Estimation of in-vivo muscle moment arms around the MCP joint using ultrasound

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A B S T R A C T

Since in the finger most muscle-tendons cross multiple joints, moment arms (MA's) of these muscle-tendons have a major influence on the distribution of joint moments over these joints. This is crucial for finger balance and therefore finger functioning. Recent developments in the technique of ultrasonic measurements have made it possible to accurately measure tendon displacements over a large range of motion *in-vivo*. The change in tendon displacement divided by the change in corresponding joint angle (dl/dθ) was used to estimate joint angle dependent MA's (MA_{est}) of the flexor digitorum superficialis (FDS), flexor digitorum profundus (FDP) and extensor digitorum communis (EDC) tendon at the metacarpophalangeal (MCP) joint of the long finger. In addition, MA's were obtained from the joint geometry for each individual subject (MA_{geo}). Two sessions of 3 repetitions of active flexion-extension motion of the long finger were conducted by each of the five subjects enrolled in this study. The intra subject repeatability between the two sessions at 0^0 of flexion for the FDS and EDC tendon was good (ICC > 0.95, p = 0.004 and 0.101 respectively) but rather weak for the FDP (ICC = 0.630, p = 0.157). The obtained MA_{est} values were underestimated in comparison to the MA_{geo} values. Thus, this method proved to be promising, but should be further validated and developed to yield sufficiently reliable results. Once fully developed, the *in-vivo* estimation of MA's can be used to determine the subject specific muscle MA balances around the finger joints. These MA balances can be an important parameter for a musculoskeletal finger model. In addition, it can be a generic measure for finger pathologies where finger balance is disturbed.

Introduction

An important parameter in any musculoskeletal finger model is the moment arm (MA) of a muscle: the shortest distance from its tendon to the relevant joint axis crossed by this muscle-tendon. Since in the finger most muscle-tendons cross multiple joints, MA's of these muscles have a major influence on the distribution of joint moments over these joints. This is crucial for finger balance and therefore finger functioning.

To determine muscle-tendon MA's, a straightforward method is to study the geometry of the joint(s) crossed by this muscle-tendon. Previously proposed imaging techniques comprised computed tomography (CT) (Marshall et al. 1990) and magnetic resonance imaging (MRI) (Rugg et al. 1990; Spoor and van Leeuwen 1992). In general, only one joint orientation is studied in this method, resulting in MA values that specifically belong to that joint orientation. Since muscle-tendon MA's are assumed to be joint angle dependent due to bowstringing tendons (Landsmeer 1961; Brand and Hollister 1993) and/or a shifting centre of rotation (COR) (Tubiana et al. 1984), it is more informative to study the change in MA over a range of joint motion. To accomplish this, the change in muscle-tendon excursion (dl_{mt}) with respect to the change in joint angle ($d\theta_{joint}$) is a generally accepted method:

$$MA(\theta) = \frac{dl_{mt}}{d\theta_{\text{joint}}} dt \qquad (1)$$

This method assumes minimal joint translations and a tendon constant length and might therefore be less accurate for joint motion with a large COR shift and/or experiments with varying tendon loads. The dl/dθ method is often applied to forearms (An et al. 1983; Brand and Hollister 1993; Buford et al. 2005; Koh et al. 2006) and broadly used as a validation for musculoskeletal models of the forearm (Lemay and Crago 1996; Holzbaur et al. 2005), wrist (Gonzalez et al. 1997) and fingers/thumb (An et al. 1979; Brook et al. 1995; Sancho-Bru et al. 2001; Wu et al. 2009). A drawback of these tendon excursion and joint angle data is that they were based on cadaver experiments; the effect of tendon elongation, co-contracting muscles or other *in-vivo* effects are not taken into account. Some studies performed *in-vivo* estimations of tendon excursions using ultrasound (Ito et al. 2000; Maganaris 2002; Lee et al. 2008). In all these studies, an anatomical land-mark such as the musculo-tendinous junction was needed for tracking purposes, which can only be well visualized for a small number of muscle-tendons. This could be one of the reasons that until recently no studies have been reported that applied the dl/dθ method to the forearm and hand.

