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Changes in intersegmental dynamics over time due to increased leg inertia

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ABSTRACT

The purpose of this study was to investigate the effects of asymmetrical loading on the intersegmental dynamics of the swing phase. Participants were asked to walk on a treadmill for 20 min under three loading conditions: (a) unloaded baseline, (b) 2 kg attached to the dominant limb's ankle, and (c) post-load, following load removal. Sagittal plane motion data of both legs were collected and an intersegmental dynamics analysis of each swing phase was performed. Comparisons of steady-state responses across load conditions showed that absolute angular impulses of the loaded limb's hip and knee increased significantly after load addition, and returned to baseline following load removal. Unloaded leg steady-state responses were not different across load conditions. However, after a change in leg inertia both legs experienced a period of adaptation that lasted approximately 40 strides before a steady state walking pattern was achieved. These findings suggest that the central nervous system refined the joint moments over time to account for the altered limb inertia and to maintain the underlying kinematic walking pattern. Maintaining a similar kinematic walking pattern resulted in altered moment profiles of the loaded leg, but similar moment profiles of the unloaded leg compared with the unloaded baseline condition.

1. Introduction

Human locomotion is a complex activity that requires coordinated motions at the hip, knee and ankle to move the body forward while maintaining balance in an upright position. An effective coordination

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Nomenclature for Eqs. (1–3):

m_f, m_s, m_t mass of the foot (f), shank (s), and thigh (t)
I_{cmf}, I_{cms}, I_{cmt} moment of inertia about the center of mass of the foot, shank, and thigh
Φ_f, Φ_s, Φ_t segment angles for the foot, shank, and thigh
ω_f, ω_s, ω_t angular velocities of the foot, shank, and thigh
α_f, α_s, α_t angular accelerations of the foot, shank, and thigh
r_f, r_s, r_t distances from the proximal joint to the center of mass of the foot, shank, and thigh
ℓ_s, ℓ_t lengths of the shank and thigh segments
a_{Xh}, a_{Yh} horizontal and vertical components of the linear acceleration of the hip
g gravitational constant (-9.8 m s^{-2})
MUS_a, MUS_k, MUS_h muscle moments acting at the ankle (a), knee (k), and hip (h)
Auxillary variables These definitions are consistent with those of Schneider, Zernicke, Schmidt, and Hart (1989)
B_1 $m_f\, r_f\, \ell_t$
B_2 $m_f\, r_f\, \ell_s$
B_3 $m_f\, r_f$
B_4 $m_f\, \ell_s\, \ell_t$
B_5 $m_s\, r_s\, \ell_t$
B_6 $m_f\, \ell_s^2$
B_7 $m_f\, \ell_s + m_s\, r_s$
B_8 $m_s\, \ell_t^2$
B_9 $m_f\, \ell_t^2$
B_{10} $m_t\, r_t + m_s\, \ell_t + m_f\, \ell_t$
B_{11} $m_s\, \ell_t + m_f\, \ell_t + m_t\, r_t$
Ω_1 $m_f\, r_f^2$
Ω_2 $m_s\, r_s^2$
Ω_3 $m_t\, r_t^2$

strategy depends on the central nervous system's ability to accurately predict the inertial properties of the limbs (Noble & Prentice, 2006). The neural representation of the limb dynamics requires continuous feedback in order to update the internal model and achieve successful movement patterns based on commands sent to the motor system by the central nervous system (CNS) (Scott, 2004). Following lower extremity amputation the internal model must be recalibrated to a new mechanical structure if the individual is to achieve a functional walking pattern after being fitted with a prosthesis. Specifically, when compared to the limb it replaced, a typical below-knee prosthesis possesses 35% less mass, contains a center of mass 35% closer to the knee, and exhibits a 65% smaller moment of inertia relative to a transverse axis through the knee (Lin-Chan, Nielsen, Yack, Hsu, & Shurr, 2003).

It has been suggested that an effective movement pattern is one in which the neuromuscular system is able to coordinate the actions of the muscle with those of passive forces (Bernstein, 1967). This is accomplished by anticipation and knowledge of mechanical properties of the limbs by the CNS, with the aid of constant feedback from the environment. Intersegmental dynamics is an analytical technique that partitions net joint moments into effects due to gravity, interactions among segments (i.e., motion dependent), and muscle. Interaction moments are likely a combination of active and passive forces (Whittlesey, van Emmerik, & Hamill, 2000) and play a large role in determining a limb's trajectory (Hollerbach & Flash, 1982; Hoy & Zernicke, 1985; Hoy, Zernicke, & Smith, 1985; Schneider et al., 1989; Whittlesey et al., 2000; Zernicke, Schneider, & Buford, 1991). Understanding how each of these moments are influenced by changes in limb inertia may shed light on mechanisms underlying locomotion and provide insights into how the CNS coordinates muscle actions with interaction and gravitational effects on limb during walking.

Previous work (Noble & Prentice, 2006; Smith & Martin, 2007, 2011) investigating effects of asymmetrical lower extremity inertia on walking patterns found that muscle moment magnitudes