Altered Kinematic Coordination in Above-Knee Amputees May Be Key to Improving Control of Powered Prostheses

Elad Siman Tov

April 10, 2025

Abstract

The kinematic coupling between the ankle, knee, and hip joints that appears in normal human gait is called *intersegmental coordination*. When the foot, shank and thigh segment angles are measured with respect to a global coordinate system (elevation angles), and plotted in a 3D graph, they appear to follow a curve that lies on a single plane, termed as the *Covariation Plane* (CVP). In [1], it was hypothesized that a higher order law relating the vertical axes (the direction of gravity) to the orientation of the limbs explains this phenomenon.

The angle of the CVP was also found to be correlated with the gait speed, where the plane of covariation angle rotates with increasing speed[2]. Accordingly, this tilt was correlated with the *metabolic cost of transport*. For this reason, it was suggested that the *Central Nervous System* (CNS) minimizes the energy costs by adapting the tilt of the CVP.

A major problem in the field of prosthetics is that gait for individuals with transfemoral amputations has been shown to have elevated metabolic cost compared to able-bodied gait [3]. The main goal of this research is to explore the relationship between intersegmental coordination and the energetics of human locomotion. It is an open question whether intersegmental coordination is the *effect* of an optimal motor control strategy or the *cause* of an optimal performance outcome, such as a lower metabolic cost. Our specific research question is whether altered intersegmental coordination is the cause of elevated amputee metabolic cost. Our *hypothesis* is that a prosthetic device controller, that is informed by the laws of intersegmental coordination will reduce the metabolic cost of walking for an amputee.

Our *rationale* is based on the correlation between kinematic laws and mechanical power, and the fact that the latter is also related to metabolic cost of movement. If a controller incorporating kinematic laws of coordination provides better performance outcomes than a suitable benchmark controller, this would be supporting evidence that the CNS control strategy may adapt according to these kinematic laws.

In our preliminary analysis, we considered amputee gait on powered versus passive prostheses and found that their coordination is altered when compared to able bodied subjects. These results emphasize the notion that powered prostheses may be unsuccessful for reducing metabolic cost versus passive since their current control seems to worsen limb coordination. We found that prosthesis controllers may be following a correct joint angle trajectory, but are not necessarily *coordinating* correctly.

The significance of this research is not limited to its vast potential of increasing adoption for powered prosthesis for lower limb amputees by reducing their metabolic costs. It could also shed light on the nature of motor control of human movement by partially answering the question of the origin of the laws of intersegmental coordination. Even a null outcome of our hypothesis would advance research and further inquiry, as it would implicate that the kinematic laws are a cause for superior energetics rather than a result of motor control of the CNS.

References

[1] N. Alberto Borghese, N. A. Borghese, Luigi Bianchi, L. Bianchi, Francesco Lacquaniti, and F. Lacquaniti, "Kinematic determinants of human locomotion," *The Journal of Physiology*, vol. 494, pp. 863–879, Aug. 1996. MAG ID: 1969042787.

[2] Luigi Bianchi, L. Bianchi, Daniela F. Angelini, D. Angelini, G. P. Orani, G. P. Orani, Francesco Lacquaniti, and F. Lacquaniti, "Kinematic coordination in human gait: relation to mechanical energy cost," *Journal of Neurophysiology*, vol. 79, pp. 2155–2170, Apr. 1998. MAG ID: 2195060912.

[3] L. Van Schaik, J. H. B. Geertzen, P. U. Dijkstra, and R. Dekker, "Metabolic costs of activities of daily living in persons with a lower limb amputation: A systematic review and meta-analysis," *PLOS ONE*, vol. 14, p. e0213256, Mar. 2019.