Recent developments in the technique of ultrasonic measurements have made it possible to quantify tendon excursions *in-vivo* without the presence of anatomical landmarks and thus over a large range of motion (Korstanje et al. 2010b). Therefore it is hypothesized that the dl/dθ method, as described above, can be conducted *in-vivo* on the forearm and hand. This way, patient specific joint angle dependent MA's can be estimated, which makes it possible to realize patient specific hand models with relative ease. In addition, it can give insight in the relationship between kinematically obtained MA's and those obtained from joint and skeletal geometry.

Once fully developed, the *in-vivo* determination of MA's can be a beneficial tool in the clinical field to estimate patient specific MA's. Moreover, these MA's can be used to determine the MA balance around the finger joints: the relation between the sum of muscle-tendon MA's acting on the metacarpophalangeal (MCP), proximal and distal interphalangeal (PIP and DIP) joints. Tendon MA balance can be an important parameter for a musculoskeletal finger model: since the tendons of the finger affect multiple finger joints, the tendon MA balance kinematically prescribes the combined finger joint coordination and therefore finger functioning. Moreover, it can be a generic measure for certain finger pathologies where finger balance is disturbed, for example in swan neck deformity (MA disbalance due to hyperextension of the PIP joint) or patients with loose pulleys (increase in MA's and therefore finger disbalance).

In this study, we investigated whether it is possible to estimate joint angle dependent MA's of the long flexors and extensor over the MCP III joint, using ultrasound. Intra subject repeatability will be assessed. The geometrical MA values are used as a "golden standard" and compared with the results from the dl/dθ method. In addition, results are compared to comparable studies in the literature.

a.

b.

Fig. 1. Experimental setup for a) the flexor tendons with the ultrasound scanhead distal tot the wrist and b) the extensor tendon with the ultrasound scanhead proximal to the wrist. The subject's arm and third digit were braced in custom made splints. Markers at the fingertip and wrist brace were used to track the MCP joint angle.

Method

Five healthy volunteers, including 3 male and 2 female subjects, age 23-28 years, were enrolled in the study. The medical ethics committee of the Erasmus MC (MEC-2008-084) approved this study. Preceding the study, an extensive explanation of method and procedure was given and informed consent was obtained from each participant. The MA's of the long finger tendons, flexor digitorum profundus (FDP), flexor digitorum superficialis (FDS) and extensor digitorum communis (EDC), were studied at the MCP joint of the long finger, assessed by the dl/dθ method, resulting in MA_{est} and validated through geometrical MA's, MA_{geo}.

dl/dθ method: MA_{est}

The experimental conditions for the dl/dθ method are shown in Fig. 1. For dl_{mt}, ultrasound video sequences were acquired using an iE33 ultrasound system (Philips Electronics, Eindhoven, The Netherlands), using a 7 MHz linear array probe at 120-280 frames per second, depending on the type and size of the imaged tendon. The subjects right forearm and hand were positioned in one of the two custom thermoplastic wrist braces (one for the flexor tendons, one for extensor tendon), with the wrist in neutral position. The third digit was braced, with the PIP and the DIP joints respectively in 22 and 8 degrees of flexion. The brace was marked with a rectangle of 20 mm by 30 mm as a measure for the orientation of the brace in relation to the digital camera. The braces did not interfere with MCP joint motion. For the flexor tendons, subjects were asked to place their right supinated forearm on the examination bench with the elbow in 90 degrees of flexion. For the extensor tendon, the arm was placed in the extensor brace, with the palm of the hand facing upwards. It was checked afterwards that the wrist brace did not move during the experiments, using the video images obtained from the digital camera.

For the measurement of the flexor tendons, subjects were asked to move their long finger from extension to flexion and back. For the extensor tendon measurement, the motion was reversed. All motions were performed **actively** in a time span of 10 seconds. Subjects were asked not to use excessive forces at the endpoint of motion and were allowed to move the other fingers with the long finger to minimize the effect of stresses in tendinous cross bridges between the neighboring tendons.

