black bars, $n = 9$) and elderly (white bars, $n = 12$) subjects. Full black line (–) shows significant differences between young and elderly ($p < 0.05$)

instructed and non-instructed finger flexion can be explained by tendon length changes, as discussed in our previous paper (van Beek et al. 2017a).

Discussion

In this study, the effects of aging on finger independence, neural control of the extrinsic finger muscles and tendon displacements of the flexor digitorum superficialis during single finger flexion movements were examined. The main outcomes of this study show in elderly (1) more non-instructed finger movement of the middle finger during index finger flexion, (2) a lower range of independent movement of the index finger,(3) a muscle activation pattern that is more evenly distributed over the finger-specific FDS and ED muscle regions and (4) a different finger movement to tendon displacement relationship, with elderly presenting a distinct period with little to no tendon displacement at the beginning of the finger flexion movement.

Changes in finger independence

Several previous studies found that enslaving during static finger pressing tasks decreased with age (Shinohara et al. 2003a, b; Oliveira et al. 2008; Kapur et al. 2010; Yu et al. 2010). This is in contrast to our results, in which enslaving was found to be higher and the range of independent movement was lower, especially for index finger flexion, for the elderly compared to the younger subjects. In a recent study from our group, higher force enslaving in elderly was also found during a static finger pressing task (Mirakhorlo et al. 2018). The opposite outcomes compared to most previous studies were explained by not restraining the arm and wrist. In addition, the present study focused on finger independence during free finger movements and not during static conditions. These conditions were selected, because they closely resemble natural finger movements.

Previous studies have related the lower enslaving effects during force pressing tasks observed in elderly to the force loss in the intrinsic compared to the extrinsic hand muscles (Kapur et al. 2010). However, free full range finger flexion is produced predominantly by extrinsic finger muscles (Schieber 1995). Moreover, in contrast to our study, one or two finger joints were often restrained during static finger pressing tasks (Shinohara et al. 2003b). Finger flexion involving all joints will increase the changes of muscle–tendon unit length and relative muscle position of the finger-specific extrinsic muscles and, consequently, enhances the role of tendon and muscle interconnections (An et al. 1983; Li et al. 2000). Therefore, the effects of aging on finger independence may be task dependent.

The observation that there is a range in which each finger can move independently has previously been interpreted

