Assessment by Finite Element Modeling Indicates That Surgical Intramuscular Aponeurotomy Performed Closer to the Tendon Enhances Intended Acute Effects in Extramuscularly Connected Muscle

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The effects of location of aponeurotomy on the muscular mechanics of extramuscularly connected muscle were assessed. Using finite element modeling, extensor digitorum longus muscle of the rat was studied for the effects of aponeurotomy performed in each of three locations on the proximal aponeurosis: (1) a proximal location (case P), (2) an intermediate location (case I), and (3) a distal location (case D). Proximo-distal force differences were more pronounced for more proximal aponeurotomy. The location also affected proximally and distally assessed muscle length-force characteristics: (1) Muscle optimum length and active slack length shifted differentially to higher lengths, increasing slack to optimum length range (for D to P: distally by 15–44%; proximally by 2–6%). (2) Muscle forces decreased at all lengths (e.g., for D to P distal optimal force = 88–68% and proximal optimal force = 87–60% of intact values, respectively). Increased length range and force decreases were highest for case P, as were effects on muscle geometry: gap length within the proximal aponeurosis; decreased proximal fiber population pennation angle. Parallel, but not serial, heterogeneity of sarcomere length was highest in case P: (a) For the distal fiber population, sarcomere shortening was highest; (b) for the proximal population, sarcomeres were longer. It is concluded that if aponeurotomy is performed closer to the tendon, intended surgical effects are more pronounced. For bi-articular muscle, mechanics of both proximal and distal joints will be affected, which should be considered in selecting the location of aponeurotomy for optimal results at both joints. [DOI: 10.1115/1.3005156]

Keywords: aponeurotomy, location of intervention, extramuscular myofascial force transmission, muscle length-force characteristics, sarcomere length distributions, finite element method

Introduction

Spasticity and contractures that may occur after neurological disorders can affect joint motion and reduce life quality. Aponeurotomy is one of the surgical techniques applied to correct such functional problems [1] aiming at lengthening of the target muscle as well as reducing its force. During this operation, the intramuscular aponeurosis is cut transversely, the joint angle is adjusted to lengthen the target muscle, and the limb is usually placed in a cast for recovery.

In recent studies on isolated rat muscles, using experimental techniques [2–4] and finite element modeling [5] important insight has been gained on the mechanical mechanism of this intervention, which was shown to be dominated by myofascial force transmission [5]. However, in its natural environment, muscle has connections to its surrounding muscles and nonmuscular structures; therefore, it is not isolated. The connections (comprised of neurovascular tracts in addition to compartmental boundaries (see Refs. [6–8] for pictures) between the muscles' extracellular matrix and the surrounding nonmuscular structures are referred to as *extramuscular connections*. Such structures form fairly stiff linkages that transmit muscle force [6,8–11]. This kind of force transmission (*extramuscular myofascial force transmission)* was shown to affect muscular mechanics substantially in not only intact muscle [6,9,11,12] but also in aponeurotomized muscle [13].

Many researchers address the effectiveness of surgical aponeurotomy using different approaches [14–19]. However, the precise location of aponeurotomy is frequently not central to the design of the operation and the role of location of intervention on the acute effects is not well known. Based on our previous work we hypothesized that the location of aponeurotomy may affect substantially the outcome of the operation because it can alter the integral system of intra- and extramuscular myofascial force transmission. The goal of the present study is to test this hypothesis using finite element modeling.

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Methods

Description of the "Linked Fiber-Matrix Mesh Model". Using the linked fiber-matrix mesh (LFMM) model [20], skeletal muscle is considered explicitly as two separate domains: (1) the intracellular domain and (2) the extracellular matrix domain. The transsarcolemmal attachments are considered as elastic links between the two domains.

Two self-programed elements were developed and were introduced as user-defined elements into the finite element program ANSYS 9.0: (1) *Extracellular matrix element* represents the collagen reinforced extracellular matrix, which includes the basal lamina and connective tissue components such as endomysium, perimysium, and epimysium. (2) *Myofiber element* models the muscle fibers. Within the biological context, each combined *muscle element* represents a segment of a bundle of muscle fibers with identical material properties, its connective tissues, and the links between them. This is realized as a linked system of extracellular matrix and myofiber elements (for a schematic 2D representation of an arrangement of these muscle elements, see Ref. [20]). A whole fascicle is constructed by putting three muscle elements in series.

In the LFMM model, the extracellular matrix domain is represented by a mesh of extracellular matrix elements (*matrix mesh*). In the same space, a separate mesh of myofiber elements is built to represent the intracellular domain (*fiber mesh*). The two meshes are rigidly connected to single layers of elements modeling proximal and distal aponeuroses: A node representing myotendinous connection sites is the common node of all three (extracellular matrix, myofiber, and aponeurosis) elements. In contrast, at the intermediate nodes, fiber and matrix meshes are linked elastically to represent the transmembranous attachments of the cytoskeleton and extracellular matrix. For these links (the model includes a total of 28 of them: 14 in each of the upper and lower model surfaces) the standard element COMBIN39 is used from the element library of ANSYS 9.0. This is a two-node spring element, which is set to be uniaxial and has linear high stiffness characteristics representing nonpathological connections between the muscle fibers and the extracellular matrix (for an analysis of the effects of stiff or compliant links, see Ref. [20]). Note that at the initial muscle length and in passive condition, these links have a length equaling zero.

Extracellular matrix and myofiber elements were described elsewhere (for a detailed description of constitutive relationships and model parameters, see Ref. [13]). In short, both elements have eight nodes, and linear interpolation functions and a large deformation analysis formulation are applied. A 3D local coordinate system representing the fiber, cross-fiber (normal to the fiber direction), and thickness directions is used. The extracellular matrix element incorporates a strain energy density function that accounts for the nonlinear and anisotropic material properties and the constancy of muscle volume. For the myofiber element, the total stress that acts exclusively in the local fiber direction is the sum of the active stress of the contractile elements and the stress due to intracellular passive tension. To represent the aponeuroses, a standard 3D eight-node element featuring hyperelastic mechanical formulation (i.e., HYPER58, from the element library of ANSYS 9.0) was used (for a detailed description, see Ref. [13]).

