Introducing intraoperative direct measurement of muscle force and myofascial force transmission in tendon transfer for cerebral palsy
Smeulders, M.J.C.

Citation for published version (APA):
CHAPTER 4

Spastic muscle properties are affected by length changes of adjacent structures

M.J.C. Smeulders\textsuperscript{1}, M. Kreulen\textsuperscript{1}, J.J. Hage\textsuperscript{1}, P.A.J.B.M. Huijing\textsuperscript{2,3}, C.M.A.M. Van der Horst\textsuperscript{1}

\textsuperscript{1}Dept. of plastic, reconstructive and hand surgery, Academic Medical Center, Amsterdam
\textsuperscript{2}Institute for Fundamental and Clinical Human Movement Sciences, VU, Amsterdam
\textsuperscript{3}Integrated Biomedical Engineering for Restoration of Human Function, Biomedisch Technologisch Instituut, Universiteit Twente, Enschede

Abstract

Recent animal experiments showed that up to 37\% of muscle force may be transmitted to adjacent structures rather than reach the muscle’s tendon insertion, and that the extent of such force transmission depends on the length and relative position of these structures. We tested whether the length-force characteristics of the distally tenotomized human flexor carpi ulnaris muscle (FCU) of nine patients with cerebral palsy varied with the change of relative length of adjacent structures induced by a change of wrist positions. In four patients, the FCU exerted up to 40\% more active force in flexed wrist position at low FCU length ($p=0.019$), whereas the active force was not significantly higher in the other five ($p=0.204$). Likewise, in spite of distal tenotomy, passive length-force characteristics of the spastic FCU changed upon changes in wrist position. This may explain part of the variability in success of the FCU-transfer.

Submitted for publication

Introduction

Throughout history, scientists and artists countless depicted studies of muscles. In most of their drawings and descriptions, the muscles were distinguished as anatomically separate structures. Likewise, mechanical studies of muscles have focused on the behavior of muscles, or even muscle fibers, that were separated from their surroundings. Both types of studies reflect the common understanding that the force transmission of a muscle is independent from adjacent muscles and structures. The anatomical truth, however, is that most muscles are connected to adjacent muscles by intermuscular connective tissue, and to bones, fascial planes, vessels, and nerves by extramuscular connective tissue. These inter- and extra-muscular connections have been ignored in muscle research and surgery and, hence, they are usually dissected without much concern. Only recently the
interaction of muscles through these connections have been shown to significantly affect muscular properties\textsuperscript{25, 48, 59, 61, 98, 106}. This has led to the idea that forces are not only transmitted to the tendon by sarcomeres that are lined up in-series within a muscle fiber but, also, to sarcomeres that are parallel to each other\textsuperscript{43, 48}. Moreover, up to 37\% of maximal muscle force may be transmitted to adjacent structures through inter- and extramuscular connective tissues\textsuperscript{43, 48}, rather than be exerted at the insertion of the muscle’s tendon\textsuperscript{80}. In experimental conditions, the extent of such inter- and extramuscular force transmission depended on the length and relative position of the involved structures\textsuperscript{49, 81}. As this may also be true in human muscle, the purpose of the current study was to test the hypothesis that length-force characteristics of the human flexor carpi ulnaris muscle (FCU) measured at its tendon varies with the relative length of its adjacent structures. For that, length-force curves of the distally tenotomized FCU were constructed at a series of FCU lengths from intraoperative force measurements during tendon transfer surgery in patients with cerebral palsy. This was done with the wrist held in extension, and in flexion. With the wrist held in extension, the flexor digitorum profundus (FDP) and the flexor digitorum sublimis (FDS), as well as extramuscular structures adjacent to the cut FCU are at high length relative to the FCU. In contrast, the FDP and FDS and the extramuscular structures are at low length relative to the FCU when the wrist is held in flexed position. Varying the wrist position thus allows us to change the position of the involved structures relative to each other.

**Materials and Methods**

**Patients**

The study protocol was approved by the AMC ethical committee and adhered to the guidelines of the 1975 declaration of Helsinki. After informed consent was obtained, six female and three male patients (mean age 16 years; range 9-23 years) with hemiplegic cerebral palsy underwent surgery for correction of a flexion deformity in the wrist. Patients were under general anesthesia without the use of muscle relaxants or a tourniquet. Although several additional surgical procedures were performed for clinical purposes in every patient, the experiments were performed first in all.

