Introducing intraoperative direct measurement of muscle force and myofascial force transmission in tendon transfer for cerebral palsy
Smeulders, M.J.C.

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The aim of the study described in Chapter 1 was to determine whether the length and function of the flexor carpi ulnaris muscle were affected by separation of the muscle 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.

Extra-muscular connective tissue and muscular fascia have been suggested to form a myofascial pathway for transmission of forces over a joint that is additional to the generally accepted myo-tendinous pathway. The consequences of myofascial force transmission for the outcome of conventional muscle tendon transfer surgery have not been studied as yet. To test the hypothesis that surgical dissection of a muscle will affect its length force characteristics, a study was undertaken in adult male Wistar rats. This study is described in Chapter 2. During progressive dissection of the flexor carpi ulnaris muscle, isometric length force characteristics were measured using maximal electrical stimulation of the ulnar nerve. After fasciotomy, muscle active force decreased by approximately 20%. Further dissection resulted in additional decline of muscle active force by another 40% at maximal dissection. The muscle length at which the muscle produced maximum active force increased by approximately 0.7 mm, (i.e. 14% of the measured length range) after dissection. It is concluded that, in rats, the fascia surrounding the flexor carpi ulnaris muscle is a major determinant of muscle length-force characteristics.

The specific relationship between force and length is one of the most important characteristics of vertebrate muscle. The only accurate method to measure the length-force characteristics is to generate a set of isometric force-time plots at different muscle lengths. In humans, such length-force characteristics mostly are based on indirect measurements that have their limitations. A method of direct, in-
vivo measurement of length-force characteristics of the human flexor carpi ulnaris muscle using relatively simple equipment during transposition surgery is presented in Chapter 3. The method is proven reproducible, with an overall estimated error of 2.8%.

For the study described in Chapter 4 we tested whether the length-force characteristics of the distally tenotomized human flexor carpi ulnaris muscle (FCU) of nine patients with cerebral palsy varied with the change of relative length of adjacent structures induced by a change of wrist positions. Recent animal experiments previously had shown that up to 37% of muscle force may be transmitted to adjacent structures rather that reach the muscle's tendon insertion, and that the extent of such force transmission depends on the length and relative position of these structures. In four patients, the FCU exerted up to 40% more active force in flexed wrist position at low FCU length ($p = 0.019$), whereas the active force was not significantly higher in the other five ($p = 0.204$). Likewise, in spite of distal tenotomy, passive length-force characteristics of the spastic FCU changed upon changes in wrist position. This may explain part of the variability in success of the FCU-transfer.

The aim of the study described in Chapter 5 was to answer the question whether the muscle contracture in patients with cerebral palsy is caused by overstretching of in-series sarcomeres. We studied the active and passive length-force relationship of the flexor carpi ulnaris muscle (FCU) in relation to its operating length range in 14 such patients with a flexion deformity of the wrist. Length-force relationship was measured intraoperatively using electrical stimulation, a force transducer, and a data-acquisition system. Muscle length was measured in maximally flexed and maximally extended position of the wrist. The spastic FCU was found to exert over 80% of its maximum active force at maximal extension of the wrist and this indicates abundant overlap of the sarcomeres. At maximal wrist extension, FCU passive force corresponded with only 0.7% to 18% of maximum active force. Both findings imply that the FCU sarcomeres are not overstretched when the wrist is extended. We conclude that the overstretching of in-series sarcomeres appears not to be the cause of contracture of the spastic FCU.

The methods and results of our research provide new insights in the in-vivo muscle characteristics of spastic muscles, and may be extrapolated to those of normal muscles. The introduction and validation of our validated method of direct, in-vivo measurement of force-length characteristics of muscles allows the accurate obtaining of data on muscle functioning in situ in a relative easy way. Moreover, the concept of myofascial force transmission has been tested for the first time in a human model and we feel that sufficient arguments support its existence. Accept-
ing such force transmission dictates a new way of looking at muscle function and likely has consequences for clinical tendon transfer surgery. These new insights and implications are discussed in Chapter 6, as are the limitations of our research to date.