On tendon transfer surgery of the upper extremity in cerebral palsy
Kreulen, M.

Citation for published version (APA):

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ON TENDON TRANSFER SURGERY OF THE UPPER EXTREMITY IN CEREBRAL PALSY
ON TENDON TRANSFER SURGERY OF
THE UPPER EXTREMITY IN CEREBRAL PALSY

A SUPPLEMENTARY SYNOPSIS OF THE FULL THESIS ON CD-ROM

Michiel Kreulen
The research presented in this thesis was carried out under the auspices of the Institute for Fundamental and Clinical Human Movement Sciences, Amsterdam (IFKB); Dept. of plastic, reconstructive & handsurgery, Academic Medical Centre, Amsterdam; Faculty of human movement sciences, Vrije Universiteit, Amsterdam; Orthopaedic Research Centre, Academic Medical Centre, Amsterdam (ORCA).

The research projects were financially supported by the Dr. W.M. Phelps Stichting voor spastici; Johanna KinderFonds.

Publication of this thesis was further made possible by the financial support of the Dr. W.M. Phelps Stichting voor spastici; Red Cross Hospital, Beverwijk, The Netherlands; Netherlands Society for Plastic Surgery; Netherlands Society for Surgery of the Hand; Universiteit van Amsterdam; Institute for Fundamental and Clinical Human Movement Sciences; Allergan Services International Ltd.; Anna-Fonds, Leiden.

Kreulen, Michiel
On tendon transfer surgery of the upper extremity in cerebral palsy
Universiteit van Amsterdam – Thesis – with summary in Dutch
ISBN: 90-804121-2-0
Layout: M. Kreulen
Print: Digital Printing Partners Utrecht, Houten

This book is a supplementary synopsis of the complete and fully illustrated academic dissertation of Michiel Kreulen, published on CD-ROM.

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ON TENDON TRANSFER SURGERY OF
THE UPPER EXTREMITY IN CEREBRAL PALSY

ACADEMISCH PROEFSCHRIFT

ter verkrijging van de graad van doctor
aan de Universiteit van Amsterdam
op gezag van de Rector Magnificus
prof. mr. P.F. van der Heijden
ten overstaan van een door het college voor promoties ingestelde
commissie, in het openbaar te verdedigen in de Aula der Universiteit
op woensdag 1 december 2004, te 10.30 uur

door

Michiel Kreulen
geboren te Geldrop
Promotiecommissie

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Faculteit Geneeskunde
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Chapter 6 Movement patterns of the upper extremity and trunk associated with impaired forearm rotation in patients with cerebral palsy.

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ics and of motor development of the maturing musculoskeletal system forms the basis of the current diagnostic algorithms and treatment regimes.

Surgery of the upper extremity in cerebral palsy is classically aimed at improvement of the range of motion of the affected joints and, if present, at the correction of joint instability. Today, a variety of procedures is available to compose the surgical plan for the correction of muscle imbalance, considering the needs of each individual patient. Tendon transfer and tendon rerouting procedures are in particular employed to balance the forces that cross a joint. Despite the progress in understanding cerebral palsy, however, knowledge of the biomechanics of tendon transfer and of the affected kinematics of the upper limb in cerebral palsy is lacking, while it is indispensable for appropriate surgical planning to meet the requirements of an optimal muscle balance.

This thesis

From this perspective, we have embarked on a research project that aims at the ultimate goal to compose an optimal combination of surgical procedures tailored to balance the forces in the upper extremity as required by the desired functional improvement of the patient. This thesis presents the results of the first step in this
process, which is to test the validity of the current biomechanical concept of tendon transfer. According to this concept, the original function of the selected donor muscle is completely eliminated by disconnecting the tendon from its insertion. Subsequently, it is assumed that the unchanged biomechanical properties of this muscle can be made available on a new location by transfer of its tendon, provided that the architecture of the muscle is not damaged and the appropriate muscle length after transfer is achieved. Furthermore, the new function of the transferred muscle is presumed to only affect movements around the rotation axes that it crosses. Vice versa, all postoperative change of these movements is attributed only to the transferred muscle function. The correction of muscle imbalance across other joints should be addressed by additional procedures. The research presented in this thesis challenges all these assumptions on the hypothesis that the classical biomechanical concept of tendon transfer is incorrect.

Outline

A prerequisite for the classical concept is that the biomechanical properties of a muscle do not change when its anatomical environment changes. The observations presented in the first two chapters of this thesis investigate the possibility that flexor carpi ulnaris muscle function is related to the surrounding fascial connective tissue. If so, both the preservation of the muscle’s anatomical environment in tenotomy (Chapter one) and its dissection during tendon transfer (Chapter two) will affect the muscle’s function differently than expected according to the classical concept.

Subsequently, upper limb kinematics are studied to assess the functional result of tendon transfer. A three-dimensional video analysis system was set up for this purpose. The selection and design of tendon transfer to correct a pronation deformity was questioned by a prospective clinical outcome study using this three-dimensional video analysis system (Chapter three) and, subsequently, by using a computer simulation of the transfer procedure on a three-dimensional biomechanical model of the arm (Chapter four). It is nearly impossible to obtain direct proof that the observed change in forearm rotation is caused directly and only by the function of the transferred muscle. However, the mechanical evaluation of the computer simulated tendon transfer should at least have been compatible to the results of the clinical outcome study. If not, alternate forces or pathways should be entertained and possibly integrated in the tendon transfer concept.

Finally, the movement patterns of the entire extremity and trunk were studied using the 3D video analysis system. For this, a completely new parameter called ‘extrinsic forearm rotation’ was introduced to study movements outside the forearm that supplement forearm rotation (Chapter five). The presence of pathological
movements directly associated with impaired forearm rotation was studied by comparison of this new parameter between ten patients with cerebral palsy and ten case-matched controls. The effect of surgical correction of the pronation deformity on these associated movement patterns was studied one year postoperatively in these patients (*Chapter six*). The degrees of freedom that are aimed to improve by surgery may not be the only degrees of freedom that are affected. If so, such an effect should be anticipated in surgical planning as it may involve deformities that are affected by the correction of others.

This thesis is concluded with an epilogue in which I discuss how the results of the presented research may dispute the aforementioned classical concept of tendon transfer, and how this may affect surgical treatment of the upper extremity in cerebral palsy in the future.

"... The loss of a lower extremity is a great privation, but experience shows that the deprivation of the use of the arm and hand is felt as a far greater affliction; so much the greater therefore must be the reward of him who, by adding to the common stock of knowledge on the remedy of this, can so largely contribute to the welfare of his fellow creatures."

WJ Little, 1843
CHAPTER 1

Restored flexor carpi ulnaris function explains the disappointing result of mere tenotomy in the spastic wrist

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Abstract

Objective: To prove that fibrous restoration of the continuity of a cut tendon may cause recurrence of flexion deformity of the wrist after mere tenotomy of the spastic flexor carpi ulnaris muscle.

Design: Case description.

Background: Mere tenotomy of the flexor carpi ulnaris tendon is insufficient to prevent recurrence of acquired spastic flexion deformity of the wrist. Subsequent restoration of the continuity of the tendon by fibrous interposition may result in the recurrence. We examined whether a previously tenotomised muscle is strong enough to cause the deformity.

Methods: Active and passive force-length characteristics of the flexor carpi ulnaris muscle were measured intraoperatively in a patient with recurrent spastic flexion wrist deformity. The observed characteristics were compared with the average in vivo force-length characteristics of fourteen spastic flexor carpi ulnaris muscles that had not previously been operated.

Results: The previously tenotomised flexor carpi ulnaris muscle was able to maximally exert 110 N force. Its active force-length curve and passive force at maximal extension were similar to those of non-operated spastic flexor carpi ulnaris muscles.

Conclusions: A previously tenotomised flexor carpi ulnaris muscle is strong enough to cause recurrence of spastic flexion deformity of the wrist in case functional fibrous restoration of the tendon occurs after mere tenotomy.

Relevance: The surgical routine of mere tenotomy should probably be modified by including the dissection of the distal muscle belly and the excision of a segment of the tendon to avoid its restoration.

Clinical Biomechanics 2004; 19: 429-32

Introduction

Tenotomy to release the deforming force of a muscle has been widespread employed since Dr. Louis Stromeyer performed a subcutaneous tenotomy of the Achilles tendon to correct a clubfoot in 1834. Mere tenotomy of the flexor carpi ulnaris (FCU) tendon is generally accepted as a means to improve the position of
the wrist during functional activities in patients with mild spastic flexion deformity of the wrist in whom active extension is still possible. During repeat surgery for recurrent flexion deformity after mere tenotomy, however, we repeatedly found formation of a fibrous interposition to have restored the continuity of the tendon. Because we accept the restored continuity to lead to the recurrence, we hypothesise that the previously tenotomised muscle is sufficiently strong to cause the deformity.

We now have a reliable technique for in vivo measurements of force-length relationship on human muscle, as well as reliable data to establish average values for spastic FCU muscle that have not previously been operated. This offers a unique opportunity to test, during repeat surgery, whether previous tenotomy of the FCU alters the muscle's mechanical properties. In this paper we present the results of in vivo force-length measurements of a FCU muscle 7 years after tenotomy and compare these results to those obtained in non-operated spastic FCU muscles.

**Methods**

*Patient*

In 1995, a then 9-year-old girl presenting with spastic flexion deformity of the wrist caused by cerebral palsy underwent tenotomy of the FCU tendon as described by Zancolli. Using a transverse incision in the palmar crease of the wrist, the FCU tendon and its paratenon were cut completely resulting in abrupt retraction of the proximal end and a satisfactory release of the flexion deformity. In 2002, the result of the tenotomy had become insufficient to balance the flexion and extension forces around the wrist and the flexion deformity had recurred. A tight strand could be palpated on the ulnovolar side of the distal forearm during active flexion, indicating that FCU function was restored. It was decided to re-operate and the patient gave informed consent for intra-operative force-length measurements in accordance with a protocol that had been approved by the Medical Ethical Committee of the Academic Medical Centre in Amsterdam.

At surgical exploration, the continuity of the previously cut FCU tendon was found to be restored by strong interposing longitudinal fibrous fibres that only slightly adhered to the surrounding soft tissues (figure 1). Repeat transection of the restored tendon again corrected the flexion deformity and, immediately following tenotomy, the FCU force-length characteristics were intraoperatively measured (see below). Because the muscle still showed to be a suitable motor for transposition surgery, the cut FCU was dissected and transposed subcutaneously to be...
Complete restoration of the continuity of the distal FCU-tendon, 7 years after tenotomy. The FCU had been only dissected until the distal tendon and its paratenon was released. Note that the muscle belly appears to barely have retracted. Additional procedure was a release of the adductor pollicis muscle, which has no influence on the wrist.

Measurement of force-length characteristics

Our method of in vivo measurement of active and passive force-length curves of the FCU has previously been validated and described in detail. In short, a series of maximal tetanic contractions of the FCU were induced at subsequent increasing muscle lengths 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 (RedDot 2560, 3Com Inc., Minneapolis, Minnesota, USA) that were pasted on the skin directly overlying the cubital tunnel of the elbow. A strain gauge was attached to a metal ring sutured on the distal tendon of the tenotomised FCU and to a metal bar that was attached to a Kirschner-wire in the medial epicondyle. The strain gauge was kept aligned with the FCU. Just prior to and during stimulation, the strain gauge signal was A/D-converted and stored in a computer. Force measurements were obtained at a series of muscle lengths, varying from that corresponding to well shorter than the length at maximal flexion.
of the wrist, to that corresponding to well beyond the length at maximal wrist extension.

Data analysis

The muscle’s operating length range, defined as the range of the length of the FCU from maximal passive flexion to maximal passive extension of the wrist was calculated and compared to the operating length range of 14 spastic FCU muscles that had not previously been operated.

Using a Microsoft Excel 2000 software package, the re-tenotomised muscle’s passive and active force-length characteristics were plotted to be compared with the average force-length characteristics of the muscles that had not previously been operated.

![Figure 2](image)

Active and passive force-length curve of the spastic FCU after previous tenotomy was restored. The marked area shows the operating length range of the FCU during range of motion (from 75 degrees flexion to 40 degrees of extension). The black dashed line indicates the FCU length at neutral position of the wrist.
Results

Operating length range

Seven years after tenotomy, the FCU operating length range of the patient was 1.4 centimeters, with the range of motion of the wrist ranging from 75 degrees flexion to 40 degrees of extension (figure 2). The operating length range was situated mainly on the descending part of the active force-length curve, and overlapped with the average operating length range of the non-operated spastic muscles.

Passive force-length characteristics

At maximum extension of the wrist, the passive force was approximately 15 N. The passive force curve fell within the 95% confidence interval of the average curve of the non-operated spastic FCU muscles (figure 3).

Figure 3

Compound graphic of the force-length curve observed after previous tenotomy in our patient (dashed), and the average force-length curve obtained from non-operated spastic FCU muscles (continuous), including the 95% confidence interval error bars. Force is normalized for maximum active force; length is expressed as deviation from optimum length.
Active force-length characteristics

The patient's FCU was able to exert 60 N to 110 N of force within its operating length range. The shape of the active force-length curve of the previously tenotomised FCU was similar to that of the average curve of the non-operated spastic FCU muscles and its values fell within the 95% confidence interval of the average (figure 3).

Discussion

We proved the force of a spastic FCU not to have decreased by mere tenotomy in our patient and, provided the severed tendon has restored, this may explain a disappointing long-term result of the tenotomy. Functional restoration by formation of a fibrous interposition between the two stumps of a severed tendon is not exceptional and conservative treatment of closed traumatic rupture of tendons even relies on it to happen\textsuperscript{34, 53}. Previously we showed that the gap between the stumps of a cut FCU tendon remained small after mere tenotomy in spastic patients and that the muscle retracted less than one centimeter even when the muscle was electrically stimulated to actively retract\textsuperscript{29}. The surrounding fascial connections of the long muscle belly apparently retain the muscle fibres at their functional length and prevent the muscle to shorten to a length at which it can only exert little force. After subsequent fibrous interposition between the stumps, therefore, the result of mere tenotomy may be compared to that of limited lengthening of the tendon.

The tenotomy gap may be increased by dissection of the distal one-third of the muscle belly as this allows the muscle to retract some two centimeters\textsuperscript{29}. Hence, we advise additional proximal dissection of the FCU muscle rather than mere tenotomy, to allow the gap between the tendon stumps to increase. Excision of part of the FCU tendon will further diminish the risk of tendon regeneration. On the basis of these unique measurements of intraoperative force-length characteristics of the functionally restored spastic FCU in a patient with recurrence of flexion deformity of the wrist we conclude that similar measurements in additional cases may prove mere tenotomy to be inadequate and, therefore, obsolete.
CHAPTER 2

Biomechanical effects of dissecting flexor carpi ulnaris

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Abstract

Our aim was to determine whether the length and function of the flexor carpi ulnaris muscle were affected by separating it from its soft tissue connections. We measured the length of flexor carpi ulnaris before and after its dissection in ten patients with cerebral palsy. After tenotomy, tetanic contraction shortened the muscle by a mean of 8 mm. Subsequent dissection to separate it from all soft tissue connections, resulted in a further mean shortening of 17 mm (p < 0.001). This indicated that the dissected connective tissue had been strong enough to maintain the length of the contracting muscle. Passive extension of the wrist still lengthened the muscle after tenotomy, whereas this excursion significantly decreased after subsequent dissection.

We conclude that the connective tissue envelope, which may be dissected during tendon transfer of flexor carpi ulnaris may act as a myofascial pathway for the transmission of force. This may have clinical implications for the outcome after tendon transfer.