It is assumed that, at the initial muscle length in the passive state, the sarcomeres arranged in series within muscle fibers have identical lengths. Fiber direction strain within the fiber mesh allows assessment of the nonuniformity of lengths of sarcomeres: Positive strain reflects lengthening and negative strain reflects shortening. Note that zero strain represents the undeformed state of sarcomeres (i.e., sarcomere length$\cong$2.5 μm) in the passive condition at initial muscle length (28.7 mm). Muscle lengths equaling 25.2 mm and 31.2 mm will be referred to as *low muscle length* and *high muscle length*, respectively.

Intact and Aponeurotomized EDL Muscle Models With Extramuscular Connections. EDL muscle of the rat was modeled. This muscle has a relatively simple geometry: It is a unipennate muscle with rather small pennation angles and minimal variation of the fiber direction within the muscle belly. The geometry of the model (Fig. 1(*a*)) is defined as the contour of a longitudinal slice at the middle of the isolated rat EDL muscle belly. Three muscle elements in series and six in parallel fill this slice. All aponeurosis elements have identical mechanical properties but using a variable thickness in the fiber–cross-fiber plane, the increasing cross-sectional area of the aponeurosis toward the tendon [21] is accounted for.

An extramuscular connective tissue connects EDL all along the muscle to the tibia, part of interosseal membrane and anterior intermuscular septum (under conditions of unphysiological loading this structure is seen as a sheet: For images, see Refs. [7,9,13]). This structure defines the anatomical path of extramuscular myofascial force transmission. The locations of the extramuscular connections to EDL muscle were determined experimentally [6] to be predominantly at one-third of the fascicle length from the most proximal end of each muscle fascicle. It was also shown that the extramuscular connective tissues supporting the major neural and vascular branches supplying the EDL muscle proximally (for an image, see Ref. [22]) are much stiffer than the distal of the connective tissue structure.

In order to model the muscles' extramuscular connections and to account for their continuity with the muscular extracellular matrix, a set of nodes of the matrix mesh was linked using spring elements (COMBIN39, from the element library of ANSYS 9.0) to a set of fixed points (Fig. 1(*a*)). Our modeling considerations were the following: (1) The set of fixed points comprising "mechanical ground" represents bone, which is assumed to be rigid. (2) The spring elements were set to be uniaxial and have linear length-force characteristics. (3) Initially (i.e., muscle length=28.7 mm, and before changing any of the tendon positions), the fixed points and the corresponding nodes of the model were at identical locations. (4) The higher stiffness of the connective tissues constituting the neurovascular tract near the EDL muscle is taken into account by making the three most proximal links to the muscle stiffer than distal ones. Stiffness values determined previously [6] were used (i.e., $k=0.286$ unit force/mm for the stiffer part and $k=0.067$ unit force/mm for the more distal links).

In surgery, after cutting its aponeurosis transversely (Fig. 1(*b*)), the muscle is lengthened passively. On activation, intramuscular connective tissue ruptures below the location of the aponeurotomy in the muscle fiber direction leading to a gap separating the two cut ends of the aponeurosis [2,5]. Such effects increase progressively after isometric activity at higher muscle length. Presumably in human patients, further rupturing occurs on activation of the immobilized muscle after the operation.

The effects of proximal aponeurotomy were modeled by disconnecting the common nodes of two neighboring aponeurosis elements in the targeted location of the proximal aponeurosis as well as the two parallel arranged muscle elements located below it (Fig. 1(*a*)). Note that in the model, the tear depth is limited by the length of these proximal muscle elements in the fiber direction. Intramuscular connective tissue rupture creates two populations of muscle fibers: *proximal population* (with intact myotendinous connections to muscle origin and insertion) and *distal population* (without myotendinous connection to the muscles' origin, but intact myotendinous connections to muscle insertion). Figure 1(*c*) shows the typical deformed shape of the modeled aponeurotomized EDL muscle after distal lengthening and illustrates these features.

Extramuscularly connected EDL muscle was studied in several conditions: Without aponeurotomy modeled (*intact*) and with the aponeurotomy modeled on the proximal aponeurosis at (i) a proximal location (case P), (ii) an intermediate location (case I), and (iii) a distal location (case D). Note that the most proximal apo-

