Connecting the dots: Musculoskeletal adaptation in cerebral palsy

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Flexor carpi ulnaris tenotomy alone does not eliminate its contribution to wrist torque.

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Abstract

Background: Flexor carpi ulnaris muscle tenotomy and transfer to the extensor side of the wrist are common procedures used to improve wrist position and dexterity in patients with cerebral palsy. Our aim was to determine whether this muscle still influences wrist torque even after tenotomy of its distal tendon.

Methods: Intra-operatively, we determined in vivo maximal wrist torque in hemiplegic cerebral palsy patients (n=15, mean age 17 years) in three conditions: 1) with the arm and the muscle intact; 2) after tenotomy of the flexor carpi ulnaris just proximal to the pisiform bone, with complete release from its insertion; and 3) after careful dissection of the belly of the muscle from its fascial surroundings up until approximately halfway its length.

Findings: After tenotomy of the flexor carpi ulnaris muscle, the maximal wrist torque decreased with 18% whereas dissection of the muscle resulted in an additional decrease of 16%.

Interpretation: We conclude that despite of the tenotomy of its distal tendon, the flexor carpi ulnaris still contributes to the flexion torque at the wrist through myofascial force transmission. Quantification of this phenomenon will help in the study of the effects of fascial dissection on the functional results of tendon transfer surgery.
Introduction
The flexor carpi ulnaris muscle (FCU) is one of the strongest forearm muscles and is presumed to be largely responsible for a flexion and ulnar deviation deformity of the wrist in patients with cerebral palsy (CP). To improve dexterity, prime goal of upper extremity surgery in patients with wrist flexion deformity is to rebalance forces around the wrist such that a work trajectory around a neutral position is achieved. Distal FCU tenotomy and transfer of its distal tendon to the extensor side of the wrist are common procedures performed to reach this new balance (Green & Banks, 1962; Beach et al., 1991). For the purpose of FCU transfer, the adjacent connective tissues are dissected up until approximately halfway the muscle belly until a straight line of pull to the receptor tendon can be achieved (Kreulen et al., 2003). Such dissection is commonly not considered to affect muscle function, and in most biomechanical models muscles are considered independent actuators (Delp & Loan, 2000). However, the connective tissue envelope of the human FCU has shown to be stiff enough to transmit force and strong enough to withstand the total amount of force that is exerted by the FCU (Kreulen et al., 2003). Moreover, fascia has been increasingly acknowledged as a secondary pathway of force transmission that affects muscle performance (Maas et al., 2005; Yucesoy et al., 2006; Smeulders & Kreulen, 2007). We hypothesize that sole tenotomy of the distal tendon of the FCU only limitedly decreases wrist flexion torque, because the intact fascial connections to the FCU will still remain to transmit force onto the wrist. Hence, subsequent dissection of the fascial connections will result in a further decrease of the wrist torque. To test this hypothesis, we measured maximal wrist flexion torque intraoperatively during upper extremity surgery in cerebral palsy patients. Wrist torque before tenotomy of the FCU (1) was compared to wrist torque after sole tenotomy, leaving the myofascial connections intact (2), and after subsequent dissection of the FCU to its adjacent connective tissue up until approximately halfway the muscle belly, leaving both innervation, and vascularization intact (3).
Methods

Subjects

Fifteen patients that were planned for a FCU procedure with distal tendon and muscle dissection were included after having given informed consent. Patients had a type Zancolli Ila or Ilib grasp and release pattern, which means active finger extension is accompanied by a wrist flexion angle greater than 20°. Furthermore, in type Zancolli Ila pattern the wrist can be actively extended with flexed fingers whereas in type Zancolli Ilib pattern there is no active wrist extension (Zancolli et al., 1987). The Manual Ability Classification System (MACS; Eliasson et al., 2006) was used to record bilateral upper-limb motor function. During surgery, force measurements were performed at the operated extremity of the patient. The study was approved by the medical ethical committee of the Academic Medical Center and adhered to the ethical guidelines of the 1975 Declaration of Helsinki.