**Method**

The conditions and validation of the experimental method were previously described in detail\textsuperscript{107}. In short, an incision from the pisiform bone along the ulnar border of the FCU was made over the distal third of the forearm. The insertion of
the most distal muscle fiber in the FCU tendon was marked with a thin suture. A Kirschner-wire was drilled in the center of the medial epicondyle. FCU muscle length was defined as the distance between this Kirschner-wire and the suture marking. A metal ring was sutured onto the distal tendon. A strain gauge was attached to the metal ring on the distal tendon of the FCU and to a metal bar that was attached to the Kirschner-wire in the medial epicondyle. The strain gauge was kept aligned with the FCU. During measurement, the elbow was held at constant angle. Initial isometric contractions were induced by transcutaneous electrical stimulation of the ulnar nerve at high and low FCU length until effects of previous activity at high length were eliminated.

Force measurements were done at consecutive FCU lengths in two experimental conditions with the wrist held 1) in 90 degrees of flexion, and 2) in maximal extension.

The order of which experimental condition was first performed alternated in each consecutive patient to exclude structural bias. At consecutive muscle lengths (0.5 cm increments), a series of maximal tetanic contractions of the FCU were induced by supra-maximal transcutaneous electrical stimulation of the ulnar nerve (140 mA, 50 Hz, 0.1 ms pulse duration 1000 ms stimulus duration), using two gel-filled skin electrodes (Red Dot 2560, 3Com Inc., Minneapolis, Minnesota, USA) that were pasted on the skin directly overlying the cubital tunnel of the elbow. Just prior to, and during stimulation, the strain gauge signal was Analogue-to-Digital converted and stored in a computer.

Data analysis

Two representative data points from each tetanic contraction were identified for use in construction of active and passive length-force curves: one just prior to stimulation representing the passive muscle force, and one at the tetanic plateau representing the total of active and passive muscle force. Active force was defined as this total, minus the passive force. Maximal FCU force was defined as the force corresponding with the top of the curve of active force, and the corresponding FCU length as the length of maximum force (LmaxF). All force values were normalized for maximal FCU force in the extended wrist position. Because the absolute length at which the measurements had started and the absolute measured range of lengths differed in every patient, the length relative to LmaxF was calculated to allow for comparison between patients. Five data points within the part of the length-force profile for which data of all patients was available at length intervals of 5 mm were used for averaging and statistical analysis. Averages and standard errors of the length-force data of each patient were calculated.
Two-way ANOVA for repeated measurements was performed to test for differences in length-force curves between the two experimental conditions. Spearman's Rank correlation was used to verify whether relations between conditions and clinical measures were present. An SPSS 11.5.1 package (SPSS Inc., Chicago, Ill, USA) was used for all statistical calculations.

Table 1
Individual force-length characteristics of the FCU of nine patients

<table>
<thead>
<tr>
<th>Pat.</th>
<th>Max extension (degrees)</th>
<th>$F_{\text{maxact ext}}$ (N)</th>
<th>$F_{\text{maxact flex}}$ (N)</th>
<th>$L_{\text{maxF ext}}$ (cm)</th>
<th>$L_{\text{maxF flex}}$ (cm)</th>
<th>Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-55</td>
<td>31</td>
<td>36</td>
<td>16.8</td>
<td>16.3</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>75</td>
<td>58</td>
<td>62</td>
<td>23.9</td>
<td>23.4</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>55</td>
<td>82</td>
<td>27.5</td>
<td>27</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>20</td>
<td>62</td>
<td>72</td>
<td>21.4</td>
<td>20.9</td>
<td>2</td>
</tr>
<tr>
<td>5</td>
<td>90</td>
<td>33</td>
<td>36</td>
<td>18.7</td>
<td>19.2</td>
<td>2</td>
</tr>
<tr>
<td>6</td>
<td>30</td>
<td>64</td>
<td>69</td>
<td>21.6</td>
<td>21.6</td>
<td>2</td>
</tr>
<tr>
<td>7</td>
<td>10</td>
<td>60</td>
<td>77</td>
<td>22.3</td>
<td>22.8</td>
<td>2</td>
</tr>
<tr>
<td>8</td>
<td>60</td>
<td>135</td>
<td>134</td>
<td>27.4</td>
<td>26.9</td>
<td>1</td>
</tr>
<tr>
<td>9</td>
<td>75</td>
<td>78</td>
<td>76</td>
<td>18.7</td>
<td>18.2</td>
<td>1</td>
</tr>
</tbody>
</table>