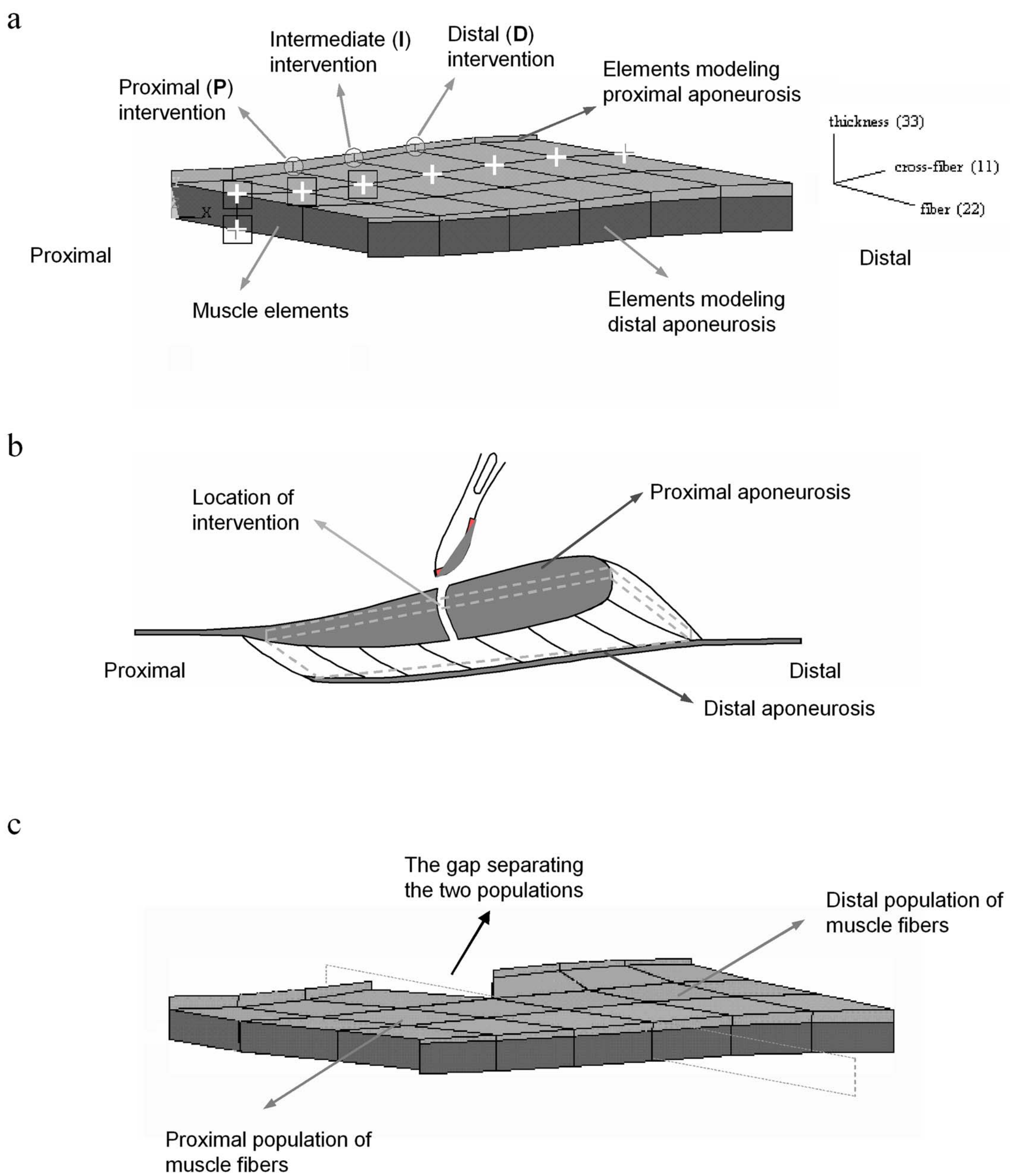

Fig. 1 Finite element modeling of extramuscularly connected EDL muscle and aponeurotomy. (*a*) The model of EDL muscle, modeled extramuscular connections, and locations of aponeurotomy. Details of the model and extramuscular connections were described elsewhere [13]. In short, the nodes of the matrix mesh marked by a white "+" sign have connections to mechanical ground representing the muscles' extramuscular connections. The nodes marked also by a black square show the stiffer proximal segment of extramuscular connections [6]. The nodes marked by a circle indicate the different locations of aponeurotomy modeled (at both upper and lower faces of the model). (*b*) The nature of aponeurotomy (using transverse incisions) shown schematically. The dashed lines illustrate the modeled longitudinal muscle slice at the middle of the muscle belly. (*c*) Typical deformed shape after distal lengthening of modeled aponeurotomized muscle (case I is the example shown). The gap between the cut ends of the aponeurosis creates two distinct populations of muscle fibers: "proximal population" and "distal population." The plane marked by dotted lines shows the interface between the two populations.

neurotomy studied is located at a third of the proximal aponeurosis from the proximal end of the muscle.

Solution Procedure. The analysis type used in ANSYS was static and large strain effects were included. During the entire solution procedure, the models studied were stable and no mesh refinement was performed. A force based convergence criterion was used with a tolerance of 0.5%.

Subsequent to maximal activation (for a description, see Ref. [13]), the proximal end of the muscles modeled was displaced distally by 2 mm, which position was then kept constant during the entire modeling. Muscle length was altered by changing the position of muscle distal tendon: first in proximal direction (i.e., to shorten the muscle) then in distal direction (i.e., to lengthen the muscle).

