Using musculo-robotics to explore the influences of dynamic mechanical loading on muscle-tendon function

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1. Introduction

Muscles move limbs via complex interactions between intrinsic muscle properties (e.g. force-length and force-velocity properties) and the external loading environment (e.g. air, water, ground). A standard approach to explore dynamic muscle function involves electrical stimulation of a muscle *in vitro* while oscillating its length to mimic limb motion [1]. Although such work has characterized how muscles produce force, work and power under controlled length conditions [2], little experimental work has addressed muscle function under unknown or poorly understood loading conditions (e.g. deformable limbs moving through fluid). In these cases, we cannot easily determine *a priori* which length change patterns are appropriate for *in vitro* testing. To address this challenge we developed a musculo-robotic platform enabling an isolated *in vitro* frog muscle to control the motions of a biologically-inspired swimming robotic frog hind limb. As a demonstration of the technique, we tested the influence of fin morphology, fin flexibility and skeletal gearing on *in vitro* force and length change patterns of *Xenopus laevis* frog plantaris muscle. Since we were only concerned with the effects of mechanical loading, we held the muscle stimulation patterns constant.

2. Methods

Upon electrical stimulation, the muscle contracts against a conventional force-length ergometer. The resulting muscle force is transmitted electronically as a torque command signal to servo motors controlling the robot (Fig. 1). Nearly simultaneously, applied torque causes the limb to move through its environment (e.g. air vs. water). After a 0.1 ms feedback delay, the limb motion is then transmitted back to the ergometer to shorten the muscle. Using this approach, the muscle 'feels' the load applied by the robotic limb via the electronic feedback. Effectively, the muscle functions as if it were physically attached to the robot. One advantage of the feedback approach is that force-displacement gain settings in the control software can be adjusted to mimic the influences of skeletal gearing (e.g. changing the muscle's moment arm or altering the compliance of a virtual tendon). This method differs from traditional *in vitro* muscle approaches in that muscle motion is not directly controlled. Rather, the length change pattern emerges from muscle-load interactions via intrinsic force-length and force-velocity properties of the muscle.

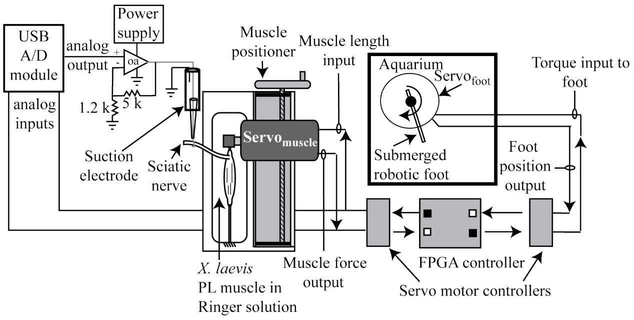

Figure 1. Schematic diagram of the muscle-robot apparatus

In particular, this musculo-robotic method is useful when the dynamic loading environment is complex such as a foot moving through fluid or against a deformable substrate (e.g. sand).

3. Results

We found, unexpectedly, that both fin morphology and the flexibility of fin webbing had little or no influence on the generation of hydrodynamic forces (Fig. 2). Yet from the muscle dynamics perspective, fin morphology (i.e. low versus high aspect ratio) caused significant shifts in muscle force and velocity. However, since these shifts changed reciprocally, muscle power (therefore hydrodynamic thrust) did not change significantly with foot aspect ratio.

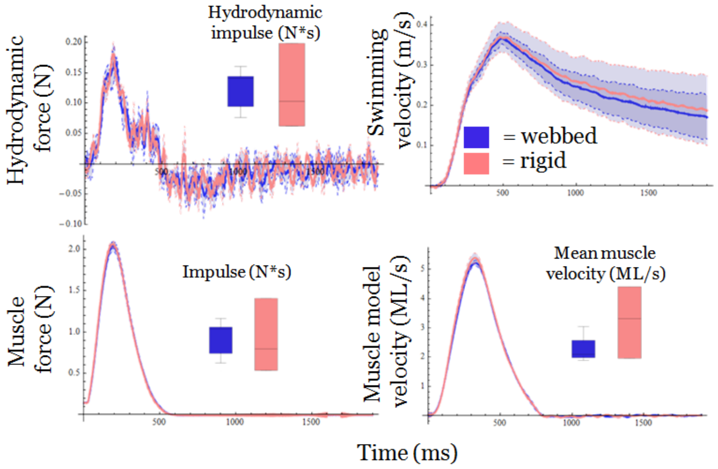

Figure 2. Hydrodynamic and muscle dynamic measurements for rigid (red) vs. compliant webbed (blue) feet

Additionally, changing the limb gearing (by changing the muscle moment arm; Fig. 3) caused dramatic shifts in muscle power output as well as hydrodynamic force [3]. Such findings have suggested that although fin morphological properties may influence muscle mechanics, the influences of skeletal gearing are far more dramatic on muscle power output as well as hydrodynamic force production.

4. Open questions

Several questions remain. In terms of the musculo-robotic method, what might be ways in which this method would be useful as a platform for testing terrestrial biomechanics questions? How might we incorporate aspects of neural feedback? In terms of the mechanics of animal swimming, what role do in-series tendons play in transferring muscle power to the fluid? What might be the influences of changing skeletal gearing dynamically (e.g. variable muscle moment arms)? If dynamic gearing were to be imposed, which functions describing dynamic gear shifts would be most appropriate or effective for modulating muscle power output against fluid loads? Would 'optimal' gearing functions change with loading environment (e.g. fluid vs. solid substrate)? What might be the interactions among the different loading conditions? For example, would changes in fin morphology (or fin webbing compliance) have greater effects if the skeletal gearing conditions were tuned differently?

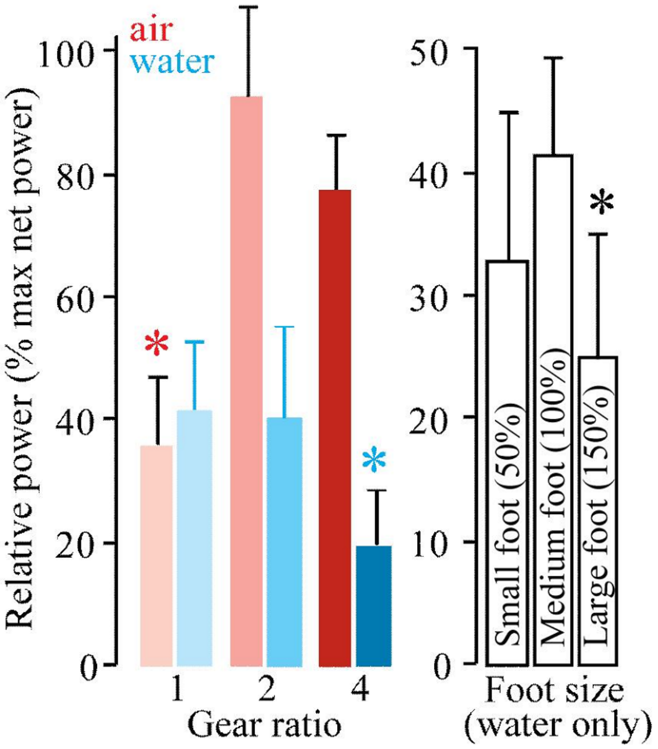

Figure 3. The influence of gear ratio, loading environment and foot size on muscle power output

References

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