Journal of Bone and Joint Surgery 2003; 85-B: 856-9

Introduction

In order to transfer a tendon, the connective tissue which surrounds the donor muscle is dissected until the line of pull to the receptor tendon is in a straight line. Animal experiments have shown that these fascial connections act as pathways for the transmission of force between the muscle and its environment. The force of a muscle was found to be transmitted not only through its tendon, but also through connective tissue to adjacent muscles and non-contractile tissues. Consequently, this pathway of biomechanical interaction may significantly affect individual muscle function. Since the success of tendon transfer surgery depends on the function of the donor muscle after transfer, we have studied the passive and active changes in the length of the muscle of flexor carpi ulnaris (FCU) during surgical dissection.

The prerequisites for myofascial connections to act as a pathway for the transmission of force are that the connective tissue is strong enough to transmit force...
and that it can transmit it to a distal target through adjacent muscles and other extramuscular tissues.

In order to test the hypothesis that the connective tissue which is dissected is strong enough to transmit force, we measured the length of the FCU muscle after simple tenotomy and after subsequent unloaded maximal tetanic contraction. Further measurements were made after dissection of the muscle and again after maximal tetanic contraction. Immediately after tenotomy, the muscle was expected to shorten passively until its passive elastic force equalled the opposing resistance from the surrounding fascia\textsuperscript{24, 45}. Maximal tetanic contraction was expected to shorten the muscle further until a new equilibrium between the active force of the muscle and the fascial resistance was reached. If progressive dissection was to result in further passive and active shortening of the FCU, it would follow that the dissected connective tissue had been able to prevent the muscle from shortening and therefore had resisted the active force exerted by the muscle. To test the hypothesis that the inter- and extramuscular connective tissue actually transmits passive force, the length of the FCU muscle was measured before and after moving the wrist passively from maximal flexion to maximal extension. For the hypothesis to be proven, the muscle would have to lengthen passively while the wrist was moved from flexion to extension with the myofascial pathways intact, even after it had been completely disconnected from the wrist. After subsequent division of the myofascial pathways by progressive dissection, FCU would no longer lengthen by passive extension of the adjacent muscles which remain connected across the wrist. We present the results of this experiment carried out during transfer of the FCU in patients with cerebral palsy.

Patients and methods

We carried out transfer of FCU to the tendon of extensor carpi radialis brevis to correct a flexion deformity of the wrist in ten patients with cerebral palsy. The four boys and six girls had a mean age of 14 years (6 to 19). Ethical approval was granted and informed consent obtained from all patients.

Operative technique

Under general anaesthesia, a longitudinal incision was made over the distal third of the forearm from the pisiform bone along the ulnar border of FCU. Care was taken not to damage the fascial surroundings of the belly of the FCU muscle. The distal part of the tendon was prepared for tenotomy. The insertion of the distal muscle fibres into the tendon was marked with a fine suture. A Kirschner wire was placed in the medial humeral epicondyle to mark the origin of FCU, and the length
Figur ee 1
Diagram showing the mean shortening of the muscle of FCU after tenotomy and after dissection, before and after tetanic contraction (ML, muscle length).

of the FCU muscle was defined as the distance between this wire and the marker in the distal tendon (figure 1).

Length of FCU muscle before and after muscle dissection

The length of the muscle was measured with the wrist in neutral (0° flexion) and the elbow at a constant angle of flexion. We undertook three series of measurements of the length of the muscle: 1) with the FCU intact; 2) after division of the tendon of FCU and its paratenon just proximal to the pisiform bone, with complete release from its insertion; and 3) after careful dissection of the belly of the FCU muscle from its fascial surroundings throughout its length allowing transfer of the tendon and muscle to the dorsal aspect of the wrist in a straight line. The length of the muscle was measured before and after maximal tetanic contraction which was induced using two electrodes (RedDot 2560 skin electrodes; 3M Corporation, Maplewood, Minnesota) placed on the skin over the ulnar nerve in the cubital tunnel and a peripheral nerve stimulator (AMC-Medical Technical Development, Amsterdam, The Netherlands). Supramaximal tetanic contraction of the ulnar nerve was provoked using biphasic, intermittent pulses of an amplitude of 125 mA at a stimulus frequency of 50 Hz, a pulse duration of 0.1 ms, and a stimulus duration of 1000 ms, with the limb free to move. All measurements were made without the use of a tourniquet or muscle relaxants.
Passive excursion of FCU before and after dissection

We defined the passive excursion of the FCU as the lengthening of the muscle on passive movement of the wrist from maximal flexion to maximal extension. Immediately after each of the above three series of measurements, the length of the muscle was measured with the wrist in flexion and extension. The angles of maximal flexion and extension of the wrist before tenotomy were the same for all series of measurements, and verified using a goniometer.

Statistical analysis

The means of the measurements were compared using paired Student's t-test. The passive excursion of the FCU was calculated by subtracting the length of the muscle at maximal passive flexion from that at maximal passive extension of the wrist. The mean passive excursion for each series of measurements was also compared using paired Student's t-test.

Table 1
Lengths of FCU in ten children with cerebral palsy with the FCU tendon intact, after tenotomy and after muscle dissection; before and after tetanic muscle contraction.

<table>
<thead>
<tr>
<th>Case</th>
<th>FCU intact</th>
<th>Before tenotomy</th>
<th>After tenotomy</th>
<th>Before dissection</th>
<th>After dissection</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>233</td>
<td>229</td>
<td>225</td>
<td>222</td>
<td>214</td>
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<tr>
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<td>Mean</td>
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<td>204</td>
<td>196</td>
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<tr>
<td>(SD)</td>
<td>(36.2)</td>
<td>(37.7)</td>
<td>(37.8)</td>
<td>(36.9)</td>
<td>(36.3)</td>
</tr>
</tbody>
</table>
Results

Length of the FCU muscle before and after dissection

The mean length of the muscle with the wrist in the neutral position before tenotomy was 221 ±36.2 mm (SD) (table 1). After tenotomy alone, it shortened to a mean of 216 ±37.7 mm and shortened further to a mean of 213 ±37.8 mm after subsequent maximal tetanic contraction (figure 1). Progressive dissection caused a further mean shortening of 204 ±36.9 mm ($p < 0.001$). These results show that the connective tissue before dissection had been strong enough to oppose the active force of the muscle and to limit shortening. Tetanic contraction after dissection yielded the most shortening (mean, 196 ±36.3 mm). These observations support the hypothesis that the connective tissue envelope is strong enough to transmit force.

<table>
<thead>
<tr>
<th>Case</th>
<th>FCU intact</th>
<th>After tenotomy</th>
<th>After dissection</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<td>1</td>
</tr>
<tr>
<td>Mean (SD)</td>
<td>18 (4.0)</td>
<td>16 (3.8)</td>
<td>2 (1.9)</td>
</tr>
</tbody>
</table>

Passive excursion of the FCU before and after dissection

The mean excursion on passive movement of the wrist, from maximal flexion to maximal extension, was 18 ±4.0 mm (table 2). After tenotomy, the mean passive excursion was 16 ±3.8 mm, which is 89% of the original excursion, despite the fact that FCU had been disconnected from its insertion at the wrist. This implies that other tissues crossing the joint transmit force from FCU. After dissection of all soft-tissue connections from the belly of the muscle, the same passive movement
of the wrist induced only 11% of the original excursion (mean, 2 ±1.9 mm) (figure 2). In four patients, the passive excursion was zero. These observations support our hypothesis that the inter- and extramuscular connective tissue acts as a pathway for the transmission of force from the adjacent muscles to the disconnected distal tendon of FCU.

**Figure 2**
Diagram showing the mean passive excursion of FCU during movement of the wrist from maximal flexion to maximal extension before tenotomy, after tenotomy and after muscle dissection (ML, muscle length).

**Discussion**

The biomechanical properties of muscles which may be calculated from parameters of their architecture, are regarded as the most important determinants of their function\(^6, 36, 37\). Thus properties, such as the available active excursion of the tendon and the force capacity calculated from the architecture of the isolated muscle belly, are used to differentiate between muscles which may be used for tendon transposition\(^6, 17, 37\). This presumes that the function of a muscle will not change so long as its architecture is not changed. The biomechanics of a muscle also depend on its adjacent connections\(^23, 24, 45, 68\). Previous studies of the brachioradialis muscle have shown that division of its antebrachial fascial connections increased its available excursion\(^15, 17, 28\).
We found that the inter- and extramuscular connective tissue around FCU also influenced the transmission of force from the muscle belly distally. This observation is in variance with the theory that fascia is too compliant to transmit force. It proved strong enough to withstand the exerted active muscle force and stiff enough to transmit this force. Only after division of the myofascial pathways by progressive dissection did the excursion of FCU caused by passive extension from the adjacent muscles, decrease dramatically. The residual lengthening of the muscle in the other patients may be explained by the fact that the dissection of fascial connections was incomplete being only undertaken until transfer to the dorsal aspect of the wrist was in a straight line.

Recently introduced, so-called myofascial pathways of transmission of force have proved to be an important biomechanical determinant of the function of muscle in patients with cerebral palsy. As such, progressive dissection of the muscle may affect the outcome of tendon transfer surgery.
"... Unfortunately, the universal tenotomists who behold, in a contracted limb, a mere piece of mechanism held in an abnormal form by certain unnaturally tense cords, have, without reflection on the etiology and pathology of these deformities, proceeded with the knife to relax the contracted part, regardless of the numerous conditions requisite for a restoration of the function. ..."

WJ Little, 1843
CHAPTER 3

Three-dimensional video analysis of forearm rotation before and after combined pronator teres rerouting and flexor carpi ulnaris tendon transfer surgery in patients with cerebral palsy

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Abstract

The effect of combined pronator teres rerouting and flexor carpi ulnaris transfer on forearm rotation was prospectively studied by comparison of pre- and postoperative three-dimensional analysis of forearm range of motion in ten patients with cerebral palsy. One year postoperatively, surgery had improved maximal supination of the forearm in all patients by an average of 63°, but this was opposed by a mean loss of 40° pronation. Forearm range of motion increased by a mean of 23°. The centre of the range of motion on average shifted 52° in the direction of supination. Based on these results of objective forearm range of motion analysis, we conclude that the common combination of pronator teres rerouting and flexor carpi ulnaris transfer in patients with cerebral palsy effectively facilitates active supination but impairs active pronation.

Journal of Hand Surgery 2004; 29B: 55-60

Introduction

Impairment of supination of the forearm severely limits the function of the upper extremity in patients with cerebral palsy¹², ¹⁹, ²⁰, ⁴⁷, ⁴⁸, ⁶⁴, ⁷⁴. Therefore, a pronation deformity in which passive supination is possible beyond the neutral position of the forearm, but active supination is not, should be surgically corrected in cases where functional improvement is the goal of treatment²⁰, ⁴⁷, ⁴⁸. Pronator teres rerouting, as was originally described in 1899 by Tubby⁷⁷, is an accepted method for correcting pronation deformity and increasing the range of motion of the forearm²⁰, ⁴⁷, ⁴⁸, ⁶⁴, ⁷⁴, ⁸¹. It combines a release of the deforming pronation force with a transformation of the pronator teres muscle into a supinator by changing the direction of pull⁸¹.
Correction of a pronation deformity is combined with a tendon transfer procedure to augment wrist extension in cases where a concomitant flexion deformity of the wrist exists. Transfer of the spastic flexor carpi ulnaris to the extensor carpi radialis brevis is most often used for this in patients with cerebral palsy. Although flexor carpi ulnaris to extensor carpi radialis brevis transfer does not release the deforming pronation forces of the pronator teres and pronator quadratus muscles, it does have an effect on forearm rotation and may restrict pronation. The effect on forearm rotation of combined pronator teres rerouting and flexor carpi ulnaris to extensor carpi radialis brevis transfer has not been prospectively assessed and, therefore, we have investigated whether or not the increase in active supination after this procedure is accompanied by a loss of active pronation.

Pronation deformity of the forearm is difficult to quantify because of the nature of cerebral palsy and there is presently no objective clinical measure for the assessment of forearm rotation. As a result of the co-contraction phenomenon and involuntary associated movements the patient can only demonstrate maximal pronation or supination when the forearm is allowed to move freely in space. Thus, constraining the extremity during objective goniometric assessment inhibits the desired function and anxiety, enthusiasm, or physical contact with the examiner may also produce involuntary muscle spasms which hamper the clinical assessment. We therefore used three-dimensional video analysis of range of motion as an accurate technique of non-contact posture measurement that is independent of movement patterns.

Patients and Methods

Patients

The inclusion criteria for this study were: 1) patients with cerebral palsy; 2) surgical indication for correction of a pronation deformity of the forearm by pronator teres rerouting and correction of a flexion deformity of the wrist by flexor carpi ulnaris to extensor carpi radialis brevis transfer; 3) impairment of active supination of the forearm beyond the neutral position; 4) passive supination well beyond the neutral position; and 5) functional improvement of the upper extremity as the aim of surgery. For this surgical aim, the ability to initiate voluntary use of the upper extremity and strong motivation of the patient were prerequisites. Our exclusion criteria were: 1) presence of primary athetosis; 2) inability to independently sit on a chair without arm support, as this was necessary for the three-dimensional video analysis protocol; and 3) the need for additional surgical procedures which are known to affect forearm rotation. In accordance with these criteria eight men and two women (mean age, 16 years: range, 5-29 years) were included in the study.
The study protocol was approved by the Medical Ethical Committee of the Academic Medical Centre in Amsterdam and adhered to the ethical guidelines of the 1975 Declaration of Helsinki. A written consent was obtained from all patients or their parents.

### Table 1
Patient characteristics and preoperative passive forearm rotation (in degrees) by manual goniometry.

<table>
<thead>
<tr>
<th>Patients</th>
<th>Preoperative passive ROM</th>
<th>Surgical procedures</th>
</tr>
</thead>
<tbody>
<tr>
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</tr>
<tr>
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</tr>
<tr>
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<td>6</td>
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</tr>
<tr>
<td>9</td>
<td>M</td>
<td>18</td>
</tr>
<tr>
<td>10</td>
<td>M</td>
<td>19</td>
</tr>
</tbody>
</table>

Legend of abbreviations: PRO, active pronation; SUP, active supination; AP, adductor pollicis release; EPL, extensor pollicis longus rerouting; MCP-I caps., capsulodesis of the first metacarpophalangeal joint; FDS-IV to EPB, transfer of the fourth flexor digitorum sublimis to the extensor pollicis brevis; FDS/P fract., fractional lengthening of all flexor digitorum sublimis and profundus tendons; FCR fract., fractional lengthening of the flexor carpi radialis tendon.

**Surgical procedure**

One surgeon (MK) performed all surgical procedures. The surgical technique for pronator teres rerouting was identical to that of Strecke et al. The pronator teres muscle was released and dissected in proximal direction to allow transfer through a spacious window in the interosseous membrane, around the radius, and back to its former insertion. The tendon was reinserted with a non-absorbable suture through a drill-hole in the radiopalmar aspect of the radius with the forearm in supination.

For flexor carpi ulnaris transfer, we used the technique described by Beach et al. The distal two thirds of the flexor carpi ulnaris muscle were dissected to allow its tendon to be transferred through a subcutaneous tunnel around the ulna and to the dorsal aspect of the wrist. Care was taken that the tension of the flexor carpi
ulnaris after insertion in the extensor carpi radialis brevis tendon was adequate to hold the wrist in neutral or slight flexion against the force of gravity\textsuperscript{4,48}. Additional procedures to correct concomitant thumb-in-palm deformity and to improve the grasp and release ability were performed in all but one patient (table 1). The extremity was immobilized using a plaster cast for 6 weeks. Physical therapy was started subsequently and a night splint was used to preserve the functional position.