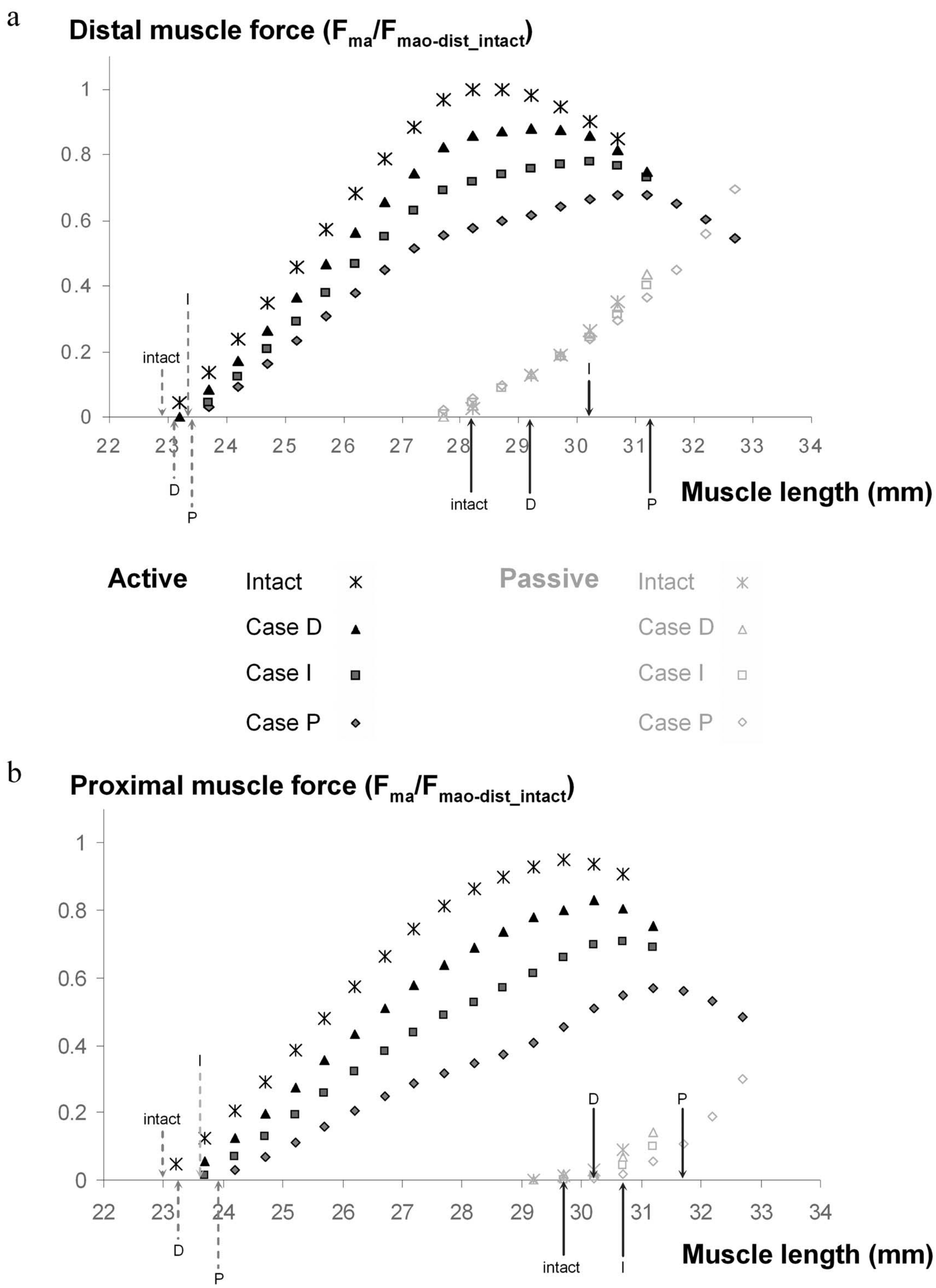

Fig. 2 The isometric muscle length-force curves of modeled aponeurotomized and intact EDL muscles. Active and passive isometric forces of aponeurotomized muscles with the aponeurotomy modeled at proximal (case P), intermediate (case I), and distal (case D) locations. (*a*) Effects on distally exerted muscle forces. (*b*) Effects on proximally exerted muscle forces. To quantify the reduction in muscle force due to different aponeurotomy cases, active and passive isometric forces of the intact muscle are considered: All sets of data are normalized for optimum distal force of intact muscle. Active slack lengths (dotted arrows) and optimum lengths (solid arrows) are marked to indicate location of aponeurotomy dependent shift to a higher length.

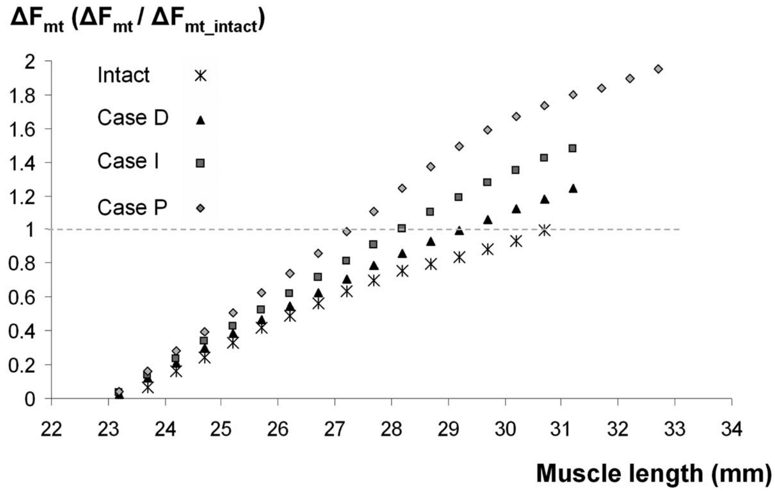

Fig. 3 The proximo-distal total force differences for modeled aponeurotomized and intact EDL muscles. Total (ΔF_{mt}) proximo-distal force differences ($F_{dist}-F_{prox}$) of aponeurotomized muscles with the aponeurotomy modeled at proximal (case P), intermediate (case I), and distal (case D) locations. Proximo-distal force differences are normalized for force difference of intact muscle encountered at muscle length=30.7 (indicated with dotted line).

Results

Effects of Location of Aponeurotomy on Muscle Length-Force Characteristics. Regarding both proximally and distally exerted active forces, the intact muscle exerts higher forces than all aponeurotomy cases, for all muscle lengths modeled (Fig. 2). However, such important effect of force reduction is manipulated largely by the location of aponeurotomy: In cases D, I, and P, respectively, distal optimal forces (Fig. 2(*a*)) represent 88%, 78%, and 68% and proximal optimal forces (Fig. 2(*b*)) represent 87%, 75%, and 60% of that of the intact muscle.

The effects of aponeurotomy also on passive forces (Fig. 2) increase for a more proximally performed aponeurotomy (e.g., at 30.7 mm, passive forces of cases D, I, and P are distally 95%, 89%, and 83% and proximally 77%, 49%, and 20%, respectively, of that of the intact muscle).

Aponeurotomy caused muscle (i) optimum length and (ii) active slack length to shift to a higher length (highest in case P). The net effect is an increase in muscle length range of active force exertion compared to intact muscle: In cases D, I, and P, respectively, $\Delta l_{\mathrm{range\_dist}}$ equals 15%, 27%, and 44% and $\Delta l_{\mathrm{range\_prox}}$ equals 2%, 3%, and 6%. It is concluded that the more proximal the aponeurotomy is performed, the higher are its active force reduction and length range effects.

Effects of Location of Aponeurotomy on Extramuscular Loads. The substantial proximo-distal total force differences due to extramuscular myofascial force transmission show the net extramuscular loads acting on the muscles (Fig. 3). Remarkably, for all muscle lengths, if the aponeurotomy is performed more proximally such loads increase (e.g., 30.7 mm total force difference of cases D, I, and P are 18%, 42%, and 74% higher than that of the intact case, respectively).

Effects of Location of Aponeurotomy on Muscle Geometry and Lengths of Sarcomeres. *Muscle Geometry.* The more proximal the aponeurotomy: (1) the bigger the distal population of muscle fibers (Fig. 4); (2) the lower is the angle of pennation (Fig. 4(*f*)) shows an illustration); and (3) the higher is the gap length (Fig. 5), e.g., at $\Delta l_{m+t}=1$ mm, the gap length of case P is higher than that of cases I and D by 7% and 19%, respectively.

Shortening of Sarcomeres in the Distal Population. Characteristic shortening of the sarcomeres in the distal population of muscle fibers becomes more pronounced if the aponeurotomy is performed more proximally: (1) The distal edge of the cut aponeurosis marks the beginning of a "zone of very short sarcomeres" limited to the proximal ends of the fascicles near that location. For both low (Figs. 4(*a*)–4(*c*)) and high muscle lengths (Figs. 4(*d*)–4(*f*)) the area of this zone is the largest for case P. (2) Even at high muscle length, almost all of the sarcomeres within the distal muscle fiber population of case P (Fig. 4(*d*)) are at the ascending limb of their length-force characteristics, whereas for case D (Fig. 4(*f*)), all sarcomeres located at the distal ends of muscle fibers are over optimum length (e.g., sarcomeres at the distal muscle end are shortened by 23% in case P and lengthened by 2% in case D).

