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Separation of rotational and translational segmental momentum to assess movement coordination during walking

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This investigation presents an analysis of segmental angular momentum to describe segmental coordination during walking. Generating and arresting momentum is an intuitive concept, and also forms the foundation of Newton-Euler dynamics. Total segmental angular momentum is separated into separate components, translational angular momentum (TAM) and rotational angular momentum (RAM), which provide different but complementary perspectives of the segmental dynamics needed to achieve forward progression during walking. TAM was referenced to the stance foot, which provides insight into the mechanisms behind how forward progression is achieved through coordinated segmental motion relative to the foot. Translational and rotational segmental moments were calculated directly from TAM and RAM, via Euler's 1st and 2nd laws in angular momentum form, respectively, and are composed of the effects of intersegmental forces and joint moments. Using data from 14 healthy participants, the effort required to generate and arrest momentum were assessed by linking the features of segmental angular momentum and the associated segmental moments to well-known spatiotemporal and kinetic features of the gait cycle. Segmental momentum provides an opportunity to explore and understand system-wide dynamics of coordination from an alternative perspective that is rooted in fundamentals of dynamics, and can be estimated using only segmental kinematic measurements.

1. Introduction

Total segmental angular momentum is a foundational concept and quantity on which Newton-Euler mechanics are based. Generating and arresting momentum is an intuitive concept that is broadly and correctly used in nonscientific arenas (e.g., sports); however, in dynamic systems, momentum is primarily used as a stepping stone through which equations of motion are calculated (forward dynamics) or moments and forces are obtained (inverse dynamics). Joint kinetics, which are calculated using an iterative Newton-Euler method via inverse dynamics, are commonly used to describe both normal and pathologic human movement patterns and depend upon the total angular momentum of the surrounding segments (Carollo &

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Matthews, 2009; Robertson, Caldwell, Hamill, Kamen, & Whittlesey, 2004). Joint moments represent the net effect of forces (active muscle forces and passive tissues that cross a joint) that are used to generate and absorb power, and are used as a surrogate representation of joint demand during movement (Winter, 1984). Joint demand is often used to quantify the demands placed on the musculoskeletal system due to external biomechanical loads or muscle forces required for stabilization/segmental motion.

Theoretically, the Newton-Euler formulation on which joint kinetics are calculated provides a direct formulation of how forces and moments regulate segmental momentum. Euler's First Law relates the forces to a segment to motion through the time rate of change of momentum:

$$\mathbf{F}_{seg} = \frac{{}^{I}d}{dt}\left({}^{I}\mathbf{p}_{seg}\right) = \frac{{}^{I}d}{dt}\left(m_{seg}{}^{I}\mathbf{v}_{seg}\right) \tag{1}$$

where ${}^{I}\mathbf{p}_{seg}$ is the linear momentum of a segment (segment mass times linear velocity) observed in an inertial reference frame. Although the aggregate effect of walking is translational (moving from point A to point B), legged locomotion is accomplished through coordinated segmental rotations relative to other segments about shared axes at the joints, which is driven by joint moments (Kadaba, Ramakrishnan, & Wootten, 1990). When a segment with mass rotates and translates, it has angular momentum that is related to external joint forces and moments through Euler's Laws. Similar to Newton's Second Law, Euler's Second Law of rotational motion relates the applied forces and moments to a segment to motion through a statement of momentum:

$$\mathbf{M}_{O} = \frac{{}^{I}d}{dt}\left({}^{I}\mathbf{h}_{O}\right) \tag{2}$$

where $\mathbf{M}_O$ is the sum of moments with respect to the inertially fixed point O applied to the segment and ${}^{I}\mathbf{h}_O$ is the total angular momentum of the segment with respect to O. Total angular momentum of a segment is composed of two independent components that result from the rotation of the segment relative to a reference point as well as the rotation about its center of mass (COM) (Kasdin & Paley, 2011), which we label as translational angular momentum (TAM) and rotational angular momentum (RAM), respectively. Considering the changes of TAM and RAM, which are separate components of segmental angular momentum, provides insight into segmental kinetics.

The change in TAM over time of a segment is roughly proportional to the net external force applied to the segment at the joints (intersegmental forces), at the muscle attachment points on the segment, and by gravity (referred to as Newton's Law in angular momentum form). The change in RAM over time is roughly proportional to the net moment provided by the muscles and connective tissue at each end of the segments.

Forward progression during walking is achieved through both translational and angular motion of individual segments, and therefore segment-based analysis of generating and arresting segmental angular momentum may provide additional insight into how the body coordinates segmental control. Because segmental angular momentum is embedded in inverse dynamic calculations that are commonly used to describe joint demand, we propose that kinetics derived from segmental momentum can provide insight into the effort required during movement (through segmental moments). Two investigations have employed a segmental angular momentum in walking by using principal component analysis (PCA) to examine contributions of total angular momentum of segment relative to the body COM to the sum of total angular momentum from all body segments, known as whole-body angular momentum (WBAM) using. Herr and Popovic (2008) concluded that despite large total segmental angular momentum with respect to the body COM, segment-to-segment cancellations occur to minimize WBAM. Bennett, Russell, Sheth, and Abel (2010) accounted for synergistic control of segmental angular momenta using three principal components in each plane, and the synergies did not change with the gait speed. Although PCA demonstrates segmental synergies in orthogonal parameter spaces created by directions of variance (principal components), to our knowledge, the actual shapes and patterns of individual segmental angular momenta over time are less commonly reported. Two recent investigations have assessed the relative contributions of grouped segmental momenta (upper and lower body) to WBAM in children with cerebral palsy (Russell, Bennett, Sheth, & Abel, 2011) and people with amputation (Pickle, Wilken, Aldridge Whitehead, & Silverman, 2016). Although this approach is useful for identifying strategies for maintaining balance and overall control of the system, we propose that more detailed analyses of individual segmental angular momentum can provide additional insight into coordinated segmental motion. The identification of individual segmental movement patterns is what is done in a clinical movement retraining setting, but has not been accomplished using individual segmental momenta.

Measurement of segmental angular momentum is relevant to both observational and instrumented analyses because it depends on segment kinematics that can be used to gain inference on joint kinetics via Euler's Laws. Assessment of segmental kinematics is common in both observational and instrumented gait analyses, which are both used to identify movement dysfunction and assess outcomes of interventions that target movement quality (Saleh & Murdoch, 1985; Shull, Jirattigalachote, Hunt, Cutkosky, & Delp, 2014). Although important for guiding clinical reasoning, observational gait analysis lacks diagnostic standardization (particularly outside of level walking) and sensitivity (Toro, Nester, & Farren, 2003), which can result in misidentification of compensatory movement patterns (Frigo, Rabuffetti, Kerrigan, Deming, & Pedotti, 1998; Holden, Gill, Magliozzi, Nathan, & Piehl-Baker, 1984; Robinson & Smidt, 1981; Shores, 1980) due to poor observer training, observer bias, parallax error, and poor intrarater reliability (Coutts, 1999; Krebs, Edelstein, & Fishman, 1985). Instrumented