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Asymmetrical loading affects intersegmental dynamics during the swing phase of walking

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ABSTRACT

Much of the work related to lower extremity inertia manipulations has focused on temporal, kinematic and traditional inverse dynamics assessments during locomotion. Intersegmental dynamics is an analytical technique that provides further insights into mechanisms underlying linked-segment motion. The purpose of this study was to determine how intersegmental dynamics during the swing phase of walking are altered during asymmetrical lower extremity loading. Participants walked overground at a speed of $1.57\ m\ s^{-1}$ with 0, 0.5, 1.0, and 2.0 kg attached to one foot. Net, interaction, gravitational, and muscle moments were computed. Moment magnitudes at joints of the loaded leg increased systematically with increasing load, whereas unloaded leg moments were unaffected by loading. With increasing load, relative contributions of interaction moments about the knee and hip and gravitational moment about the ankle increased (i.e., 21%, 8%, and 44% increases, respectively), whereas the relative contributions of muscle moments about all three joints declined (i.e., −4%, −13%, and −8% decreases for the ankle, knee, and hip, respectively for unloaded vs. 2.0 kg). These results suggest that altered inertia properties of the limb not only affected the amount of muscular effort required to swing the leg, but also changed the nature of the interaction between segments.

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1. Introduction

The swing phase of level walking is a highly automatic neuromuscular process that requires little attention from higher centers and resembles the motion of a free-swinging pendulum (Mena, Mansour, & Simon, 1981; Mochon & McMahon, 1980a, 1980b). However, accurate predictions of swing phase kinematics require muscular control to be incorporated into models of the swing phase, particularly near swing initiation and termination (Piazza & Delp, 1996; Selles, Bussmann, Wagenaar, & Stam, 2001; Whittlesey, van Emmerik, & Hamill, 2000). Although neuromuscular responses during swing are small in comparison to stance (Mochon & McMahon, 1980a, 1980b), the presence of neuromuscular control during swing suggests that swing is not produced through purely passive mechanisms.

Intersegmental dynamics is an analytical technique that allows for quantification of mechanisms underlying multiple-linked segment interactions and provides insight into how acceleration and velocity of one segment influences the motion of other segments during multi-joint movements (Hollerbach & Flash, 1982; Hoy & Zernicke, 1985, 1986; Hoy, Zernicke, & Smith, 1985; Putnam, 1991; Sainburg, Ghez, & Kalakanis, 1999; Schneider, Zernicke, Schmidt, & Hart, 1989; Whittlesey et al., 2000). More specifically, the technique offers a means of assessing linked segment motion, such as the swing phase of walking, by considering muscular, gravitational, and motion-dependent contributions. This approach has been used to study numerous fundamental movement patterns such as walking (Eng, Winter, & Patla, 1997; Putnam, 1991; Whittlesey et al., 2000), running (Putnam, 1991), throwing (Putnam, 1993), kicking (Putnam, 1991), and goal-oriented reaching tasks (Hollerbach & Flash, 1982; Sainburg, Ghilardi, Poizner, & Ghez, 1995; Sainburg & Kalakanis, 2000; Sainburg et al., 1999), and offers a useful mechanism for studying the effect of lower extremity inertia changes on gait dynamics.

The effect of limb design, as reflected by mass and mass distribution characteristics, on swing phase dynamics during walking has not been fully investigated. Normal growth and development produce substantial changes in limb inertia properties, which are generally symmetrical bilaterally. In contrast, lower extremity amputation, because of injury or disease, results in considerable asymmetry in limb structure. Powered ankle–foot exoskeletons have also been of interest in the research literature (Gordon & Ferris, 2007; Gordon, Sawicki, & Ferris, 2006; Kao, Lewis, & Ferris, 2010; Malcolm et al., 2009; Sawicki & Ferris, 2008, 2009a, 2009b). These devices are designed to restore ankle function to the user during locomotion, but significantly increase the limb's inertia distally. These exoskeletons are often used unilaterally to study how the neuromuscular system of a healthy individual responds to perturbations during walking (e.g., Gordon & Ferris, 2007; Gordon et al., 2006) and how these devices can restore ankle function in persons with a functional disability at the ankle, such as someone recovering from a brain lesion (e.g., Sale, Franceschini, Waldner, & Hesse, 2012; Schmidt, Werner, Bernhardt, Hesse, & Kruger, 2007). The effects of inertia changes, particularly asymmetrical changes, on walking mechanics and swing phase dynamics have received little attention. Understanding the influence of limb inertia on walking mechanics and swing phase dynamics would provide further insight into how individuals, such as lower limb amputees, compensate for altered limb inertia.

The purpose of this study was to determine the effects of asymmetrical lower extremity inertia manipulations produced by distal limb load on intersegmental dynamics as reflected by interaction (also commonly referred to as motion-dependent or inertial moment), gravitational, muscle, and net moments during the swing phase of walking. It was hypothesized that changes in intersegmental dynamics are limited to the leg to which the additional mass is added. Specifically, we expected the interaction, gravitational, and muscle moment magnitudes at the ankle, knee and hip of the loaded leg to increase systematically as foot mass increased. Because other researchers (Eng et al., 1997; Hirashima, Kudo, & Ohtsuki, 2003; Hirashima, Ohgane, Kudo, Hase, & Ohtsuki, 2003; Hollerbach & Flash, 1982; Hoy & Zernicke, 1985; Hoy et al., 1985; Phillips, Roberts, & Huang, 1983; Schneider et al., 1989) have often reported muscle moments typically counteract the effects of the interaction moments during free-swinging motions, we further hypothesized that the relative contributions of the interaction moments at each joint of the loaded leg increase whereas those for muscle moments decrease as foot mass increases. In other words, our expectation was that the neuromuscular system