On tendon transfer surgery of the upper extremity in cerebral palsy

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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).

![Graphical display of tendon tension tuning](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 in ‘$x$’ 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\textsuperscript{24, 46} and clinical observations in humans\textsuperscript{15, 17, 28} have shown that an \textit{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 can not be regarded as an independent mechanism with an invariably 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\textsuperscript{45}. The maximal active force capacity of the rat flexor carpi ulnaris muscle dropped 20 to 60% at progressive stages of muscle dissection\textsuperscript{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\textsuperscript{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-
nature 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\(^7\). It was not until the work of Dr. Paul Brand that sound mechanical principles were introduced into the clinical practice of hand surgery.\(^7\) Moment arms and distance between origin and reinsertion have been studied for a variety of transfer procedures in the upper extremity.\(^1,22,27,37,86\) 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.\(^51,59,66\) 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)

**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. 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