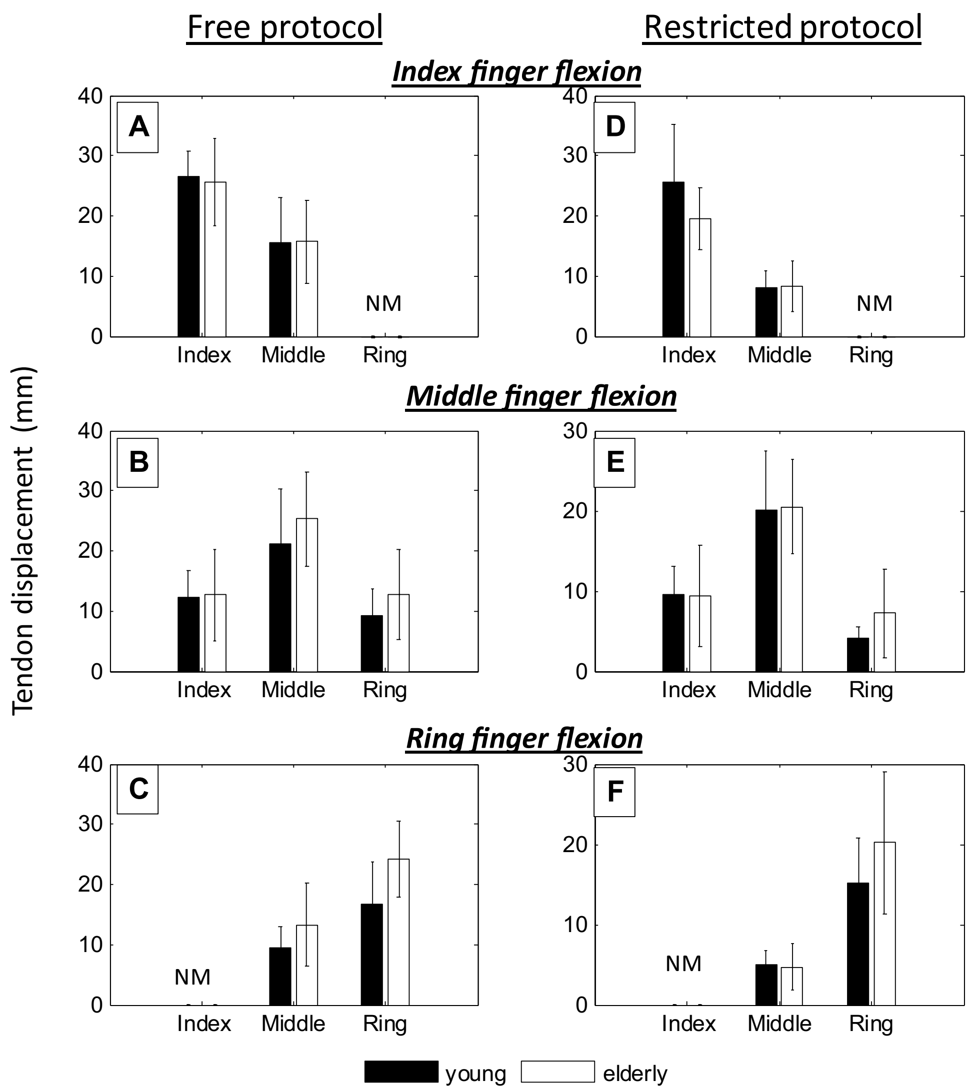

Fig. 5 The maximal tendon displacement (mm) of the instructed and non-instructed finger(s) of young ($n = 9$) and elderly ($n = 12$) subjects during the free and restricted condition for all finger tasks (index, middle and ring finger flexion). Little finger tendon displacement was not measured. Ring finger tendon displacement during index finger flexion and index finger tendon displacement during ring finger flexion was not measured (= NM)

as evidence for mechanical connections between the muscle heads or tendons that are initially slack and are pulled taut after a certain amount of relative displacement (van den Noort et al. 2016). In the present study, the range of independent movement for the index finger was lower in the elderly compared to the young subjects. This can be explained by (1) an earlier coactivation of the FDS muscle regions corresponding to the other fingers and (2) a change in the stress–strain properties of the linkages between muscle heads or tendons. These features are discussed in more detail below.

Changes in neural control of extrinsic finger muscles

For both FDS and ED muscles, activation levels of the different regions were more evenly distributed in the elderly, specifically during index and middle finger flexion. In elderly, no significant differences in muscle activation of the instructed and non-instructed finger muscle bellies were observed. In other words, more co-activation between the finger-specific muscle regions was found. Such an activation pattern seems to be in agreement with the enhanced finger movement enslaving of the non-instructed fingers. Studies on the lower limbs have also shown that aging increases the extent of coactivation of synergist muscles (Spiegel et al. 1996; Tang and Woollacott 1998; Klein et al. 2001; Vanden Noven et al. 2014). Higher muscle coactivation could be explained by the neuromuscular changes that occur with aging (see introduction), such as MU remodeling (Hortobagyi and Devita 2006), or by an increase in the simultaneous timing of MU activation and, thus, an increase in MU synchronization (Semmler et al. 2000). A high amount of MU synchronization within the FDS muscle has been reported for young subjects (McIsaac and Fuglevand 2007), but the effects of aging on such common drive are still unknown.

Fig. 6 Finger tendon displacement (mm) shown as a function of ∑θ for the index, middle and ring finger. Tendon displacement of a finger is shown for two conditions [during free instructed movement (black), during non-instructed movement (grey)] and for young (continuous line; $n=9$) and elderly subjects (dashed line; $n=12$).For all tasks, the task during which the non-instructed finger tendon displacement was measured, is given in the legend embedded in each graph

