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Effects of tendon and muscle belly dissection on muscular force transmission following tendon transfer in the rat

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ABSTRACT

The aim of the present study was to quantify to what extent the scar tissue formation following the transfer of flexor carpi ulnaris (FCU) to the distal tendon of extensor carpi radialis (ECR) affects the force transmission from transferred FCU in the rat. Five weeks after recovery from surgery (tendon transfer group) and in a control group, isometric length–force characteristics of FCU were assessed for progressive stages of dissection: (i) with minimally disrupted connective tissues, (ii) after full dissection of FCU distal tendon exclusively, and (iii) after additional partial dissection of FCU muscle belly.

Total and passive length–force characteristics of transferred and control FCU changed significantly by progressive stages of dissection. In both groups, tendon dissection decreased passive FCU force exerted at the distal tendon, as well as the slope of the length–force curve. However, force and slope changes were more pronounced for transferred FCU compared to controls. No additional changes occurred after muscle belly dissection. In contrast, total force increased in transferred FCU following both tendon and muscle belly dissection at all lengths studied, while dissection decreased total force of control FCU. In addition, after tendon and muscle belly dissection, we found decreased muscle belly lengths at equal muscle–tendon complex lengths of transferred FCU.

We conclude that scar tissue limits the force transmission from transferred FCU muscle via the tendon of insertion to the skeleton, but that some myofascial connectivity of the muscle should be classified as physiological.

1. Introduction

Tendon transfers are surgical procedures intended to improve gait or upper extremity function in individuals with severe disabilities. Ideally, transferred muscles convert completely from their previous mechanical effect (e.g., joint flexion and adduction) into moment generators according to their new path and relocated insertion (e.g., joint extension and abduction). This criterion is assumed to be fulfilled in modeling tendon transfers biomechanically (e.g., Herrmann and Delp, 1999; Holzbaur et al., 2005; Veeger et al., 2004). However, such models consist of muscles that are connected to the skeleton exclusively at their origin and insertion, ignoring effects of epimuscular myofascial force transmission (Huijing, 2009; Maas and Sandercock, 2010) and postoperative tissue responses such as scar tissue formation.

Scar tissue, linking the transferred muscle to surrounding structures, is considered as a factor that limits the functional success of tendon transfer surgeries (Khanna et al., 2009; Strickland, 2000). Such connective tissues are held responsible for unexpected outcomes following transfer of rectus femoris (RF) from its extensor to a flexor site of the knee (Asakawa et al., 2002; Huijing, 1999). Both computer simulations and anatomical studies indicated that RF should have become a knee flexor after that surgery (Delp et al., 1994). However, one year or more post operation, intramuscularly stimulated RF still generated a knee extension moment (Riewald and Delp, 1997). Abnormal low signal intensity in T2-weighted magnetic resonance images near RF muscle was interpreted as evidence of scar tissue formation following tendon transfer (Gold et al., 2004). Such tissues are likely to hamper force transmission to the new insertion. However, studies aimed at quantifying effects of scar tissue on mechanical characteristics of transferred muscle after recovery from the surgery are not available.

Therefore, the aim of the present study was to quantify to what extent the scar tissue formation following an agonist-to-antagonist tendon transfer affects force transmission from transferred muscle. Specifically, transfer of flexor carpi ulnaris muscle (FCU) to the distal tendons of extensor carpi radialis brevis and longus muscles (ECR) was studied in the rat. We hypothesized that due to the presence of scar tissue, not all force generated by myofibers of transferred FCU is transmitted onto its new insertion. Accordingly, dissection of its distal tendon and muscle belly will change the transmission of FCU force onto its distal tendon.

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2. Methods

2.1. Animals

Data were obtained from 12 male Wistar rats that were divided in a tendon transfer group ($n=7$) and a control group ($n=5$). Surgical and experimental procedures were in strict agreement with the guidelines and regulations concerning animal welfare and experimentation set forth by the Dutch law and were approved by the Committee on Ethics of Animal Experimentation at the VU University.

2.2. Surgical procedures for FCU-to-ECR tendon transfer

Tendon transfer surgery was performed under aseptic conditions, while the rats (body mass at the time of surgery 181 ± 15 g) were deeply anesthetized (respiration of 1–3% isoflurane). At the same time, the rats were treated with a single dose (0.03 ml) of buprenorphin (Temgesic®, Schering-Plough, Maarssen, The Netherlands; 0.3 mg/ml solution) for pain relief. Body temperature was monitored and the anesthetic state was checked routinely by evaluating withdrawal reflexes. The distal tendon and distal half of the muscle belly of FCU was dissected free and transferred to the distal tendons of ECR. Details of surgical and experimental procedures are presented in Supplementary materials.

2.3. Surgical procedures in preparation for assessing FCU mechanical characteristics

Five weeks after tendon transfer, FCU length–force characteristics were assessed. Body mass of the tendon transfer group at this time of the experiment was 356 ± 17 g. For the control group, body mass at the time of assessing FCU characteristics was similar (i.e., 359 ± 5 g; not significantly different from transfer group).

The right forelimb of deeply anesthetized (intraperitoneally injected urethane) rats was shaved and the skin was resected from the shoulder to the wrist. To assess FCU length–force characteristics, the distal tendon of FCU was identified, released from the skeleton, and attached to Kevlar thread. Within the brachial compartment, the ulnar and median nerves were identified and placed in a bipolar cuff electrode.

2.4. Experimental conditions

The rat was placed on a heated platform and the right forelimb was secured rigidly to the experimental setup (for details see legend Fig. 1). Using the Kevlar threads in series with steel rods, the distal tendons were connected to a force transducer (BLH Electronica, Canton, MA, USA; maximal output error $<0.1\%$, compliance of 0.0162 mm/N). The orientation of the forelimb in each group was adjusted to enable force measurement in the muscle's line of pull (Fig. 1).