Preceding the measurements, FDS and FDP tendon locations of the long finger were identified just below the wrist by palpation as a starting point for the scanhead of the ultrasound scanner. To distinguish the FDS tendon from the FDP tendon, the orientation of both tendons were used, with the FDS tendon parallel and close to the surface of the skin and the FDP in an angle, deeper in the forearm. Once the tendon of interest was thought to be located, the MCP joint angle of the long finger was altered passively. When the tendon moved synchronous to the joint motion, it was identified as the targeted tendon. As a final check the MCP joint angles of the other fingers were also altered and compared to the resulting tendon excursion. In all experiments, the tendon of interest did not move considerable to the joint motion of the other fingers, confirming that the correct tendon was localized. The EDC tendon was identified in the same manner, but just distal to the wrist joint. The scanhead was maneuvered until a point was found where the lateral movement of the EDC tendon, induced by the presence of tendinous cross bridges, was minimal. This was done to minimize the effect of out of plane motion of the EDC tendon with respect to the scanhead. Due to possible skin motion with respect to the metacarpal bones and therefore also motion of the scanhead, the recorded bone movement was subtracted from the recorded tendon excursion.

To determine the tendon excursions, uncompressed audio-video interleave (.avi) files were imported into Matlab, and a region of interest on the tendon was manually assigned to the first frame. Frame-to-frame displacement was estimated by using multiple overlapping small kernels. Each kernel was compared with a search region in a subsequent frame using normalized cross-correlation as a similarity measure. A correlation of one indicated a perfect match and a correlation of 0 indicated no match. In a previous study, correlations larger than 0.7 were considered to be good matches (Korstanje et al. 2010a). In this study no correlations below 0.85 were found.

For $d\theta_{joint}$, a digital camera captured at 30 frames/s the trajectory of two markers: one at the finger tip, the other on the wrist brace. Images were imported in Simi motion (Simi Reality Motion Systems GmbH, Unterschleissheim, Germany). The fingertip and wrist brace marker were tracked and corrected for any out of plane position of the arm splint with respect to the digital camera. The tracked data was exported as a text file (.txt) and imported in Matlab (7.7.0, R2008b; The MathWorks, Inc., Natick, MA). It was ensured that the wrist brace marker was stationary during the experiment. The offset of the fingertip marker with respect to the proximal phalanx was determined (20^0 in the direction of flexion). A circle was fitted on the tracked data of the fingertip, with the centre of the circle as the centre of rotation (COR) for the MCP III joint. It was assumed that the metacarpal bones were in a horizontal position in the wrist brace. Therefore, the extended (or 0^0 flexion) position was taken as the position where the proximal phalanx was horizontal and thus in line with the metacarpals. With the COR and fingertip marker trajectory known, corrected for the 20^0 marker offset, the joint angle θ_{joint} was calculated.

Video and ultrasound synchronization was conducted manually with an accuracy of +/- 5 frames, corresponding to ≤ 0.04 sec. When the similarity between the two signals was low, such that manual synchronization became difficult, the experiment was discarded. Start and end phases of the signal were left out of the results, to prevent computational errors for joint angle rotational velocities close to zero. Each muscle-tendon was measured three times per session. Each subject underwent the session twice. For each experiment the MA was calculated separately by numerical differentiation of the joint angle-tendon excursion plot (see Fig. 3) The total of six raw MA estimations were fitted with the highest order polynomial for which the reduction of the standard error was larger than 5%. This amounted to a first order polynomial in all cases and was used as the estimated joint angle dependent moment arm, MA_{est}.

Geometrical method: MA_{geo}

For each subject, longitudinal ultrasound images of the MCP III joint were obtained from the palmar and dorsal side with the long tendons visible. For a good visibility of the joint articulation, on the palmar side the joint was in a slightly overextended position and for the dorsal side in 90^0 flexion. The images were imported as JPEG files in Matlab. First, a circle was fitted on the articulation of the distal part of metacarpal III. The centre of the circle was taken as the COR of the MCP joint. Then, the shortest distances from the COR to the FDP, FDS and EDC were measured, resulting in the geometrical MA's, MA_{geo}. MA_{geo} was used as a validation for MA_{est}, see Fig. 5.