Experimental setup

Previous to surgery, the palmar side of the head of the third metacarpal bone and the distal palmar crease of the wrist were marked. For this setup, the distal palmar crease of the wrist was assumed to be the palmar projection of the wrist flexion axis. Surgery was done under general anesthesia without administration of muscle relaxants and measurements were performed without a tourniquet.

Two gel-filled skin electrodes (Red Dot 2560, 3M Inc, Mineapolis, Minessota) were placed on the skin over the cubital tunnel of the elbow and connected to a custom-built, constant current peripheral nerve stimulator. For safety, the stimulator was isolated from the electric mains using an isolation transformer. The electrodes were covered with plastic foil to allow for a sterile surgical field. To provoke wrist flexion, the ulnar nerve was supramaximally stimulated provoking FCU and the flexor digitorum profundus (FDP) of the 4th and 5th digit to maximally contract. It should be noted that the ulnar nerve also activates intrinsic muscles in the hand that do not contribute to wrist torque. The palmar side of the head of the third metacarpal bone was marked and an S-shaped strain gauge connected to a computer for data registration (Epel Industrial S.A., Barcelona, Spain) was used as a hand-held dynamometer and placed at this point while the surgeon manually fixated the
forearm in neutral position. The distal part of the forearm was placed on a solid cylinder to assure that the hand was not blocked dorsally (Figure 4.1). Furthermore, care was taken not to move the strain gauge laterally during contractions. The force at the impact point was measured during supramaximal electrical stimulation (140 mA, 50 Hz, 0.1 ms pulse duration, 1000 ms stimulation duration). Measurements were done with intervals of one minute to allow for recuperation of the muscle.

**Wrist torque determination**

Force at the impact point was measured in three conditions: 1) with the arm and the FCU intact; 2) after tenotomy of the FCU just proximal to the pisiform bone, with complete release from its insertion; and 3) after careful dissection of the belly of the FCU from its fascial surroundings up until approximately halfway its length. Care was taken that the innervation and vascularization was kept intact. Each condition was repeated three times. One surgeon (MK) performed all measurements. Wrist torque (T in Nm) was calculated using the following formula:

\[ T = F \times a \]

In this formula, \( F \) represents measured force at the impact point (in N) and \( a \) represents the moment arm, which is defined as the distance (in m) of the impact point of the force transducer to the wrist crease (Figure 4.2). Maximal passive wrist extension (°) was measured in each condition.

**Data analysis**

Raw signals were forward filtered and maximal force was determined for every signal (Figure 4.3). Statistical analysis was performed using SPSS (SPSS Statistics 17.0). To determine reliability of measurements, Cronbach’s \( \alpha \) was calculated for each condition. The maximum torque was calculated and averaged over all three trials in each condition. Change of torque was expressed as a percentage relative to the torque before tenotomy. Percentages were compared using a Student t-test.
Figure 4.1. Schematic drawing of the intraoperative experimental setup. The surgeon fixates the forearm in neutral position. The forearm is positioned so that the hand is not blocked dorsally. The ulnar nerve is stimulated supramaximal.

Figure 4.2. Schematic drawing of the forearm with moment arm (a) between impact point on the head of the third metacarpal bone and the distal palmar crease which is taken as the palmar projection of the wrist flexion axis.

Fig. 4.3. Typical example of the measured signals after forward filtering in the intact, tenotomy and dissection condition. The horizontal lines at the peak of the signals represent the maximal force. These maxima were averaged over three trials per condition.
Results

Three patients were excluded per-operatively, because they needed muscle relaxants during surgery. Data analysis was thus conducted on 12 patients (mean age 17, range 9 – 40, 5 male). Patient characteristics together with outcome measures are shown in Table 4.1.