\textit{Pre- and postoperative video registration}

The preoperative video of forearm rotation was performed on the day before surgery. The postoperative video of forearm rotation was performed on average 14 months after surgery (range, 11-19 months). For both assessments, the patient was seated with both feet on the ground on a chair without arm supports. Ink markings were made on the skin over the acromion, the medial and lateral epicondyles of the humerus, and the ulnar and radial styloid processes. Two synchronized S-VHS video cameras were positioned approximately 180 centimetres above the floor and in front of the patient at an angle of 60° (figure 1).

Prior to the actual registration, the fields of view of both cameras were calibrated using a 60 x 60 x 60 centimetres frame with twenty markers. The field

\textbf{Figure 1}

Illustration of the experimental set-up for three-dimensional video registration of forearm rotation.
of view was set as small as was allowed by the borders of the calibration frame, after which the position and settings of the cameras were not changed. The examiner was seated in front of the patient at a distance of approximately 3 metres. After a demonstration by the examiner, the patient was asked to alternately pronate and supinate both forearms twice (figure 2). After a short relaxation time, the demonstration and forearm rotation task were repeated.

Data processing

One researcher (MJCS) performed all data processing. To prevent bias, the surgeon had no knowledge of the results until all data processing was completed. An S-VHS videocassette recorder (Panasonic AG-7130, Matsushita Electric Industrial Co., Osaka, Japan) was connected to a Macintosh Quadra 650 computer (Apple Computer Inc., Cupertino, Ca., USA). Data processing consisted of the following five steps:

Step 1: The recorded markers of the calibration frame (i.e. a global coordinate system) and those on the patient were identified and digitized using custom-made software. Identification was repeated five times for each marker. For both video recordings, a set of average values of the digitized data of each marker was used for further calculations, after correction for outliers.

Figure 2
Illustration of the position in which the patient alternately pronates and supinates the forearm during video registration.
Step 2: From these two sets of digitized video coordinates, the three-dimensional positions of the anatomical landmarks in space relative to the global coordinate system were reconstructed using the Direct Linear Transformation method\textsuperscript{50}. Overall precision of static and dynamic error of the 3D coordinates was estimated to be within 5 millimetres or 0.3% of the field of view\textsuperscript{14}.

Step 3: Forearm motion was determined relative to the upper arm. For that, the upper arm was considered as a local coordinate system that consisted of three axes: a horizontal axis through the medial and lateral epicondyle markers, a vertical axis through the acromion marker and the centre of a line between the medial and lateral epicondyle markers, and a forward axis perpendicular to the plane between the horizontal and vertical axes. In order to accurately calculate the actual position of the forearm relative to the upper arm, the rotation axes for elbow flexion-extension and for forearm rotation\textsuperscript{26} were defined as fixed hinges relative to the anatomical landmarks\textsuperscript{50, 83, 84}, and were based on the average anatomical rotation axes reported in a cadaver study\textsuperscript{83, 84}. This procedure ensured an estimation of a rotational angle around actual anatomical axes that was corrected for the use of landmarks on the upper arm and was not influenced by the carrying angle\textsuperscript{26}.

Step 4: The zero position (0 degrees elbow flexion, 0 degrees forearm rotation) is defined as the position in which the ulnar and radial styloid processes were in one plane with the medial and lateral epicondyles and the acromion. The degree of forearm rotation was calculated by mathematically rotating the 3D coordinates of the radial styloid process from this zero position around both the anatomical elbow flexion-extension axis and the anatomical forearm rotation axis until the calculated position of the radial styloid process fitted the position of the marker on the radial styloid process on the patient.

Step 5: Finally, the angles were expressed in pronation-supination angles according to standardized terminology for hand surgery\textsuperscript{9}. The 95% confidence interval of the calculated angles for pronation-supination estimates is below 5 degrees.

Statistical analysis

Four parameters that represent the differences between the preoperative and postoperative situations were calculated: 1) the change in maximal active supination of the forearm (ΔSup); 2) the change in maximal active pronation of the forearm (ΔPro); 3) the change in forearm active range of motion (ΔROM); and 4) the shift of the centre of active range of motion (ROM-shift). The pre- versus postoperative differences were statistically tested for significance using a paired Student’s $t$-test.
Results

Range of motion increased significantly \((p = .013)\) by a mean of \(23^\circ\) (SD, 22.2) (figure 3). Maximal active supination of the forearm from a pronated position towards a supinated position increased in all patients (table 2). Eight patients showed partial loss of active pronation of the forearm \((-90^\circ < \Delta \text{Pro} < 0^\circ)\), one had a complete loss of active pronation \((\Delta \text{Pro} < -90^\circ)\) and the final patient had no loss of pronation \((\Delta \text{Pro} = 0^\circ)\). Both the mean increase in active supination of the forearm \((\Delta \text{Sup} = 63^\circ\), SD = 35.1\), and the mean loss of active pronation \((\Delta \text{Pro} = -40^\circ\), SD = 37.5\) were statistically significant \((p < .001, \text{respectively} p = .011)\). The centre of the range of motion shifted towards a more supinated position by a mean of \(52^\circ\) \((p = .0015)\).

Table 2
Maximal active forearm rotation (in degrees) by 3D video analysis before and after surgery.

<table>
<thead>
<tr>
<th>Patients</th>
<th>Maximal active rotation</th>
<th>Maximal rotation difference</th>
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<td></td>
<td>preoperative</td>
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<td>Sup</td>
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<td>-28</td>
</tr>
<tr>
<td>4</td>
<td>83</td>
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<td>-2</td>
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<tr>
<td>10</td>
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<td>-14</td>
</tr>
</tbody>
</table>

Legend of abbreviations: PRO, active pronation; SUP, active supination; ΔPRO, difference between postoperative and preoperative active pronation; ΔSUP, difference between postoperative and preoperative active supination.
Figure 3

Graphical display of the mean preoperative range of motion and the mean postoperative range of motion. Note that the trajectory of the mean range of motion has shifted towards the neutral position.

Discussion

Three-dimensional motion analysis is an accurate technique of non-contact posture assessment and is accepted as the most valid method for gait analysis⁵. It has also been validated for the analysis of upper extremity movements¹¹. However, for patients with cerebral palsy, the accuracy of this technique may be biased by fluctuations in muscle tone related to the patient’s level of enthusiasm or anxiety in the clinical environment. Therefore, we made sure that our patients felt at ease with the setting, and allowed ample time for each patient to adapt. With this technique, we found the patients to be much more relaxed than during manual goniometric measurements. Hence, we believe that three-dimensional video
analysis is the best available technique for assessment of forearm rotation in patients with cerebral palsy, though, we view the observed changes in forearm rotation as a significant tendency in the observed direction rather than as the actual quantification of it.

The alleged supinator function of the rerouted pronator teres muscle has been subject to scepticism. Enriquez de Salamanca postulated that adhesions around the interosseous membrane might nullify the potential supination effect of the rerouted muscle. Unlike Enriquez de Salamanca, both Sakellarides et al. and Strecker et al. retrospectively reported satisfactory releases of the pronation deformity with marked increases in active supination after pronator teres rerouting. These studies, however, carry the restrictions of a retrospective design. Sakellarides et al. did not mention whether pronator teres rerouting was the only procedure and admitted that the surgical technique was modified during their series. Although no preoperative pronation data were recorded and although the postoperative pronation data on an ordinal scale showed impaired pronation ability, the authors claimed no pronation loss. Strecker et al. studied a population of 41 patients after pronator teres rerouting, of which seven also underwent a transfer of the flexor carpi ulnaris or extensor carpi ulnaris to the extensor carpi radialis brevis. They did not mention how the supination data were acquired and no preoperative or postoperative pronation data were recorded. Again, the authors reported no loss of pronation. A retrospective study that explicitly evaluated pronator teres rerouting as the only procedure reported a gain of active supination without loss of pronation, but did not provide preoperative or postoperative data.

So far, only Roth et al. has retrospectively studied the loss of pronation after pronator teres rerouting combined with a flexor carpi ulnaris transfer routed through the interosseous membrane. This routing has less effect on forearm rotation than routing the flexor carpi ulnaris subcutaneously around the ulna as was done in our series. Roth et al. recognized the difficulties in assessing the upper extremity range of motion in these patients. They actually advocated abandoning assessment of range of motion and focusing on the functional result of surgery. We agree that functional improvement is the goal of surgery and should be the measure for success. However, knowledge of how surgery changes the ability to move the forearm is essential for selecting the right combination of procedures to meet the patient's specific functional desires, especially when a loss of forearm motion might be anticipated. It is important to note that loss of pronation must be anticipated when a combination of pronator teres rerouting and flexor carpi ulnaris transfer is planned. The combination is contra-indicated in patients who require full pronation in their daily activities. The obvious function that will
be comprised is that of using a computer or communication board or the like. As many of these patients have lower limb impairment and are confined to chairs for significant periods of their life, a loss of pronation may become a significant disability.

Rather than a change in the total active range of motion, Roth et al.\textsuperscript{52} observed a shift in the arc of the range of motion towards supination as the reason for the gain in supination. Therefore, the gain in maximal active supination is not a reliable measure of the ability to rotate the forearm from a pronated position towards a supinated position. In our series, we found a loss of pronation as well as a significant increase in range of motion which contrasts with the observations of Roth et al.\textsuperscript{52}.

What caused this loss of pronation? It may be due to the synergetic action of both the transferred spastic flexor carpi ulnaris and pronator teres on forearm rotation, which suggests that the combination of these procedures carries the risk of overcorrection. It may also be explained by adhesions of the pronator teres or flexor carpi ulnaris along their new route\textsuperscript{12}, or by fixation of the transposed muscles under too much tension\textsuperscript{16}. A considerable tenodesis effect is suggested by the significant loss of pronation in our patients, but our study was not designed to differentiate between the results of the separate procedures. It should be emphasized that even a follow up of 1 year is relatively short for evaluating transfer of spastic muscles and the long-term effect of muscle adaptation on our results, especially in a maturing musculoskeletal system, requires further study. We feel that neither flexor carpi ulnaris transfer, nor pronator teres rerouting can be assumed to have caused all the improvement in supination function. The original supinator muscles themselves could have contributed to the gain in active supination as their function may have been facilitated by the surgical release of the constraining pronation forces.
CHAPTER 4

Mechanical evaluation of the pronator teres rerouting tendon transfer

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Abstract

We simulated Pronator Teres rerouting using a three-dimensional biomechanical model of the arm. Simulations comprised the evaluation of changes in muscle length and the moment arm of Pronator Teres, dependent on changes in forearm axial rotation and elbow flexion. The rerouting of Pronator Teres was simulated by defining a path for it through the interosseous membrane with attachment to its original insertion. However, the effect of moving the insertion to new positions two centimetres below and above the original position was also assessed. The effect on the total internal rotation and external rotation capacity was determined by calculating the potential moments for Pronator Teres, Supinator, Pronator Quadratus, Biceps Brachii and Brachioradialis. Pronator Teres was found to be a weak internal rotator in extreme pronation, but a strong internal rotator in neutral rotation and in supination. After rerouting, Pronator Teres was only a strong external rotator in full pronation and not at other arm positions, where the effects of rerouting were comparable to a release procedure.

Journal of Hand Surgery 2004; 29B: 257-62

Introduction

Pronator teres rerouting is used to correct pronation deformity of the forearm in patients with cerebral palsy⁴⁷, ⁶⁴, ⁷⁴. It is claimed that the rerouted pronator teres enables active supination and does not restrict pronation, such that it increases the forearm’s range of motion⁴⁷, ⁶⁴, ⁷⁴. However, retrospective study by Roth et al.⁶² reported loss of pronation.

In a kinematic study on the effect of pronator teres rerouting in combination with flexor carpi ulnaris transfer to the extensor carpi radialis brevis, we found that supination increased from −25° to 38°, or by 63°. However pronation reduced from 70° to 29°, or by 41° ⁴². It is unclear how this loss of pronation and increase in supination occurs. Van Heest et al.⁸¹ rerouted pronator teres in cadavers and suggested that, after transfer, the muscle functions as an external rotator through a
windlass, or winch, effect in which pronator teres is wound around the radius as a rope around a cylinder. A second assumption underlying the pronator teres rerouting (or release) procedure is that pronator teres is an important internal rotator over the whole range of motion of pronation and supination and certainly in the critical area relevant for interventions. If this is true, pronator teres must have a considerable moment arm when the forearm is pronated. However, recent anatomical studies have suggested that this might not be the case.

The aim of this study was to evaluate the effect of pronator teres rerouting on the moment arms and potential moment balance for internal-external rotation. Also, the effect of repositioning its insertion proximally and distally was evaluated.

**Methods**

Forearm pronation-supination angles were defined using the International Federation of Societies for Surgery of the Hand criteria. Since these criteria do not make a clear distinction between joint position and rotation, we decided to use the terms internal rotation and external rotation for the motor function of muscles. External rotation and external rotation moments were defined as negative, whereas internal rotation and internal rotation moments were defined as positive.

![Figure 1](image-url)

*The simulation procedure*
Model evaluations were performed with a three-dimensional model of the shoulder and arm. The anatomical structure of the model is based on data from an extensive parameter study. The elbow joint and pronation-supination axis were modelled as two hinge joints. Part of the radius was modelled as a cylinder with a diameter of 1.4 cm to allow pronator teres to wrap around the radius.

Pronator teres was modelled with two elements, one with an origin on the humerus and the second with an origin on the ulna. These elements each had an insertion point on the radius and together they represented a linear insertion. Other relevant muscles: biceps brachii, supinator, brachioradialis and pronator quadratus were modelled following the same principle.

Pronator teres function was assessed on the basis of nine series of supination-pronation angles (-80° to 80°), each at a different elbow angle, ranging from 10° to 170° elbow flexion (figure 1). This was done to investigate the effect of elbow flexion on the length of the proximal part of pronator teres. Outputs of the model were muscle lengths, muscle moment arms, and potential maximal moments (PMMs).

For the normal situation, pronator teres was allowed to wrap around the anterior margin of the radius. The rerouting procedure was simulated on the computer by passing pronator teres through the interosseous membrane and wrapping it around the posterior surface of the radius. This introduces a windlass effect. In addition, we simulated the effect of repositioning the insertion to a position 2 cm proximal or 2 cm distal to the original insertion.

Moment arms for each muscle element were estimated from the changes in muscle length relative to the induced changes in joint rotations, or model degrees-of-freedom:

Equation 1: \[ ma = \frac{\delta L}{\delta \phi}, \]
where \( L \) = muscle length,
and \( \phi \) = flexion, or pronation angle

The Potential Maximal Moments for the biceps brachii, brachioradialis, pronator teres, supinator and pronator quadratus were calculated as:

Equation 2: \[ PMM = ma \ast PCSA \ast c, \]
where \( ma \) = moment arm,
\( PCSA \) = physiological cross sectional area for the muscle,
and \( c \) = a constant which represents the force per unit \( PCSA \)
\( (= 100 \text{ N cm}^{-2}) \)
Results

Both the humero-ulnar and the ulno-radial parts of pronator teres became shorter when the forearm was pronated. The humero-ulnar part also shortened with elbow flexion (figure 2). After simulated transfer, both parts of pronator teres showed a small increase in length with pronation, but this was only about 20% of the normal decrease in length which occurs with pronation.