Serial and Parallel Sarcomere Length Distributions. At low muscle length (Figs. 4(*a*)–4(*c*)), for the more proximal fascicles of the proximal population of muscle fibers, differences in serial sarcomere length distributions among the aponeurotomy cases are minor. However, for the distal population of muscle fibers, the serial sarcomere length heterogeneity is most pronounced in case P: E.g., in the more distal muscle fibers, sarcomere shortening range is from 29% to 42% and from 33% to 40% in cases P and D, respectively. In contrast, the ranges of parallel distribution of sarcomere lengths for different aponeurotomy cases are similar (Fig. 6(*a*)).

At high muscle length (Figs. 4(*d*)–4(*f*)), for the proximal fiber population, in case P going from proximal ends of muscle fibers to the distal ends, sarcomeres encountered range from long to short (maximally from 27% to 8% of lengthening), whereas this is reversed and more heterogeneous in case D (from 5% shortening to 34% lengthening). For the distal population, for the fascicles including the zone of very short sarcomeres, more sarcomeres are at different lengths in case P, whereas for more distal fascicles, case D shows the highest serial distribution. However, the parallel distribution of sarcomere lengths for case P is the most pronounced: Fiber direction mean strains range from 0.18 to −0.26, −0.22, and −0.17, respectively, for cases P, I, and D (Fig. 6(*b*)).

Effects of Location of Aponeurotomy on Active Force Exertion Within Muscle Fibers. The area under mean fiber stress versus fascicle number curve (Figs. 6(*c*)–6(*e*)) represents an index of the overall potential of active force production. Such potential decreases the most if the aponeurotomy is more proximal (the area

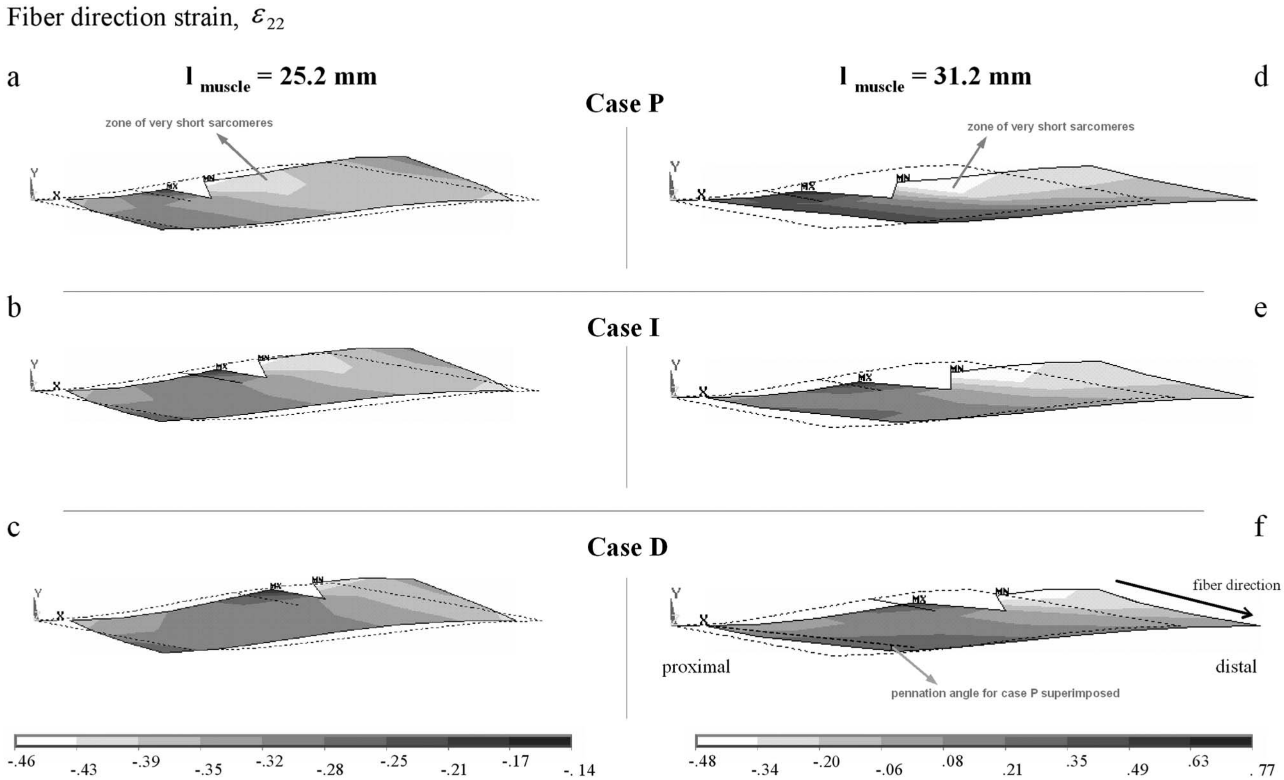

Fig. 4 Fiber direction strains within modeled muscles aponeurotomized at different locations. (Left) The strain distributions within the fiber mesh of active aponeurotomized muscles for low muscle length (i.e., 25.2 mm). (Right) The strain distributions within the fiber mesh of active aponeurotomized muscles for high muscle length (i.e., 31.2 mm). Contour plots are shown for the aponeurotomy modeled at proximal (case P, i.e., (*a*) and (*d*)), intermediate (case I, i.e., (*b*) and (*e*)), and distal (case D, i.e., (*c*) and (*f*)). The dotted line contour indicates passive muscle geometry at the initial length. The local fiber direction, as well as the proximal and distal ends of the muscle, is indicated (*f*). The decreased pennation angle of the most proximal muscle fibers in case P compared to case D is shown (*f*). "Zone of very short sarcomeres" is indicated in (*a*) and (*d*). MX, MN, X, and Y represent maximal and minimal strains and the global coordinates.

for cases I and P, respectively, are 87% and 77% of that of case D at low muscle length and 91% and 77% of that of case D at high muscle length).