Max Extension = Maximum passive extension angle during anesthesia
$F_{\text{maxact ext}}$ = FCU maximum active force in extended wrist position
$F_{\text{maxact flex}}$ = FCU maximum active force in flexed wrist position
$L_{\text{maxF ext}}$ = FCU length corresponding with maximum active force in extended wrist position
$L_{\text{maxF flex}}$ = FCU length corresponding with maximum active force in flexed wrist position
Group = division in two groups based on the maximum passive force and the shape of the active force-length curve

Results

Although there was considerable difference in FCU length-force curves among the patients (figure 1), the maximum active force that the FCU exerted on the force transducer was highest when the wrist was held in flexion in all but two patients (table 1). In three patients (#3, #8 and #9), little or no active force was exerted at the tendon at low FCU length when the wrist was held in extension, while this force was high at the identical FCU length when the wrist was held in flexed position (figure 1). Average maximum active force of all patients was 64.0 N
Figure 1
Individual active and passive FCU force-length curves of 9 patients with cerebral palsy with the wrist held in two positions: in flexion (solid line), and extension (dashed line). The X-axes show FCU lengths (cm), the Y-axes show the FCU forces (N). Note the large individual differences in active and passive force and in muscle length.

(Standard deviation: 27.2 N) when the wrist was held in extended position, and 71.6 N (Standard deviation: 25.1 N) when it was held in flexion.

The effect of the wrist position on passive FCU force was less uniform. In a first group of five patients (table 1) the mean peak passive force was 5.6 N (Standard Deviation, 2.7 N) higher when the wrist was held in flexion. In contrast, in the other group of four patients (table 1) the mean peak passive force was on average 6.3 N (Standard Deviation, 1.5 N) higher when the wrist was held in extension. Still, the greatest difference between the force with the wrist in extension and that with the wrist in flexion was found at higher FCU length in both groups (figure 1).

The effect of the position of the wrist on the active FCU force, likewise, varied at different FCU lengths. In the first group of five patients (figure 2a) the muscle exerted 40% more active force in flexed wrist position at short FCU (i.e. -1.0 cm below LmaxF of the curve with the wrist held in extension), whereas the active force in flexed wrist position was 0-15% higher at higher FCU length (i.e. 0, 0.5,
and 1 cm from LmaxF of the curve with the wrist held in extension). In the second group of four patients the FCU exerted 0-10% more active force at the distal tendon in flexed position than in extended wrist position at short FCU length up to FCU LmaxF of the curve with the wrist held in extension, and up to approximately 40% more active force at higher FCU length (figure 2b).

Analysis of variance indicated that active length-force curves of the FCU were not significantly affected by changing wrist position in the first group ($p = 0.204$), although a clear trend is present towards a higher active force in flexed wrist position. Passive length-force curves, however, were significantly different for the two

![Figure 2](image)

**Figure 2**
Mean active and passive force-length curve of the spastic FCU patients with cerebral palsy with the wrist held in two positions: in flexion (solid line), and in extension (dashed line). Two groups were distinguished based on the shape of the curves of the individual patients.
wrist positions in this group \((p = 0.022)\). Moreover, the maximum active force in this group was attained at 0.5 cm shorter FCU length in flexed wrist position, as compared to the extended wrist position. In the second group, active length-force curves and passive length-force curves of the FCU were affected significantly by changing wrist position \((p = 0.019, p = 0.002\) respectively). In this group, the maximum active force was reached at approximately 0.5 cm higher FCU length when the wrist was held in flexed position, as compared to the extended wrist position.

There was no correlation between the type of effects (i.e. group 1 or group 2) and the order at which the measurements were performed \((r = 0.04, p = 0.93)\). Likewise, clinical measures of the severity of the wrist deformity such as the maximal wrist extension angle and the presence of contracture of finger muscles in spastic patients did not significantly correlate with the type of effects \((r = 0.16, p = 0.82; \text{and } r = 0.09, p = 0.73)\).

These results indicate that varying the length of the muscles and other structures adjacent to the FCU results in a change of FCU active and passive length-force characteristics.

**Discussion**

The present study shows that the length-force characteristics of spastic muscles change as a result of relative length difference to its surroundings. As a result of a change in wrist position, the length of the FDS and FDP muscles and the extramuscular tissues adjacent to the FCU varies relatively to that of the distally cut FCU, thereby straining or relaxing the inter- and extramuscular connections between the FCU and its adjacent tissues\(^{49}\). Such straining of connections may alter their compliance and make them stiffer\(^{13}\). Because the structure that is stiffest transmits the highest force, the fraction of force that may be transmitted through the inter- and extramuscular connective tissues depends on the relative length and positions of the muscles and adjacent structures involved. Depending on the relative compliance and direction of pull of these connections, force generated by the FCU may either ‘leak out’ of the FCU, or force that is exerted by structures other than the FCU may be ‘added’ to it. This, in turn, results in different forces being exerted at the FCU tendon for different wrist positions.

