

Journal of Biomechanics 32 (1999) 71-79

JOURNAL OF BIOMECHANICS

Acute effects of intramuscular aponeurotomy on rat gastrocnemius medialis: Force transmission, muscle force and sarcomere length

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Received in final form 14 October 1998

Abstract

Acute effects of intramuscular aponeurotomy on muscle force and geometry as a function to muscle length were studied in rat m. gastrocnemius medialis (GM). Acutely after aponeurotomy, activation of the muscle at increasing lengths (acute trajectory) showed a spontaneous and progressive but partial tearing of the connective tissue interface between the fibres inserting directly proximally and distally to the location of the section. After this the muscle consisted morphologically of a stable proximal and a distal part (post-aponeurotomy). Post-aponeurotomy mean active sarcomere length within fibres of the proximal part was shown to be unaffected. In contrast, mean sarcomere length within the distal part was reduced substantially after aponeurotomy. However active sarcomeres in the distal part were still attaining higher lengths with increasing muscle lengths (p < 0.005), indicating myofascial force transmission through the intact part of the connective tissue interface of the muscle parts. Post-aponeurotomy optimum muscle force was reduced substantially to less than 45% of pre-aponeurotomy values. During the acute trajectory the muscle yielded approximately 20% higher forces than post-aponeurotomy, indicating that myofascial force transmission was related to the area of connective tissue interface. It is concluded that after aponeurotomy of the proximal aponeurosis of rat GM, fibres without direct myotendinous connection to the origin of the muscle are still able to contribute to muscle force. As the magnitude of reduction in muscle force can only be explained partially by the spontaneous rupture of the connective tissue interface between proximal and distal muscle part, other factors causing a decrease of muscle force are present. Clinical implication of acute effects of intramuscular aponeurotomy are discussed. (C) 1999 Elsevier Science Ltd. All rights reserved.

Keywords: Intramuscular aponeurotomy; Myofascial force transmission; Sarcomere length; m. Gastrocnemius medialis; Rat

1. Introduction

In orthopaedics several techniques are used to lengthen overly short muscles. One such surgical intervention is intramuscular aponeurotomy (Baumann and Koch, 1989; Majestro et al., 1971; Scherb, 1935). Depending on the type of muscle and the clinical diagnosis the aponeurosis is transsected perpendicular to its length at one or more locations. Even though such operations are clinically successful in restoring more normal patterns of gait in spastic children (Barnes and Herring, 1991;

ann and neurosis, part of the muscle fibres loose their direct myotendinous connection to either muscular origin or insertion. However, the intramuscular network of connective tissue, consisting of endomysium and per-

imysium, stays intact partially. This means that the fibres without direct myotendinous connection still have parallel connections via the intramuscular connective tissue to the tendon. On the basis of experiments using small fascicles it is known that fibres are able to transmit force laterally onto the network of endomysium which is shared with adjacent fibres (Street, 1983). Furthermore, it has been shown that after tenotomy of heads of the in situ m. extensor digitorum longus (EDL), muscle force was

Nather et al., 1984; Nene et al., 1993; Reimers, 1990; Ruda and Frost, 1971), relatively little is known about the

mechanisms active and their effects on muscle mechanics.

Due to transverse sectioning of an intramuscular apo-

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reduced by only a small amount which means that the released heads were still contributing to the muscle force (Huijing et al., 1998). These findings show that in whole muscle, fibre force is transmitted through the network of endomysium and perimysium.

If such myofascial force transmission mechanisms are also operational after aponeurotomy of a muscle, it is expected that the muscle fibres without direct myotendinous connection to either origin or insertion still contribute to muscle force. The aim of the present study is to investigate the acute effects of aponeurotomy of the proximal aponeurosis of the very pennate rat gastrocnemius medialis muscle (GM) on muscle force and muscle geometry, and find evidence for myofascial force transmission across the location of intervention.