In each experiment several sets of FCU length–force data were collected: (1) with minimally disrupted connective tissues (i.e., the condition after *surgical procedures*), (2) after full dissection of FCU distal tendon exclusively, and (3) after additional dissection of the distal half of FCU muscle belly, leaving the muscle's primary blood supply and innervation intact. Dissection was performed in such a way that FCU muscle belly and tendon were not damaged (for details see Supplementary materials).

2.5. Length–force characteristics of FCU muscle

Before acquiring data, FCU muscle and structures linking muscle belly and tendon to its surroundings were preconditioned by several isometric contractions near optimum length to minimize effects of previous activity at high length (Huijing and Baan, 2001).

FCU was excited by supramaximal stimulation of the ulnar and median nerves via a cuff electrode connected to a constant current source (0.3 mA, pulse width 100 μs). Isometric forces of FCU were measured at various muscle–tendon complex lengths (ℓm+t). To minimize effects of stress relaxation in intra- and epimuscular connective tissues, FCU was excited up to the length that corresponded to a passive force of maximally 0.2 N.

In the tendon transfer group, a marker was placed on the most distal end of FCU muscle belly to assess changes of muscle belly length ($\Delta\ell$m) (Fig. 1B). In the control group, prior to dissection the muscle belly of FCU is covered entirely by the antebrachial fascia and, hence, ℓm could not be assessed. Marker position was recorded before and during isometric contractions at each ℓm+t using a digital camera (Sony HC53E Digital Camcorder, 25 frames/s, 720×76 pixels, resolution 1 pixel$\sim$0.1 mm).

2.6. Treatment of data and statistics

Mathematical functions were fitted to the experimental data for further treatment and averaging (see Supplementary materials). To assess the effects of tendon and muscle belly dissection, ℓm+t was expressed as the deviation from the length corresponding to zero total force exerted at the distal tendon in the minimally disrupted condition.

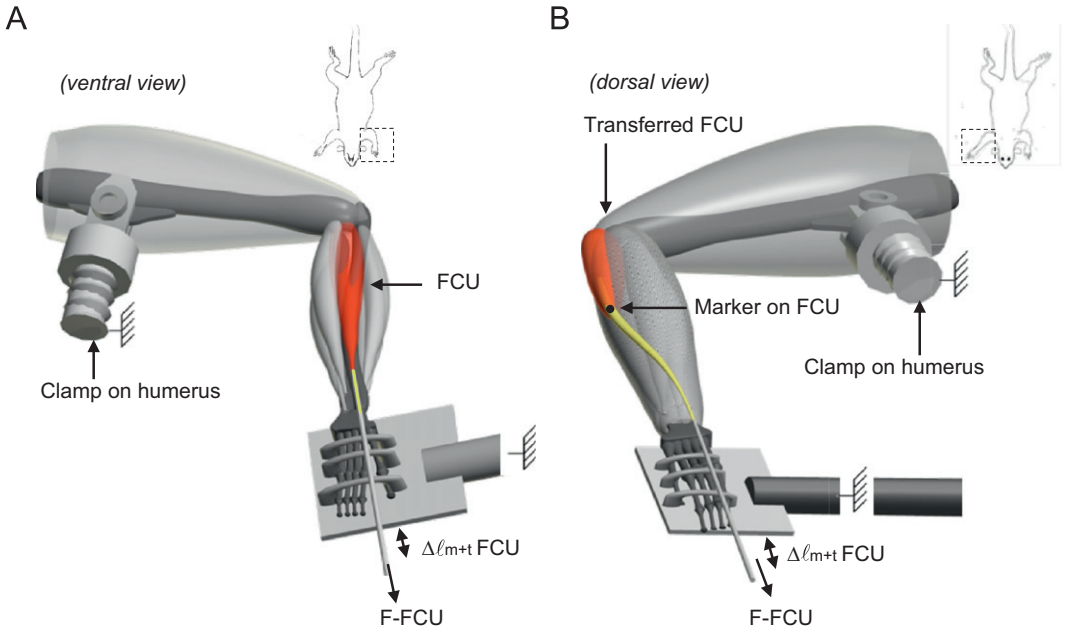

Fig. 1. Schematic view of right forelimb in experimental setup. The right forelimb was secured rigidly by clamping the humerus and by firmly tying the manus to an aluminum plate with 1-0 silk suture. The forearm was secured in horizontal position, the wrist in neutral position (i.e., 180° flexion), and the elbow joint at approximately 90°. The distal tendon of m. flexor carpi ulnaris (FCU) was connected to a force transducer, which was mounted on a single axis micropositioner. In the experiment, the muscle–tendon complex length of FCU was varied ($\Delta\ell$m+t FCU). The connective tissues enveloping the muscle bellies were left intact. In the tendon transfer group (B), a marker (●) was placed at the most distal end of the FCU muscle belly. Orientation of body and forelimb in each group was adjusted to enable force measurement in the direction of the muscle's line of pull. In the control group (A), the rat was lying supine (i.e., body to the left of the schematic; see drawing whole rat, mouth visible) and the lower arm was secured with the palmar side of the manus and forearm faced upwards. Thus, a ventral view of the forearm showing the wrist flexors and the palmar side of the manus is shown. In the tendon transfer group (B), the rat was lying prone (i.e., body to the right of the schematic; see drawing whole rat, eyes visible) and the lower arm was secured with the dorsal side of the manus and forearm facing upwards. Thus, a dorsal view of the forearm showing the wrist extensors and the dorsal side of the manus is shown.