Preoperative maximal passive wrist extension was 36° (SEM 7.3°). After general anesthesia the passive wrist extension angle increased significantly (57°, SEM 5.2°, P<0.01). All patients had a passive wrist extension beyond neutral (0°) after anesthesia, so that measurements could be performed with the wrist in a neutral position.

Figure 3 shows a typical example of the filtered signals in the three conditions. Measurements in all conditions had a high Cronbach’s α (0.96; 0.98 and 0.95 for the intact, tenotomy and dissection condition respectively).

Mean maximal wrist flexion torque with an intact FCU was 5.8 Nm (SEM 0.36 Nm). After tenotomy, the wrist flexion torque decreased on average to 4.9 Nm (SEM 0.45 Nm) corresponding to 82% (SEM 4.5%) of the intact FCU torque (Figure 4.4). After dissection of the FCU from its surrounding structures halfway up the muscle belly, the torque decreased further to 4.0 Nm (SEM 0.45 Nm), or 64% (SEM 6.1%) of the torque with an intact FCU. The 16% difference between the condition after tenotomy and after dissection was significant (P<0.05; Figure 4.4).

![Figure 4.4](image.png)

Figure 4.4. The average maximal intraoperative wrist torque in the intact wrist, after tenotomy of FCU, and after subsequent dissection of FCU in spastic patients. Intact torque is set as 100% and torque after tenotomy and dissection are presented relative to intact torque. Error bars represent SEM, * indicates P<0.05, ** indicates P<0.01.
Table 4.1. Patient characteristics and outcome measures. The % wrist torque after tenotomy and after dissection both are relative to the wrist torque in the intact condition.

<table>
<thead>
<tr>
<th>Subject no.</th>
<th>Age (yr)</th>
<th>Diagnosis</th>
<th>MACS</th>
<th>Zancolli</th>
<th>Treatment of FCU</th>
<th>Passive extension angle (*)</th>
<th>% Torque relative to intact torque after tenotomy</th>
<th>% Torque relative to intact torque after dissection</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>16</td>
<td>hemiplegic</td>
<td>IV</td>
<td>Ila</td>
<td>FCU-t</td>
<td>75</td>
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<td>50</td>
<td>82.1</td>
<td>66.0</td>
</tr>
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<td>Iib</td>
<td>FCU-ECRB</td>
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<td>77.2</td>
<td>64.6</td>
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<tr>
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<td>FCU-t</td>
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<td>89.0</td>
<td>87.1</td>
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</table>

MACS = Manual Ability Classification System (1-5, whereas 1= easy and successful handling of objects and 5= no handling of objects); FCU-t = flexor carpi ulnaris tenotomy with subsequent dissection; FCU-ECRB = distal flexor carpi ulnaris transfer to extensor carpi radialis brevis; FCU-EDC = distal flexor carpi ulnaris transfer to extensor digitorum communis.

Discussion

The measurements performed in this study were designed to reveal the extent to which connections between FCU and its environment affect the forces that generate wrist torque at the spastic arm. Surgery aims to improve function by improving the balance of forces exerted by the spastic flexor muscles on one side, and the paretic extensor muscles on the other (Zancolli, 2003). The spastic FCU is often used to correct flexion deformity of the cerebral palsied wrist, as FCU tenotomy or transfer is believed to properly adjust the balance of forces around the wrist. However, previous intraoperative study of the FCU showed that fascial connections keep the muscle in its original position after tenotomy, even after maximal electrical stimulation (Kreulen et al., 2003). The results from present study, on an entirely new included population, show that even after tenotomy of the distal tendon FCU still contributes to flexion torque via connections to neighbouring muscles and other structures that cross the wrist joint. Hence, the connections that were earlier proven to be stiff enough to conduct passive force are now proven to actively influence the function of FCU and its adjacent muscles.
As can be seen in Table 1, our population included two relative outliers in age. Based on those two outliers, we cannot conclude whether age could influence the force transmission. However, excluding the two outliers (subject 3 and subject 4) did not affect the outcomes of our study. Further inspection of the data showed that there could be a relation between MACS-level and the amount of decrease in wrist torque after dissection. However, this apparent trend turned out not to be significant ($P=0.11$).