2. Materials and methods

2.1. Animals and experimental set-up

All surgical and experimental procedures were performed in strict agreement with Swiss law and regulations concerning animal welfare. Wistar rats (n = 10, body mass 340-385 g) were anaesthetised by intraperitoneal injection of sodium-pentobarbitone (initial dose 8 mg/100 g body mass) and ventilated mechanically. The medial head of GM of the right leg was dissected, leaving its origin intact. The blood supply was left undisturbed whereas the sciatic nerve was cut as proximally as possible. The achilles tendon with a piece of calcaneal bone still attached was connected by a metal wire to a force transducer (A&D Company LC-4101). Small copper markers were inserted into the muscle to mark the origin of the muscle, the distal end of the proximal aponeurosis and the distal end of the distal fibre (Fig. 1a).

The animal was positioned in the experimental set-up by rigidly clamping the femur. Ambient temperature was controlled at 27°C. The proximal end of the nerve was stimulated supramaximally (100 Hz, 0.15 ms square wave pulse) using silver electrodes connected to a constant current source. Tetanic isometric contractions of 600 ms were induced at a series of muscle lengths, beginning near active slack length and ending at the length at which



Fig. 1. Intact GM and schematic models of muscle geometry of the mid-longitudinal plane. (A) Laterodorsal view of the active muscle, near optimum length before aponeurotomy. Small copper markers were inserted into the muscle to mark: (1) the origin of the muscle, (2) the distal end of the proximal aponeurosis and (3) the distal end of the distal fibre. (B) Geometric parameters in the mid-longitudinal plane of GM before aponeurotomy. Direct measurement of the distances between the markers provides estimates of muscle length (lma), length of proximal aponeurosis (la-prox), and of distal fibre (lf-dist). The length of muscletendon-complex is indicated as the distance between origin and insertion (loi). Based on findings of Zuurbier and Huijing (1993) and our own pilot data the length of the distal aponeurosis (la-dist) was assumed to be 1.11 times the length of la-prox. Distal end of la-dist was estimated 0.5 mm below the distal end of distal fibres. Taking this point as the centre, a circle of radius (la-dist) was drawn. The longitudinal direction of the proximal part of distal aponeurosis was estimated in the image (thick dotted line). The intersection between this direction and the circled la-dist indicates the distal end of the most proximal fibre (lfprox). The length of intermediate proximal (lf-ip) and intermediate distal fibres (lf-id) are defined as the distance between the midpoints of proximal and distal aponeurosis. (C) Geometric parameters in midlongitudinal plane of GM after aponeurotomy. The proximal aponeurosis is cut approximately at its middle, with the muscle positioned at optimum length. A gap between the two ends of the proximal aponeurosis (lgap) arises, dividing the proximal aponeurosis into a proximal (la-prox-prox) and distal part (la-prox-dist). Due to this, also on the distal aponeurosis a proximal (la-dist-prox) and distal part (la-dist-dist) can be distinguished. Their length was estimated by assuming them to be equal to 1.11 times la-prox-prox (based on our own pilot data). The position of the location of the distal end of the most proximal fibre was estimated in a fashion similar to that described for the intact muscle (1B). In intermediate region fibre lengths (lf-ip and lf-id) were estimated on the basis of distances between appropriate ends of the parts of proximal and distal aponeurosis.

force was about 90% of maximum force (1 mm increments). Each tetanic contraction was preceded by two twitches with a 1 s interval to allow adjustment of the muscle to that length. Three seconds after the last twitch, a tetanic contraction was evoked. The interval between two subsequent tetanic contractions was 2 min, during which the muscle was allowed to recover at short length. The muscle was photographed (Cannon A1 camera, macro lens, exposure time 1/125 s, 400 ASA slide film) in passive state (2 s before activation) and in fully active state (200 ms after evoking tetanic stimulation). A microcomputer was used to collect all force data, using an AD-converter (Validyne Engineering Corp. UPC601-G, sampling frequency of 1000 Hz and resolution of force 0.0071 N).

2.2. Experimental protocol

First, length–force characteristics of the intact gastrocnemius medialis were determined. Subsequently, the muscle was lengthened to about its optimum length and the proximal aponeurosis was transsected using a scalpel blade (number 23) at its middle perpendicular to its length (Fig. 1c). Acutely after aponeurotomy the muscle was activated at increasing muscle lengths (acute trajectory). After this length–force characteristics were determined again (post1-aponeurotomy). In eight animals measurement of length–force characteristics was subsequently repeated (post2-aponeurotomy).