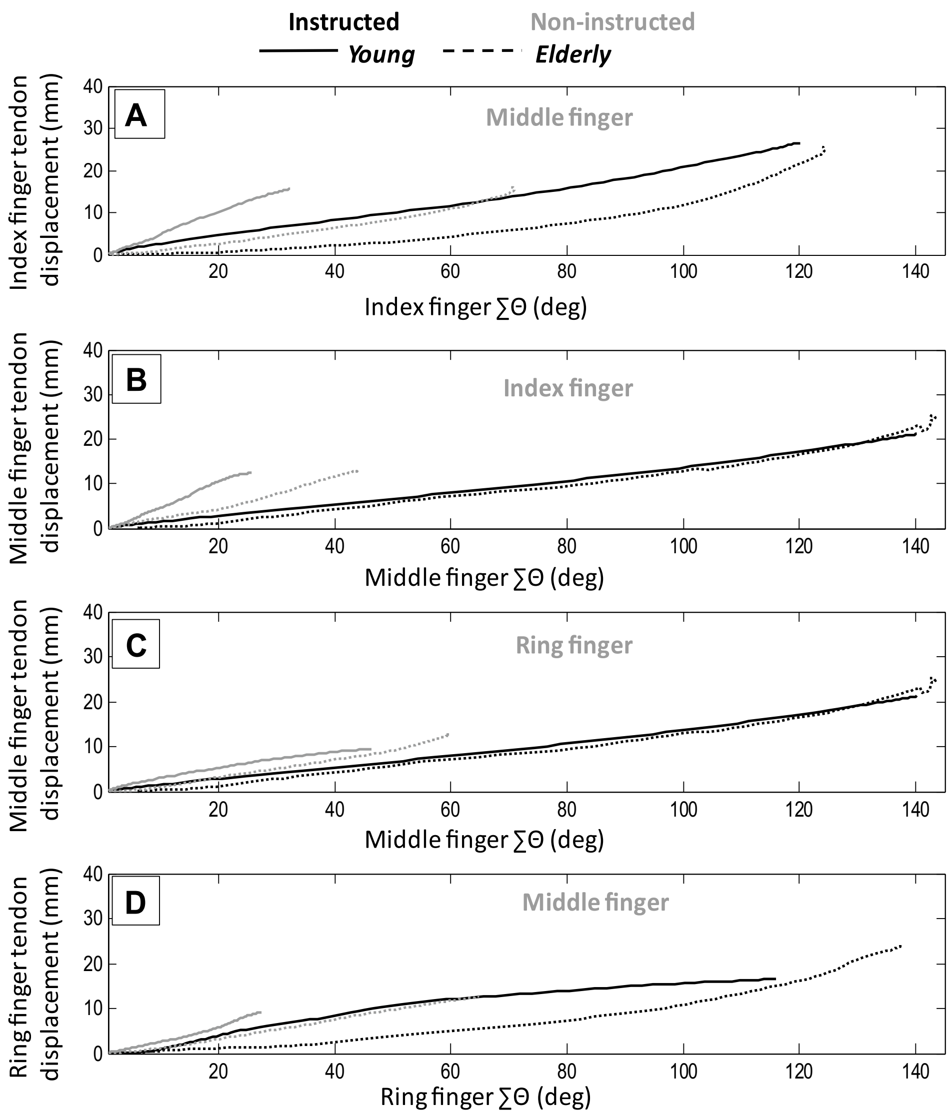

Table 3 Table showing the average slope [tendon displacement (mm) over 0–15° ∑Θ (°)] for the index, middle and ring finger when the finger was instructed ($Slope_i$) and non-instructed ($Slope_{ni}$) for young ($n=9$) and elderly ($n=12$) subjects

Finger	Yong $Slope_i$	Elderly $Slope_i$	P value
Index finger	0.38 ± 0.20	0.04 ± 0.04	0.07
Middle finger	0.30 ± 0.19	0.05 ± 0.06	0.50
Ring finger	0.78 ± 0.44*	0.16 ± 0.24*	< 0.001
Non-instructed (instructed) finger	$Slope_{ni}$	$Slope_{ni}$	
Index (middle) finger	0.92 ± 0.34*	0.28 ± 0.29*	< 0.001
Middle (index) finger	1.04 ± 0.13*	0.13 ± 0.06*	< 0.001
Middle (ring) finger	0.50 ± 0.12	0.28 ± 0.18	0.88
Ring (middle) finger	0.48 ± 0.14	0.19 ± 0.17	0.40

The asterisk (*) indicates significant differences between young and elderly in slope

Changes in tendon displacement

If the tendons become more compliant with aging, the tendon length changes more and hence more tendon displacement is expected. The opposite can be predicted if the tendons become stiffer with age. However, we found no differences in the amount of measured tendon displacement of the instructed and non-instructed fingers in both free and restricted protocols between young and elderly. Despite minimal joint movements ($\sum\theta \leq 5°$) of the restricted non-instructed fingers, substantial tendon displacements were still observed. As these results are indicative for tendon stretching, they show similar tendon lengthening for both groups. Assuming similar dimensions and material properties, as well as similar muscle forces, our data suggests that the stiffness of FDS tendons was not affected by aging, as has been reported for other tendons (Carroll et al. 2008; Couppe et al. 2009).