Torque measurement was needed in an intraoperative sterile environment and commercial handheld dynamometry devices are not suitable for this purpose. Therefore, a custom made device based on a reliable force transducer connected to a computer for continuous data registration was developed for torque measurement. Reliability of the device was confirmed by the high Cronbach’s alpha presented in our results.

Following the classical assumption that muscles are independent actuators, one would expect that tenotomy of the distal tendon of the FCU would eliminate the contribution of the FCU to flexion torque, as all force exerting connections of the FCU muscle to the wrist are disconnected. The remaining muscles that span the wrist would then solely be responsible for the remaining wrist torque. Our results can only be explained when such a classical assumption of force exertion is abandoned. Intermuscular myofascial pathways have previously been proposed to play a significant role in force transmission and their contribution to torque (Huijing & Baan, 2001; Kreulen et al., 2003; Yucesoy & Huijing, 2007; Maas & Huijing, 2012). For example, force measured at proximal rat extensor digitorum longus (EDL) muscle was found to be unequal to the force measured distally at the same muscle (Maas et al., 2001), proving a secondary pathway of force transmission somewhere along the muscle. This proximo-distal difference in force decreased after damaging the connective tissue compartment around the muscle, which led to the conclusion that inter- and extramuscular connective tissue may transmit force (Maas et al., 2001).

The present study is the first in actually showing the role of myofascial force transmission in the generation of joint torque in humans. Studies on muscle of rat and cat show that this force transmission is not solely an attribute of spastic muscle (Maas & Huijing, 2012), and substantial fraction of force (up to 30-40%) may be
transmitted from a muscle without passing either origin or insertion of the muscle (Maas et al., 2001).

Apparently, FCU could influence wrist flexion torque through its inter- and extramuscular connections with the environment even after tenotomy of its distal tendon. This resulted in a wrist torque after tenotomy of FCU that was not generated only by the ulnar nerve innervated FDP muscles. It has been shown that these connections exist between synergists and even between antagonists (Huijing & Jaspers, 2005; Huijing, 2007; Meijer et al., 2007; Rijkenhuizen et al., 2007). Hence, existence of such connections explains our results because after sole tenotomy of FCU, part of the force that is generated by the FCU fibers is transmitted to the neighboring FDP and flexor digitorum superficialis (FDS) that still have a flexion moment at the wrist.

In tendon transfer surgery, the distal tendon and muscle are always dissected in proximal direction until the desired line of pull is achieved. Our data show that such dissection alone significantly affects joint torque. In the clinical situation this may be helpful to further tailor the torque reduction to the desired goal. Clinical observations during surgery for recurrent flexion deformity after mere tenotomy repeatedly showed formation of a fibrous interposition that restored the continuity of the tendon. This restored connection of FCU over the wrist was proven to be strong enough to cause recurrent wrist flexion deformity (Kreulen et al., 2004). In these cases, it is suggested that sole tenotomy of the FCU does not achieve enough reduction of flexion torque and subsequent dissection of the distal part of the FCU is required. Furthermore, it may be hypothesized that limited dissection of FCU during a transfer procedure allows for the distal part of the muscle that is transferred to the extensor side to exert an extension torque at the wrist, while the proximal part that remains at the flexion side and connected to its fascial surroundings to exert a flexion torque. Hence, the original function of a transferred muscle might not be fully eliminated (Riewald & Delp, 1997). Quantification of these phenomena will help in the study of the effects of fascial dissection on the functional results of tendon transfer surgery.
Conclusions
It is concluded that after tenotomy of FCU, this muscle can still influence the intraoperative wrist torque measured during stimulation of the ulnar nerve. The myofascial connections may play a role in the development of deformities in the spastic arm of cerebral palsy patients.

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