TOWARDS A COHESIVE, MULTI-SCALE UNDERSTANDING OF MOVEMENT BIOMECHANICS

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INTRODUCTION

A grand challenge in the field is to develop a cohesive, multi-scale understanding of movement biomechanics. *Multi-scale* refers to our ability to examine, quantify and think about movement at various physiological measurement scales (e.g., molecular, cellular, muscle-tendon, joint or whole-body). Each scale offers a complementary perspective. *Cohesive* signifies that our qualitative understanding at one scale should be consistent with our understanding at other scales. Likewise, our empirical estimates at one scale should be quantitatively consistent with estimates at other scales. Discrepancies between scales suggest inaccurate estimates or incomplete understanding.

Stated simply, biomechanical estimates should add up properly. If our empirical estimates at one scale are sufficiently accurate and comprehensive, then they should add up to reflect estimates at a larger scale. Similarly, biomechanical estimates at a larger scale should be decomposable into constituents at a smaller scale. For instance, I would like to be able to (i) quantify whole-body energy change during movement, then (ii) decompose this whole-body energy change into contributions from each individual joint- or segment-level work source, then (iii) further decompose work done about each joint into contributions from individual muscles, tendons and/or ligaments. Experimentally there are many sources of error in estimating biomechanical work and energy, so perfect quantitative agreement seems unreachable, but compatibility across scales seems like an admirable and attainable goal. Traditionally, whole-body biomechanics (i.e., composite dynamics of the entire biological system) represented the largest scale at which to examine human (or other organism) movement. However, wearable technologies such as prostheses and exoskeletons effectively introduce a larger scale, referred to here as the *augmented-body* scale (i.e., the entire human-device system). Augmented-body dynamics should also be decomposable into biological contributions from the person vs. synthetic contributions from the device; though to experimentally partition human vs. device contributions, care must be taken to account for human-device interface dynamics, as discussed more below.

METHODS

This abstract summarizes efforts to bridge between various scales of biomechanical understanding. My objective is to discuss progress, limitations and challenges related to coalescing: (i) joint and whole-body perspectives, (ii) whole-body and augmented-body perspectives, and (iii) joint and muscle-tendon perspectives. Several experiments on human locomotion will be discussed; though challenges and results presented are also believed to be relevant to non-human animals, to additional movement tasks, and to simulation-based efforts to advance multi-scale biomechanical understanding. One series of gait analysis studies sought to synthesize whole-body dynamics with joint-level dynamics by integrating various empirical estimates of work and energy. Another study explored human-exoskeleton interface dynamics to bridge between (biological) whole-body dynamics and augmented-body dynamics. Most recently, we have integrated ultrasound imaging with motion capture and force measurements in efforts to decompose joint dynamics into contributions from individual muscle-tendon units, and then to further partition muscle vs. tendon work.

RESULTS AND DISCUSSION

Discrepancies between whole-body energy change and summed joint work estimates indicated that energy absorption during the collision phase of walking (just after foot contact) may be dominated by soft tissues in the body [1], as opposed to by muscle or joint work. Corroborating evidence of soft tissue energy absorption has since been observed in experiments on jump landing, running, and obese vs. non-obese gait. Discrepancies between whole-body and joint work also suggested that conventional 3 degree-of-freedom (3DOF) inverse dynamics failed to capture a surprisingly large amount of positive work (e.g., >30% of the net positive work done on/about the body's center-of-mass during the push-off phase of gait, [2]). We found that by extending commonly-used 3DOF inverse dynamics estimates to full 6DOF (rotational and translational power) analysis of the hip, knee, ankle and foot that we were able to resolve the work discrepancy [2]. The 6DOF analysis provided a more complete estimate of work production during walking, revealing that the hip and foot both contribute more to gait kinetics than conventionally estimated. These findings have important implications for assistive technology development and biomechanical simulations. In a separate study on robotic exosuits (soft exoskeletons), we found that in order to decompose augmented-body dynamics into biological vs. device contributions it was critically important to quantify and understand the human-device interface dynamics. The human-device interface absorbed and returned substantial amounts of energy (due to biological soft tissue deformation and synthetic material stretching), which affected estimation and interpretation of the biological work performed by the user [3]. Finally, our recent ultrasound imaging studies have reemphasized the complexity and difficulty of noninvasively partitioning joint kinetics into contributions from individual muscles and tendons [4]. Efforts are ongoing to resolve surprising discrepancies and to unravel non-intuitive findings.

CONCLUSIONS

A central theme of this work is that discrepancies between physiological measurement scales represent opportunities for new insights and learning. In my opinion we should acknowledge and embrace discrepancies, then collaborate to resolve them, in order to move the field closer to a cohesive, multi-scale understanding of movement biomechanics.

REFERENCES

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