The key determinant of this effect is the distal population of muscle fibers: Substantial sarcomere shortening yields a major decrease in the fiber stress values calculated (Fig. 7), which effect becomes more pronounced if the aponeurotomy is more proximal: (1) The fraction of the muscle volume undergoing such active stress reduction increases. (2) Also the stress values themselves decrease. For example, even the stresses at the most distal segments of muscle fibers (the location of peak stress within the distal population) show a sizable decrease in case P compared to cases I and D: at high muscle length, fiber stress range in this fascicle section from 0.98 to 0.56 for case P, from 0.99 to 0.75 for case I, and from 1.04 to 1.02 for case D (Figs. 7(*d*)–7(*f*)).

It is concluded that a more proximal aponeurotomy increases substantially the number of muscle fibers located in the distal population and associated sarcomere shortening yielding a substantial reduction in the potential of muscle for active force exertion.

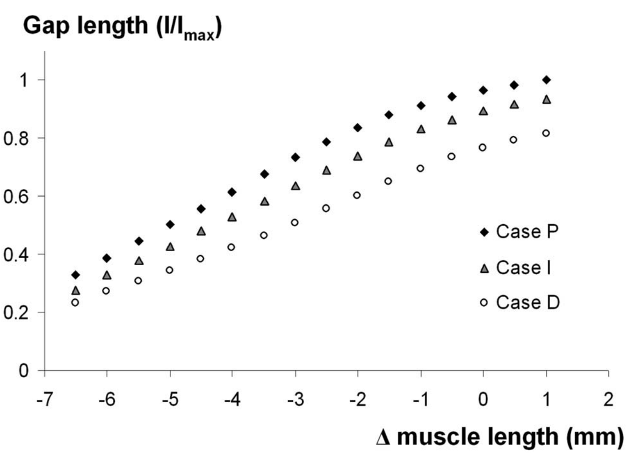

Fig. 5 Length of the gap within the EDL proximal aponeurosis as a function of muscle length. The effects of location of aponeurotomy on the length of the gap between the two cut ends of the proximal aponeurosis are shown. The data are normalized for maximum gap length of case P. Note that for each case EDL length is expressed as a function of deviation from its own muscle optimum length (0 mm).

Discussion

A Location of Intervention Closer to the Tendon Enhances the Intended Acute Effects of Aponeurotomy. *Lengthening of the Target Muscle.* Hypertonia is a common symptom (e.g., in cerebral palsy), leading to muscle contractures that restrict joint motion. Therefore, a major goal of aponeurotomy is muscle lengthening. Our present results show that an aponeurotomy performed closer to the tendon serves that goal better (e.g., for distal muscle force, the increase in the length range of force exertion in case P was approximately three times that in case D). Two coupled factors are responsible for the following.

