Non-rigid work in human walking: are hard collisions in fact soft?

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INTRODUCTION

Muscles and tendons perform work about the lower-limb joints to power gait, but significant work may also be done by non-rigid deformations elsewhere in the body. Steady level-ground walking requires zero net mechanical work per stride, yet rigid-body estimates yield less negative joint work than positive [1]. This suggests that joint work measures fail to capture all the work performed by the body. We propose that work is done by soft tissue deformations, which could influence walking economy or risk of tissue injury. We hypothesize that these non-rigid bodies perform significant negative work during the collision of the leg with the ground after heelstrike. We investigated soft tissue work in human walking, specifically the role of the ankle-foot-shoe.

METHODS

We use two measures to indicate work not captured by standard inverse dynamics. The first, inter-segmental work, estimates work done by the ankle, foot and shoe on the rest of the body. This includes non-rigid deformations (e.g., compression of shoe or heel pad) in addition to rotational ankle work. The second measure, center-of-mass (COM) work, quantifies work done by the entire leg on the body, regardless of whether or not it is from joint rotations. We propose that the differences between these two measures and conventional, rigid-body joint work can serve as indicators of non-rigid deformations.

We measured healthy subjects walking on an instrumented treadmill at various speeds (N=10, 0.7-2.0 m/s). Rigid-body joint powers for the ankle, knee and hip were calculated from conventional inverse dynamics using Visual3D software. We computed COM work rate for each limb, the 3D dot product of each limb's ground reaction force with COM velocity. Inter-segmental work rate from ankle-foot-shoe is defined as summed translational and rotational work performed on the distal shank [2]. Work values were integrated from powers during each phase of gait – Collision, Rebound, Preload, Push-off – as defined by alternating regions of positive/negative COM work (Fig. 1).

RESULTS & DISCUSSION

We found strong evidence of non-rigid work performed during the Collision phase of gait (Fig. 1). At 1.25 m/s, summed ankle-knee-hip work failed to capture about 7.5 J, or 60% of the negative COM Collision work [3]. And rigid-body ankle joint work failed to account for about 2 J of negative inter-segmental work, so ankle-foot-shoe deformation may perform about 15% of the total negative Collision work. By both measures, non-rigid Collision work increased with speed. The overall results suggest that soft deformations may in fact dominate walking collisions.

We also observed evidence of a non-rigid elastic response after Collision. Based on differences between COM and summed joint work, about 4 J of the total non-rigid Collision work may be stored and then returned elastically during the Rebound phase. On average, less than half of the ankle-foot-shoe work (<1 J) contributed to elastic energy return. In summary, we believe non-rigid deformations play a significant energetic role in both positive and negative work during walking.

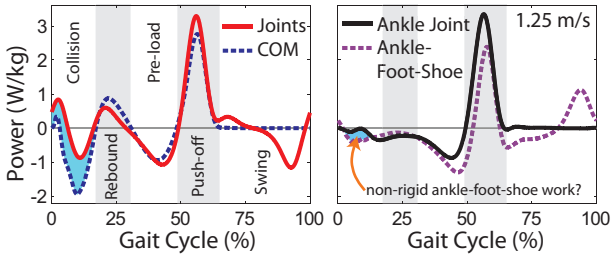

Fig. 1: Average COM vs. summed ankle-knee-hip joint power (left), inter-segmental work rate from ankle-foot-shoe vs. rigid-body ankle joint power (right). Fluctuating regions of positive and negative COM work define phases of gait.

REFERENCES

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