Statistical analyses

An intraclass correlation coefficient (ICC) with a check on absolute agreement was used to quantify the intra subject repeatability of MA_{est} between the two sessions at 0^0 and 60^0 of flexion. In the same manner, the similarity between MA_{est} and MA_{geo} was quantified. Correlations higher than 0.95 were accepted as sufficiently high to assume similarity.

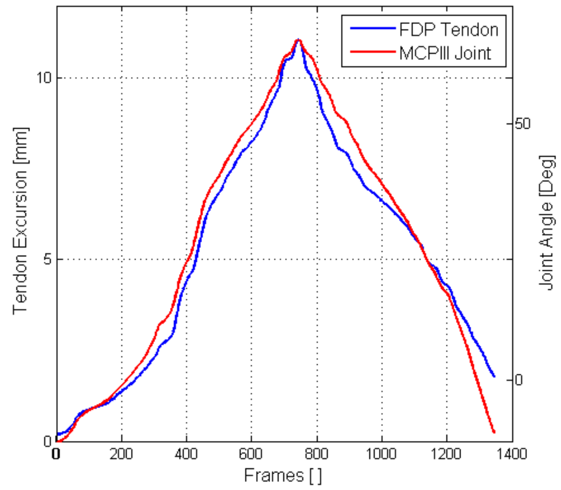

Fig. 2. Signal for the tendon excursion (blue line) and the joint angle in the direction of flexion (red line). Both signals are sampled at 180.4 Hz

Results

In Fig. 2, the typical raw signals of the joint angle and tendon excursion are shown for the FDP tendon, which is representative for all three tendons. The first, inclined, part of the curve corresponds to MCP flexion and therefore active motion, the second part corresponds to MCP extension and is therefore passive (the extensor is active). It can be seen that for the active part the time series were comparable. A slightly lower similarity was found in the passive part, most likely due to muscle-tendon relaxation and re-tensioning. This will evidently influence the MA result (Appendix II). Since particular interest goes out to the MA's of the tendons which are moved actively by its muscle, only the active part of the signals was used for analysis.

The data for the six times repeated measurements of one subject are shown in Fig. 3 in a joint angle-tendon excursion plot. On average, the slopes of the FDS and FDP signals increased a little over the range of motion of the MCP joint, leading to a small joint angle dependency, which can also be seen in Fig. 4, where the resulting MA's are given for the same subject.

Intra subject repeatability

In Table 1 an overview of the estimated MA's is given for all subjects. It can be seen that the intra subject repeatability between the two sessions at 0^0 of flexion for the FDS and EDC tendon was good (ICC > 0.95, p = 0.004 and 0.101 respectively) but rather weak for the FDP (ICC = 0.630, p = 0.157).In all cases, the repeatability at 60^0 of flexion was worse compared to the repeatability at 0^0 of flexion.

Comparison to the geometrical MA

Looking at Table 1, the MA_{est} values in comparison with MA_{geo} can be seen, which is visualized in Fig. 5 for one of the subjects. It can be seen that for all muscle-tendons the ICC values were very low (ICC < 0.1 in all cases), indicating that MA_{est} and MA_{geo} are not equal. For all values MA_{est} was underestimated, especially for the EDC tendon MA, which is visualized in Fig. 4: the anatomical position of the estimated EDC MA is located within the joint articulation.

