CHANGING ENVIRONMENT DYNAMICS CAN SPONTANEOUSLY SHIFT MUSCLE-TENDON FUNCTION DURING CYCLIC CONTRACTIONS

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INTRODUCTION

The ability of the neuromuscular system to adapt quickly to external changes in load allows for efficient movement and protects against injury [1]. For example, in many terrestrial animals, the environment in which locomotion occurs may change instantly (*i.e.*, from land to water), resulting in a change in locomotion pattern [2]. Determining whether shifts in locomotion mode are the result of adapted neural commands versus shifts due to intrinsic mechanical properties of muscle is difficult to determine *in vivo*.

The goal of this study was to use a modeling approach to examine how changes in the environment from forces dominated by gravity to those dominated by fluid drag impact the interaction between muscle and tendon during cyclic locomotion.

We hypothesized that with no change in motor control, in a gravity-dominated world (terrestrial), muscle (CE) would act as a rigid strut, while in a drag-dominated world (fluid) the CE would act as a motor producing significant net work.

METHODS

A muscle-tendon model containing a parallel elastic element (PEE), a contractile element (CE), and a series elastic element (SEE) was employed. In terrestrial conditions, the muscle tendon unit (MTU) acted in opposition to a point mass experiencing constant gravitational force, simulating MTU dynamics of the ankle extensors in bullfrogs during cyclic contractions [3]. In fluid conditions, the point mass experienced a drag force during MTU contraction. An antagonist spring was used in both conditions to restore the MTU back to longer lengths after the power stroke (Fig. 1). Force was generated

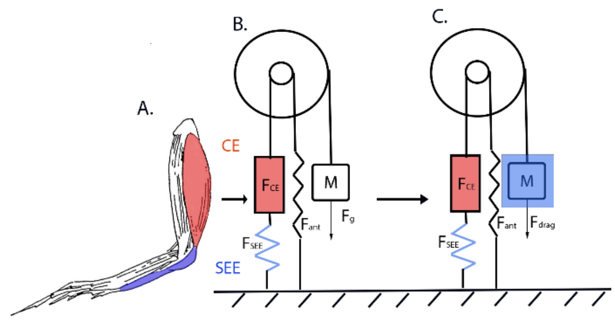

Figure 1. Bullfrog plantaris (A) is basis for MTU model. (B) Terrestrial environment (C) Fluid environment. A body mass in gravity operating with a fixed mechanical advantage simulates bullfrog MTU dynamics during cyclic contractions. In terrestrial implementation, gravitational forces dominate (B) while in fluid implementation, drag forces dominate during MTU shortening, and antagonist spring forces return the MTU to longer lengths (C). Simulations were performed with a K value of 1.875.

in the CE by a Hill-type muscle with classic force-length and –velocity relationships and stimulation modeled as a square wave pulse with a duty of 10% relative to the cycle period. The PEE and SEE had non-linear force-displacement relationships taken from literature. The antagonist spring was modeled according to Hooke's law with a starting length equal to the starting length of the MTU (0.08 m), and a stiffness of 9000 N/m (estimated to be total MTU stiffness). Drag forces experienced by the point mass were modeled by: $F_{drag} = \pm Kv^2$, where v was the velocity of the mass, and K was the lumped drag coefficient (kg/m). Drag only acted when the MTU was shortening, and diminished to zero when the system reset against the antagonist spring (*i.e.*, a fin tuck). To address the role of environmental changes on MTU interaction dynamics, we drove the system at 2 Hz and then spontaneously shifted external load from terrestrial to fluid with a K value of 1.875. To address the hypothesis, we compared the force, length, and power dynamics from steady state contractions before and after the transition.

RESULTS

In terrestrial simulations, the MTU produced large peak forces with a significant passive contribution and the CE operated at longer lengths over a large range (Fig. 2A, E). Under a constant gravitational load, the CE performed little work, with greater contributions coming from elastic energy cycling in and out of the SEE (Fig. 2A, C). In fluid simulations, the MTU generated much lower peak forces with no passive contribution. Additionally, the CE operated at shorter lengths and higher shortening velocities (Fig. 2B, E, F), and generated significant net positive work (Fig. 2D). In terrestrial simulations the CE operated on the lengthening side of the force-velocity curve, but in fluid the CE only shortened (Fig. 2C, D, F).

CONCLUSIONS

These results strongly support our hypothesis that without changes in motor patterns, the CE can shift to and from generating net work (*i.e.*, acts as a motor) in fluid, to performing little net work (*i.e.*, acts as a strut) while in terrestrial conditions. Our results demonstrate that spontaneous changes in dynamics of contraction can occur within the MTU due to changes in the environment alone. Thus motor control architecture need not be complicated for robustness in changing environments as the MTU has inherent properties that provide automatic accommodation.