In the normal conditions, the moment arm of pronator teres ranged from 0.6 cm in extreme supination (-80°) to approximately 0 cm at 80° pronation. The peak moment arm lay around the neutral position. Differences between the humero-radial and ulno-radial parts of pronator teres were small. In addition, the effect of elbow angle on the moment arm was negligible (figure 2). After simulated rerouting, pronator teres became an external rotator, i.e. the moment arm was negative, when the arm was in pronation (figure 2). When the arm was in supination, the moment arm of pronator teres was small but positive, indicating that the muscle still acted as an internal rotator, although much less effectively than in normal conditions. The effect of repositioning of the insertion site to a more proximal or distal insertion site on average muscle length was considerable (figure 3). The effect on moment arms was, however, minimal. Only with a more distal insertion and with the arm in supination was the moment arm smaller than the original moment arm (figure 3). For the simulated transfer, the moment arms were hardly influenced by more distal, or proximal, insertions. A more proximal insertion increased the external rotation effect of the transfer, but did not turn pronator teres into an external rotator over the full range of motion.

The PMMs (figure 4) for pronation around the forearm are produced primarily by pronator teres and pronator quadratus. Pronator teres is primarily effective in supination, pronator quadratus in pronation. Brachioradialis functions as an internal rotator in supination and as external rotator in pronation (figure 4). Biceps is the strongest external rotator, followed by supinator. When pronator teres was rerouted, the internal rotator PMM for this muscle was reduced and changed to an external rotation function for pronated arm positions, adding to the already existing PMMs for supinator, biceps and brachioradialis (figure 5). In supination the rerouting did not produce an external rotation PMM for pronator teres, but it strongly reduced its internal rotation PMM.
Figure 2
Length and moment arm for the humeral (left) and ulnar (right) parts of pronator teres. The different lines for the humeral part indicate the effect of elbow flexion (from 10° to 170°). The results for rerouting are given as dashed lines.

Figure 3
Effect of insertion site on muscle length and moment arm.
Discussion

The aim of this study was to evaluate the effect of pronator teres rerouting on moment arms and potential moment balance for internal and external rotation of the forearm. To do this we used a musculoskeletal model of the arm, which is based on a number of assumptions and limitations that will influence results. Firstly, the model is based on the anatomy of one specimen, and describes the mechanical relationships between the geometry and the muscles of that specimen. The model treats each muscle as a separate actuator and does not consider the possibility of direct force transmissions between, or within them. Secondly, although the simulations consider the effects of changes in moment arms and changes in length, they do not estimate the physiological effects of length changes, such as the force-length relationship of muscles and the effect of optimum length on the moment generating capacity of each muscle. This will result in an overestimation of PMM values when the muscles are shortened and an underestimation of the PMMs when the muscles are lengthened. However, the extent of this under- or overestimation

![Graph showing maximal obtainable moments of five arm muscles for the normal case (top) and after simulated pronator teres rerouting. Values are the product of moment arm and muscle cross-sectional area, multiplied by a constant force value of 100 N cm⁻².](image)
of length effect is unknown, given the uncertainties regarding the physiological adaptations to length changes. Thirdly, the model does not consider the possibility of pathological reflex effects on muscle behaviour.

Despite these limitations, the model does provide an accurate description of the mechanical effects of rerouting and of the relationships between moment arms and joint angles for the most relevant muscles.

In the normal case, the moment arm of pronator teres was largest near the neutral position and smallest in extreme pronation (figure 2). This supports the results of cadaveric dissection experiments which concluded that pronator teres has a small moment arm in pronation and that pronator quadratus is the most important internal rotator when the forearm is in pronation (figure 4). It is not clear what causes the limited range of motion and extremely pronated forearm position in children with cerebral palsy. Pronator teres could be responsible for this as a result of muscle contracture or shortening, or because of dysfunctional reflex activity during active external rotation.

![Potential Maximal Moment balance, elbow 90°](image)

**Figure 5**
Net potential moments for pronation and supination at an elbow angle of 90°. The sum of potential moments is always lower than zero, which indicates a stronger supinator function.
If an extremely pronated arm position is the result of a shortened pronator teres, either rerouting or release will result in an increase in range of motion and supination. Stretching pronator teres in the process of rerouting might reduce pronation but, since the winch effect is small, the muscle length of the rerouted pronator will only change moderately with pronation (figure 2). Consequently, forearm pronation will not be significantly restricted by limited lengthening of the rerouted muscle. Also, these effects would be difficult to predict due to the peroperative uncertainty on the exact muscle length and arm position and the relationship between pronation angle and muscle length (figure 2): large angle changes are related to minor length changes. As a consequence, the effect of rerouting on range of pronation might show large inter-individual variation, which was indeed the case for a group of 10 patients, in whom the standard deviation for the postoperative range of pronation was $40^{\circ}\pm32$. If dysfunctional reflex activity is limiting pronation then the dysfunctional pronator teres would counteract the activity of the external rotators, but only if pronator teres acts as a strong internal rotator in the neutral position (figures 3 and 4). Rerouting would remove any (dys)functional internal rotating effect of pronator teres and convert this muscle into a functional external rotator. However, both rerouting and release would decrease the total PMM for internal rotation (figures 4 and 5).

In our previous study on the effect of rerouting in children with cerebral palsy, the pre-operative range of forearm rotation ranged from $70^{\circ}$ (SD, $14^{\circ}$) pronation to $25^{\circ}$ (SD, $24^{\circ}$) pronation (no supination possible)$^{32}$. Surgical procedures, which included pronator teres transfer, improved forearm range of motion to $29^{\circ}$ (SD, $40^{\circ}$) of pronation to $38^{\circ}$ (SD, $28^{\circ}$) of supination. Based on these results, the clinically relevant moments of the pronator teres would be around the neutral position, where the results of this study suggest that the effect of rerouting is only marginally better than that of a release. In this position the rerouted pronator teres could only contribute marginally to external rotation. In fact, the improvement found in this study is almost completely due to the release effect, and not the rerouting of pronator teres. At $25^{\circ}$ pronation, the limit of supination in our clinical group, pronator teres would function as an important internal rotator (figure 2), but rerouting would not turn it into a strong external rotator. Thus the $38^{\circ}$ of supination achieved in these patients following surgery would hardly have been influenced by the new function of pronator teres since rerouting this muscle changed it from a strong internal rotator into a weak internal rotator (figures 3 and 4). We thus consider that the value of rerouting is limited and predominantly due to the release effect of the procedure.
The results of the present study are somewhat different to those reported by Van Heest et al. They performed a cadaver study and concluded that rerouting of pronator teres did produce supination. It was proposed that this effect was based on the windlass imposed by the transfer. However, this could have been accompanied by a decrease in origin-insertion distance for pronator teres during pronation due to the slanted angle of the pronation axis relative to the long axis of the forearm. This might cancel out or reduce the windlass effect of the transfer and thus make the procedure ineffective. Since length change relative to angle change is in fact the muscle’s moment arm (equation 1), the lengthening due to the windlass effect and the shortening due to the rotation of the radius might lead to a far smaller length change relative to the amount of pronation and thus to a smaller moment arm.

A possible explanation for van Heest et al.’s different results might be related to their technique. The use of a weight to study the effect of transfers implies that the moment balance was determined by the added weight, gravity and the resisting forces of other structures, which are dependent on the amount of joint rotation. Pronator quadratus would have lengthened during supination and thus produced an increasing resistive force during this motion.

On the basis of the results of our study, applying a pulling force of 500 g to the rerouted pronator teres would cause only marginal changes in supination, since the moment arm of pronator teres was approximately zero, or even positive, after transfer. Repositioning the muscle to a more palmar position would not have changed this effect since this would have increased the overall length of the muscle (due a larger wind-up), but not the amount of shortening.

As mentioned previously, the pronated position of the forearm in children with cerebral palsy might be related to an extremely short pronator teres, which can be corrected by either a release or by rerouting. Lengthening of pronator teres without rerouting by moving its insertion proximally, might lead to an increase in maximal supination, but only if the muscle was extremely shortened. Given the results in figure 3, this procedure would only have a limited effect on the moment arm of the muscle. Whether this option is a feasible procedure and an alternative to a release or rerouting remains subject for further study.
"... in the case of the hand, every individual, from the day-labourer to the watchmaker, or the workman in the minutest branch of the arts, avails himself constantly, not only of flexion and extension, but of pronation and supination. If you, at the same time, bear in mind that, nonwithstanding the analogy in these movements of the upper and lower extremities, the acts of pronation and supination are far more delicate and elaborate than the analogous movements of the foot; if you remember that not only are the movements of the hand much more complicated, but that the several fingers possess each their allotted muscles and consequent functions, you will at once perceive that although in principal orthopaedic operations are equally applicable to the hands, the difficulty of applying the method must be immeasurably greater."

WJ Little, 1843
CHAPTER 5

Movement patterns of the upper extremity and trunk associated with impaired forearm rotation in patients with cerebral palsy

Part I: a comparison to healthy controls

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Abstract

The aim of this study was to assess the relation between impaired forearm rotation and concomitant movement patterns of the upper arm and trunk in patients with cerebral palsy. For this purpose, ‘extrinsic forearm rotation’ is introduced as a parameter to quantify the cumulative result of all movements that supplement forearm rotation. The results of three-dimensional video analysis of the upper extremity and trunk in different reaching tasks in eight male and two female patients (mean age, 16 years and 2 months) are compared to those of ten case-matched controls. The active forearm rotation impairment in the patient group as compared to the controls was combined with a significantly higher value for extrinsic forearm rotation. Based on this observation, we conclude that impaired forearm rotation is associated with movement patterns that externally supplement forearm rotation and advocate to assess the overall movement strategy rather than just the forearm deformities in patients with cerebral palsy.

Submitted for publication

Introduction

As a result of disturbed inter-joint coordination⁸, ⁷³ and limited available range of motion of the joints⁷³, ⁸², the affected upper extremity of patients with hemiplegic cerebral palsy moves in complex patterns during functional activities. To compensate for the lack of available range of motion of the affected joints, additional degrees of freedom are integrated in the movement strategy to complete a task⁸, ⁷³. Compensatory trunk movements are recruited when the range of motion of the upper extremity joints is insufficient, or when the effort of bringing the required range of motion into action exceeds the effort of recruitment of the trunk⁴⁹.
This study was set up to objectify whether, and how, the upper arm and trunk are recruited for compensation of impaired forearm rotation in surgically untreated patients with cerebral palsy. For this purpose, we introduced a parameter called 'extrinsic forearm rotation' that quantifies the collective result of all body movements that rotate the hand except forearm rotation. As such, 'extrinsic forearm rotation' supplements or counteracts the effect of forearm rotation on the rotational position of the hand in space. Patients with impaired forearm rotation were expected to have higher values for extrinsic forearm rotation compared to subjects without impairment. If this proved true, the recruited degrees of freedom that constitute this increased extrinsic forearm rotation may be considered as pathological movements directly associated with impaired forearm rotation. The linking of associated movements to a specific joint deformity implies that treatment aiming at the correction of that single impairment will have effect on all degrees of freedom involved in these associated movements.

In this paper we present the results of three-dimensional analysis of forearm rotation, its concomitant recruitment of the upper arm and trunk, and the extrinsic forearm rotation in ten patients with cerebral palsy and compare them to those in ten case-matched controls.

Methods

Patients and age-matched controls

Eight male and two female patients (mean age, 16 years and 2 months; range, 11 - 27 years) were included in the study. Inclusion criteria were: 1) hemiplegic cerebral palsy, 2) impaired active supination of the forearm, 3) the ability to initiate voluntary use of the upper extremity, 4) no prescription medicine known to affect the musculoskeletal system, and no history of trauma or surgery of the upper extremities or trunk, and 5) the ability to independently sit on a stool, as this was a prerequisite for the three-dimensional movement analysis. Patients who were not able to perform the measurement protocol using the required grips were excluded from the study.

Inclusion criteria for the ten age- and sex-matched healthy controls (mean age, 16 years and 5 months; range, 11 - 27 years) were: 1) unrestricted forearm rotation, and 2) no history of trauma, surgery, disease or prescription medicine known to affect the musculoskeletal system. In the control group, movement patterns of the non-dominant upper extremity were examined for this study.

The study protocol was approved by the Medical Ethical Committee of the Academic Medical Centre in Amsterdam. Informed consent was obtained from all included patients and controls.
3D video registration

To allow for unrestricted movements in order to explore the full adaptive capacity of the disordered movement system, we used three-dimensional video analysis of range of motion as an accurate technique of non-contact posture measurement of the forearm, upper arm, and trunk. The method we used has previously been used and reported and adheres to recommendations for standardisation. In short, the subject was seated on a stool without arm or back support with both feet on the ground. Ink markings were placed on the skin over the manubrium sterni, the xiphoid process, the acromion of both shoulders, the medial and lateral epicondyles of the humerus, and the ulnar and radial styloid processes on the affected arm (figure 1). The skin markings in all patients were made by the

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**Figure 1**

Illustration of the anatomical markings on the patient and the orientation of the global and local coordinate systems. Legend: Xg, Yg and Zg: x-, y- and z-axes of the global coordinate system; Xt, Yt and Zt: x-, y- and z-axes of the local coordinate system for the trunk; Xu, Yu and Zu: x-, y- and z-axes of the local coordinate system for the upper extremity.
same two examiners (MK & MJCS). Two synchronised S-VHS video cameras were positioned in front of the subject at an angle of 60 degrees. Prior to video registration, the field of view was calibrated and set to match the borders of a 60 x 60 x 60 centimetres calibration frame, after which the position and settings of the cameras were not changed. The patients were allowed ample time to familiarise with the experimental set-up. After a demonstration by the examiner and a trial session by both the examiner and the subject, each of the following four tasks were performed twice. First, the subject was asked to maximally supinate both forearms. Then, a table was placed directly in front of the subject with its surface at elbow height. A drinking glass was placed on the table within reach of the affected arm. The subject was asked to pick up the glass using a cylinder grip and to steadily hold it as vertical as possible (as if to avoid spilling the beverage) requiring a neutral position of the forearm. After that, the subject was asked to maximally pronate both forearms. Subsequently, a wooden disk of 8 centimetres diameter and 1 centimetre height was placed flat on the table for the fourth and last task. The subject was asked to pick up the wooden disk by placing the thumb and fingers around it in a spherical grasp requiring forearm pronation.

**Data analysis**

An S-VHS videocassette recorder (Panasonic AG-7130, Matsushita Electric Industrial Co., Osaka, Japan) was connected to a Macintosh Quadra 650 computer (Apple Computer Inc., Cupertino, CA, USA). Five images from both video recordings and of each session were selected for further analysis of upper extremity and trunk position (figure 2): the subject 1) while sitting on the stool in a resting position just before performing the tasks, 2) at the moment of maximal active supination, 3) at the moment of grasping the glass and stabilising it in vertical position, 4) at the moment of maximal active pronation, and 5) at the moment of grasping the wooden disk. The recorded markers of the calibration frame (i.e. a global coordinate system) and those on the subjects in all selected images were identified and digitized. Identification was repeated five times for each marker to increase accuracy. A set of average values of the digitized data of each marker was used for further calculations. From the two sets of digitized video coordinates (one set for each camera), the three-dimensional positions of the anatomical landmarks relative to the global coordinate system were reconstructed using the Direct Linear Transformation method. Overall precision of static and dynamic error of the 3D coordinates was estimated to be within 5 millimetres or 0.3% of the field of view. This way, the positions of the forearm, upper arm, and trunk in the five selected images could be calculated using the 3D coordinates of the anatomical landmarks.
Illustrations of the five selected images from the video recordings. Legend: Image #1 = resting position; Image #2 = maximal supination; Image #3 = grasping the glass in supination; Image #4 = maximal pronation; Image #5 = grasping the disk in pronation.