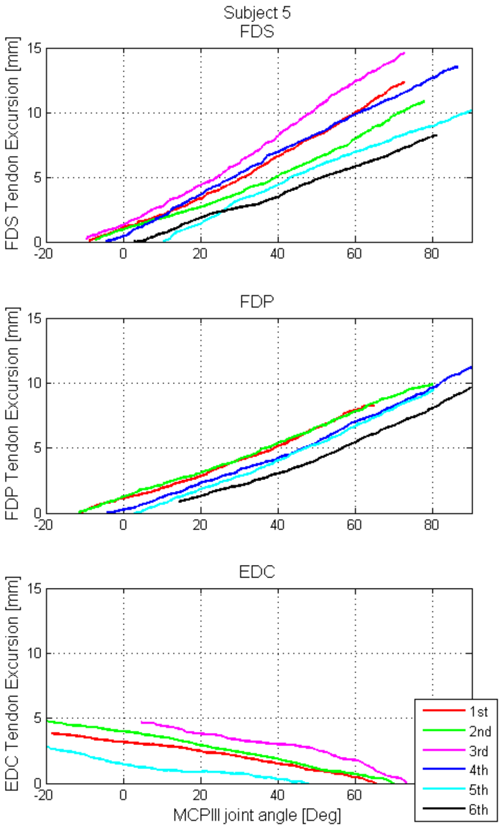

Fig. 3. Typical tendon Excursion – Joint Angle relations for the FDS, FDP and EDC tendon of Subject 5, for six repeated measurements (1-3 session 1; 4-6 session 2).

Table 1: Overview of the MA results for the FDS, FDP and EDC tendon.

FDS [mm]	*Intra subject repeatability*				*Golden standard*	
	$\theta = 0^0$ flexion		*$\theta = 60^0$ flexion*			
	MA_{1tm3}	MA_{4tm6}	MA_{1tm3}	MA_{4tm6}	MA_{est}	MA_{geo}
Subject 1	6.94	7.71	10.32	11.22	7.0	10.2
Subject 2	7.24	-	9.15	-	7.2	9.2
Subject 3	3.96	4.28	5.23	5.37	5.1	8.9
Subject 4	6.70	6.73	10.56	7.50	6.5	10.1
Subject 5	6.85	7.86	10.41	7.36	8.4	9.7
ICC	0.952		0.774		0.063	
p-value	0.004		0.114		0.261	

FDP [mm]	*Intra subject repeatability*				*Golden standard*	
	$\theta = 0^0$ flexion		*$\theta = 60^0$ flexion*			
	MA_{1tm3}	MA_{4tm6}	MA_{1tm3}	MA_{4tm6}	MA_{est}	MA_{geo}
Subject 1	6.06	6.31	9.09	8.51	6.1	8.8
Subject 2	3.56	3.2	6.38	7.19	3.5	8.0
Subject 3	5.13	-	9.19	-	4.2	7.2
Subject 4	5.93	3.66	10.22	4.40	4.9	8.7
Subject 5	6.74	4.94	7.15	8.23	5.0	8.0
ICC	0.630		-4.596		0.064	
p-value	0.157		0.836		0.104	

EDC [mm]	*Intra subject repeatability*				*Golden standard*	
	$\theta = 0^0$ flexion		*$\theta = 60^0$ flexion*			
	MA_{1tm3}	MA_{4tm6}	MA_{1tm3}	MA_{4tm6}	MA_{est}	MA_{geo}
Subject 1	-4.89	-5.63	-1.07	-0.41	-5.2	-7.2
Subject 2	-1.03	-	-1.72	-	-1.0	-8.3
Subject 3	-2.99	-2.14	-2.12	-2.26	-2.6	-8.0
Subject 4	-2.12	-2.34	-.79	-2.68	-2.8	-9.2
Subject 5	-3.42	-2.77	-1.86	-1.62	-2.2	-8.8
ICC	0.971		0.194		-0.044	
p-value	0.101		0.443		0.843	

