SCALING OF JOINT MECHANICS AND MUSCLE ARCHITECTURE IN THE HUMAN KNEE

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INTRODUCTION

Skeletal muscle performance depends on a variety of intrinsic and extrinsic factors. One important intrinsic factor is the degre of actin and myosin overlap. This length-dependent behavior was quantified in isolated frog muscle fibers Gordon *et al.* (1966) and Edman (1966).

In situ, the relationship between sarcomere length (Ls) and joint angle dictates the length-dependent behavior of muscle. In this situation, Ls changes are the result of an initial Ls-joint angle configuration modified as length changes are imposed by joint motion. Although it has been suggested that Ls-joint angle relationships are stereotypic in humans, this has only been experimentally demonstrated in the wrist (Lieber, *et al.*, 1997). Mechanically, if this is assumption is true, length changes imposed upon a muscle and muscle fiber length (Lf) must scale linearly.

Recently, indirect measurements of excursion and Lf measured by ultrasound suggested that this assumption was not true in the human lower extremity (Maganaris *et al.,* 2006). Here we directly measure muscle excursion and Lf in identical specimens to define the scaling relationship (if any) between lower extremity muscle architecture and joint kinematics.

METHODS

Ten cadaveric lower quarters were harvested and used for the following procedures. First, muscle architecture measurements were made on the four vasti and four hamstring muscles according to methods previously described (Lieber *et al.* 1997). Most importantly, Ls was measured in each fiber bundle using laser diffraction and was used to normalize muscle fiber length (L_{fn}) to 2.7 µm. (Eq. 1):

$$L_{fn} = L_f \times \frac{2.7\mu m}{L_s} \qquad \text{(Equation 1)}$$

Physiological cross-sectional area (PCSA), a measure of a muscle's capacity for force generation [Which reference?], was calculated according to (Eq. 2), where M is mass, θ is pennation angle and ρ is muscle density (1.055 g/cm^3).

$$PCSA = \frac{M \times \cos\theta}{\rho \times Lf} \qquad \text{(Equation 2)}$$

After architectural measurements, each knee was instrumented in a custom jig and the tendon excursion-joint angle relationship of each muscle was measured (Fig. 1).

Following these measurements, data were log transformed and linear regression was used to define the mathematical relationship between tendon excursion, mass, fiber length, and PCSA in the exponential form originally described by Alexander *et al.* (1979).

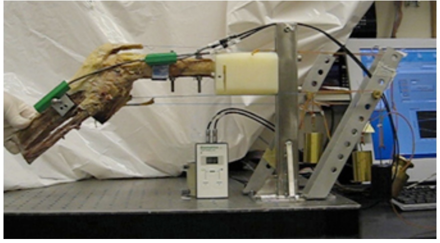

Figure 1. Experimental apparatus to measure simultaneously all tendon excursions and joint angles.

RESULTS AND DISCUSSION

Excursion and muscle mass were not related for any muscle studied (Table 1). This suggests that muscle mass and volume are relatively constant relative to the amount of excursion imposed on these muscles.

Surprisingly, excursion was negatively related to muscle fiber length in the quadriceps muscles (r^2 0.26-0.59) and not related to fiber length in the hamstring muscles (Table 1, Fig. 2). This suggests that *larger* changes in muscle length are associated with *shorter* muscle fibers in the quadriceps and are unrelated to fiber length in the hamstrings.

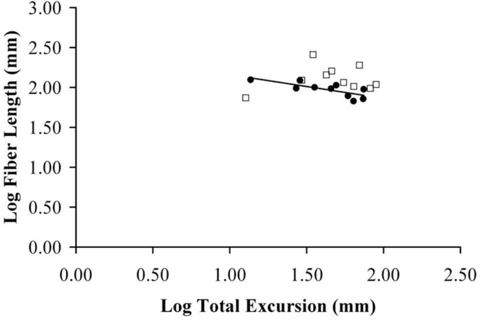

Figure 1. Total excursion versus Lf in the vastus lateralis (filled circles) and semitendinosus (open squares).

Muscle excursion was significantly positively related to PCSA in the vastus lateralis muscle, but not related to PCSA in any other muscle (Table 1, Fig. 3). This suggests that larger changes in muscle length are associated with greater force producing capacity in the key antigravity muscle.

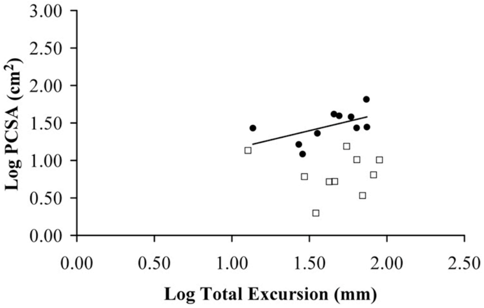

Figure 3: Total excursion versus PCSA (B) in the vastus lateralis (filled circles) and semitendinosus (open squares).

SUMMARY/CONCLUSIONS

Joint mechanics and muscle architecture do scale in some human lower extremity muscles. However, the scaling rules are; 1) not intuitive, 2) appear to vary by muscle and muscle group, and 3) may have profound functional implications.

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Table 1. Relationships between muscle excursion and muscle architectural features in the form $y = Excursion^X + C$

	Exponent	Constant	r^2	Exponent	Constant	r^2	Exponent	Constant	r^2
rectus femoris	0.11 ± 0.27	1.85 ± 0.45	0.02	**-0.15 ± 0.60***	2.15 ± 0.10	0.43	0.26 ± 0.29	0.65 ± 0.47	0.09
vastus lateralis	0.18 ± 0.28	2.20 ± 0.45	0.05	**-0.30 ± 0.09***	2.46 ± 0.14	0.59	0.50 ± 0.27#	0.65 ± 0.44	0.30
vastus intermedius	0.03 ± 0.23	2.29 ± 0.37	< 0.01	**-0.16 ± 0.10#**	2.23 ± 0.16	0.26	0.19 ± 0.28	1.02 ± 0.46	0.05
vastus medialis	< 0.01 ± 0.24	2.33 ± 0.39	< 0.01	**-0.30 ± 0.15#**	2.48 ± 0.25	0.33	0.25 ± 0.32	0.82 ± 0.53	0.07
biceps femoris (LH)	0.15 ± 0.29	1.76 + 0.40	0.03	0.05 ± 0.07	1.94 ± 0.10	0.07	0.10 ± 0.29	0.79 ± 0.40	0.02
biceps femoris (SH)	0.17 ± 0.18	1.53 ± 0.26	0.09	0.04 ± 0.13	1.95 ± 0.18	0.01	0.14 ± 0.19	0.54 ± 0.27	0.06
semitendinosus	0.02 ± 0.23	1.95 ± 0.38	< 0.01	0.11 ± 0.22	1.93 ± 0.36	0.03	-0.08 ± 0.39	0.95 ± 0.65	< 0.01
semimembranosus	-0.16 ± 0.18	2.30 ± 0.27	0.09	-0.31 ± 0.27	2.22 ± 0.41	0.14	0.18 ± 0.27	1.01 ± 0.41	0.05