INTRODUCTION

Several daily human tasks require movements of fingers relative to each other. Finger movements are caused by multi-tendoned extrinsic muscles in the forearm. Such muscles are characterized by multiple muscle heads connected proximally to one origin (e.g., aponeurosis, tendon, bone). Distally, these heads are connected to multiple aponeuroses continuous with tendons that insert on different digits in the hand or foot. The heads are named after their insertions on the digits.

Recent experiments on fully dissected rat extensor digitorum longus muscle (EDL), a multi-tended muscle with distal insertions on digit II to V of the toes (Balice-Gordon & Thompson, 1988), clearly indicated intramuscular myofascial force transmission: force transmission between muscle heads via their shared connective tissue (Huijing et al., 1998, Jaspers et al., 2002). In vivo, skeletal muscles are surrounded by synergists and embedded within connective tissues of the compartment. In addition to the tendons, inter- and extramuscular connective tissues may also transmit force from muscle fibers to bone (Huijing & Baan, 2001, Maas et al., 2001).

In the present study, effects of distal length changes of head III of rat EDL muscle (EDL III), operating within an intact anterior crural compartment, on force transmission to the distal tendon of EDL III were studied. We tested the null hypotheses that all force exerted at the distal tendon of EDL III originates from muscle fibers of head III, and that no force is transmitted via intra-, inter- or extramuscular myofascial pathways to the distal tendon.

METHODS

The distal tendon of EDL III and the proximal tendon of whole EDL muscle were exposed, and connected to force transducers (Fig.1). The distal tendons of EDL head II, IV, and V were left attached to their insertions. The distal tendons of tibialis anterior (TA) and extensor hallucis longus (EHL) muscles were also dissected free from surrounding tissues, tied together and connected to a force transducer (referred to as TA+EHL). Connective tissue of the anterior crural compartment as well as connective tissue at the muscle bellies was left intact.

For several muscle-tendon complex lengths (l_m + t) of EDL III, isometric forces exerted at the distal tendon of EDL III were measured. Simultaneously, isometric forces exerted at the proximal tendon of whole EDL and the distal tendons of TA+EHL were assessed. Supramaximal stimulation of the peroneal nerve excited all muscles maximally and simultaneously. TA+EHL length as well as the position of the proximal tendon of EDL muscle were kept constant. After the experimental measurements, the mass of the individual EDL muscle heads was measured and expressed as a percentage of total muscle mass. This was used as an estimate of normalized physiological cross-sectional area.

RESULTS AND DISCUSSION

ANOVA indicated significant effects of EDL III muscle-tendon complex length on active force of distal EDL III, proximal EDL, and distal TA+EHL. Proximal active EDL force (Fig. 2, upper panel) increased as a function of EDL III length: from 2.37 ± 0.09 N (at Δ l_m + t = 0 mm) to a maximum of 2.53 ± 0.10 N (at Δ l_m + t = 5.9 mm). A further increase of EDL III length caused a decrease in proximal EDL force (to 2.36 ± 0.15 N). These results show that substantial changes of length of EDL III (Δ l_m + t = 9 mm) caused only minor effects on isometric force exerted at the proximal tendon of EDL muscle.

EDL III optimum length deviated 8.3 mm from active slack length (Δ l_m + t EDL III = 0 mm) and optimal active force of distal EDL III was 1.03 ± 0.07 N (Fig. 2, upper panel). In a previous study, optimal active force of whole EDL muscle was 2.60 ± 0.14 N for rats with similar body mass (Maas et al., 2001). This indicates that at optimum length of EDL III 40% of the potential active EDL force is exerted at the distal tendon of head III of EDL muscle. The estimated relative physiological cross-sectional area of EDL III, which is a measure of the maximal relative contribution to total EDL active muscle force, was only 16 ± 2.2 % of whole EDL muscle. It is concluded that at optimum length a substantial fraction of force exerted at the distal tendon of EDL III originated from other sources than muscle fibers from head III. This must be mediated by intra-, inter- and/or extramuscular myofascial force transmission.
Our present experiments yielded more evidence for such a conclusion. If all force generated within the muscle fibers of EDL III was transmitted exclusively onto the proximal EDL tendon, changes of force exerted at the proximal tendon of EDL should equal the changes of force exerted at the distal tendon of EDL III. A comparison between proximal EDL and EDL III forces (Fig. 2, upper panel) indicates that changes of proximal EDL force were much (= 5 times) smaller than changes of EDL III force.

Distal force of TA+EHL, kept at constant length, decreased significantly (i.e. from 5.62 ± 0.27 to 5.22 ± 0.32) with lengthening EDL III (Fig. 2, lower panel). The high standard errors are caused by differences in the initial level of TA+EHL force. These results indicate mechanical interactions between EDL III and the TA+EHL complex, typical for intermuscular myofascial force transmission.

Figure 2: Length-distal active force ($F_{ma}$) characteristics of EDL III as well as the simultaneously measured active forces of proximal EDL and distal TA+EHL. Note that in the upper panel different y-axes with different scaling factors are shown for active force of EDL III (left axis) and active force of proximal (right axis). Values are shown as mean ± SE (n = 6).

In conclusion, a substantial fraction of force can be transmitted between a single head of a multi-tendoned muscle and surrounding muscle heads, adjacent synergists and extramuscular structures, via intra-, inter- and extramuscular myofascial connections. It has been reported that it is hardly possible to move a single digit without movements of adjacent digits (e.g. Kilbreath & Gandevia, 1994). In addition to limitations of neuromuscular control, this has been frequently attributed to force transmission via tendinous connections between the distal tendons of multi-tendoned extensors and flexors of the human fingers (Kilbreath & Gandevia, 1994, Kilbreath et al., 2002, Leijnse, 1997, Schieber, 1991). The present findings show that myofascial force transmission should also be considered as a mechanism, which explains that during single finger tasks movements are measured also in the non-test fingers.

SUMMARY

The major results of the present study are that (1) lengthening EDL III distally caused relatively high changes of EDL III force, but only minor changes of force exerted at the proximal tendon of whole EDL muscle, (2) maximal active force exerted at the distal tendon of EDL III was more than twice the force expected on the basis of the physiological cross-sectional area of EDL III muscle fibers and (3) distal force of the TA+EHL complex decreased significantly as a function of distal lengthening of EDL III. These mechanical interactions between the muscle belly of EDL III and adjacent tissues are explained in terms of myofascial force transmission.

REFERENCES