Discussion

In this study MA's were estimated by the dl/dθ method as shown by equation 1. From Table 1 it can be seen that MA_{est} from the dl/dθ method was significantly smaller than MA_{geo}, for all subjects. MA_{geo} was found to be within the range of values from previous studies (An et al. 1983; Brand and Hollister 1993; Buford et al. 2005). In addition, in some cases MA_{est} was estimated within the articulation of the MCP joint. From these findings it can be concluded that the MA values of the dl/dθ method were structurally underestimated. It is assumed that the motions during the experiments were conducted with very little force, resulting in relatively low tensions in the tendons, making it vulnerable for influences from surrounding tissues and/or cross bridges to other tendons, hereby decreasing the amount of recorded tendon excursion proximal to the wrist. This was tested in a pilot study where the protocol, as described in the method section, was carried out with the addition of an applied external force on the fingertip of the long finger and after that with electro stimulation on the medialis nerve (see Fig. 6). In this figure it can be seen that indeed the slope of the curve of the FDP tendon was steeper with external applied force than for the initial measurements, yielding to larger MA's. Unfortunately, the MA result for the FDS tendon did not increase compared to the experiment without external force. Further testing is needed to understand why this occurred. Furthermore, the results for the experiments with the applied external load and electro stimulation show good resemblance.

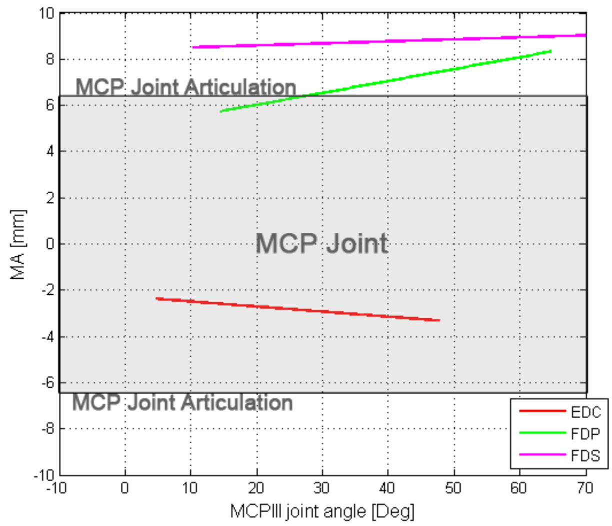

Fig. 4. Joint angle dependent moment arms, MA_{est} of the FDS, FDP and EDC tendons for Subject 5. MA's within the grey area are estimated within the bony part of the MCP joint.

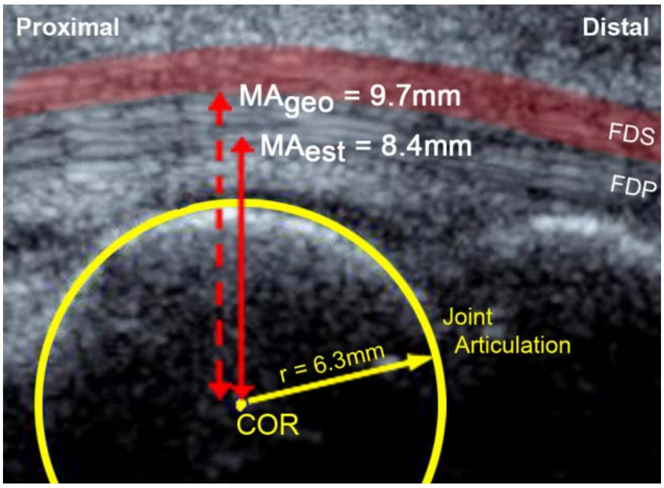

Fig. 5. Longitudinal ultrasound image of the MCP III joint in extension. The Centre of Rotation (COR) is obtained by a circle fit on the distal articulation of metacarpal III. The geometrical FDS moment arm (MA_{geo}) derived from this figure is indicated by the dashed arrow. The estimated FDS moment arm (MA_{est}) obtained by the dl/dθ method (at 0 degrees of flexion) is indicated by the solid arrow.

It is assumed that the results for the EDC tendon would improve as well under external load or electro stimulation. Measurement difficulties are expected though: it will be troublesome to align the probe of the ultrasound scanner and the EDC tendon due to transverse motions of the tendon by tendinous crossbridges.