Although no changes in total tendon displacement were found, elderly subjects did have a substantially lower slope at the beginning of the $\sum\Theta$–tendon displacement relationships. Thus, little to no tendon displacement occurred during the first phase of finger flexion. A lower slope could be explained by a change in the relationship between tendon movement and tendon length changes caused by an alteration in the interaction between the muscle belly and the in-series tendon. A lower slope could also be explained by changes in mechanical coupling between tendons (Leijnse et al. 1997) and/or muscle bellies (Maas and Sandercock 2010). Lastly, as the measured tendon displacement is the net result of tendon movement and tendon length changes (van Beek 2018a), both aspects may also counteract each other.

It should be noted that solely the tendon displacements of the FDS muscle were studied and, thus, the flexor digitorum profundus tendon displacement as well as effects of intrinsic finger flexors were not taken into account. In addition, tendon displacements were measured at only one location, at the wrist crease where the tendon is close to the muscle belly. We can therefore not exclude the possibility that tendon displacement occurred at another location between the finger tip and the wrist crease. Tendon displacement measurements at more locations in the hand and wrist may give us more information about tendon movements, stretch and possible tendon interconnections.

Applications

In elderly, the quality of finger and hand motor control gradually declines (Shiffman 1992). This causes difficulties in performing everyday tasks, such as grasping and fine handicraft. To understand the underlying cause for this decline, it is necessary to take both the musculoskeletal system (muscles and tendons) and the central nervous system into account. The data presented in this article concerning finger movement and muscle activations may be useful for clinicians and scientists who are focused on hand function and revalidation. Using the range of independent movement of healthy elderly as a baseline, the effects of arthritis or stroke on finger independence could be further studied.

Limitations

By not actively restricting the wrist, part of the activity of the extrinsic finger flexors and extensors may be related to stabilization of the wrist and not to movements of the fingers. When the wrist is fixated, the function of these muscles is limited to solely create finger movements. Higher finger enslaving could be caused by a higher activation of the FDS, needed for both finger motion and wrist stabilization. The higher demands imposed by not restricting the wrist in our setup might induce a higher need of stabilization that in the elderly requires additional recruitment of the FDS muscle.

It could be argued that sEMG cannot be selective enough to measure activity of individual compartments of FDS. Better selectivity may be obtained using intramuscular EMG electrodes (Reilly and Schieber 2003). However, the complexity of FDS muscle could also pose a problem for intramuscular EMG as several EMG leads per compartment would be necessary (Nawab et al. 2008). Our approach to deal with the complex anatomy of FDS muscle was to apply a large grid of electrodes and later on identify unique regions corresponding to the different fingers for each subject individually (for a detailed description see van Beek et al. 2018b). With this approach, we aimed to select only those channels that picked up EMG signals from finger-specific muscle bellies. Our results of the muscle locations generally corresponded quite well to the underlying anatomy as described previously in the literature (Bickerton et al. 1997; Kristi; Henzel et al. 2010; Gazzoni et al. 2014).

With the applied EMG approach there is a risk of crosstalk. Because the distances between the selected channels for each finger were rather large (an average distance of 5 cm on the proximal–distal axis and 3 cm on the medial–lateral axis), we deem the effects of crosstalk minimal. It has been shown that with a distance of ± 2 cm between electrodes the contribution of the neighboring electrodes to the RMS amplitude decreased to 10–20% (Roeleveld et al. 1997; Lowery et al. 2004). As we found similar coactivation between distant muscle regions, also in the signals from the more proximate channels, contamination by cross talk is expected to be limited.

In the present experiment, the wrist was not secured to the setup. As a consequence, part of the activity of the extrinsic finger flexors and extensors may be related to stabilization of the wrist and not to the finger movements (Mirakhorlo et al. 2018). When the wrist is fixed, the function of these muscles is limited to solely produce finger movements. The higher finger enslaving that was found in our results in comparison to previous studies could, thus, be caused by a higher activation of the all FDS muscle regions, needed for wrist stabilization.

Conclusions

Significant changes in finger movement independence with aging were found only for the index finger. As the index finger also has the highest movement independence (Li et al. 2004; Kim et al. 2008; van den Noort et al. 2016), it is possible that effects of aging will become noticeable first in the index finger. The sEMG data show an activation pattern that is more evenly distributed between the muscle regions corresponding to the instructed and non-instructed fingers. This corresponds to the higher amount of finger enslaving of the non-instructed fingers we found in the elderly. No changes in total tendon displacement were found with age, although elderly subjects did have a substantially lower slope at the beginning of the $\sum\Theta$–tendon displacement relationships. Besides being a consequence of aging, the changes in neuromuscular control could also point to a possible compensation mechanism, as aging might involve changes in the mechanical connections between tendons.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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