1. Calculation of forearm position

The forearm was represented by the markers of the medial and lateral epicondyles combined with those of the radial and ulnar styloid processes. Forearm rotation and elbow flexion were determined relative to the upper arm$^{32, 84}$. For this, a local coordinate system for the upper arm was constructed using the markers of the
medial and lateral epicondyles and the acromion (figure 1). The axes of forearm rotation and of elbow flexion-extension were based on the average actual rotation axes relative to anatomical landmarks. This method ensured a value for a rotational angle around actual anatomical axes that was corrected for the use of skin markers and was not influenced by possible carrying angles. The zero position (0 degrees flexion, 0 degrees rotation) was defined as the virtual position of the arm in which the ulnar and radial styloid processes were in one plane with the medial and lateral epicondyles and the acromion. The degree of forearm motion was calculated by first mathematically rotating the 3D coordinates of the ulnar styloid process from the zero position around the anatomical elbow flexion-extension axis, until its position fitted the actual position of the ulnar styloid process of the patient. Second, the coordinates of the radial styloid process were mathematically rotated around the anatomical forearm rotation axis until its calculated position fitted the position of the marker of the radial styloid process on the patient. Finally, the angle of rotation around the anatomical forearm axis was expressed as forearm pronation-supination with 0 degrees rotation from the zero position equalling 90 degrees of supination and 180 degrees rotation from the zero position equalling −90 degrees (i.e. 90 degrees pronation). Elbow flexion angles were expressed in positive values equalling the degree of flexion relative to the zero position, whereas elbow extension angles were expressed in negative values.

2. Calculation of extrinsic forearm rotation

Thus, forearm rotation is determined relative to the local coordinate system of the upper arm. Although the hand is rotated by the forearm, it is also rotated by movements of the rest of the body, supplementing or counteracting the effect of forearm rotation on the position of the hand in space. Any movement of the body outside the forearm that rotates the hand is reflected by rotation of the upper arm coordinate system. Hence, we introduced the 'extrinsic forearm rotation' parameter as the rotation of the upper arm coordinate system in a vertical plane through its x-axis (the line through the medial and lateral epicondyle). The degree of this rotation can be recognised as the angle of the upper arm y-axis with a vertical plane that both includes the acromion and the ulnar styloid process, as that is the plane perpendicular to the plane of rotation (figure 3). This extrinsic forearm rotation was expressed as a positive value if it supplemented forearm supination, and as a negative value if it supplemented pronation.
3. Calculation of upper arm position

The position of the upper arm was calculated from its local coordinate system relative to the global coordinate system after mathematically rotating the trunk back to its resting position. For this, the trunk was represented by the markings of the contralateral acromion, the manubrium sterni, and the xiphoid process. From these markings, a local coordinate system for the trunk was constructed centred over the manubrium sterni (figure 1). The position of the upper arm relative to the...
trunk could then be expressed by three angles in the following sequence: the plane of upper arm elevation, the angle of elevation, and the angle of upper arm rotation\textsuperscript{11,58}. This way, the upper arm position could be interpreted as longitudes and latitudes of a globe projected around the shoulder (figure 4a). The plane of elevation is not necessarily the plane in which the action is taking place as it, rather, is only a mathematical rotation around an axis parallel to the trunk through the acromion needed to define a particular static position\textsuperscript{7}. As such, it was indicated in degrees relative to the coronal plane (figure 4b). The plane of elevation corresponds with the longitudes in the globe system, and the angle of elevation corresponds with the latitudes (figure 4c). The zero position for upper arm elevation was defined as the position at which the upper arm axis between the acromion and the middle of both epicondyles was parallel to the $y$-axis of the global coordinate system. The angle of upper arm rotation was defined by the angle of the $z$-axis of the upper arm coordinate system and a line perpendicular to the plane of elevation\textsuperscript{58}. From the position of 0 degrees rotation (upper arm $z$-axis perpendicular to the plane of elevation), exorotation was expressed as positive values and endorotation as negative values (figure 4d).

4. Calculation of trunk position

The orientation of the trunk in resting position (image #1) relative to the global coordinate system was used to adjust the local coordinate system of the trunk to the anatomical planes. Starting from that position, trunk recruitment in the four tasks was determined by the displacement of its local coordinate system. The angles of forward trunk flexion were expressed in degrees as positive values. Likewise, lateral flexion angles were expressed as positive values in the direction of the affected extremity, and axial rotation angles were expressed as positive values in the direction moving the affected extremity posteriorly.

Statistical analysis

For each of the selected images the average values for all parameters were collected: 1) trunk flexion, 2) lateral trunk flexion, 3) trunk rotation, 4) plane of upper arm elevation, 5) upper arm elevation, 6) upper arm rotation, 7) elbow flexion, and 8) forearm rotation. Extrinsic forearm rotation was calculated only for images #3 and #5. Comparison of these parameters between the patient group and the control group was performed by a two-tailed Student's $t$-test for paired observations. The correlation between impaired forearm rotation and increased extrinsic forearm rotation as compared to the matched controls was verified using two-tailed Spearman's rho correlation coefficient. For all analyses, an alpha level of $p < 0.05$ was used for determining statistical significance.
Figure 4
Illustration of the 'globe system' that expresses the position of the upper arm relative to the trunk by three angles. Legend:
A: longitudes and latitudes of a globe;
B: the plane of upper arm elevation is the angle of the upper arm relative to the coronal axis in the transverse plane (longitudes);
C: upper arm elevation is expressed as the angle of the upper arm with the vertical axis in the coronal plane (latitudes);
D: upper arm rotation can be visualised with the elbow in 90° flexion by the angle (α) of the forearm and a horizontal line perpendicular to the plane of elevation.
Results

Control group

Task 1. All controls were able to supinate their forearm well beyond the neutral position (mean, +91°; SD, 23.3), and this was achieved without any significant trunk motion (table 1). Upper arm elevation was small (mean, 11°; SD, 6.3), and thus approached a gimbalm lock position where the axes of humeral rotation and plane of elevation coincide\(^2\). This means that differentiation between the humeral rotation and plane of elevation angles is frustrated. These angles were, therefore, not used in further analysis of this task.

Task 2. Grasping the drinking glass required elbow extension as well as forearm supination towards zero degrees (table 1). The movement pattern for this task in all our control individuals included upper arm elevation not directed in a straight line towards the glass, but in a plane of elevation below 90°, i.e. containing upper arm abduction (mean, +68°; SD, 20.7). Subsequently, endorotation of the upper arm (mean, -52°; SD, 21.1) directed the forearm back to the glass, bringing the hand in position to grasp it. This movement pattern resulted in a marked negative extrinsic forearm rotation (mean, -11°; SD, 3.0) (table 3).

Task 3. Like active forearm supination, maximal active forearm pronation (mean, -87°; SD, 10.4), did not induce marked recruitment of trunk movement.

Task 4. Reaching for the wooden disk with the forearm in pronation (mean, -59°; SD, 7.7) resulted in a movement pattern similar to grasping the drinking glass. Marked upper arm elevation (mean elevation, 34°; SD, 6.6) was now even less directed towards the target (mean plane of elevation, +62°; SD, 10.6) resulting

<table>
<thead>
<tr>
<th>Task</th>
<th>Trunk</th>
<th>Upper Arm</th>
<th>Forearm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lateral flexion</td>
<td>Flexion</td>
<td>Rotation</td>
</tr>
<tr>
<td></td>
<td>ave. (sd)</td>
<td>ave. (sd)</td>
<td>ave. (sd)</td>
</tr>
<tr>
<td>#1: sup.</td>
<td>-3 (4.7)</td>
<td>1 (4.2)</td>
<td>0 (5.3)</td>
</tr>
<tr>
<td>#2: glass</td>
<td>-2 (3.5)</td>
<td>-3 (2.0)</td>
<td>5 (3.0)</td>
</tr>
<tr>
<td>#3: pron.</td>
<td>-3 (4.4)</td>
<td>1 (4.2)</td>
<td>-1 (5.3)</td>
</tr>
<tr>
<td>#4: disk</td>
<td>-1 (2.4)</td>
<td>-6 (5.3)</td>
<td>7 (4.9)</td>
</tr>
</tbody>
</table>
in more negative values for extrinsic forearm rotation (mean, -18°; SD, 4.7), supplementing forearm pronation.

**Patient group**

**Task 1.** Compared to the control subjects, all patients had impaired maximal active forearm supination (mean, -25°; SD, 37.1; \( p < 0.0001 \)) that coincided with a significantly marked trunk lateral flexion (mean, 14°; SD, 11.3; \( p < 0.005 \)), endorotation of the upper arm (mean, -61°; SD, 43.7; \( p < 0.0001 \)), and elbow flexion (mean, 129°; SD, 16.1; \( p < 0.0005 \)) (table 2).

**Task 2.** Subsequent reaching for the drinking glass was reflected by increased upper arm elevation in an increased plane of elevation, and elbow extension. In addition, the already marked trunk lateral flexion was supplemented by a significantly increased trunk flexion (mean, 12°; SD, 10.4; \( p < 0.005 \)) and rotation (mean, 10°; SD, 14.7; \( p < 0.01 \)), although the drinking glass was within reach of the affected arm. Significantly less active supination was used to grasp the glass compared to the maximal available supination in the first task (mean, -55°; SD, 20.9; \( p < 0.05 \)). Extrinsic forearm rotation in this movement pattern supplemented forearm supination significantly more than observed in the controls (mean increase, +13°; \( p < 0.05 \)) (table 3). The extent of variation of the extrinsic forearm rotation data was considerable within the patient group, but the data correlated reasonably well with the extent of forearm rotation impairment as compared to the controls (Spearman's rho correlation coefficient, 0.73; \( p < 0.05 \)).

**Task 3.** Active forearm pronation was not impaired (mean, -80°; SD, 8.9) and did not induce obvious trunk recruitment.

Table 2
Averaged data on the patient group (in degrees)

<table>
<thead>
<tr>
<th>Task</th>
<th>Trunk</th>
<th>Upper Arm</th>
<th>Forearm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>lateral flexion</td>
<td>flexion</td>
<td>rotation</td>
</tr>
<tr>
<td></td>
<td>ave. (sd)</td>
<td>ave. (sd)</td>
<td>ave. (sd)</td>
</tr>
<tr>
<td>#1: sup.</td>
<td>0 (6.5)</td>
<td>14(11.3)</td>
<td>1 (7.4)</td>
</tr>
<tr>
<td>#2: glass</td>
<td>12(10.4)</td>
<td>14(10.7)</td>
<td>10(14.7)</td>
</tr>
<tr>
<td>#3: pron.</td>
<td>2 (5.4)</td>
<td>5 (5.6)</td>
<td>3 (7.9)</td>
</tr>
<tr>
<td>#4: disk</td>
<td>14(10.2)</td>
<td>3 (7.5)</td>
<td>2(11.0)</td>
</tr>
</tbody>
</table>
Task 4. As active forearm pronation was comparable between patients and controls, extrinsic forearm rotation did not differ significantly at subsequent reaching for the wooden disk (table 3). However, forward flexion of the trunk did increase significantly (mean, 14°; SD, 10.2; \( p < 0.01 \)). Again, data on extrinsic forearm rotation correlated well with active forearm pronation data (Spearman's rho correlation coefficient, -0.76; \( p < 0.05 \)).

Table 3
Data on extrinsic forearm rotation

<table>
<thead>
<tr>
<th>Subjects</th>
<th>Task 2</th>
<th>Task 4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>the drinking glass (image #3)</td>
<td>the wooden disk (image #5)</td>
</tr>
<tr>
<td></td>
<td>controls (degrees)</td>
<td>patients (degrees)</td>
</tr>
<tr>
<td>No.</td>
<td>age / sex matched</td>
<td>#1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>#2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>#3</td>
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<tr>
<td></td>
<td></td>
<td>#4</td>
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<td>#5</td>
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<td>#6</td>
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<td>#8</td>
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<td></td>
<td>#9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>#10</td>
</tr>
<tr>
<td>Ave.</td>
<td></td>
<td>-11</td>
</tr>
<tr>
<td>SD</td>
<td></td>
<td>3.0</td>
</tr>
<tr>
<td>( p &lt; 0.05 )</td>
<td></td>
<td>( p &lt; 0.360 )</td>
</tr>
</tbody>
</table>

Discussion

Interest in three dimensional motion analysis of the upper extremity has increased rapidly in recent years, but the complexity of upper extremity movements and the lack of standardized functional tasks hinders the establishment of a universal standard in upper extremity motion analysis. For this study, we adopted recommendations from reports on this topic to design a method for three-dimensional assessment that meets our purpose. Our method is suitable for an accurate three-dimensional posture assessment of the upper extrem-
ity and trunk in patients with cerebral palsy, but it has its limitations. As such, it analyses the end result of a movement pattern, but it does not address the velocity of movement or the timing and sequencing of degrees of freedom. Moreover, table height, target distance, and type of grasp will greatly influence the movement strategy of the upper extremity and trunk. Thus, even though we strived for three-dimensional positional analysis under optimally standardized circumstances, it is safest to view the studied movement patterns as significant tendencies in the observed direction rather than as the actual quantification of it.

The 'globe system' for describing the position of the upper arm relative to the trunk provides an unambiguous definition of rotation axes that is easy to visualise. It is preferred over the use of the clinically familiar angles of flexion in the sagittal plane and abduction in the coronal plane because there is no anatomical description in-between these planes\(^2\).\(^{11}\). It should be noted, however, that a system describing the position of the upper arm relative to the trunk disregards rotations of the scapula and clavicle. Like any Euler description system, the 'globe system' also harbours gimbal lock positions where the axes of humeral rotation and plane of elevation coincide, causing their values to be sensitive to measurement errors. In this convention, the arm is either not, or fully elevated in gimbal lock position. Since elevation close to zero degrees occurred in some of our tasks, and 'humeral rotation' and 'plane of elevation' are hardly relevant for this particular position, these parameters were not used for those tasks.

The musculoskeletal system is considered abundant, since it potentially has a larger number of ways to combine individual joint movements than necessary to complete one specific task\(^8\). This permits the body to adapt to different environmental conditions or to compensate for functional deficits. We have introduced the 'extrinsic forearm rotation' as a parameter to objectify that part of the movement strategy outside the forearm itself that is supplementary to (impaired) forearm rotation. As yet, we can not state that supplementation is the same as compensation because we do not know what part of this extrinsic forearm rotation is compensatory strategy for impaired forearm rotation and what part is the consequence of other task specific movement strategies that rotate the forearm. For example, our controls used a movement pattern for the 'supinative' task of grasping the drinking glass that resulted in negative values for extrinsic forearm rotation correlated with 'pronative' movement. This negative extrinsic forearm rotation is part of the movement pattern for that specific task and not a compensation for impaired rotation. In fact, the movement pattern put the forearm in a pronated position in space, opposite to the unimpaired forearm supination itself. This is in agreement with
earlier reports on upper extremity movement patterns during reaching tasks in healthy subjects.\textsuperscript{3,10,63}

Michaelson et al.\textsuperscript{49} compared movement patterns during a reaching task between hemiplegic stroke patients and healthy controls. In contrast to healthy controls, trunk restraint altered the pattern of inter-joint coordination and increased the recruited range of motion in the elbow and shoulder in all hemiparetic patients. This may indicate that these hemiparetic patients did not use their potential joint range for free arm movements during a reaching task because this required more effort than compensatory trunk recruitment\textsuperscript{49}. Likewise, maximal recruitment of the available forearm supination in cerebral palsy during reaching might be so labour-intensive, that recruitment of other degrees of freedom is preferred. Accordingly, the insufficient active forearm supination that was recruited during reaching for the drinking glass by the patients in our study was less than the available active forearm supination with the upper arm next to the body. Alternatively, the required forearm rotation might even not have been available during this reaching task that also required elbow extension. Either way, standard assessment of forearm rotation with the upper arm next to the body and the elbow in 90° flexion is not a valid representation of the functionally available forearm rotation to cerebral palsy patients during a reaching task.