For all subjects, consistent results were found over the repeated measurements for at least one of the flexors (FDS or FDP). The other flexor result showed less consistency. Probably, the tendon with the inconsistent results did not or not always actively contributed to the MCP joint flexion. This is possible since this studied musculo-skeletal system is over actuated with one degree of freedom and five muscles: FDP, FDS, lumbrical, volar- and dorsal interosseous. Less or no contribution of one of the muscles would result in buckling of the tendon, less tendon displacement and therefore an underestimation for the MA (Ito et al. 2000). To overcome this, it was tested in a pilot study to apply electro stimulation on the medialis nerve during the experiment, hereby assuring that the muscle-tendon units are activated and no tendon buckling will occur. This indeed resulting in a better consistency between measurements, see Fig. 6, curve 4-6. Thus, it is expected that the intra subject repeatability, especially for the FDP tendon, will increase when the experiments are conducted with the application of electro stimulation.

On average, the slopes of the FDS and FDP MA's increased a little over the range of motion of the MCP joint, resulting in a small joint angle dependency, which can be seen in Fig. 4 and agrees with MA values found *in-vitro* (An et al. 1983; Brand and Hollister 1993; Buford et al. 2005). After examining the data from this study, a linear relation was found for the MA's of the long tendons, although a better quality of the data in this study might have resulted in second order fits. In a previous cadaver study, the joint angle dependent MA of the FDS and FDP tendon over the MCP joint are just a fraction non linear (An et al. 1983), which is close to our findings.

By using the dl/dθ method, two assumptions were made that will be briefly discussed here. First of all, it was noticed that this method does not take any joint translations into account; therefore, more accurate results will be obtained when the joint acts as a perfect hinge. Looking at Fig. 7, it can be seen that the tracked arc of the fingertip marker was close to a perfect circle segment, making this assumption justified. Secondly, it was assumed that the tendons were at a constant length. When they would elongate, a larger tendon excursion would be recorded, resulting in larger estimated MA's. The experiments in this study are conducted with no external applied forces, resulting in relatively low tendon stresses, making it plausible that indeed no significant tendon elongation was present during the experiment.

It should be kept in mind that the quality of the ultrasonic images could have influenced the results for several reasons. First of all, due to out of plane motion of the tendon with respect to the scanhead less tendon excursion could be recorded than occurred in reality (Friemel et al. 1998). Secondly, the EDC tendon is recorded very close to the scanhead and therefore out of the focus of the scanner used in this study. It is suggested for future work to use a different scanner with a higher frequency range, specialized for imaging small, superficial structures,