We found that the active force that is exerted at the FCU tendon at the same FCU length may vary up to 40% with varying lengths of its adjacent structures. The actual effect of wrist position on the FCU length-force characteristics was not the same in every patient. In some patients, the length-force curves were affected most for short FCU, whereas the effects were most significant at high FCU length.
in others. This corresponded with an opposing effect of wrist position on passive length-force curves. That the passive force in wrist flexion in some patients was higher than that in extended position of the wrist at longer FCU length, whereas it was lower in others, may be explained by the individual differences among patients of relative length and direction of pull of the inter- and extramuscular tissues. As such, they may add to the passive FCU force pulling on its tendon in some patients, while in others, they may diminish the passive FCU force resulting in a lower force measured at the tendon. Initial length differences between the FCU and its surroundings due to differences in clinical measures of the severity of the wrist deformity such as the maximal wrist extension angle and the presence of contracture of finger muscles in spastic patients may explain these differences. However, we were unable to further substantiate this possibility as the non-parametric correlation coefficients of the effect of the wrist position and the clinical measures were not significant. Hence, the explanation for the individual variation in the differences in active and passive length-force characteristics during wrist flexion and wrist extension remains subject to further study.

Implications for muscle models

Direct measurement of active human muscle forces have seldomly been performed\textsuperscript{24, 62, 85, 107, 108} because direct access to muscle is limited exclusively to the operation theatre. Performing tendon transposition of the FCU in patients with cerebral palsy yields a unique opportunity to directly measure active and passive muscle forces because the FCU is relatively easy to stimulate electrically, and the muscle's distal tendon is cut, allowing for a force transducer to be positioned in-series with it\textsuperscript{107}. Muscles of cerebral palsy patients may not be similar to healthy muscle and the results of the present study may not be extrapolated to healthy muscles without due consideration. Still, inter- and extramuscular connections also exist in healthy rat muscle\textsuperscript{51} and are expected to also be present in healthy human limbs. Moreover, differences in length and position of the FCU to the FDS and FDP commonly occur in-vivo as a result of the differences in muscle excursion during flexion and extension of the fingers, and of the differences in moment arms at the wrist\textsuperscript{10}. Although the effects in healthy muscle may be different from those observed in the present study, the effects described may impede the efforts of quantifying individual muscle forces with indirect, in-vivo measurements. For example, the minimum length at which the FCU is able to exert any active force (its 'slack' length) seems to be shorter when the wrist is in flexion than when it is in extension in some of the studied patients. Observation of such a shift of the slack length would not be possible when muscles were studied that are isolated from their surroundings. The relative position to its surroundings may, hence, be
an additional parameter that has to be taken in consideration when predicting in-vivo muscle function on the basis of conventional muscle models.

Implications for clinical practice

After transposition of the FCU to the extensor carpi radialis brevis muscle in cerebral palsy patients, the FCU is expected to become an antagonist to the FDS and FDP. This implies that whenever the FCU shortens, the FDS and FDP are being stretched and vice versa, thus increasing their difference in relative length and position. As a result, significant inter- and extramuscular force transmission may affect the force that is exerted at the transposed tendon in these patients. Although the distal part of the transferred FCU has a new route and, thus, new structures adjacent to it, almost half the muscle is still situated at its original location with all the intermuscular connections to the FDS and FDP intact. It may, therefore, be assumed that at least part of the inter- and extramuscular force transmission remains intact. Through this part the FCU force that is transmitted from the muscle through the inter- and extramuscular pathways remains to exert a flexion moment over the wrist joint, rather than the intended extension moment. The individual variation in the differences in active and passive length-force characteristics during wrist flexion and wrist extension may, as such, explain part of the variability of the success of the FCU-transfer that is often observed among patients with cerebral palsy. Obviously, any prediction of FCU muscle function after transfer is further hindered by the fibrosis and newly formed connections during rehabilitation. To what extent these remaining and newly formed connections influence the function of the re-routed FCU also remains subject to further study.

In conclusion, the present study shows the active and passive length-force characteristics of the spastic flexor carpi ulnaris muscle to change upon changes in wrist position in spite of the distal tendon of the FCU being disconnected from the wrist. We found two seemingly contradicting ways in which these changes actually present in patients with cerebral palsy.