On tendon transfer surgery of the upper extremity in cerebral palsy
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Citation for published version (APA): Kreulen, M. (2004). On tendon transfer surgery of the upper extremity in cerebral palsy
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, intraoperative 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 correction.

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 optimally 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.