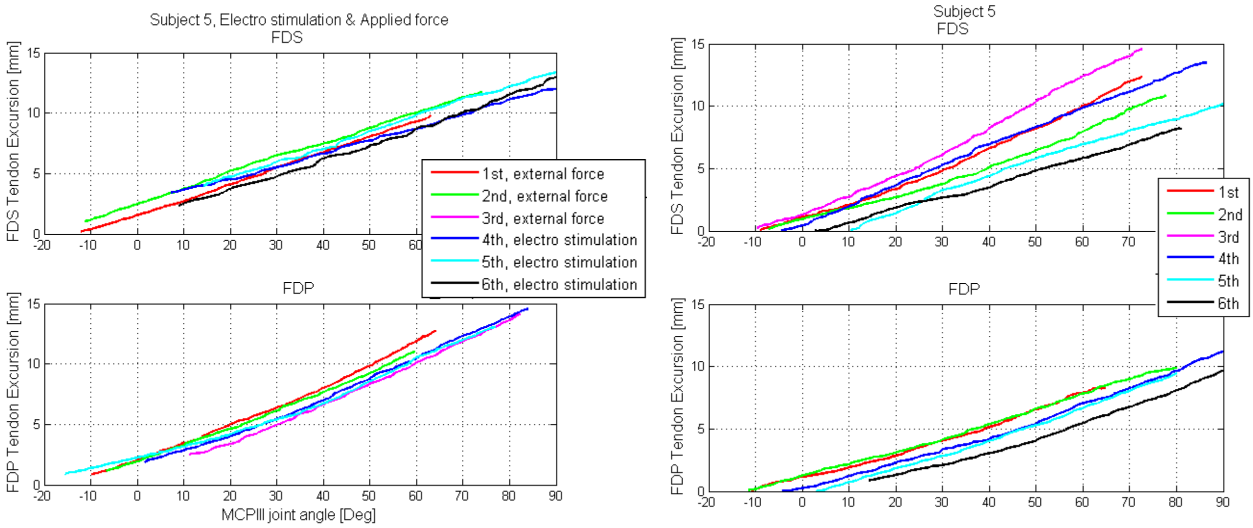

Fig. 6. Tendon excursion – joint angle relations for the FDS and FDP tendon for Subject 5. Left, for curve 1-3, the experiment was conducted with an external applied force. For curve 4-6, the experiment was conducted with electro stimulation on the medialis nerve. At the right, for comparison, the results of subject 5 are shown without electro stimulation and external applied force.

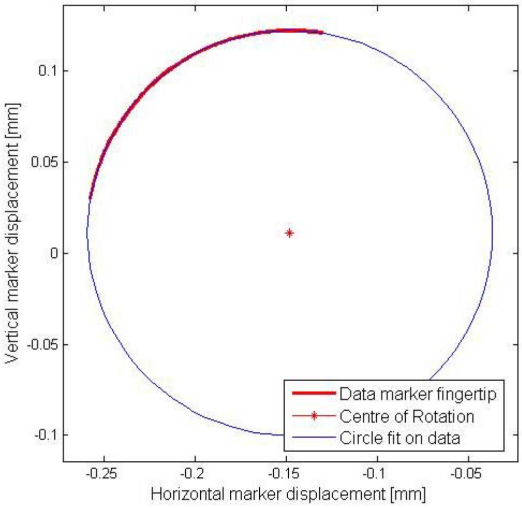

Fig. 7. Typical data of the finger tip marker and a circle fit on this data. A good fit is obtained, suggesting that the assumption of a fixed MCP III Centre of Rotation is correct.

hereby resulting in higher quality EDC tendon images. Thirdly, the different zoomfactors used on the ultrasound scanner probably have influenced the results (appendix VI). Finally, since it is virtually impossible to overestimate tendon displacement by speckle tracking as performed in this study, any errors in the tracking would evidently result in an underestimation of the tendon excursion and thus in smaller MA's (personal conversation with J. Bosch, Erasmus MC, Thoraxcenter Biomedical Engineering, Appendix IV).

When widening the scope of this study, an effort is made to determine the MA balance of the finger joints. This can be of added value to the existing literature for two reasons. First, it can result in values that are less dependent on subject specific data, hereby giving an alternative for the large range of reported MA values in the literature (Ketchum et al. 1978; An et al. 1983; Li et al. 2000; Buford et al. 2005). Secondly, since finger coordination is kinematically defined by muscle MA balances, insight in the muscle MA balance between the three interphalangeal joints can increase our understanding of hand functioning. For example, the added value of the lumbrical muscle still remains relatively unclear in the functioning of the hand. From the field of under actuated hand robotics, it is found that for stable finger pinch in different finger positions, it is crucial to be able to alter the moment balance between finger joints (presentation of G.A. Kragten at the Delft University of technology, 2011). It is hypothesized that the lumbrical muscle is responsible for this delicate change in moment around the MCP, DIP and PIP joint.

From a clinical point of view, the dl/dθ method combined with ultrasound has several advantages, which could make it a useful diagnostic tool for patients who suffer from finger pathologies caused by imbalanced fingers. First of all, the method was easy to apply for a trained therapist, harmless and relatively inexpensive. Secondly, no information is needed about the position of the COR (An et al. 1983) and, to a certain extent, if there is a fixed COR or not. This might be of special importance for the clinical field, since it could be expected that the articulations of patients with finger pathologies are affected and may therefore show a shifting joint axis.

Conclusion

The *in-vivo* application of the dl/dθ method to determine MA's of the long flexors of the fingers proved to be promising, but should be further validated and developed to yield sufficiently reliable results. Consistent estimations for the MA of the FDS and FDP tendon were obtained, showing the robustness of the method. The absolute MA values of the FDS, FDP and EDC tendon were underestimated compared to the geometrical MA's and findings from the literature. With improvement this method can be used to provide valuable insights in muscle MA balance and hand pathologies.

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