FROM MUSCLE-TENDON TO WHOLE-BODY DYNAMICS: TOWARDS A MULTI-SCALE EMPIRICAL UNDERSTANDING OF HUMAN BIOMECHANICS

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INTRODUCTION

A grand challenge in the field of biomechanics is to develop a cohesive, multi-scale understanding of human movement that links muscle-tendon, joint and whole-body dynamics. Empirical and computational methods have been developed to estimate biomechanics at a single scale (e.g., joint work), and in some cases to bridge between scales (trans-scale, e.g., to link muscle-tendon to joint work). However, a critical challenge remains to overcome: empirical biomechanical estimates at one scale often do not agree quantitatively with estimates at another. For instance, using traditional 3D analysis methods, net mechanical work computed about the joints when a person climbs a set of stairs overestimates the work performed to raise the center-of-mass against gravity [1]. Even for level ground walking, work discrepancies of 25-35% have been observed [2]. Likewise, muscle-tendon work derived from ultrasound and force transducers may not be fully consistent with joint work from inverse dynamics. Evidence suggests that there may also be discrepancies between empirically-estimated muscle-tendon dynamics, and known tissue properties. For example, one study employing commonly-used methods estimated that the Achilles tendon (a passive, spring-like structure) was performing net positive work during calf raises (i.e., behaving like an active muscle/motor, [3]). It is critical to resolve these trans-scale discrepancies in order to develop a comprehensive, multi-scale understanding of movement. The goal of this abstract is to summarize our recent progress towards coalescing multi-scale estimates.

METHODS

This abstract summaries results from a series of recent experiments. In one study we analyzed biomechanical walking data from 10 healthy participants (7 males, 3 females, 24±2.5 years old, 73.5±15 kg, 1.76±0.11 m height) over a range of speeds (0.9-2.0 m/s). We integrated various empirical estimates of work and energy in order to synthesize whole-body (center-of-mass) dynamics (from Fenn, and Cavagna traditions) with joint- and segment-level kinetics (from Braune & Fischer, and Elftman traditions). In a second study we focused on developing an EMG-driven musculoskeletal analysis to partition joint kinetics into contributions from individual muscle-tendon units. This involved performing a gait analysis study on 6 healthy participants (3 males, 3 females, 24±5 years, 88±14 kg, 1.8±0.1 m height), then using these data as inputs to a custom musculoskeletal model, which provided insight on the kinetics of mono- and multi-articular muscle-tendon units. We are now working to parse muscle fiber vs. tendon work by integrating ultrasound with motion capture and force measures.

RESULTS AND DISCUSSION

We demonstrated, for the first time, that joint-segment estimates could reliably capture whole-body gait dynamics (work done on/about the center-of-mass, [1]). We found that the key to resolving work discrepancies was using 6 degree-of-freedom (rotational and translational) analysis of the hip, knee, ankle and foot (Fig. 1); which revealed that the hip and foot contribute more to human gait kinetics than conventionally estimated. These findings have important implications on how/which muscles power walking, as well as inform the design of assistive devices such as prostheses and exoskeletons. Next, we demonstrated that a new EMG-driven analysis could reproduce inverse dynamics sagittal ankle power with high fidelity during walking (R^2=0.98), while providing estimates of individual muscle-tendon unit contributions. This study provided new insights on ankle-foot interplay during walking, which have implications for the design of prosthetic feet. Future work remains to validate this approach for different joints, activities, and additional planes. The next challenge is to parse muscle fiber vs. tendon work. We will discuss ongoing efforts (using ultrasound) to quantify muscle-tendon length changes and forces during movement, and to synthesize these with our multi-scale biomechanical understanding.

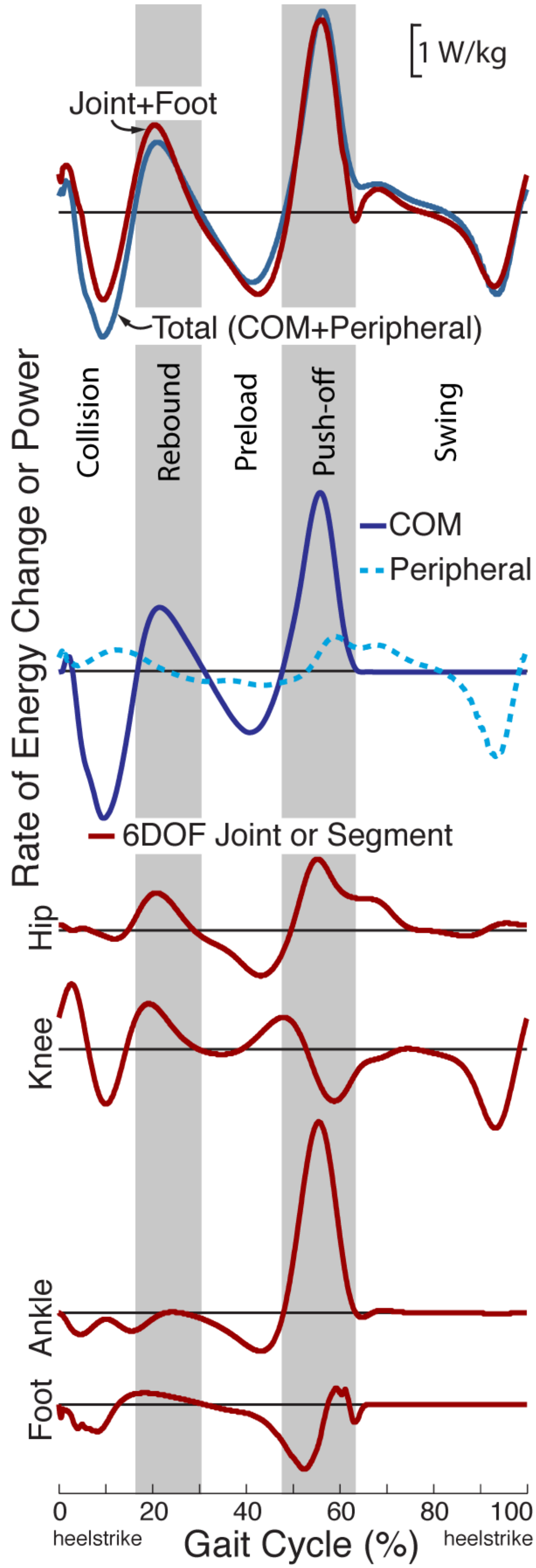

Figure 1: A new Energy Accounting analysis enables us to link individual joint and segment power contributions to total energy changes of and about the center-of-mass (COM and Peripheral) [2].

CONCLUSIONS

Empirical measures provide the basis for our scientific understanding of biomechanics, as well as inform the design of assistive/rehabilitative devices, musculoskeletal simulations and clinical care. Developing a comprehensive understanding of biomechanics requires us to coalesce knowledge across multiple measurement scales, from whole-body to muscle-tendon dynamics (and eventually beyond, including muscle fascicles, fibers, etc.). We face considerable challenges in realizing this cohesive understanding, as evidenced by trans-scale discrepancies discussed above. However, advances in measurement and imagining modalities, along with a burgeoning biomechanics community, offer new promise in synthesizing our understanding from muscle-tendon to whole-body dynamics.

REFERENCES

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