(1) *Increased gap length.* Rupturing of intramuscular connec-

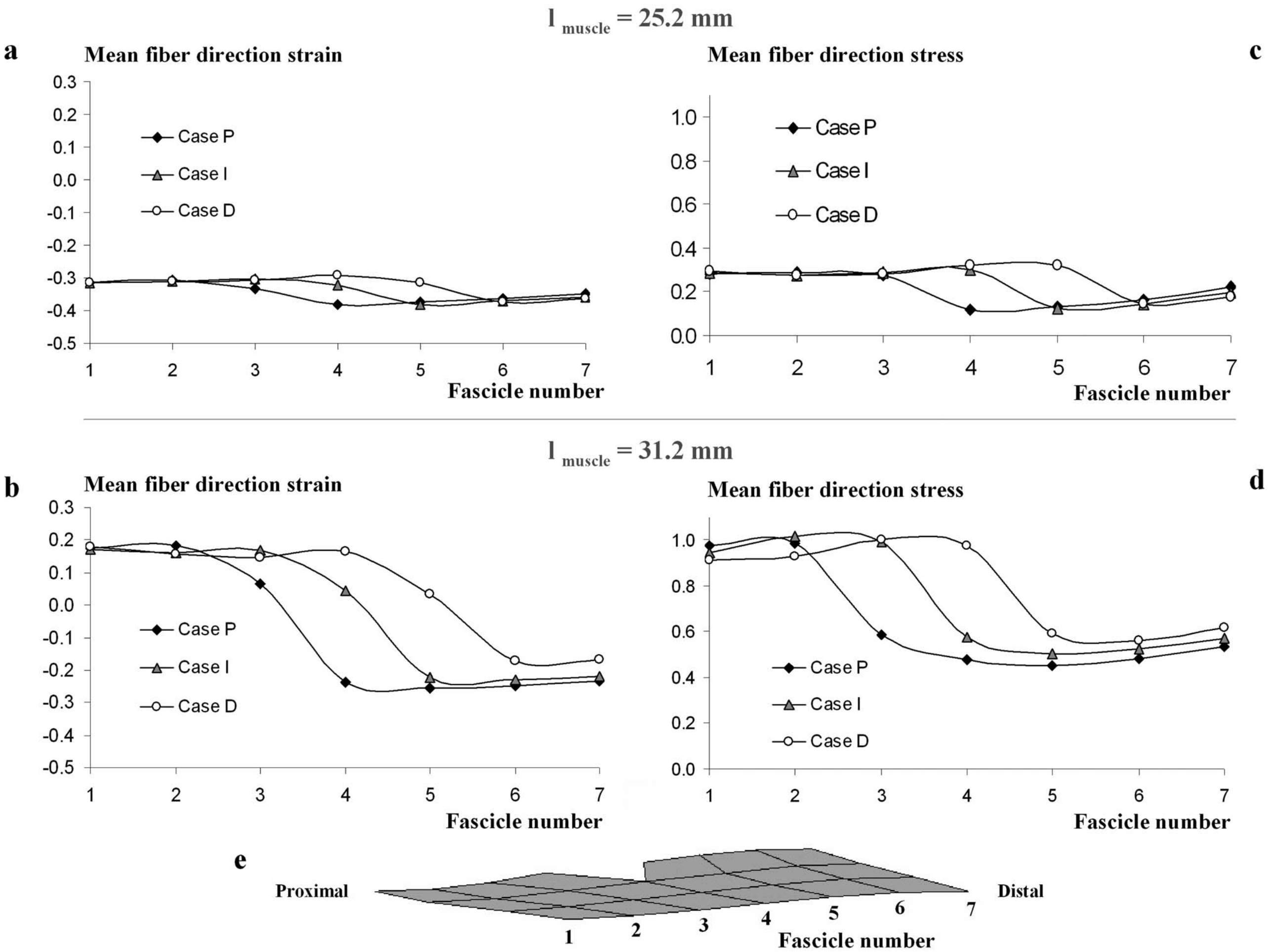

Fig. 6 Distributions of mean fiber direction strain and stress within fascicles of modeled aponeurotomized muscles. Mean fiber direction strains (left panel: (*a*) and (*b*)) were used to assess the heterogeneity of mean sarcomere lengths of different fibers within the muscle (i.e., parallel distribution of sarcomere lengths). Mean fiber direction stress (right panel: (*c*) and (*d*)) was used to assess the overall potential of active force exertion. (*e*) Definition of fascicle numbers within muscle geometry (case I is shown). Each fascicle interface is indicated (from 1 to 7). Mean fiber direction strains and stresses were calculated at nodes of the myofiber elements in series (i.e., within the fiber mesh) representing a muscle fascicle. Note that for the fascicle corresponding to the location of aponeurotomy (e.g., fascicle 4 for case I), the mean of nodal strain or stress values includes the values calculated for the two cut ends of the proximal aponeurosis in addition to the strain or stress values calculated for the remainder of three nodes (i.e., a mean of five strain values). For other fascicles, however, the mean includes only the strains or stresses in the four nodes for the same fascicle interface.

tive tissues [2,3] following aponeurotomy causes acutely a major change in muscle geometry. This is the primary determinant of the effects of the intervention. Previous modeling [5] showed that effects of cutting the aponeurosis exclusively (without intramuscular connective tissues rupturing) were minor. The length of the gap within the aponeurosis characterizes the changes in muscle geometry. Our present results show that if the aponeurotomy is performed closer to the tendon, the enhanced gap length will shift the whole length-force curve to higher lengths.

(2) *More pronounced parallel distribution of sarcomere lengths*. Aponeurotomy performed closer to the tendon causes increased heterogeneity of mean sarcomere length of different muscle fibers. This is explained by two effects: (a) an increased range of sarcomere lengthening in populations of muscle fibers with normal myotendinous connections to muscle origin or insertion and (b) a decreased range of sarcomere shortening in populations of muscle fibers without such normal myotendinous connections. It was shown experimentally [23,24], as well as with finite element modeling [25], that increased parallel distribution of sarcomere lengths in intact muscle enhances the muscle length range of active force exertion.

Force Decrease in the Target Muscle. Force imbalance of antagonistic muscles may also cause unusual positions of a joint and contractures. In such conditions, aponeurotomy has been indicated as a clinical means of weakening of the agonist muscle (i.e., reducing muscle force) [26]. Our present results show also for a greater muscle weakening effect that an aponeurotomy performed closer to the tendon is more effective. The primary explanation for this effect is the increase in population of muscle fibers without normal myotendinous connections. Typically, aponeurotomy causes substantial sarcomere shortening yielding a major force reduction in that population of muscle fibers. The secondary explanation is that an intervention closer to the tendon decreases substantially actual fiber direction stress values in both types of postaponeurotomy population of muscle fibers.

Extramuscular Myofascial Loads on the Muscle are Highest if the Location of Intervention is Closer to the Tendon. A major effect of extramuscular myofascial force transmission on muscular