For the functional tasks in our study, the patient was not asked to rotate his forearm but to pick up an object, and thus a task-specific movement pattern was composed from all available degrees of freedom. This allows for the study of the recruitment of forearm rotation in cooperation with related degrees of freedom. Active forearm supination in the patient group was always accompanied by active elbow flexion. This is easy to understand when considering that the also spastic biceps brachii muscle is a strong supinator.\textsuperscript{56} Elbow flexion, however, prevents positioning of the hand at table top height in a reaching task. In all patients we observed that less forearm supination was recruited to allow for more elbow extension and the trunk was flexed anteriorly and laterally to bring the supinated hand to the object on the table. Obviously, the trunk contributed to a compensatory strategy for the lack of elbow extension, as well as the lack of forearm supination. In some patients the upper arm was also recruited to supplement forearm supination by elevation in a plane that includes humeral adduction (>90°). In other patients, the trunk lateral flexion used to compensate for the lack of elbow extension even exceeded the required compensation for the limited forearm supination. In those patients, the upper arm was recruited to compensate for the extensive trunk lateral flexion by elevation in a plane of marked abduction (<90°).
The trunk was also recruited in the reaching task with the forearm in pronation. This time, trunk forward flexion compensated for the lack of elbow extension, as trunk lateral flexion would work against forearm pronation.

Comparing values between patients and matched controls performing the same tasks will identify that part of extrinsic forearm rotation related to forearm impairment. The difference in extrinsic forearm rotation has then become a quantitative measure for the compensatory movement strategy directly related to impaired forearm rotation during that specific functional task. This was confirmed in our study by a statistically significant correlation between the difference in extrinsic forearm rotation and the difference in forearm rotation itself. Our observations show that all patients recruited compensatory movement strategies, as was objectified by this difference in extrinsic forearm rotation. However, the involvement of the trunk and upper arm in such a strategy varied between patients and this, we surmise, is explained by the variety of concomitant joint impairments between the patients in our group.

The invariably associated movements of active forearm supination and elbow flexion creates an upper extremity posture unfit for reaching and grasping tasks or bimanual activities that require forearm supination. Many patients with hemiplegic cerebral palsy use the affected extremity mainly as an assisting hand in bimanual activities. It is, therefore, imperative to assess available forearm rotation in concert with elbow extension during the desired functional tasks when considering treatment of a pronation deformity. The movement pattern will be adapted to a new equilibrium, and this may involve alteration of the muscle imbalance around concomitant deformities. Detailed assessment of movement patterns combined with the range of active joint movement used is indispensable in planning therapy for the upper extremity in cerebral palsy. To evaluate the effect of surgical treatment on the movement patterns related to the corrected deformity we compared the postoperative to the preoperative associated movements as presented in this report. The results of this subsequent study are presented in part II of this report.

In conclusion, we compared movement patterns of the upper extremity and trunk in cerebral palsy patients with impaired forearm supination to those in case-matched healthy controls performing the same tasks. Based on the significant difference of extrinsic forearm rotation between these groups, we objectified that the movement strategy in patients with cerebral palsy contains pathological movements that are directly associated with their impaired forearm rotation.
"... Every species of voluntary exercise of the muscles which is calculated to restore power or harmony to the movements of the limbs and trunk, alternately vaunted and decried, will ever hold an important place in the estimation of the orthopaedic practitioner. ..."

WJ Little, 1861
CHAPTER 6

Movement patterns of the upper extremity and trunk associated with impaired forearm rotation in patients with cerebral palsy

Part II: the results of corrective surgery

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³Dept. of plastic & reconstructive surgery, Antoni van Leeuwenhoek Zkh., Amsterdam

Abstract

The effect of surgical correction of impaired forearm rotation on associated body movement patterns was prospectively studied by comparison of pre- and postoperative three-dimensional video analysis of the upper extremity and trunk in eight male and two female patients with cerebral palsy (mean age, 16 years and 2 months). The 'extrinsic forearm rotation' parameter was used to quantify all pathologically associated movements that supplement forearm rotation. Postoperatively, active forearm supination during a functional reaching task had improved by a mean of 37° in combination with a significantly decreased extrinsic forearm rotation by a mean of 13°. Also, an average loss of 16° of active pronation in combination with an increased extrinsic forearm rotation (mean, 8°) was observed.

Based on these results we conclude that the postoperative change of rotational range of motion of the forearm alters the upper arm and trunk movement strategies supplementary to forearm rotation.

Submitted for publication

Introduction

In part one of this report, we defined 'extrinsic forearm rotation' as a parameter to quantify the cumulative result of all body movements outside the forearm that supplement forearm rotation. Using it, we showed that movement patterns of the upper arm and trunk in patients with cerebral palsy feature pathological movements directly associated with impaired forearm rotation. Hence, surgical correction of a pronation deformity in patients with cerebral palsy is hypothesised to not only affect forearm rotation, but also these associated movements. If this is true, such an effect on the movement pattern should be anticipated in the planning of multiple procedures as these may involve deformities that are affected by the
correction of others. To date, the effect of such surgery on the movement patterns of the upper extremity and trunk has never been investigated. Our hypothesis that correction of a pronation deformity affects compensatory movement patterns typical for that deformity was tested by comparison of the pre- and postoperative extrinsic forearm rotation using three-dimensional video analysis.

In this paper we present the outcome of a prospective clinical outcome study investigating these patterns before, and one year after, surgical correction of the pronation deformity in ten patients with cerebral palsy.

**Method**

**Patients**

Ten patients with hemiplegic cerebral palsy (mean age, 16 years and 2 months; range, 11 – 27 years) that had also been included in the first part of this study were subjected to surgical correction of their pronation deformity of the affected forearm. The surgical procedures performed in these eight male and two female patients were aimed at functional improvement of the upper extremity (table 1). The study protocol was approved by the Medical Ethical Committee of the Academic Medical Centre in Amsterdam. Informed consent was obtained from all included patients.

**Pre- and postoperative 3D video registration & data analysis**

Three-dimensional video analysis of the movement patterns of all patients was performed in accordance with previously reported methods one day preoperatively and after one year postoperatively. Thus, two synchronised S-VHS video cameras registered 1) maximal active supination of both forearms, 2) picking up a drinking glass from a table top, and holding it steady in vertical position, 3) maximal active pronation of both forearms, and 4) picking up a wooden disk that was placed flat on the table top, all performed by the patient while seated on a stool in front of a table. Special care was taken to standardize preoperative and postoperative table top height and target distance for each patient.

Five images from these video recordings were selected for three-dimensional analysis of the upper extremity and trunk position: 1) while sitting on the stool just before performing the tasks, 2) at the moment of maximal active supination, 3) at the moment of grasping the glass and stabilising it in vertical position, 4) at the moment of maximal active pronation, and 5) at the moment of grasping the wooden disk. Local coordinate systems relative to anatomical landmarks on the patient were defined allowing for calculation of the three-dimensional positions of the trunk, upper arm and forearm on the selected images. In this way, the move-
ment pattern could finally be expressed as a collection of eight parameters: 1) trunk flexion, 2) lateral trunk flexion, 3) trunk rotation, 4) plane of upper arm elevation, 5) upper arm elevation, 6) upper arm rotation, 7) elbow flexion, and 8) forearm rotation. The parameters 4, 5, and 6 together constitute an interdependent sequence of angles expressing the position of the upper arm relative to the trunk as longitudes and latitudes of a globe projected around the shoulder. Movement patterns related directly to impaired forearm rotation are identified on images #3 and #5 by using the previously defined 'extrinsic forearm rotation' parameter. Part of this extrinsic forearm rotation is compensatory strategy for impaired forearm rotation. Any change in this compensatory movement strategy related to a change in impairment of forearm rotation can be identified by calculating the difference between postoperative and preoperative values for extrinsic forearm rotation. A postoperative change in extrinsic forearm rotation for each patient will indicate whether surgical correction of a pronation deformity did also affect these associated movements.

Statistical analysis

Statistical pre- and postoperative comparison of the average values for all parameters was performed by a 2-tailed Student’s *t*-test for paired observations. For all analyses, an alpha level of *p* < 0.05 was used for determining statistical significance.

Results

Task 1. Maximal active forearm supination was preoperatively impaired in all patients (mean, -25°; SD, 37.1), but increased significantly after surgical correction (mean, 22°; SD, 29.1; *p* < 0.0005) (table 1). The typical trunk lateral flexion, endorotation of the upper arm, and elbow flexion observed preoperatively to occur in our patients upon active forearm supination, had subsided postoperatively (table 2). Trunk lateral flexion (mean, 8°; SD, 4.8; *p* < 0.05) and elbow flexion at maximal active supination (mean, 111°; SD, 16.8; *p* < 0.05) both decreased significantly (table 3).

Task 2. Compared to the preoperative situation, more active forearm supination was used postoperatively to grasp the drinking glass (mean, -19°; SD, 30.9; *p* < 0.05). Still, it was less when compared to the postoperatively maximal available supination in the first task (*p* < 0.01). The increased postoperative forearm supination while grasping the glass occurred in combination with a decrease of extrinsic forearm rotation to a mean of -13° (SD, 12.5; *p* < 0.01) (table 4). The marked postoperative changes in the movement pattern to pick up the glass were a significantly
decreased need for trunk lateral flexion (mean decrease, 9°; $p < 0.005$), a decrease in endorotation of the upper arm (mean decrease, 25°; $p < 0.01$), and a decrease of elbow flexion (mean decrease, 13°; $p < 0.05$) (table 3). The plane of elevation also decreased indicating that less adduction of the upper arm was used to grasp the drinking glass. Still, this decrease was not statistically significant (mean decrease, 16°; $p = 0.079$).

**Table 1**

Patient characteristics & data on forearm rotation (in degrees).

Legend of abbreviations: PT, pronator teres; FCU, flexor carpi ulnaris; TIP, correction of thumb-in-palm deformity; FDS/P, flexor digitorum sublimis and profundus tendons; ECRB, extensor carpi radialis brevis; APON, aponeurectomy of the flexor/pronator muscle group; EDC, extensor digitorum communis; -r, rerouting; -t, tenotomy; -fr, fractional lengthening.

<table>
<thead>
<tr>
<th>Patients</th>
<th>Preoperative forearm rotation</th>
<th>Surgical procedures</th>
<th>Postoperative forearm rotation</th>
</tr>
</thead>
<tbody>
<tr>
<td>No.</td>
<td>Sex</td>
<td>Age</td>
<td>Pro (neg)</td>
</tr>
<tr>
<td>1</td>
<td>M</td>
<td>11</td>
<td>-85</td>
</tr>
<tr>
<td>2</td>
<td>F</td>
<td>11</td>
<td>-75</td>
</tr>
<tr>
<td>3</td>
<td>M</td>
<td>11</td>
<td>-77</td>
</tr>
<tr>
<td>4</td>
<td>M</td>
<td>13</td>
<td>-88</td>
</tr>
<tr>
<td>5</td>
<td>M</td>
<td>14</td>
<td>-81</td>
</tr>
<tr>
<td>6</td>
<td>M</td>
<td>17</td>
<td>-94</td>
</tr>
<tr>
<td>7</td>
<td>M</td>
<td>19</td>
<td>-88</td>
</tr>
<tr>
<td>8</td>
<td>M</td>
<td>19</td>
<td>-67</td>
</tr>
<tr>
<td>9</td>
<td>M</td>
<td>19</td>
<td>-65</td>
</tr>
<tr>
<td>10</td>
<td>F</td>
<td>27</td>
<td>-75</td>
</tr>
<tr>
<td>Ave.</td>
<td>16.1</td>
<td></td>
<td>-80</td>
</tr>
<tr>
<td>(SD)</td>
<td>(4.9)</td>
<td></td>
<td>(8.9)</td>
</tr>
<tr>
<td>p-value</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Task 3.** Surgical correction of the pronation deformity also resulted in a significant decrease of maximal active pronation (mean decrease, 17°; $p < 0.005$). This loss induced a decreased elbow flexion (mean decrease, 14; $p < 0.05$) and a decreased upper arm endorotation (mean decrease, 28°; $p < 0.05$) during the attempt to maximally pronate the forearm (table 3).

**Task 4.** The same loss of forearm pronation was seen while grasping the wooden disk (table 3). This induced the need for new compensatory strategies, reflected by a significant postoperative change in extrinsic forearm rotation in the same direc-
tion as forearm pronation itself (mean, -8°; SD, 10.6; \( p < 0.05 \)) (table 4). The movement strategy selected to compensate for this loss of pronation differed between patients. Trunk lateral flexion in opposite direction (mean change, -6°; \( p = 0.09 \)) and a decreased plane of elevation of the upper arm towards more abduction (mean change, -10°; \( p = 0.178 \)) contributed to directing the extrinsic forearm rotation towards pronation, but these were not both recruited by all patients. As a result these changes were not significant. As in maximal active pronation, upper arm endorotation and elbow flexion both decreased significantly compared to the preoperative movement pattern while grasping the disk (table 3).

**Table 2**

Averaged postoperative data (in degrees)

<table>
<thead>
<tr>
<th>Task</th>
<th>Trunk</th>
<th>Upper Arm</th>
<th>Forearm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>lateral flexion</td>
<td>plane of elevation</td>
<td>elbow flexion</td>
</tr>
<tr>
<td></td>
<td>rotation</td>
<td>rotation</td>
<td>forearm rotation</td>
</tr>
<tr>
<td>ave.</td>
<td>(sd)</td>
<td>ave.</td>
<td>(sd)</td>
</tr>
<tr>
<td>#1: sup.</td>
<td>1 (6.0)</td>
<td>34 (73.6)</td>
<td>111 (16.8)</td>
</tr>
<tr>
<td>#2: glass</td>
<td>7 (8.5)</td>
<td>64 (28.4)</td>
<td>95 (21.6)</td>
</tr>
<tr>
<td>#3: pron.</td>
<td>3 (4.9)</td>
<td>50 (23.6)</td>
<td>85 (27.3)</td>
</tr>
<tr>
<td>#4: disk</td>
<td>12 (9.6)</td>
<td>45 (18.6)</td>
<td>97 (20.1)</td>
</tr>
</tbody>
</table>

**Table 3**

Difference between postoperative and preoperative data (\( \Delta \) in degrees) and their statistical significance: * = \( p \)-value < 0.05; ** = \( p \)-value < 0.01; *** = \( p \)-value < 0.005; **** = \( p \)-value < 0.0005

<table>
<thead>
<tr>
<th>Task</th>
<th>Trunk</th>
<th>Upper Arm</th>
<th>Forearm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>flexion</td>
<td>plane of elevation</td>
<td>elbow flexion</td>
</tr>
<tr>
<td></td>
<td>lateral flexion</td>
<td>rotation</td>
<td>elevation</td>
</tr>
<tr>
<td>( \Delta )</td>
<td>( \Delta )</td>
<td>( \Delta )</td>
<td>( \Delta )</td>
</tr>
<tr>
<td>#1: sup.</td>
<td>+1</td>
<td>-6 *</td>
<td>-6 *</td>
</tr>
<tr>
<td>#2: glass</td>
<td>-5</td>
<td>-9 ***</td>
<td>-6</td>
</tr>
<tr>
<td>#3: pron.</td>
<td>+2</td>
<td>-3</td>
<td>-5</td>
</tr>
<tr>
<td>#4: disk</td>
<td>-3</td>
<td>-6</td>
<td>+2</td>
</tr>
</tbody>
</table>
We conclude that one year after surgical correction of a pronation deformity, active forearm supination increased in combination with a decreased use of movement strategies that supplement forearm supination in nine out of ten patients. The use of movement strategies to compensate for the observed loss of pronation, however, increased.

