MR Phase Contrast Study of Differences in Structure-Function Relationship during Isometric and Passive Movement of Lower Leg.

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Introduction: The triceps surae muscle has significant structural complexity, arising from an intricate organization of intramuscular connective tissue within the compartments of the muscle. Its complex multipennate architecture, often over simplified in anatomical publications, possibly results in heterogenous distribution of functionality within the compartment. The soleus muscle alone consists of two separate compartments, a bipennate anterior and unipennate posterior compartment. The complex muscle structure requires equally complex connective tissue structure. We correlated the 3-D structure as determined by high resolution MRI with spatial distribution of functionality, as determined by peak shortening velocity, in the triceps surae muscle during isometric and passive movements using cine phase-contrast, velocity-encoded MRI.

Methods: With both legs of the subject inserted into the head coil of a Siemens Quantum, 1.5T scanner, the ankle joint of the subjects (total N=11) was immobilized at an angle of 90° with a fiberglass cast. High resolution axial images were acquired for 3D volume rendering of the tendon-aponeurosis complex in a Vitrea workstation for structural information. We have confirmed anatomical observations from two cadavers. The subject was trained to exert isometric contractions timed to a computer generated audio cue. The output of an optical force transducer, imbedded in the sole of the cast, was used to measure force exerted and to gate the scan. It also provided a feedback to the subject via a LED bar-graph, both for timing and for consistency of force exerted as a fraction of MVC, and for subsequent force-strain analysis. Subjects exerted repetitive isometric contraction-relaxation cycles at 20 and 40 % of maximal voluntary contraction. Passive, and unloaded voluntary ankle extension-flexion movements were done with a separate cast allowing 5° or 14° ankle joint movement. During the movement, tissue velocities from several sagittal and axial locations of the lower leg were acquired using segmented (4 views/segment), velocity encoded (VENC=10cm/s S/I), Phase Contrast imaging[1], with TE/TR/Flip angle of 5.3/11.3/30^o, 2 Avg, 22 cm FOV, 5 cm Sl.Thk, 20 phases/"R-R". Velocity information was used to calculate the displacement and strain in the muscle-tendon unit. The PC images were analyzed and mapped onto the anatomical images using an in-house built software.

Results

The velocity distribution differed between passive and isometric tests (Fig. 1, sagittal slice). In isometric contractions, the highest velocities were found always near the aponeurosis of insertion (posterior margin of soleus). In passive ankle joint rotations the highest velocities were found in distal ends of the muscles. The displacement of aponeurosis revealed non-uniform strain along the length of the muscle in both conditions. In isometric condition the movement of mid aponeurosis was the smallest but in passive condition the proximal aponeurosis moved the least. It seems that the aponeurosis between soleus and gastrocnemius is functionally coupled in isometric but not in passive contractions. The cadaver dissections revealed that this is possible because the aponeurosis is not one structure, but both muscles appear to have separate apoeneurosis. Digital dissection of the soleus aponeurosis-Achilles tendon from MR images revealed a complex 3-D structure. Proximally to the Achilles tendon, a part of the aponeurosis starts to protrude anteriorly into the muscle, often dividing the muscle into two separate compartments. In more proximal region, the protrusion separates from the posterior aponeurosis and locates in the middle of the anterior soleus compartment as a central tendon. The muscle fibers are arranged radially around the central tendon. In the distal soleus and proximal gastrocnemius, the fiber arrangement was found very complex.

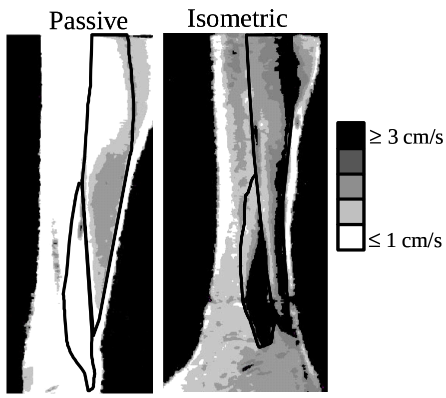

Fig. 1. Velocity distribution at a time of peak velocities expressed in gray scale during passive and isometric task. Dark indicates fast movement proximally. Soleus and deep plantarflexor muscles are outlined.

Discussion: During the isometric and passive plantarflexion tasks the distribution of muscle tissue velocity and movement was not uniform, but distinct areas in the muscle were relatively stationary while other areas showed large movements. In isometric contractions the fastest moving tissues within the triceps surae were found in close proximity of the aponeurosis structure that was connected to the Achilles tendon whereas the slowest movements occurred close to the aponeurosis of origin. We have previously reported non-uniform strain in the posterior aponeurosis of the soleus during isometric contractions and shown anatomical variability in muscle-tendon structure between individuals[1]. Together with the present results these data provide information required in building anatomically correct and functionally realistic muscle models.

References

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