SKELETAL MUSCLE ARCHITECTURE OF THE GOAT HINDLIMB

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INTRODUCTION

With the increased availability of software for generating muscle-driven simulations [e.g., 1], many investigators are creating biomechanical models and simulating movements, with the hope of preventing injuries or improving the efficacy of treatments. However, very few are validating the predictions of their models by comparing results to key parameters, such as the muscle forces and fascicle length changes measured *in vivo*. These parameters are difficult to quantify in humans, since they generally involve invasive techniques. Simulation-based studies of animals — which could be compared, for example, to sonomicrometry, EMG, or tendon force buckle measurements during *in vivo* experiments [e.g., 2] — are needed to test and refine techniques for modeling and simulation.

With this aim in mind, we have characterized the skeletal geometry, segment masses and inertias, joint kinematics, and muscle force-generating properties of the hindlimb of a goat *(Capra hircus),* as necessary to create a 3D musculoskeletal model. This abstract describes new insights gained from analyzing the muscle architecture.

METHODS

Dissections were performed on the formalin-fixed pelvis and right hindlimb of one adult male specimen (mass = 46 kg). After measuring the specimen's joint angles at their fixed orientations, the origins and insertions of all the major hindlimb muscles (divided into 43 muscle-tendon units) were digitized. The muscles were removed and their architectural properties determined as described by Lieber *et al.* [e.g., 3]. For each muscle unit, we isolated 2-3 fascicle bundles, measured raw fiber length with a digital caliper, and averaged these data. Under magnification, we freed 5-8 small fiber bundles from each fascicle, and we assessed bundle sarcomere length using laser diffraction (VHK circular beam diode laser, wavelength = 635 nm, power = 4.9 mW, *Coherent Inc.*). We calculated the physiological cross-sectional area (PCSA) of each muscle unit from its measured mass (m), density (ρ = 1.056 g/cm^3 [4]), optimal fiber length (l_o^f), and surface pennation angle (α) as follows:

$$PCSA = \frac{m}{\rho * l_o^f} * \alpha$$

We estimated the optimal fiber length of each muscle unit from its raw fiber length (l_{raw}^f), bundle sarcomere length (l_{raw}^s), and optimal sarcomere length (l_o^s) as follows:

$$l_o^f = \frac{l_{raw}^f}{l_{raw}^s} * l_o^s$$

The measured sarcomere lengths of the muscles, after averaging across fiber samples, ranged from 1.78 – 3.18 μm. We assumed an optimal sarcomere length of 2.4 μm; this is similar to the optimal lengths reported for cat and monkey [5], and it appears consistent with our laser diffraction data.

RESULTS AND DISCUSSION

Examination of the muscles' architectural features is informative (e.g., Fig. 1). These data reveal, for example, that the goat's biarticular rectus femoris (RF) has the largest PCSA, and thus the greatest force-generating capacity of all the hindlimb muscles. The massive gluteobiceps (GBi) and gluteus medius (GMED) also have substantial force-generating capacity. At the ankle, the goat's biarticular gastrocnemius (LG and MG), the short-fibered fibularis tertius (FibT), and the superficial and deep digital flexors (SDF and the combined heads of DDF) are the strongest muscles.

The goat's hamstrings (SM, ST, and BF), by contrast, have the longest optimal fiber lengths. The sartorius (SAR) and adductor (ADD) also have relatively long fiber lengths; these muscles are presumably designed to undergo large excursions.

Comparison of the PCSAs for groups of muscles indicates that the goat's ankle plantarflexors are substantially stronger than the ankle dorsiflexors (i.e., the plantarflexors have a greater total PCSA). Also, the goat's knee extensors, as a group, are stronger than the knee flexors. These results are consistent with analogous data derived from human studies [6], and likely reflect the important anti-gravity function of these muscle groups. At the hip, the goat's flexors and extensors have similar total PCSAs; this result differs from human studies.