2.3. Treatment of data

2.3.1. Dimensions of anatomical structures

Post-experimentally, morphological variables were estimated by determination of the marker positions on projected photographic images (magnification 15×) using a digitiser tablet (Microgrid III Summagrafics Co., mean error 0.017 mm) and a software program (Autocad 12.0). For the pre- and post-aponeurotomy condition different models were used to estimate muscle geometry of the mid-longitudinal plane.

The lengths of the muscle, the proximal aponeurosis and the distal fibre were measured directly from the marker positions, neglecting any effects of curvature (Fig. 1a). Pilot experiments showed that the length of the distal aponeurosis was 1.11 times the length of the proximal aponeurosis at all muscle lengths, which is in accordance with results of Zuurbier and Huijing (1993). Estimation of the length of proximal and intermediate fibre is indicated in Fig. 1b and c.

2.3.2. Muscle force

Data relating passive force to muscle length were leastsquares fitted using an exponential function (Eq. 1):

$$y = e^{b0 + b1x} + b_2 \tag{1}$$

where y represents passive force, b_0 , b_1 and b_2 are constants determined during the fitting procedure. Active muscle force (Fma) was calculated by subtracting passive force (Eq. 1) from total muscle force for the appropriate muscle lengths. The relationship of active force with muscle length was fitted by a polynomial (Eq. 2):

$$y = b_0 + b_1 x + b_2 x^2 + b_3 x^3 + b_4 x^4 + b_n x^n,$$
 (2)

where b_0 through b_n are constants selected in a leastsquares fitting procedure. The order of the polynomial most adequately describing the relationship was selected (see statistics). Muscle optimum length (lmao) was defined as that length at which the maximum of the selected polynomial curve describing active muscle force was encountered within the muscle length range of the experiment. Muscle active slack length (lmas) was determined by fitting muscle force using Eq. 1 over the range of muscle lengths at which active muscle force ranged between zero and 30% of maximal muscle force. Muscle active slack length was defined at the intercept of the fitted curve and the x-axis. These calculated values are shown in Fig. 7. The relationships between morphologic variables and active muscle length were fitted with a third-order polynomial. Fitted curves were used to calculate mean data + S.E.

2.4. Fibre mean sarcomere length

To determine the mean sarcomere length of proximal, intermediate proximal, intermediate distal and distal fibres (Fig. 1) the number of sarcomeres in series were determined for a sample of four fibres of each region. According to the method described by Huijing (1985), the muscles were fixed (4% formaldehyde, 15% absolute alcohol and 1.5 gl^{-1} thymol) for at least 2 weeks. Fibre bundles taken out of the muscle were exposed to a 17.5% KOH solution (modification to Huijing (1995)) for 4 h after which they were stored in a 50% glycerol solution for 2-4 days to soften connective tissue. From every region four isolated fibres were teased out for their whole length. The number of sarcomeres in series was counted semi-automatically using a microscope (Zeiss, magnification 20×) connected to an image-analyser (lowpass filter of grey levels) counting number of A-bands every 120 µm along the fibre.

2.5. Statistics

To select the polynomial most adequately describing the length–force data, the fitting was started with a first order and the power was increased up to a fifth order. One way ANOVA was performed to select the highest polynomial order that yielded a significant improvement of the length-force data. One-way and two-way ANOVA for repeated measurements (Neter et al., 1996) were performed to test for differences between the four experimental conditions. Post hoc tests were performed using the Bonferroni procedure to locate significant differences (P < 0.05).

3. Results

3.1. General effects of aponeurotomy

Before aponeurotomy the muscle can be considered to consist of a single population of muscle fibres. Acutely after aponeurotomy the muscle was not a stable morphological unit anymore. Below the location of the aponeurotomy intramuscular connective tissue ruptured progressively along the direction of the muscle fibres. A gap between the distal and proximal part of the muscle appeared which increased at higher muscle lengths and forces (Figs. 2 and 3). The data describing this phase is referred to as 'acute trajectory' in Figs. 3–7. It should be noted that in the clinical situation a similar effect is seen: As the muscle is spastic, its activity will tear the muscle spontaneously after aponeurotomy.