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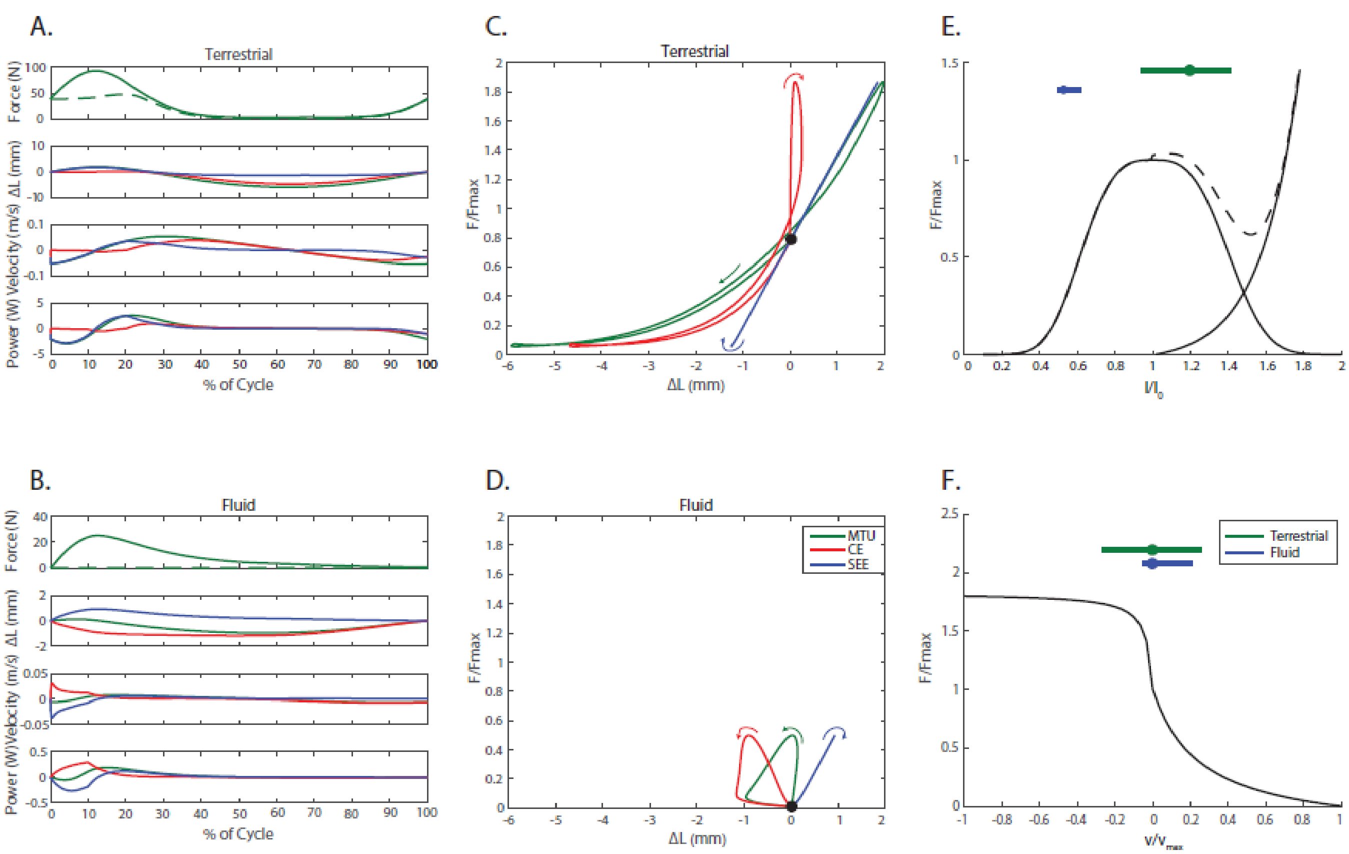

Figure 2. **Time series (A and B), work loops (C and D), CE operating length (E), and CE operating velocity (F) from terrestrial and fluid simulations.** Force, length change, velocity, and power (top to bottom, A and B) from a steady cycle of stimulation; MTU (green), CE (red), and SEE (blue) are shown. Force is decreased in fluid simulations, with little passive contribution and subsequent decreases in overall MTU length change, velocity and power. Work loops from terrestrial simulations demonstrate little work performed by CE, while fluid simulations produce more net work. Arrows indicate direction of the work loop, with black dots representing the start of the work loop. Fluid simulations operated at shorter CE lengths than terrestrial, while also operating over smaller CE velocity ranges.