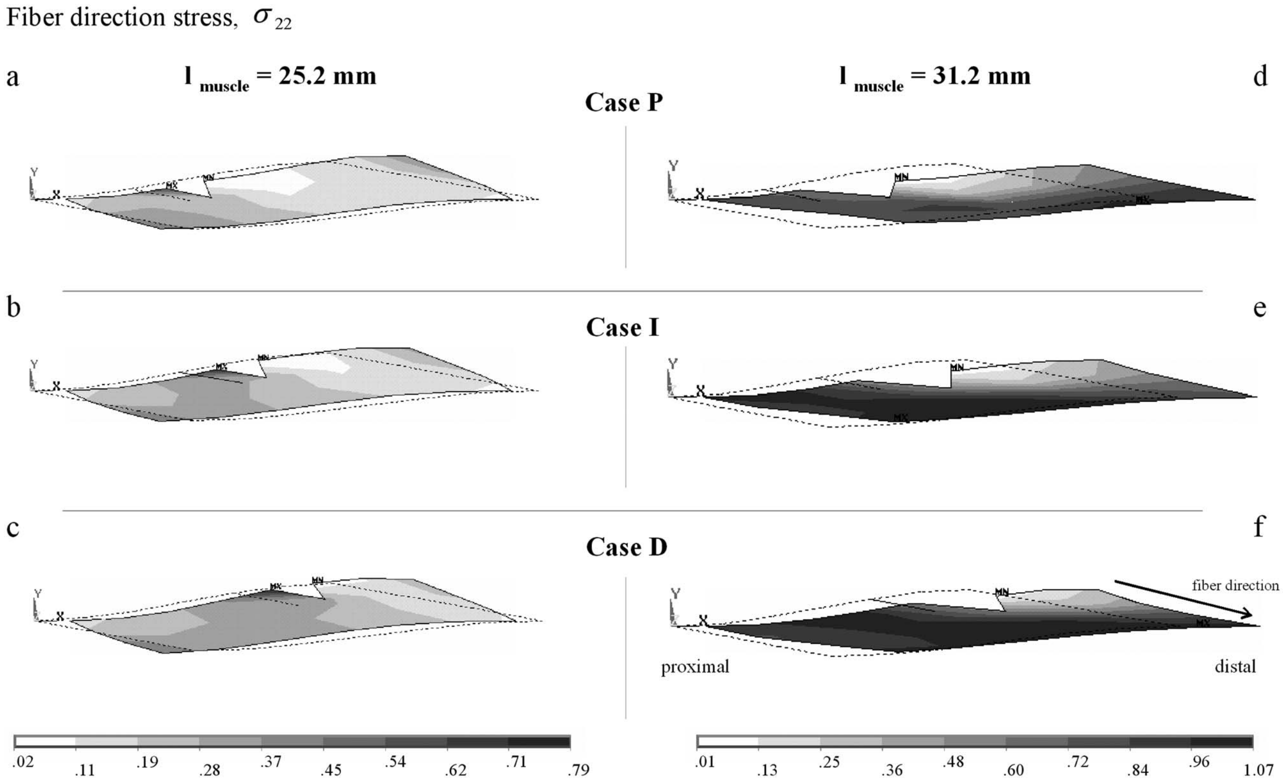

Fig. 7 Fiber direction stresses within modeled aponeurotomized muscles. (Left) The stress distributions within the fiber mesh of active aponeurotomized muscles for low muscle length (i.e., 25.2 mm). (Right) The stress distributions within the fiber mesh of active aponeurotomized muscles for high muscle length (i.e., 31.2 mm). Contour plots are shown for aponeurotomy modeled at proximal (case P, i.e., (*a*) and (*d*)), intermediate (case I, i.e., (*b*) and (*e*)), and distal locations (case D, i.e., (*c*) and (*f*)). The dotted line contour indicates passive muscle geometry at the initial length. The local fiber direction, as well as the proximal and distal ends of the muscle, is indicated (*f*). MX, MN, X, and Y represent maximal and minimal stresses and the global coordinates.

mechanics is the occurrence of proximo-distal force differences [6,9,10]. Such force differences favoring the distal force (as found in the present study) indicate a proximally directed net extramuscular myofascial load acting on the target muscle. Note also that aponeurotomy caused higher net extramuscular myofascial loads on the target muscle than in intact muscle. This is because all linking elements representing extramuscular connections are stretched to higher lengths (e.g., at EDL length=31.2 mm, in case P, the most proximal and distal extramuscular links were lengthened by 31% and 169% due to the aponeurotomy).

In addition, near the stiffer extramuscular links (three most proximal ones) decreased angles of pennation were found compared to the other link locations.

The combination of the enhanced aponeurosis gap length and the decreased angle of pennation causes extramuscular myofascial loads acting on aponeurotomized muscle to be highest when the intervention is closer to the tendon. Important implications of this are discussed as follows.

Implications of Our Present Results. Several authors assessed the success of aponeurotomy by using gait analysis [14,15], by comparing pre- and postoperative ankle dorsiflexion angle [19] or knee angle [16,17] or studied the surgery associated morbidity [18]. It can be derived from their description of the surgical procedures that the precise location of aponeurotomy was not always a central issue in designing the operation. However, our present results suggest that a careful choice of location of aponeurotomy is highly important in determining the outcome. Nevertheless, despite lack of specific information, typically the location of incision on the skin as described by, e.g., Baddar et al. [14] and Dhawlikar et al. [16] indicates a distal aponeurotomy performed at a more distal location (i.e., a location closer to the tendon). Rush et al. [18] did provide specifics and chose intentionally for a location closer to the tendon (at the distal third of gastrocnemius muscle belly, a condition in principle equivalent to case P studied presently). According to our model results such a choice is a favorable one.

In addition, aponeurotomy is also performed as multiple interventions [15,17]. Our present results show that the main variable of enhanced acute effects of a single aponeurotomy is having a high enough number of muscle fibers distal to the location of intervention. If this is true in multiple aponeurotomy needs to be tested.

Huijing [27] recently hypothesized that, in concert with the distally directed myofascial loads on spastic muscle (originating from synergistic muscles), a major contributor to restricted joint motion may be simultaneous, high proximally directed myofascial loads on that muscle (originating from sarcomeres within antagonistic muscles). Our present results indicate that for conditions studied presently the closer the aponeurotomy location to the tendon, the higher proximal loads are, suggesting that this would not decrease the severity of the movement limitation as much. On the other hand, the complex effects of enhanced parallel distribution of sarcomere lengths cause muscle force to decrease and thus limit the effects of those myofascial loads. The effects of epimuscular myofascial force transmission between antagonistic as well as between synergistic muscles on the acute effects of aponeurotomy need to be studied.

Aponeurotomy is performed frequently on bi-articular muscles, e.g., gastrocnemius [1] and hamstrings [15,16,28]. Proximo-distal muscle force differences imply asymmetric effects of aponeurotomy on the proximal and distal joints spanned. Due to proximally directed extramuscular myofascial loads, aponeurotomy weakens the proximal muscle force even more for conditions studied presently. This indicates important functional implications for patients suffering from spastic paresis affecting multiple joints. For example, in a case of combined equinus gait and crouch, aponeurotomy of gastrocnemius [14] will help correction of abnormal plantar flexion. Our present results indicate reduced gastrocnemius contributions to knee flexion moment, which effect will be more pronounced if the aponeurotomy is performed at a more proximal location. Therefore, such choice of incision is likely to be more effective for a combined functional deficiency in the ankle and the knee. On the other hand, in a case of combined crouch and hip flexor tightness, aponeurotomy of, e.g., the semimembranosus [15] will reduce knee flexion deformity. However, this may lead to a decrease in hip extension force (again higher decrease if the aponeurotomy is performed at a more proximal location). This effect counters the additional purpose of correcting hip flexor tightness. In such a case a balance may need to be found between the corrective effects in the distal joint and conceivable unfavorable effects in the proximal joint by manipulating the location of aponeurotomy. It should be noted that the operation may involve multilevel surgery including lengthening of psoas muscle also [15], which step is expected to counteract the unfavorable effects of the preceding steps. We suggest that especially when operating bi-articular muscles, the proximo-distal force differences caused by extramuscular myofascial force transmission should be taken into account as a parameter to determine the location of aponeurotomy.

In conclusion, our model results show that if performed closer to the tendon, the muscle lengthening as well as force decreasing effects of aponeurotomy are more pronounced. Major determinants of these effects are increased gap length, increased parallel distribution of sarcomere lengths, increase in size of the population of muscle fibers without myotendinous connection to either origin or insertion, and decreased active fiber stress. In addition, the closer to the tendon the aponeurotomy location, the more pronounced are the effects of extramuscular myofascial force transmission, i.e., increased proximo-distal force differences and changes in sarcomere length distributions. This may be of particular importance in selecting the location of aponeurotomy for bi-articular muscle.

These conclusions are based on results from modeling performed to analyze details that are not easily studied experimentally. The purpose of the model is to enhance our understanding of processes deemed important for the acute effects of surgery. It is clear that such conclusions require further experimental and clinical consideration before application should be executed.

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