Analyses of the goat's muscle architecture, in combination with musculoskeletal modeling and simulation tools, may offer new insights in comparative biomechanics studies. For instance, in bipedal humans, Ward and colleagues [6] have argued that soleus is the most important force generator at the ankle (due to its exceptionally large PCSA), and vastus lateralis is the most important force generator at the knee. However, the quadrupedal goat does not have an equivalent soleus at the ankle, and its rectus femoris is substantially stronger than any of its vasti. Observations such as these may help guide future studies aimed at elucidating general principles of musculoskeletal function and design. Also of note, Eng and colleagues [7] have examined whether architectural features of selected muscles scale with body mass; in their study, data from mouse, rat, cat, human and horse were included. The goat data reported here help "fill the size gap" between cat and human, and thus could make a contribution to future scaling studies.

CONCLUSIONS

We have analyzed the architectural features of all the major muscles in the goat hindlimb. Our next step is to incorporate these data into a detailed, 3D model that characterizes the muscles' force- and moment-generating capacity over a functional range of limb positions.

ACKNOWLEDGEMENTS

We gratefully thank Carlos Moreno, Maria deBoef, Jennifer Carr, James Wakeling, Sabrina Lee, and Pedro Ramirez for their assistance.

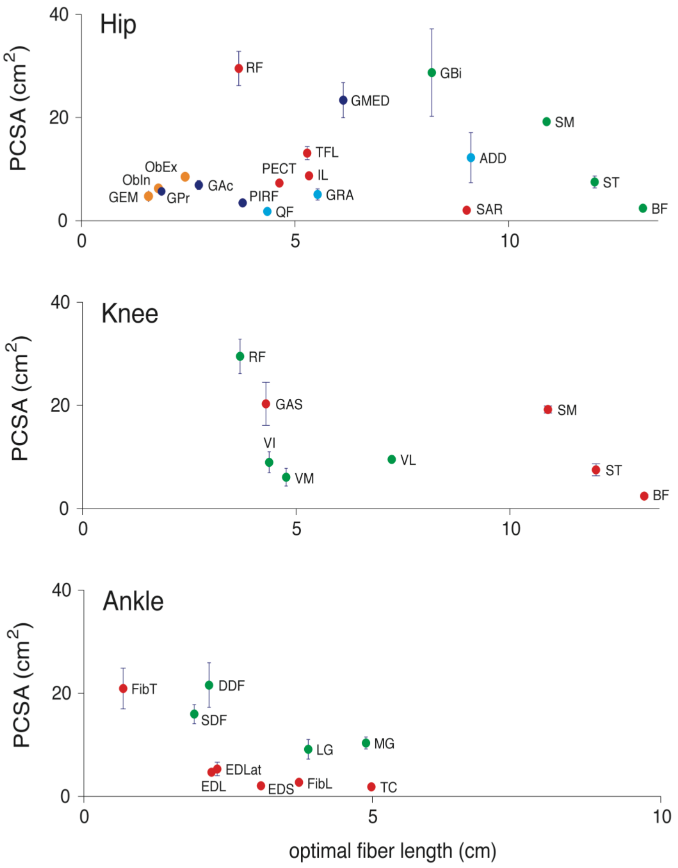

Figure 1: Plots of PCSA vs optimal fiber length for selected goat muscles at the hip, knee, and ankle. Error bars (± 1 SD) reflect variability in the lengths obtained from sampling 2-3 regions per muscle-tendon unit; some muscles that were divided into multiple units (e.g., gluteobiceps, gluteus medius, gastrocnemius, and deep digital flexors) have been combined here for clarity. To aid interpretation, muscles that primarily extend a joint are shown in green, muscles that primarily flex are shown in red, and the hip abductors, adductors, and rotators are shown in blue, cyan, and orange, respectively.

REFERENCES

1. Delp SL, et al. *IEEE Trans Biomed Eng* **54**, 1-11, 2007.
2. McGuigan MP, et al. *J Exp Biol* **212**, 2092-2104, 2009.
3. Lieber RL, et al. *J Hand Surg Am* **15**, 244-250, 1990.
4. Ward SR and Lieber RL. *J Biomech* **38**, 2317-2320, 2005.
5. Burkholder TJ and Lieber RL. *J Exp Biol* **204**, 1529-1536, 2001.
6. Ward SR, et al. *Clin Orthop Relat Res* **467**, 1074-1082, 2009.
7. Eng CM, et al. *J Exp Biol* **211**, 2336-2345, 2001.