During the subsequent determination of the lengthforce characteristics (post1), particularly at low lengths, the length of the gap was shown to be significantly higher than for the acute trajectory. However, repeating this part of the experiment (post2) showed only marginal changes regarding the relationship of muscle length and gap width (Fig. 3). This indicates that after the acute trajectory the connective tissue did not rupture any further and the muscle became a stable entity again yielding reproducible results. However, now the muscle consisted



Fig. 2. Tearing of the muscle after aponeurotomy. (A) Active muscle at low length during the acute trajectory. The connective tissue at the interface of both muscle parts has just started to rupture resulting into a separation of the aponeurosis ends creating a gap (arrow) within the proximal aponeurosis. (B) Active muscle near optimum length during the acute trajectory. Comparison with Fig. A shows the progression of the rupture along the intermediate fibres and a substantial increase in the gap in the proximal aponeurosis and the deepening of the tear into the muscle.



Fig. 3. Length of the gap between aponeurosis ends. Active gap length (mean + SE) in the proximal aponeurosis is plotted against muscle length. During the acute trajectory, aponeurosis gap length increased progressively with higher muscle length due to partial rupture of the connective tissue interface between the proximal and distal muscle part. Active gap length was significantly higher in the post1-aponeurotomy condition than in the initial phase of the acute trajectory. This indicates the progressive effect of rupturing. Subsequently in the post2-aponeurotomy condition active gap length is still a function of muscle length but showed only marginal change, indicating that the muscle had stabilised.



Fig. 4. Distal fibre length in the passive and active muscle before and after aponeurotomy. Distal fibre length (mean value) for passive (pas) and active (act) muscle is plotted as a function of muscle-tendon-complex length. Muscle-tendon-complex length is expressed as deviation (Δ loi) from its value at active muscle slack length. Values corresponding to the acute trajectory are indicated by dashed curves. After aponeurotomy the distal fibres still shortened approximately 2 mm on activation indicating that the intramuscular motor nerves innervating the distal part of the muscle were still functional after aponeurotomy. Note that in the pre-aponeurotomy shortening was similar over the whole length range studied.

of two distinct populations of muscle fibres (proximal and distal groups). It should be noted that these two populations were completely separated for quite a distance along the length of the fibre, but were still sharing a partial connective tissue interface along the fibre length closest to the distal aponeurosis.



Fig. 5. Active fibre mean sarcomere lengths in the proximal muscle part before and after aponeurotomy. Aponeurotomy did not affect mean sarcomere length (mean +SE) of either the proximal (A) or the intermediate proximal fibre (B) indicating that the contribution of the proximal muscle part to muscle force was not affected. The acute trajectory is indicated by a dotted line. For reference, the thin dotted line indicates optimum sarcomere length as determined by Zuurbier et al. (1995, 1998) for small bundles of fibres from GM.

Comparison of the relationship of distal fibre length and muscle-tendon complex length for the passive and active muscle showed that after aponeurotomy fibres in the distal part shortened substantially on activation (Fig. 4). This indicates that the intramuscular motor nerves innervating the distal part of the muscle were still functional after aponeurotomy and the tearing of the muscle belly.

3.2. Fibre mean sarcomere length

3.2.1. Proximal muscle part

No significant effects of aponeurotomy could be shown for the curves relating mean sarcomere length of the proximal and intermediate-proximal fibres to muscle length (Fig. 5). It is concluded that after aponeurotomy the contribution of the fibres in the proximal part to muscle force was not affected.

3.2.2. Distal muscle part

Acutely after aponeurotomy fibre mean sarcomere length of both intermediate-distal fibres (Fig. 6a) and distal fibres (Fig. 6b) dropped significantly at most muscle lengths. As these fibres generally remained below their optimum length, the lower fibre length indicates a substantial reduction in force exerted by these fibres. It should be noted that, despite the finding that fibres were not able to maintain their original length, it was shown that both intermediate-distal fibres (Fig. 6a) and distal fibres (Fig. 6b) still attained higher lengths with increasing muscle lengths. Regression analysis of mean sarcomere length change as a function of muscle length, showed these increases to be significant (Fig. 6c and d, p < 0.005).

