Differential Muscle and Tendon Adaptation after Tendon Transfer Surgery
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Introduction: Tendon transfers provide a functional solution to paralysis from upper or lower motor neuron injury and from limb dysfunction after primary muscle or tendon damage. It has been reported that a transferred muscle commonly loses one strength grade [1] and the reported effectiveness of tendon transfers are varied. Specifically, intraoperative measurements demonstrated that transferred muscles are typically overstretched to the point where they are predicted to produce less than 30% of their maximum force [2]. It is possible that inconsistent surgical attachment length explains the variability in this functional outcome [3]. This is puzzling, in light of that fact that it is well-established that muscles adapt to new environments such as chronic length changes produced by joint immobilization [4]. However, there are almost no experimental studies that determined whether or how muscles and tendons adapt to transfer outside of the physiologic range, which commonly occurs in tendon transfer surgery [2]. Therefore, the purpose of this study was to define both the muscle and tendon adaptation after tendon transfer surgery.

Materials and Methods: Methods used in this study were performed in accordance with the UCSD Institutional Animal Care and Use Committee. Briefly, the distal tendon of the rabbit EDII muscle was transferred to the ankle extensor retinaculum at a sarcomere length (Ls) of 3.7 μm measured using a laser diffraction device (Fig. 1)[5], which was chosen to be well-outside the physiological range of 2.6-3.1 μm. Suture markers were placed on 1) the proximal end of the muscle, 2) the muscle-tendon junction and 3) the periosteum beside the extensor retinaculum to enable measurement of the muscle and tendon length changes. Animals were sacrificed at 1 day, and 1, 2, 4 and 8 weeks after the surgery (n=7 or 8/time-point). After formalin fixation, while maintaining joint configurations, the muscle was detached from the tibia, and muscle architectural analysis was performed. After fiber micro-dissection (from three regions of each muscle) raw fiber length was measured with a digital caliper. Ls was measured by laser diffraction in these dissected fibers and serial sarcomere number (Ns) calculated by dividing raw fiber length by Ls. Paired t-test and one-way ANOVA were used for comparison between the sides and between time-points, respectively. Data are presented as mean±SEM.

Results: Muscles were stretched by -3 mm to achieve transfer at a Ls of exactly 3.7 μm (±0.6 μm beyond the physiologic range). After one day, no sarcomeres had been added to the muscle (Fig. 2A), but Ls had decreased by about 0.4 μm, presumably due to tendon stress-relaxation (Fig. 2B). Within the first week, a rapid synthetic response ensued with the muscle rapidly adding ~1000 serial sarcomeres (Fig. 2A). This rapid increase in serial sarcomeres caused a rapid decrease in Ls (Fig. 2B). From this time point until 8 weeks, serial Ns paradoxically decreased until it nearly reached the initial level after 8 weeks (Fig. 2A). Interestingly, Ns decrease was accompanied by both a muscle length (Fig. 3A) and tendon length increase (Fig. 3B) over the 2-8 week time period. Control experiments demonstrated that this "delayed" increase in tendon length represented tendon growth rather than the suture failure (not shown). In addition, the increase in muscle length was apparently due to an increase in the number of muscle fibers in parallel, which led to an increase in physiological cross-sectional area (data not shown).

Discussion: These data clearly demonstrate a relatively rapid and systematic adaptation of the muscle-tendon unit to tendon transfer. Interestingly, the muscle and the tendon both adapted to the transfer albeit with different timings. Early after transfer (the first week), the muscle adapted to by adding tremendous serial sarcomeres. This process was completed within the first week. This muscle adaptation was not affected by the slight tendon elongation seen in this early phase. Later after transfer (weeks 2-8) the tendon began to adapt to the stretched tendon transfer. The tendon elongation began after about 2 weeks and was significant by 8 weeks (Fig. 3B). As a result of the tendon elongation, the muscle then had to "readjust" by subtraction of the serial sarcomeres that had been added. This readjustment is paradoxical in the sense that the muscle appears to have "wasted" a tremendous amount of synthetic activity. However, the benefit might be that, using this approach, independent adaptation of the muscle and tendon keeps the muscle tendon unit completely functional during the adaptation process. Further experiments are required to understand the mechanistic basis for both the muscle's and tendon's mechanosensing of tendon transfer.


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