| Table 4 |
|---|---|---|
| Difference between postoperative and preoperative extrinsic forearm rotation |

<table>
<thead>
<tr>
<th>Patients</th>
<th>Task 2</th>
<th>Task 4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>the drinking glass</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(image #3)</td>
</tr>
<tr>
<td>No.</td>
<td>postop. – preop. (degrees)</td>
<td>postop. – preop. (degrees)</td>
</tr>
<tr>
<td>#1</td>
<td>-2</td>
<td>-7</td>
</tr>
<tr>
<td>#2</td>
<td>-13</td>
<td>13</td>
</tr>
<tr>
<td>#3</td>
<td>-35</td>
<td>1</td>
</tr>
<tr>
<td>#4</td>
<td>-13</td>
<td>-8</td>
</tr>
<tr>
<td>#5</td>
<td>-16</td>
<td>-19</td>
</tr>
<tr>
<td>#6</td>
<td>-28</td>
<td>-15</td>
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<td>#7</td>
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<td>#8</td>
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<td>-8</td>
</tr>
<tr>
<td>#9</td>
<td>-19</td>
<td>-27</td>
</tr>
<tr>
<td>#10</td>
<td>-13</td>
<td>-2</td>
</tr>
<tr>
<td>Ave.</td>
<td>-13</td>
<td>-8</td>
</tr>
<tr>
<td>SD</td>
<td>12.5</td>
<td>10.6</td>
</tr>
<tr>
<td>p-value</td>
<td>( p &lt; 0.01 )</td>
<td>( p &lt; 0.05 )</td>
</tr>
</tbody>
</table>

**Discussion**

Many surgical procedures have been described for the correction of a pronation deformity of the forearm. Today, the choice between these available procedures depends on the extent of the deformity and the preference of the surgeon. Surgical treatment of the upper extremity in our series typically consisted of a combination of multiple procedures. Each focused on the increase of available range of motion of a joint. Surgical procedures other than those aimed directly at the correction of the pronation deformity may well have had their effect on forearm rotation as well. However, our study was not an evaluation of the clinical
outcome of one specific surgical procedure. Rather, we set out to study whether a postoperative change in rotational range of motion of the forearm also affected associated movements outside the forearm. Likewise, the timing and sequencing of these movements were not the subject of our study. Instead, positional analysis of the end result of movement patterns during a reaching task was used to objectify whether the use of compensatory strategies was reduced by improvement of forearm rotation. Obviously, even a follow-up of one year may be relatively short to evaluate the outcome of surgical treatment in patients with cerebral palsy, and the long-term development of movement patterns in a maturing musculoskeletal system requires further study.

Change in extrinsic forearm rotation was the parameter used for the quantification, in each patient, of the surgery-induced change in associated compensatory movement strategies for well-defined functional tasks. Thus, a decreased extrinsic forearm rotation after surgical improvement of active supination implied that movements that were associated with the originally impaired forearm supination had subsided. Extrinsic forearm rotation decreased in nine out of ten patients performing a reaching task that requires forearm supination. The one patient with an increased extrinsic forearm rotation had a slight postoperative improvement of maximal active supination by 12 degrees. However, he did not recruit this potential advantage at all during the functional task and actually invested more effort in compensation, possibly encouraged by an improved wrist position and grip function.

Surgical correction of a pronation deformity significantly improved the ability of active forearm supination, but it also resulted in a loss of maximal active pronation in eight out of ten patients. This is in agreement with previously reported observations in a comparable group of patients. The loss of active pronation occurred in combination with a change in extrinsic forearm rotation in the same direction while performing a reaching task that required forearm pronation. This indicates that the observed loss of active forearm pronation resulted in the recruitment of additional degrees of freedom to compensate for this loss during functional tasks.

Clinical implications
A postoperative decrease in compensatory movement patterns may either be caused by an increased range of motion or by facilitation of the already available range of motion. Either way, compensatory movement patterns only decrease when the improved available active supination is actually employed during the functional tasks that were aimed to be improved by surgery. From this perspective, maximal active supination alone may not be a valid parameter for the success of
surgical treatment of a pronation deformity. Our data confirms that movement patterns observed during functional tasks should be additional outcome measures for the success of upper extremity surgery in patients with cerebral palsy\textsuperscript{30}. This is in agreement with the observations of Michaelsen et al.\textsuperscript{49} in a study on movement patterns of stroke patients. A limited elbow extension during activities that require some degree of forearm supination, for example, may very well be a pathological movement associated with an impaired forearm supination. In that case, it will improve by the correction of the pronation deformity, and may not need a separate surgical correction. Such associated limitation of elbow extension should be differentiated from true impairment of the elbow joint that is independent of forearm rotation. Furthermore, a changed movement pattern may also indirectly affect manual dexterity. The observed significant postoperative decrease in compensatory movements of the upper arm and trunk alters the positional demands for the hand during functional activities.

The postoperative changes in positioning of the trunk and upper extremity while grasping the glass (task 2) in our patients approached the data for the healthy control group described in part one of this report\textsuperscript{30}, indicating that surgery had changed the recruitment of degrees of freedom towards normative values. Still, the movement patterns of the upper extremity in patients with cerebral palsy remain a complex task-specific assembly of interacting degrees of freedom that are neurologically impaired. If a pronation deformity is the most prominent feature limiting the functional capacity of the upper extremity, it may be advisable in selected patients to only correct this pronation deformity and anticipate a favourable effect on the overall movement pattern and hand function.

Conclusions

Based on the results of our study we conclude that a postoperative change in the rotational range of motion of the forearm is coupled directly with a change in the movement pattern that was related to the original pronation deformity. This should be anticipated at the preoperative planning of procedures for multiple deformities, as this change in movement pattern may involve deformities that are also eligible for surgical correction.
EPILOGUE

M. Kreulen

The experiments presented in this thesis have yielded several new insights of which the implications and limitations have been discussed in the corresponding chapters. The currently accepted biomechanical concept of tendon transfer in general, and when employed to correct complex movement patterns of the upper limb in particular, appears to be much more enigmatic than classically assumed. This is a troubling statement. How can a century of experience with successful tendon transfers be based on an incorrect concept? What is the problem when an experienced surgeon working in a multidisciplinary hand-unit can objectively claim success with tendon transfers for correcting muscle imbalance? Scepticism is easily raised on the clinical importance of our observed phenomena. This epilogue is added to elaborate on this issue and to philosophize on how a better understanding of the consequences of tendon transfer may provide tools to tailor the success of surgery to meet the desired balance in the movement pattern.

Needless to say, this thesis only addressed aspects of the surgical technique and of combinations of tendon transfers. Other important parameters that determine the clinical outcome of tendon transfer, such as selection criteria for surgical candidates, the timing of surgery, selection of the appropriate donor muscle, and postoperative regime were not discussed. Furthermore, only acute effects of the surgical tendon transfer technique on muscle function are discussed. Postoperative effects induced by scar tissue behaviour, attenuated tendon healing, and (long-term) neuromuscular adaptation are yet to be studied.

1. Tuning tendon tension

Muscle architecture is classically conceptualized as a typical assembly of muscle fibres converging into a tendon. Each isolated muscle is considered to have a unique capacity to exert a pulling force, produced by shortening of the muscle belly and transmitted through its tendon to a target outside the muscle. Fibre length and cross sectional area of parallel fibers are used as parameters of muscle architecture to calculate the available excursion of muscle length and the maximally available generation of force. For each separate muscle, the relationship between muscle length and force has then become an invariable characterization of its functional capacity.
At this point, the most basic assumption of tendon transfer is that this functional capacity of the selected donor muscle is invariable and thus preserved during transfer to a new location. For this, the only surgical prerequisites are 1) not to violate the ‘architecture’ of the muscle belly, its vascularization or innervation, 2) to transfer the muscle and tendon along an unhampered and fluent line directed toward its new target, and 3) to fix the tendon at optimal muscle length. This last requisite, in particular, is considered to be the major determinant of the functional outcome of the transferred donor muscle and, therefore, the ultimate challenge of tendon transfer surgery. If all this is true, the first tool to tailor the clinical outcome of tendon transfer would be the tuning of tendon tension until the desired operating range of the target joint coincides with an optimal trajectory of the length-force profile of the donor muscle (figure 1).

![Figure 1](image)

**Figure 1**

Graphical display of the tuning of tendon tension in case of a fixed active and passive force-length curve. $\alpha =$ point of fixation of the tendon at passive tension ($F$) and muscle length ($l$) with the joint at 'x' degrees of extension. This results in an operating range on the descending branch of the active force-length curve. The arrows display the possibilities of tuning this operating range by varying the fixation point at a different muscle length, and a different degree of extension 'x'.

Therefore, the first step was to test the validity of this classical biomechanical concept. Tendon tensioning at a specific joint angle can only be used as a tailoring tool when the passive and active force-length relationships are indeed invariable, or at least predictable after transfer. Moreover, it requires a fixed relationship between the passive and active curves since peroperative tensioning is based on
passive resistance alone. The passive resistance is classically presumed to commence near optimal muscle length (figure 1) but this might very well depend on the position of the muscle relative to its anatomical environment.

The key feature of the classical concept above is that a muscle acts as an isolated entity, independent of its anatomical environment. However, previous animal experiments\(^{24,46}\) and clinical observations in humans\(^{15,17,28}\) have shown that an *in situ* muscle-tendon unit biomechanically interacts through inter- and extramuscular connections with its environment. This is supported by our observations on the FCU in patients with cerebral palsy. A muscle cannot be regarded as an independent mechanism with an invariable functional capacity if it interacts with its environment.

What is actually happening? A shortening muscle fibre pulls at everything to which it is connected. Not just at adjoining muscle fibers, connective tissue within the muscle, and ultimately the tendon, but also at all other connections between the muscle and its anatomical surroundings. However, pulling at surrounding connective tissue is only of mechanical importance if force is transmitted. For this, the connections need to be strong and stiff enough. Our observations indicate that, the fascial connections around the tenotomized human flexor carpi ulnaris muscle were strong enough to keep the muscle at length against maximal tetanic contraction. Those same connections subsequently proved to be stiff enough to transmit force from neighbouring muscles that still crossed the passively extended wrist joint.

Such inter- and extramuscular myofascial force transmission implies that a single muscle does not have an independent functional capacity that can be preserved during transfer. The clinical importance of this phenomenon depends on the amount of force engaged in the interaction through myofascial pathways. This will be related to the muscle’s position and the characteristics of its anatomical environment. In experimental conditions, the extensor digitorum longus muscle in the rat hind limb transmitted up to 37% of its optimal force through such myofascial pathways\(^{45}\). The maximal active force capacity of the rat flexor carpi ulnaris muscle dropped 20 to 60% at progressive stages of muscle dissection\(^{64}\). Most of the inter- and extramuscular myofascial pathways of force transmission are transsected during tendon transfer surgery. Such conclusive animal experiments and our clinical observations have already prompted further research on this topic by intraoperatively measuring force-length characteristics of the human flexor carpi ulnaris muscle during tendon transfer in cerebral palsy\(^{69,70}\).

Tendon transfer alters the pathways of force transmission, but it may also introduce even more determinants of muscle function. The changed alignment and cur-
vature of the muscle could easily result in a changed orientation of muscle fibers and sarcomere distribution. All co-determinants of the force-length characteristics of a donor muscle during the surgical process of tendon transfer should be identified and quantified before any ‘tailoring tool’ based on these characteristics can be entertained. A vast area of research evolves.

2. Transfer design

The second means to tailor surgery is to customize the design of the tendon transfer with reference to the kinematic parameters of the newly constructed muscle-tendon unit. As such, the design of tendon transfer can be defined as the three-dimensional anatomical alignment of the selected donor muscle-tendon unit along its new route from origin to the final insertion of the recipient tendon, especially in relation to joint rotation axes. Initially, this design was foremost dictated by the desire for a straight or at least fluent route of the most appropriate donor muscle. It was not until the work of Dr. Paul Brand that sound mechanical principles were introduced into the clinical practice of hand surgery. Moment arms and distance between origin and reinsertion have been studied for a variety of transfer procedures in the upper extremity. This has enabled an adequate discrimination between different optional transfer procedures designed for the same purpose.

The next step is to customize the kinematics of each selected transfer procedure by varying the route or attachment site of the donor muscle. At least three issues need to be well documented before these parameters of transfer design can be used as tailoring tools: 1) the change in distance between origin and reinsertion along the desired range of motion, 2) the moment arm of the transferred musculo-tendinous unit for its intended function and how it changes along the desired range of motion, and 3) the actual contribution of the functioning tendon transfer to the changed range of motion around the rotation axes of the crossed joint. It is quite disappointing, and challenging, to realize how little is known about these issues for common tendon transfer procedures in cerebral palsy. Clinical outcome studies that attribute all postoperative changes in range of motion to the function of the transferred muscle neglect the phenomenon that the function of other muscles crossing the same rotation axis may be affected by the procedure. The actual result of the transferred muscle function may be very different from the observed clinical result. For example, part of the clinical outcome may be caused by antagonist muscles facilitated by the release of the donor muscle. Our clinical findings combined with the presented computer simulation (figure 2) suggested that a tendon transfer (at least in case of pronator teres rerouting) should, thus, be considered as
a combination of two procedures: 1) the release of the donor muscle, and 2) the construction of a new functional musculotendinous unit. Each has its own extensive biomechanical consequences. Future study should aim to distinguish between the effects of the separate procedures. Both are affected by the degree of surgical dissection, but only the latter by varying donor muscle route and attachment site.

The true clinical result of the transferred muscle function combined with a computer aided mechanical evaluation with reference to moment arms and muscle lengths, will make it possible to identify which part of the clinical outcome may be customized by varying the transfer design.

![Figure 2](image_url)

**Figure 2**
Artist impression of the process that transforms the outline of forearm anatomy and its main pronator and supinator muscles into input parameters for a computer simulation model

### 3. Combining procedures

Yet another misconception is that tendon transfer procedures are considered to only affect movements around the rotation axes crossed by the donor muscle-tendon unit. In that view, muscle imbalance across other rotation axes are to be corrected by additional procedures. Based on the alleged independent action of a tendon transfer, a combination of different surgical procedures is tailored to
address all concomitant deformities to the need of each patient. However, the observations presented in this thesis describe three phenomena that seriously dispute this presumed independence of a tendon transfer. First, the mechanical interaction between muscles by force transmission is altered during surgery. This not only affects donor muscle function, but will also affect its neighbouring muscles that act on the same or different rotation axes\textsuperscript{67}. Second, balancing the forces around a rotation axis by tendon transfer is not simply a matter of subtracting function on one side, and adding it to the other side. Agonist and antagonist muscles around the same axis will be inhibited or facilitated in this new equilibrium. These may also affect movements around other rotation axes. For example, facilitation of the biceps brachii supinator function after pronator teres release will also affect elbow flexion-extension. Third, the complex movement patterns of the entire extremity and trunk feature multiple pathological movements directly associated with each specific deformity. Correction of that deformity by tendon transfer also affects this synergistic recruitment of compensatory degrees of freedom. The entire movement pattern will be adapted to the new equilibrium, and this may involve alteration of the muscle imbalance around concomitant deformities. That way, different surgical procedures will affect each other's results.

Although these phenomena complicate matters substantially, they also initiate the challenge to understand what we are actually changing in the balance of forces by performing a tendon transfer. Such comprehension will yield the necessary insight to compose the optimal combination of surgical procedures tailored to balance the desired motion.

Three-dimensional motion analysis allows for the assessment of functional ranges of motion during the act of performing specific activities. Methods that simultaneously analyse the position of multiple upper extremity and trunk segments will also be able to assess the collaboration of different degrees of freedom recruited for goal directed movements. However, there are no standardized and validated methods available. The very complex movement patterns of the upper extremity and the lack of universally standardized functional outcome measures require a customized set-up and analysis procedure for each specific research objective. As such, each study of upper extremity movement patterns also contributes to the emerging field of expertise on its three-dimensional motion analysis.

