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

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Introduction

Pronator teres rerouting is used to correct pronation deformity of the forearm in patients with cerebral palsy²⁰,⁴⁷,⁶⁴,⁷⁴. 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.

![Diagram](image)

**Figure 1**
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: \[ ma = \delta L / \delta \phi, \]

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: \[ PMM = ma * PCSA * c, \]

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.
Muscle length: humero-radial part PT

**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.

Muscle length: ulno-radial part PT

**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\(^\text{25}\). 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

![Normalized moment comparison](image)

**Figure 4**

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\(^2\).
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.

![Figure 5](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°. 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° (SD, 14°) pronation to 25° (SD, 24°) pronation (no supination possible). Surgical procedures, which included pronator teres transfer, improved forearm range of motion to 29° (SD, 40°) of pronation to 38° (SD, 28°) 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° 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° 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, notwithstanding 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