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Substantial effects of epimuscular myofascial force transmission on muscular mechanics have major implications on spastic muscle and remedial surgery

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Abstract

The specific aim of this paper is to review the effects of epimuscular myofascial force transmission on muscular mechanics and present some new results on finite element modeling of non-isolated aponeurotomized muscle in order to discuss the dependency of mechanics of spastic muscle, as well as surgery for restoration of function on such force transmission.

The etiology of the effects of spasticity on muscular mechanics is not fully understood. Clinically, such effects feature typically a limited joint range of motion, which at the muscle level must originate from altered muscle length–force characteristics, in particular a limited muscle length range of force exertion. In studies performed to understand what is different in spastic muscle and what the effects of remedial surgery are, muscle is considered as being independent of its surroundings. Conceivably, this is because the classical approach in muscle mechanics is built on experimenting with dissected muscles. Certainly, such approach allowed improving our understanding of fundamental muscle physiology yet it yielded implicitly a narrow point of view of considering muscle length–force characteristics as a fixed property of the muscle itself.

However, within its context of its intact connective tissue surroundings (the in vivo condition) muscle is not an isolated and independent entity. Instead, collagenous linkages between epimysia of adjacent muscles provide direct intermuscular connections, and structures such as the neurovascular tracts provide indirect intermuscular connections. Moreover, compartmental boundaries (e.g., intermuscular septa, interosseal membranes, periost and compartmental fascia) are continuous with neurovascular tracts and connect muscular and non-muscular tissues at several locations additional to the tendon origins and insertions. Epimuscular myofascial force transmission occurring via this integral system of connections has major effects on muscular mechanics including substantial proximo-distal force differences, sizable changes in the determinants of muscle length–force characteristics (e.g. a condition dependent shift in muscle optimum length to a different length or variable muscle optimal force) explained by major serial and parallel distributions of sarcomere lengths. Therefore, due to epimuscular myofascial force transmission, muscle length–force characteristics are variable and muscle length range of force exertion cannot be considered as a fixed property of the muscle.

The findings reviewed presently show that acutely, the mechanical mechanisms manipulated in remedial surgery are dominated by epimuscular myofascial force transmission. Conceivably, this is also true for the mechanism of adaptation during and after recovery from surgery. Moreover, stiffened epimuscular connections and therefore a stiffened integral system of intra- and epimuscular myofascial force transmission are indicated to affect the properties of spastic muscle. We suggest that important advancements in our present understanding of such properties, variability in the outcome of surgery and considerable recurrence of the impeded function after recovery cannot be made without taking into account the effects of epimuscular myofascial force transmission.

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1. Major effects of epimuscular myofascial force transmission on muscular mechanics

1.1. Muscle length–force characteristics are not unique properties of individual muscles

In classical muscle mechanics experiments performed to determine muscle isometric length–force characteristics and dynamic characteristics, muscle force is measured in the following conditions: (1) the targeted muscle is fully dissected except for its innervation and blood supply (2) muscle force is measured at one tendon exclusively. In such approach, the muscle studied in situ is considered as "fully isolated" from its surroundings (e.g. Frueh et al., 2001). As a consequence, two idealizations have been made, which became in time the established principles of skeletal muscle mechanics: (1) with the implicit assumption: the muscle force exerted at the tendon from which measurements are taken was considered to be equal to the force exerted at the other tendon. (2) Length–force characteristics determined were considered as unique properties of the specific target muscle studied. As a consequence, muscles have been considered commonly as fully independent functional units. Also distinguishing the muscles morphologically contributed to them as being regarded as distinct functional units.

However, recent studies have shown that, due to myofascial force transmission, such functional independence and unique muscle length–force characteristics are not representative, if the muscle is considered within the context of its intact surroundings (the condition in vivo). The effects of this type of force transmission on muscular mechanics will be considered below.

1.1.1. Unequal forces exerted at origin and insertion of a muscle

In order to address the effects of myofascial force transmission, recent muscle mechanics experiments have been designed differently than the classical approach: (i) the experimental muscle belly was not dissected (i.e., its epimuscular connections were left intact) and (ii) instead of measuring the force exerted at only one tendon, the forces exerted at both proximal and distal tendons were measured simultaneously. This approach showed the characteristic effect of epimuscular myofascial force transmission on muscle length–force characteristics: proximo-distal force differences (e.g. Huijing and Baan, 2001a, 2003; Maas et al., 2001, 2003a; Yucesoy et al., 2003b,a; Meijer et al., 2006). Such force differences showed to be substantial in the experimental conditions studied provide a clear evidence for the existence of a potentially important pathway for force transmission additional to the myotendinous pathway.

Such proximo-distal force differences are indicative of differential mechanical effects at muscle origin and insertion. For bi- or polyarticular muscle this has special functional consequences in both healthy and pathological conditions, since such differential effects are exerted at the joints spanned.

A potentially even more important effect of epimuscular myofascial force transmission is that muscle has additional origins and\or insertions since a part of the muscular force is transmitted from the muscle and is exerted at other muscles or non-muscular structures see also elsewhere in the present issue of this journal (Huijing, 2007; Huijing et al., 2007; Meijer et al., 2007; Rijkelijkhuizen et al., 2007).

On the other hand, even in experiments performed on fully dissected muscle (like in most of the classical tests), the minimal condition is to keep blood supply and innervation of a muscle intact as much as possible, since otherwise, the physiological state of the muscle cannot be sustained. For that reason, specific parts of the neurovascular tract (i.e., extramuscular connective tissues in which blood vessels and nerves are embedded) was always left intact (usually proximally located with respect to the muscle). Therefore, the fully dissected experimental muscle in situ cannot actually be considered to be truly isolated mechanically from its surroundings, as the remaining extramuscular connections are still capable of transmitting muscle force, leading to notable proximo-distal force differences (Yucesoy et al., 2003b). Despite that, in the majority of earlier experimental work, it was assumed that a muscle in situ is not different from a truly isolated muscle for which proximal and distal forces has to be identical because of the serial arrangement of muscle fibers and tendons. However, work on fully dissected rat medial gastrocnemius muscle (GM) indicates that physiologist, almost intuitively, may have selected conditions (i.e. knee joint angles) at which extramuscular myofascial effects were minimal (Rijkelijkhuizen et al., 2005). At the knee angle commonly selected in earlier experiments (Woittiez et al., 1985; Jaspers et al., 1999; Haan et al., 2003) the myofascial effect was negligible. Nevertheless, deviation of GM relative position with respect to the neurovascular tract enhanced the extramuscular myofascial effects (Rijkelijkhuizen et al., 2005).

1.1.2. Length range of force exertion is a condition dependent variable rather than a fixed muscle property

Major parameters of muscle length–force characteristics are *muscle optimal force* (the maximum force exerted by an active muscle), *muscle optimum length* (the length at which the muscle exerts its optimal active force) and *muscle active slack length* (the shortest length at which the muscle can still exert non-zero force) as well as the maximal length