

Comments on “Biomechanics and Muscle Coordination of Human Walking: Parts I and II”.

Zajac et al. [1,2], in their review of the biomechanics and muscle coordination of human walking, encouraged the use of dynamical simulations to perform muscle-induced segmental acceleration and power analyses to infer muscle coordination principles. They state that a major function performed by a muscle arises from the instantaneous segmental accelerations and redistribution of segmental energy throughout the body caused by force generation, and this function can be fundamentally invariant to whether the muscle is shortening, lengthening, or neither. Examples were provided, including energy delivery to the crank by non-energy producing muscles in pedaling and forward acceleration of the trunk (referred to as forward “progression” in Zajac et al. [2]) by eccentric muscle activity in walking.

Although Zajac et al. [1,2] present a reasonable interpretation of muscle function during locomotion using induced acceleration analyses of multi-linked, muscle-based models, I feel that some of their interpretations should be placed more strongly in the context of understanding established in simple, non-muscle-based models (e.g., inverted pendulum model in walking) and muscle-based models with fewer degrees of freedom (e.g., ankle-locked model in pedaling). The interpretations drawn from such simplified models do not presume that muscular activity is not needed at the joints modeled as constraints, but that muscle forces acting at these joints primarily provide postural support. Moreover, seemingly novel concepts, such as a muscle’s role in redistributing segmental energy, can map fairly well into concepts revealed by these simplified models. For example, in the analysis of pedaling in Zajac et al. [1], the interpretation that the plantarflexors redistribute energy from the leg to the crank is not fundamentally different from the simpler view that the plantarflexors lock the ankle, so that the proximal muscles at the hip and knee accelerate the crank. In their interpretation, the instantaneous cancellation of energy distributed to and from the leg, as energy is delivered to the crank, does not appear to be physically relevant in differentiating between these two mechanically-equivalent descriptions of energy delivery. Moreover, in tasks that are not as well-understood as pedaling, the concept that a muscle simultaneously accelerates and decelerates segments (i.e., redistribute energy) when it fundamentally supports the posture of a joint can be misleading, since energy redistribution by the muscle may not contribute importantly to net changes in individual segmental energy. In these instances, relating the results from induced acceleration analysis of multi-linked models to understanding established in simpler models can be particularly helpful.

For example, in the analysis of walking in Zajac et al. [2], the interpretation that the proximal muscles that support the hip and knee (i.e., the vasti group and gluteus maximus) contribute importantly to forward acceleration of the trunk by decelerating the leg during the first half of stance (0-30% of gait cycle) does not seem appropriate. Based on understanding derived from an inverted pendulum model, muscles that provide postural support of the leg during the first half of stance are expected to lift and decelerate the forward motion of the trunk. In agreement with this notion, the trunk is observed experimentally to decelerate for much of this interval, and the ground reaction force from the leg is directed backward, decelerating the center of mass. The question that we should be asking is, “If the leg doesn’t function to accelerate the trunk forward

during the first half of stance, is it appropriate to emphasize the important contribution of the proximal muscles to forward acceleration?”

From about 15-30% of the gait cycle, the uni- and biarticular plantarflexors were found to accelerate the trunk backward more strongly than the proximal muscles accelerate it forward (see Fig. 3 in part II of the review) [2]. Therefore, during this interval, the net effect of stance limb muscles (i.e., the proximal muscles and plantarflexors) support and lift the trunk and decelerate its forward motion, which is consistent with an inverted pendulum model of walking. However, Zajac et al. [2] chose to emphasize the important individual contributions to forward acceleration provided by the proximal muscles, as if to imply that accelerating the trunk forward during this interval was necessary to maintain its forward motion.

From about 0-15% of the gait cycle, the presentation in Zajac et al. [2] that proximal muscles at the hip and knee contribute importantly to forward acceleration is even more perplexing. Other muscles do not appear to decelerate the trunk during this interval (see Fig. 3 in part II of the review) [2], and the contributions of other, non-muscular forces (i.e., passive torques, velocity effects, or gravitational forces), which might explain the net effect of the leg, were not shown. Assuming that non-muscular forces decelerate the trunk and cancel the forward acceleration contributed by muscles during this interval, it would still seem inappropriate to emphasize the important individual contributions of muscles to forward acceleration, when the net effect of the leg decelerates the trunk, while it continues to progress forward through its momentum.

I believe that the energy redistribution from the leg to the trunk by the proximal muscles during the first half of stance result indirectly from postural support, since they cancel instantaneously with energy distributed away from the trunk by other forces. The energy redistribution should not be interpreted to contribute importantly to forward acceleration of the trunk to fulfill presumed task requirements of progression. These issues have been communicated to Dr. Zajac and, hopefully, will be addressed in future work.

Currently, the interpretation of muscle function during locomotion using induced acceleration analysis is in its infancy, and its ultimate utility may depend on a better understanding of the nature of the results and of the strengths and limitations of the technique. As a first step, I feel that an appreciation of the mapping between interpretations drawn from simple and complex models is needed before induced acceleration analysis can be expected to advance our understanding of locomotion. Indeed, the concept of synergistic muscle action in Zajac et al. [1], in which the net accelerations induced by a group of co-excited muscles are interpreted to act as a functional unit, can help clarify some of the important relationships between interpretations drawn from different models of a task. I hope this commentary encourages further debate between biomechanists and clinicians interested in the use of induced acceleration analysis.

References

- [1] Zajac FE, Neptune RR, Kautz SA. Biomechanics and muscle coordination of human walking. Part I: Introduction to concepts, power transfer, dynamics and simulations. *Gait Posture* 2002; 16: 215-232.

- [2] Zajac FE, Neptune RR, Kautz SA. Biomechanics and muscle coordination of human walking. Part II: Lessons from dynamical simulations and clinical implications. *Gait Posture* 2003; 17: 1-17.

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