It is concluded that at higher muscle length some force prevented fibres of the distal muscle part from shortening to their lowest length attainable in this experiment. Such a force will equilibrate with any force generated within the fibres. It will also allow transmission of this fibre force to the outside world, despite the fact that the proximal fibre attachments to the aponeurosis are no longer in direct connection with the muscle origin. It is concluded that the endomysial-perimysial apparatus surrounding the muscle fibres is the carrier of such transmission (myofascial force transmission).

3.3. Length-force characteristics

Fig. 7 shows length-force characteristics before and after aponeurotomy. In agreement with results of mean sarcomere lengths of fibres within the distal muscle part, muscle optimum length shifted significantly to higher muscle lengths (by 2 mm). Muscle optimum force dropped to 44% of the pre-aponeurotomy condition. Note that muscle active slack length also shifted to higher lengths (by 1 mm). After aponeurotomy, passive forces were shown to be significantly lower (by approximately 50%) in the range of muscle lengths studied.

In contrast with results for fibre mean sarcomere lengths, the decrease in active muscle force found did not yield any clear evidence for a remaining contribution of force by the distal muscle part and the transfer of force to the origin. The actual value of 56% reduction of optimum force was in the same order of magnitude as expected when cutting the aponeurosis 50% of the way along its length and no myofascial force transmission would be present.

The post2 length-force curve was similar to that of the post1-condition. This finding yields another indication that the muscle did stabilise after the progressive changes of the acute trajectory. The post-aponeurotomy active length-force curves show the cumulative effect of aponeurotomy per se and the tearing of the muscle connective tissue apparatus during the acute trajectory.



Fig. 6. Active fibre mean sarcomere length of distal (lsa-dist) and intermediate-distal (lsa-id) fibres. After aponeurotomy, mean sarcomere length (mean + SE) of the intermediate distal fibre (A) as well as distal fibre (B) decreased substantially for almost the whole range of muscle lengths studied. After aponeurotomy sarcomeres still attained higher lengths with increasing muscle length, indicating that they were prevented from shortening to their active slack length. During the acute trajectory (dotted line) intermediate distal fibre had significantly higher mean sarcomere lengths than in the post-aponeurotomy condition. For reference, the thin dotted line indicates optimum sarcomere length as determined by Zuurbier et al. (1995, 1998) for small bundles of fibres from GM. Individual data for the intermediate-distal (C) and distal fibre (D) shows mean sarcomere length changes (Δ lsa) with changes to muscle length compared to the lowest length attained after aponeurotomy. Significant slopes of regression lines (p < 0.005) show that post-aponeurotomy both lsa-id and lsa-dist increased with higher muscle length.

Muscle force during the acute trajectory was significantly higher at all muscle lengths studied (by approximately 20%). This is in accordance with the finding that for the acute trajectory sarcomeres attained higher lengths at higher muscle lengths than in the postaponeurotomy conditions. The higher mean sarcomere length is related to a larger area of intact connective tissue interface between proximal and distal parts of the muscle available at most muscle lengths. This is in agreement with expectations regarding myofascial force transmission.

It is concluded that after aponeurotomy muscle force drops substantially. However, fibres of the distal part without tendinous connection to the origin of the muscle are still able to contribute to muscle force via myofascial force transmission. Therefore, the magnitude of the decrease of muscle force can only be understood if additional factors causing a decrease of muscle force are present.

4. Discussion

The present results indicate that aponeurotomy of the proximal aponeurosis of GM dramatically affected both morphology and mechanical behaviour of the muscle. Due to the aponeurotomy, approximately half of the muscle fibres lost their direct myotendinous connection to the origin of the muscle. However two major findings indicate that these fibres were still contributing to muscle force. Firstly, fibres distally to the section were still able to attain higher length with increasing muscle lengths. Some force prevented the fibres from shortening. Secondly, during the acute trajectory the muscle yielded higher forces than in the post1 and post2 conditions.

