HUMAN LOWER EXTREMITY MUSCLE DESIGN

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INTRODUCTION. Models of the musculoskeletal system depend on accurate skeletal dimension and muscle architectural inputs. To date, models of the human lower extremity are based on the muscle architecture of either two [2] or three [1] cadaveric specimens of unknown age, gender, and size. As models become more sophisticated, accurate depiction of inter- and intra-muscular architectural features is critical [3]. The purpose of this project was to develop an internationally accessible, high resolution database of human lower extremity muscle architecture and their associated skeletons. This database, consisting of nearly 500 muscles, will enable high-resolution modeling for decades.

METHODS. Seventeen formaldehyde-fixed cadaveric lower extremities were used for this project (age: 82 ± 10 yrs.; gender: 10 female - 7 male; height 169.5 ± 9.7 cm; weight 82.7 ± 15.3 kg). The use of human tissue was approved by the Anatomical Services Committee of the University of California, San Diego.

Each specimen was scanned via computed tomography and magnetic resonance imaging with a resolution of 1 cubic millimeter. Datasets were registered and segmented for extraction of bony and muscular anatomy. Muscle architectural measurements were made on twenty-seven key lower extremity muscles according to methods previously described [4]. Briefly, mass (M) and muscle length (L_m) were measured for each muscle. Fiber bundles from three to five predetermined regions of each muscle were microdissected and sarcomere length (L_s) was measured in each fiber bundle using laser diffraction [4]. L_s was then used to normalize muscle fiber length (L_{fn}) to 2.7 µm, the optimal length for human muscle (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 [5], was calculated according to Eq. 2:

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

where θ is pennation angle and ρ is muscle density, 1.055 g/cm^3 for formalin-fixed human tissue [6].

Since this analysis created a huge database, here we limit our presentation to L_{fn}, PCSA, and fiber length variability (coefficient of variation) among quadriceps and hamstring muscles using analyses of variance (ANOVA). When significant differences were observed, *post hoc* Tukey tests were performed to determine where the differences existed. All results are shown as mean ± standard error, and the significance level was $\alpha = 0.05$.

RESULTS. In contrast to previous reports [1,2] muscle fiber lengths were not significantly different between quadriceps and hamstrings groups. However, within the quadriceps, rectus femoris fiber lengths (73.9 mm ± 3.2 mm) were significantly shorter than the vastus lateralis (100.3 mm ± 4.5 mm), vastus intermedius (98.1 mm ± 5.2 mm), and vastus medialis (95.3 mm ± 6.3 mm) (Fig. 1, $P < 0.05$). Similarly, within the hamstrings, semimembranosus fiber lengths (70.1 mm ± 5.5 mm) were significantly shorter than the semitendinosus (99.4 mm ± 6.1 mm), biceps femoris short head (109.6 mm ± 5.6 mm), and biceps femoris long head (95.4 mm ± 7.9 mm) (Fig. 1, $P < 0.05$).

Physiological cross sectional areas (PCSA) were significantly larger in the quadriceps compared to the hamstrings ($P < 0.05$). Within the quadriceps, vastus lateralis PCSA (35.2 cm^2 ± 4.4 cm^2) was significantly greater compared to rectus femoris (14.0 cm^2 ± 1.3 cm^2), vastus intermedius (17.2 cm^2 ± 1.9 cm^2), and vastus medialis (21.2 cm^2 ± 2.1 cm^2) (Fig. 1, $P < 0.05$). Within hamstrings, the semimembranosus had significantly larger PCSA (19.0 cm^2 ± 2.1 cm^2) compared to biceps femoris short head (5.4 cm^2 ± 0.5 cm^2, Fig. 1, $P < 0.05$) and was not significantly larger than any of the quadriceps muscles. Interestingly, fiber length variability was small (7%-11%) for all muscles except the semitendinosus which had the greatest variability of all muscles studied (35% ± 4%; $P < 0.05$).

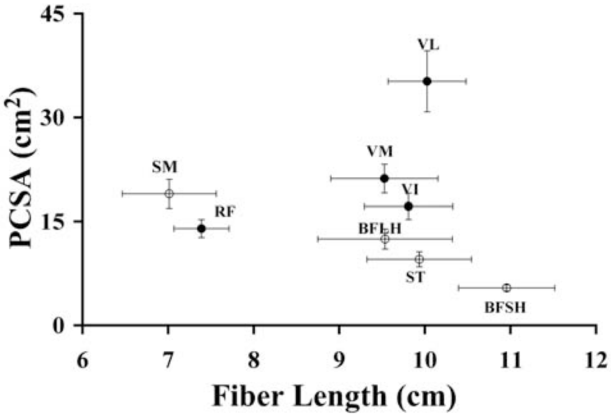

Figure 1: Scatter plot of normalized muscle fiber length *versus* physiological cross sectional area. Quadriceps muscles (filled circles); vastus lateralis (VL), vastus medialis (VM), vastus intermedius (VI), and rectus femoris (RF). Hamstring muscles (open circles); short head of biceps femoris (BFSH), long head of biceps femoris (BFLH), semitendinosus (ST), and semimembranosus (SM). Values for each muscle are plotted as mean ± standard error.

DISCUSSION. Quadriceps and hamstring muscle architecture differs primarily in physiological cross sectional area. This is not surprising, as the quadriceps (which had the largest PCSA) are antigravity muscles at the knee. Muscle fiber lengths did not differ between muscle groups, contrary to previous reports [1,2]. This is surprising because the hamstring muscles are largely comprised of two-joint muscles. It is also interesting that the only two-joint muscle in the quadriceps (rectus femoris) had the shortest fiber length of all quadriceps (Fig. 1).

Within muscle groups, hamstrings demonstrated the classic trade-off between PCSA and fiber length. For example, the semimembranosus muscle had a large PCSA and short fibers. Functionally, this would be reflected by a large force-generating capacity and short excursion. Quadriceps did not follow this pattern. The vastus lateralis muscle had the largest PCSA and the longest fibers. Functionally this would translate into a large force generating capacity and a relatively high excursion. This is perhaps due to the need for large knee extension forces through a relatively large arc of joint motion.

Clinically these data are important for a number of reasons. First, these data support the notion that the vastus lateralis muscle is the "key" to knee function. Second, the previous report that hamstring muscles are designed for excursion is not supported by these data. In fact, as a whole, they are no different from quadriceps muscles, despite their two joint functions. Additionally, semimembranosus has very short fibers and semitendinosus has a wide range of muscle fiber lengths. It is possible that these features are related to the relatively high occurrence of muscle strains in the hamstrings, particularly in semimembranosus and semitendinosus. These data will undoubtedly provide clinicians and scientists with a new view of lower extremity muscle design in these eight muscles and the other 19 documented in this series.

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