In our experiments, we used a passive optical system that registered anatomical landmarks with two synchronized video cameras. This system allowed for the study of completely unrestricted movements, but required manual frame to frame identification and digitization of the anatomical ink markings on the patient. The accuracy of manual marker identification was compared to fully automated marker
tracking by an OPTOTRAK active optical system (NDI, Waterloo, Canada). Static and dynamic accuracy was tested by repeatedly measuring a known segment length in different positions. Our three-dimensional video analysis set-up proved suitable for an accurate upper extremity posture assessment. It enabled the identification of a new parameter to objectify that part of the movement strategy outside the forearm that is supplementary to forearm rotation. This ‘extrinsic forearm rotation’ supplementary to (intrinsic) forearm rotation is only the first of similar parameters that are yet to be identified. For example, ‘extrinsic wrist extension’ and ‘extrinsic thumb abduction’ might be employed to study the interaction of different compensatory movement patterns and other pathological movements associated with their specific deformities. Knowledge of interference between the results of different tendon transfer procedures with reference to the desired movement pattern is not only useful for surgical planning, but also for postoperative therapy and orthotic regimes. The feasibility of such more detailed study of the complex biomechanics of interacting degrees of freedom in the upper extremity will be increased by expanding the set-up with one or two additional video cameras and maybe a small electrogoniometric device for the hand. Clearly, the clinical and scientific study of the upper extremity in cerebral palsy has entered the era of three-dimensional motion analysis.

Are we doing it all wrong?

It would neither be respectful nor accurate to state that all the pioneering work on the biomechanics of muscle function and tendon transfers was wrong. Rather, it is to be concluded that it has been incomplete. Too much knowledge is lacking to reliably predict the contribution to the final outcome of an interacting set of surgical procedures affecting the recruitment of all cooperating muscles in the abundantly versatile musculoskeletal system. Well then, should we refrain from performing tendon transfers on the basis of the current (mis-)understanding of their merits? Are we really doing it all wrong?

Obviously NOT! A well performed tendon transfer is an ingenious remedy for the dysbalanced extremity crippled by the partial loss of its muscle-tendon action. It is a relatively easy and well-tolerated surgical procedure allowing for reanimation of a functionally incapacitated extremity. Rehabilitation programs thrive on its success. A reserved attitude towards tendon transfer procedures as a last resort in the handicapped upper extremity is inappropriate. They do not replace or oppose, but rather advance conservative and coping regimes. No, we’re not doing it wrong but in order to control and to further improve tendon transfer surgery we should know exactly what we are doing right!
"... A wide field, however, remains open for future research and experience, and although I would strenuously discountenance all rash and wholesale division of tendons in these cases, I recommend the matter to the attention of those among you who are possessed of an intimate knowledge of the anatomy of the parts, and are endowed with a large share of patience to watch and elaborate results. ..."

WJ Little, 1843
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This thesis is the first in a multidisciplinary research project that aims at the ultimate goal to compose an optimal combination of surgical procedures that balances the forces in the upper extremity as required by the desired functional improvement of the patient with cerebral palsy. The first step in this process was to test the validity of the classical biomechanical concept of tendon transfer. The clinical observations and experimental studies presented in this thesis showed that the biomechanics of tendon transfer are much more enigmatic than classically assumed.

The first, and most basic, assumption is that the prevailing classical concept regards the selected donor muscle as an isolated functional unit that is independent of its anatomical environment. If this is true, simple tenotomy will allow the muscle to retract to slack length, incapacitating it completely. However, intra-operative measurement of the length-force characteristics of a spastic human flexor carpi ulnaris muscle, seven years after tenotomy, demonstrated that it was still able to exert 60 to 110 N force within its operating range (Chapter one). Furthermore, its length-force profile matched the average profile of fourteen non-operated spastic flexor carpi ulnaris muscles. This observation suggested that surrounding fascial connections of the long muscle belly apparently retained the muscle fibres at their functional length after tenotomy. As such, the muscle could not be regarded to be independent of its anatomical environment.

This prompted a clinical intraoperative experiment in which the fascial connections between the flexor carpi ulnaris muscle and its environment proved to be strong enough to keep the muscle at length, even against the force of maximal tetanic contraction (Chapter two). Subsequent partial dissection for tendon transfer purposes released the muscle from its surrounding connective tissue, allowing it to retract an additional 17 mm on average ($p < 0.001$). Passive extension of the wrist still lengthened the muscle after tenotomy (89% of the original excursion), whereas this excursion significantly decreased after subsequent dissection (11% of the original excursion). These results showed that the muscle-tendon unit biomechanically interacted through inter- and extramuscular connections with its environment. Tendon transfer surgery alters these pathways of force transmission and, thus, the biomechanical properties of the donor muscle.

The second major assumption is that the only change in the musculoskeletal system is the transfer of the selected donor muscle from one location to another.
All postoperative change in range of motion around the crossed rotation axes is, thus, attributed to the transferred muscle's function. The effect of combined pronator teres rerouting and flexor carpi ulnaris transfer on forearm rotation was prospectively studied by comparison of pre- and postoperative three-dimensional analysis of forearm range of motion in ten patients with cerebral palsy (*Chapter three*). One year postoperatively, surgery had improved maximal supination of the forearm in all patients by an average of 63°, but this was opposed by a mean loss of 40° pronation. Computer simulation of the pronator teres rerouting procedure on a three-dimensional biomechanical model of the upper extremity demonstrated that, after rerouting, pronator teres was only capable of external rotation (supination) with the forearm in full pronation and not at other arm positions (*Chapter four*). The clinically observed gain in active supination was probably caused by facilitation of the original supinator muscles after release of the constraining pronator teres force. It appears that a rerouted pronator teres is not able to perform its intended function. At least, clinical outcome can not be attributed solely to the transferred pronator teres function. This calls for a reconsideration of the design of tendon transfer procedures with reference to kinematic parameters such as moment arms and muscle lengths.

The last assumption addressed in this thesis is that tendon transfer procedures are considered to only affect movements around the rotation axes crossed by the donor muscle-tendon unit. For this, a three-dimensional video analysis set-up and data analysis procedure was customized to evaluate the complex movement patterns of the upper extremity in cerebral palsy by comparison of the starting and end position of a standardized movement. A new parameter, *extrinsic forearm rotation*, was introduced to assess the relation between impaired forearm rotation and pathologically associated movement patterns (*Chapter five*). The active forearm rotation impairment in a group of 10 patients with cerebral palsy as compared to 10 age and sex-matched controls induced a significantly higher value for extrinsic forearm rotation (mean difference, +13°). It is concluded that the observed movement patterns feature pathological movements directly associated with impaired forearm rotation. Subsequently, the effect of surgical correction of the impaired forearm rotation on these associated movements was studied in the same 10 patients (*Chapter six*). One year postoperatively, active forearm supination during a functional reaching task had improved by a mean of 37° in combination with a significantly decreased extrinsic forearm rotation by a mean of 13°. Also, an average loss of 16° of active pronation in combination with an increased extrinsic forearm rotation (mean, 8°) was observed. It is concluded that tendon transfer procedures of the forearm may directly affect movements around other rotation
axes then those crossed by the transfer procedure. This should be anticipated at the
preoperative planning of procedures for multiple deformities, as such change in
movement pattern may involve deformities that are also eligible for surgical cor-
rection.

In general, it is concluded that the classical biomechanical concept of tendon
transfer is based on incorrect assumptions (Epilogue). However, a well performed
tendon transfer procedure remains an ingenious remedy for the dysbalanced
extremity crippled by the partial loss of its muscle-tendon action. In order to opti-
mally comprehend and control its merits, new fields of expertise need to emerge
from the collaboration of clinical and biomechanical sciences. Intraoperative force-
length measurements of human muscles during tendon transfer, kinematic analysis
of surgical procedures by computer aided musculoskeletal modelling, and clinical
three-dimensional motion analysis of pathological movement patterns of the upper
extremity will ultimately result in a comprehensive understanding of what we are
exactly achieving with tendon transfer surgery.
SAMENVATTING

Dit is het eerste proefschrift dat voortkomt uit een multidisciplinair onderzoek naar de optimale combinatie van chirurgische ingrepen aan de bovenste extremiteit van patiënten met cerebrale parcse. Een optimale combinatie van ingrepen zal de verstoorde spierbalans zodanig corrigeren dat de hulpvraag van de patient maximal tegemoet gekomen kan worden. De eerste stap in dit onderzoek was een inventarisatie van de validiteit van het klassieke biomechanische concept van peestranspositie chirurgie. Uit de klinische observaties en de resultaten van de studies die gepresenteerd werden in dit proefschrift blijkt dat de biomechanica van peestranspositie chirurgie veel ingewikkelder is dan wat er volgens het klassieke concept wordt aangenomen.

De eerste, en meest fundamentele veronderstelling van het klassieke concept is dat de geselecteerde donorspier, onafhankelijk van zijn anatomische omgeving, als een zelfstandige eenheid functioneert. Volgens dit concept zal de spier spontaan verkorten tot zijn rustlengte na distale tenotomie waardoor zijn functionele capaciteit volledig wordt uitgeschakeld. Zeven jaar na tenotomie van een spastische flexor carpi ulnaris (FCU) spier bleek, echter, bij peroperatieve krachtlengte metingen dat de spier nog altijd in staat was om binnen de excursie van zijn huidige lengte 60 tot 110 N kracht te produceren (Hoofdstuk één). Het profiel van de kracht-lengte relaties van deze spier kwam bovendien overeen met het gemiddelde profiel van veertien spastische FCU spieren die nooit eerder geopereerd waren. Deze bevindingen suggereren dat de spierevezels van de FCU op een functionele lengte gehouden werden door fasciale verbindingen rondom de lange spierbuik. Als zodanig mag de spier niet onafhankelijk van zijn anatomische omgeving beschouwd worden.

Vervolgens is in een klinisch peroperatief experiment aangetoond dat de fasciale verbindingen tussen de FCU en zijn omgeving sterk genoeg zijn om de spier, zelfs na maximale tetanische contractie, op lengte te houden (Hoofdstuk twee). Met het vrijprepareren van het distale deel van de spier ten behoeve van peestranspositie werd een deel van deze verbindingen losgemaakt en kon de spier gemiddeld nog 17 mm extra verkorten ($p < 0.001$). Bovendien werd ondanks tenotomie nog steeds een excursie van de FCU spierlengte gezien tijdens passieve extensie van de pols (89% van de originele excursie vóór tenotomie). Na gedeeltelijke dissectie van de spier uit zijn fasciale omgeving verminderde deze excursie significant tot gemiddeld 11%. De FCU heeft blijkbaar een biomechanische interactie met zijn anato-
mische omgeving via inter- en extramusculaire verbindingen. Door peetranspositie chirurgie verandert de omgeving en zodoende ook de biomechanische eigenschappen van de spier.

De tweede veronderstelling van het klassieke concept is dat het verplaatsen van een spier wordt gezien als de enige verandering binnen het bewegingsapparaat. Op basis van deze veronderstelling wordt alle verandering van beweging rond de rotatieassen die door de verplaatste spier gekruist worden toegeschreven aan de functie van die spier. Het effect van de combinatie van pronator teres rerouting samen met FCU transpositie op de rotatie van de onderarm is prospectief bestudeerd bij 10 patiënten met cerebrale parese (Hoofdstuk drie). Met behulp van driedimensionale video analyse zijn de postoperatieve en de preoperatieve resultaten met elkaar vergeleken. Een jaar na de operatie was de actieve supinatié van de onderarm met gemiddeld 63° verbeterd. Hier tegenover stond echter een gemiddeld verlies van 40° pronatie. Naar aanleiding van dit resultaat is de pronator teres rerouting procedure gesimuleerd met behulp van een driedimensionaal biomechanisch computermodel van de bovenste extremiteit (Hoofdstuk vier). De pronator teres bleek na rerouting alleen maar in staat om een supinerend moment te creëren in maximale pronatie, en niet in andere posities van de onderarm. De winst in actieve supinatié bij de patiëntengroep is mogelijk toe te schrijven aan de reeds bestaande supinerende spieren die gefaciliteerd worden door het uitschakelen van de pronerende kracht van de pronator teres. De simulatie suggereerde immers dat de pronator teres na rerouting niet in staat kan zijn om de klinisch geobserveerde supinatié uit te voeren. Het is dus niet vanzelfsprekend dat alle verandering van beweging rond de beoogde rotatieas veroorzaakt wordt door de getransponnerde spier. Deze resultaten vragen om een kritische revisie van het driedimensionale ontwerp van peetranspositie procedures.

De laatste veronderstelling die in dit proefschrift behandeld wordt is dat peetranspositie alleen maar invloed heeft op de beweging rond de rotatieassen die door de getransponnerde spier gekruist worden. Met behulp van driedimensionale video analyse werden de complexe bewegingspatronen van de bovenste extremiteit bij patiënten met cerebrale parese bestudeerd. Hiermee werd ‘extrinsic forearm rotation’ (EFR) geïntroduceerd als een nieuwe parameter om de aanwezigheid van pathologische bewegingspatronen te bestuderen die direct gerelateerd zijn aan een beperkte rotatie van de onderarm (Hoofdstuk vijf). Bij 10 patiënten met cerebrale parese en beperkte actieve onderarm rotatie was de EFR-waarde significant hoger in vergelijking met 10 gezonde proefpersonen, gepaard op sexe en leeftijd (gemiddeld verschil, +13°). Dit geeft aan dat een deel van het complexe en pathologische bewegingspatroon bij cerebrale parese direct gerelateerd is aan de beperkte rotatie
van de onderarm. Bij dezelfde groep van 10 patiënten werd vervolgens bestudeerd of deze pathologische bewegingspatronen veranderen na chirurgische correctie van de beperkte onderarm rotatie (Hoofdstuk zes). Een jaar na de operatie werd een verbetering gezien van de actieve supinatie bij het reiken naar een glas op tafel (gemiddelde toename, 37°). Dit bleek gecombineerd te zijn met een significante daling van de EFR (gemiddelde daling, -13°). Ook bij deze groep patiënten werd tevens een verlies van actieve pronatie (gemiddeld verlies, 16°) gezien, welke gecombineerd was met een toename van de EFR (gemiddeld, 8°). Blijkbaar kan een peestranspositie in de onderarm tevens invloed uitoefenen op bewegingen elders in het lichaam. Hiermee dient rekening gehouden te worden bij het samenstellen van een combinatie van chirurgische procedures voor verschillende deformiteiten. Het is immers mogelijk dat verschillende procedures die gericht zijn op de correctie van een deformiteit elkaar beïnvloeden.

In het algemeen moet geconcludeerd worden dat het klassieke biomechanische model van peestranspositie chirurgie gebaseerd is op onjuiste veronderstellingen (Epiloog). Dit laat onverlet dat een goed uitgevoerde peestranspositie nog altijd een vernuftige en succesvolle methode is om een verstoorde balans in de bovenste extremiteit te corrigeren. Verdere samenwerking tussen klinische en wetenschappelijke disciplines is nodig om peestranspositie chirurgie maximaal te beheersen en de beoogde functie van de getransponeerde spier te controleren. Peroperatieve kracht-lengte metingen van de donorspier tijdens transpositie, kinematische evaluatie van chirurgische procedures met behulp van computermodellen, en klinische driedimensionale analyse van pathologische bewegingspatronen zullen uiteindelijk een volledig inzicht geven in wat er daadwerkelijk veranderd in het bewegingsapparaat na een peestranspositie.