4.1. Myofascial force transmission

Acutely after aponeurotomy fibres distally to the section were no longer able to transmit force via their



Fig. 7. Length-force characteristics of the rat m. gastrocnemius medialis before and after aponeurotomy of the proximal aponeurosis and data describing the acute trajectory of muscle tearing. Comparing intact and post-aponeurotomy conditions shows that active muscle force (Fma, mean + SE) dropped by more than 50% at any muscle length. Passive force curves shifted slightly to higher muscle lengths leading also to substantially lower passive forces at higher muscle lengths. Note that separate scaling was used for active force (left *y*-axis) and passive force (right *y*-axis).

myotendinous junctions (MTJ) onto the proximal the aponeurosis to the origin of the muscle. It is generally accepted that the MTJ of the fibre is very suited for transmitting force because of its increased contact surface due to the invaginations of the sarcolemma. However, besides transmission at the end of the fibre, single fibre experiments showed that myofibrillar force is transmittable through the sarcolemma-endomysium complex along the fibre (Street and Ramsey, 1965). It was even demonstrated that fibres are able to transmit laterally nearly all of the force generated through the connective tissue surrounding the fibre (Street, 1983). Detailed studies revealed the presence of several types of glycoproteins (reviewed by Patel and Lieber, 1997) possibly involved in the mechanical coupling of the myofibrillar apparatus to the extra-cellular matrix. As yet their function in force transmission has to be elucidated. The subsequent transmission from the extra-cellular matrix via the intramuscular connective tissue consisting of endomysium and perimysium is proposed to occur by shearing of these structures (Huijing, 1998; Purslow and Trotter, 1994; Trotter, 1993; Trotter et al., 1995; Trotter and Purslow, 1992).

Experimental evidence for myofascial force transmission in whole muscle has been provided after tenotomy performed on m. extensor digitorum longus (EDL) (Huijing, 1998; Huijing et al., 1998). Subsequent tenotomy of heads of EDL in proximal-distal order caused only minor reductions in muscle force indicating myofascial force transmission.

After aponeurotomy the intramuscular connective tissue ruptured spontaneously and muscle force was substantially reduced, which was not observed during the tenotomy experiments on EDL (Huijing et al., 1998). These authors also reported that only interference with the connective tissue between intact and tenotomised heads (myotomy) led to a substantial reduction in muscle force but did not fully obliterate myofascial force transmission. This strongly confirms the relationship between the tearing of the interface and the decrease in force transmittable through the network of intramuscular connective tissue. The question arises how to explain the spontaneous tearing and its accompanying reduction in muscle force after aponeurotomy. As yet experimental determination of type and magnitude of stresses present at the interface is not possible. A high stress concentration due to the presence of the cut is expected from simple fracture mechanics considerations. Finite element modelling should be applied to investigate the cause of the spontaneous rupturing in detail.

4.2. Reduction in muscle force and intra-fibre distribution of sarcomere lengths

In case of an intact intramuscular connective tissue surface, such as like after tenotomy, one would expect fibre length to decrease with increasing distance from the location of the intervention due to shearing. After tenotomy of several heads of the EDL this has been argued to be the major factor explaining the minor reduction in muscle force (Huijing et al., 1998).

After aponeurotomy, an additional factor explaining reduced muscle force is the decreased length of the connective tissue interface of both muscle parts due to the rupture. Due to this rupture, the proximal ends of the fibres in the distal part shift distally. At any given muscle length this is expected to lower length of parts of these fibres.

For small fibre bundles, Zuurbier et al. (1995, 1998) showed that the mean length of sarcomeres at active slack length and optimum length ranged from 1.27 to 2.38 µm. Comparison of the present results to those values would lead to the conclusion that the distance between markers indicating the ends of the intermediate fibres would on average not attain values over active slack length. This would implicate that these fibres, in contrast to distal fibres, would not contribute to muscle force as has been argued for proximal and or intermediate fibres in intact muscle at low lengths (Zuurbier and Huijing, 1993). However, given present evidence for myofascial force transmission, effects of distribution of length of sarcomeres in series within a muscle fibre have to be taken into account as well. Fibre-splint experiments of Street (1983) suggest that for the active splinted fibre, sarcomeres within the isolated part shortened, whereas within the part connected by myofascial force transmission, sarcomeres maintained their original length. Furthermore finite element modelling of Van der Linden et al. (1997) showed that the magnitude of fibre force, exerted on its surrounding is the net result of the dynamic equilibrium of active forces and internal and external resistance forces. This implicates that active slack length of a fibre within a muscle will be highly dependent on the conditions of surrounding tissue. Therefore comparison of such parameter values may not be valid.

Insight in local conditions of sarcomeres is necessary to understand the reduction in muscle force after aponeurotomy. As it is technically not feasible to measure intramuscular sarcomere length distributions in whole muscle, finite element modelling of effects of aponeurotomy may be a useful application.

4.3. Clinical implications

Intramuscular aponeurotomy is one way to lengthen overly short muscles (Baumann and Koch, 1989; Majestro et al., 1971). Acutely we find a moderate increase of muscle optimum and slack length. For a higher increase of muscle length additional treatment is necessary. At the same time the muscle should not be overloaded because the rupturing of the connective tissue is related to the magnitude of stretch.

In case of restricted range of joint motion due to overly short, spastic muscles, three different approaches are distinguished regarding mechanisms of restoration of the range of joint motion. (1) Lengthening of a short muscle (Graham and Fixsen, 1988; Tardieu et al., 1979), (2) Weakening of the short muscle (Nather et al., 1984; Sharrard and Bernstein, 1972), (3) Reducing the degree of spasticity (e.g. Peacock and Staudt, 1990; Young, 1994).

The present results show that intramuscular aponeurotomy includes aspects of all three ways of restoring the range of motion and allow insight in the mechanism active. (1) Muscle optimum length shifted to higher muscle lengths with about 10% of its active range of force production. Such lengthening of a short muscle would directly shift the range of active muscle force production to a more preferable range of joint angles. (2) Muscle force was reduced to half its original force. Acute weakening of the short muscle would increase the relative strength of antagonist muscles allowing the short agonist to be stretched. Nather et al. (1984) indicated intramuscular aponeurotomy as a clinical mean of lowering force of a target muscle in a controlled fashion. Our results indicate that the depth of tearing of the muscle at the location of the aponeurotomy determines the force decrease obtained acutely. As full control of the depth of the tear is difficult, such graded control of muscle force is not likely. (3) Reduction of mean sarcomere length in the distal part implicates that within this part, muscle spindles attain the same level of stretch only at much higher muscle lengths than before aponeurotomy. Such reduction of stretch of muscle spindles within the short muscle will reduce the degree of spasticity and allow a less impeded

access to the muscle's length range. In comparison to other methods such as pharmacological treatment (reviewed by Young, 1994) aponeurotomy has the advantage of avoiding negative side effects such as for example genotoxicity and possible carcinogenity of phenol (Dutch, 1996) and more general complaints (Kilburn, 1994).

It is concluded that acute effects of intramuscular aponeurotomy are favouring restoration of the joint range of motion. However, it should be realised that the acute situation after aponeurotomy is also the starting point for recovery of the muscle. After aponeurotomy most fibres in the distal part were intact and able to produce force. This is confirmed by the finding that after six weeks of recovery both parts of the proximal aponeurosis were reconnected and muscle optimum force was restored to at least its pre-aponeurotomy value (Brunner, 1998; Brunner et al., 1998). This adaptation indicates that the initial attainment of the clinical goal of weakening the muscle (as expressed by Barnes and Herring, 1991; Nather et al., 1984; Ruda and Frost, 1971) is not maintained for the longer term. Therefore, the clinical long-term success reported by these authors must be related to other mechanisms which may be related to post-operative stretching.

The short-term weakening after aponeurotomy facilitates stretching of the spastic muscle compared to the pre-aponeurotomy condition. In addition adaptation of sarcomeres in series may occur during recovery. Due to the distribution of length of sarcomeres in series within fibres, as well as the distribution of fibre mean sarcomere length, adaptation of number of sarcomeres in series within muscle fibres is expected to be influenced by many local effects. More detailed information about sarcomere length distributions and long-term adaptations of number of sarcomeres in series is necessary to understand fully the mechanisms of the clinical benefit of intramuscular aponeurotomy.

Acknowledgements

The authors gratefully acknowledge George Meier-Hofmann for his technical support during the experiments and the treatment of data, Guus Baan and Marianne Six-Dijkstra for their assistance with the determination of number of sarcomeres. The financial support of Ciba Geigy (now Novartis) and the Stichting Het Burgerweeshuis Meppel is also acknowledged.

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