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Proximal lower limb muscle energetics and the adaptation of segment elevation angle phasing for obstacle avoidance

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ABSTRACT

The purpose of this study was to better understand phase differences in the previously shown reorganization of elevation angles for obstacle avoidance and to relate them to active and passive energetic contributions at proximal lower limb joints. Ten healthy young adults stepped over obstacles of different heights. The fundamental harmonics representing elevation angles of the thigh and shank segments, their relative phase relationship as well as joint and muscle mechanical power and related work at the hip and knee joints were calculated. As higher obstacles were cleared, phase shifts between the thigh and shank increased due to a greater lead by the thigh for the leading limb and a greater lag by the shank for the trailing limb. While kinematic patterns were relatively constant, mechanical work differed greatly with passive energy transfer from the shank to the thigh during mid-swing dominating in the leading limb, but passive energy transfer from the shank to the thigh segment during toe-off coupled with active hip flexor generation in the trailing limb. Shank elevation angle waveform shifts were related to active knee flexor power in both limbs. However, different power bursts appeared to be related to thigh elevation waveform shifts in the leading (shank to thigh passive transfer offset) and trailing (active hip flexor offset) limbs. These results suggest limb specific temporal organization and underlying energetic patterns to realize thigh-shank phase shifts necessary for obstacle avoidance further supporting the theory of independent bilateral control.

1. Introduction

Anticipatory locomotor adjustments (or ALAs) are required in order to step over obstructions in a locomotor path [1,2]. Although tasks such as these are performed numerous times throughout a person's day, very little is known about how the central nervous system (CNS) controls and coordinates these locomotor adjustments.

Previous studies examining obstacle clearance have generally focused on joint angle data [3–7] with control from muscles about the joints. When stepping over obstacles, work done by knee extensor absorption (K3; [8]) and hip flexor generation (H3; [8]) muscle power bursts around toe-off are decreased and a new knee flexor energy generation burst (K5) generates the energy needed to flex the knee and hip joints [2,9] in both limbs. In the trailing limb, hip flexor generation and knee flexor absorption bursts at toe-off are delayed (termed K3D and H3D [10]) due to the close proximity of the trailing foot. These observations led to the suggestion [10] of joint specific control whereby the K5 muscle power burst acts to elevate the limb and the hip flexor power (H3 or H3D) acts to progress the limb through swing. The relation of hip power to limb swing has also been suggested in computer modeling [11].

A different perspective of lower limb motion can be obtained by using absolute segment angles. In particular, the arrangement of segment elevation angles during lower limb movement has led to the planar law of intersegmental coordination [12–14]. The significance of this law is that it suggests a simplification of control [13–15] and that neural oscillators in the CNS may control spatial and temporal characteristics of lower limb segment elevation angle waveforms [15].

The planar law has recently also been applied to obstacle clearance showing increases in the phase difference between the thigh and shank segments as well as increases in elevation angle ranges when stepping over higher obstacles [16,17]. MacLellan and McFadyen [17] suggested that a basic locomotor pattern is adjusted for stepping over obstacles by specifically manipulating phase differences between segment elevation angle trajectories. However, little attention has been given to obstacle avoidance, and it is still not clear exactly how segment trajectories are shifted to achieve such phase differences. In addition, no one has attempted

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to relate such intersegmental coordination to joint energetics to attempt to understand the role of muscle input to the observed kinematic organization and phase differences.

The purpose of this study was to gain a better understanding of segmental phase shifting for obstacle avoidance and the role of active and passive energetics to the reorganization of segment elevation angle trajectories during adapted locomotion. Initially, individual phase shifts of the thigh and shank segments will be identified to determine how each contributes to phase differences as higher obstacles are cleared. Secondly, active and passive mechanical work will be identified at the knee and hip and related to phase shifting of segmental elevation angle waveforms to explore the role of such energetics in adapting lower limb segment trajectories. It was hypothesized that the leading and trailing limbs will display separate temporal organization in order to increase the phase difference between the thigh and shank segments and these will be sub-served by different passive and active energetic inputs. Thus, this work provides a different perspective of mechanical energetic contributions to locomotor adjustments than previously reported from the perspective of joint movement.

2. Methods

Ten healthy young adults (6 female/4 male, 27.7 ± 5.7 years, 72.0 ± 16.0 kg, 1.72 ± 0.07 m in height) participated in the study. Prior to data collection, all participants provided informed consent according to ethical guidelines from the Quebec Rehabilitation Institute and Laval University.

2.1. Protocol

The experimental protocol used in this study has previously been presented [17]. In brief, participants were asked to walk during 9 obstacle conditions in which obstacle height (0, 10 and 20% of leg length) and obstacle depth (0, 10 and 20% of step length) were manipulated. The current study uses the same data set with new analyses and focuses only on obstacle height changes with an obstacle depth of 0.025 m corresponding to the minimal depth for the adjustable obstacle used. The zero percent height condition referred to level walking with no obstacle present. Each obstacle condition was presented in a block of 5 trials.

Full body three-dimensional kinematic data were collected at 75 Hz using a 3-bar Optotrak camera system (Northern Digital Inc., Waterloo, Canada). Triads of non-collinear infrared emitting diodes (markers) were affixed to rigid plastic plates and attached to the feet, shanks, thighs, pelvis, trunk, and head segments. After a calibration trial was collected, anatomical landmarks (5th metatarsal, medial/lateral malleolus, medial/lateral femoral condyles, left/right iliac spine, and left/right anterior superior iliac spine) were digitized to create segmental principle axes

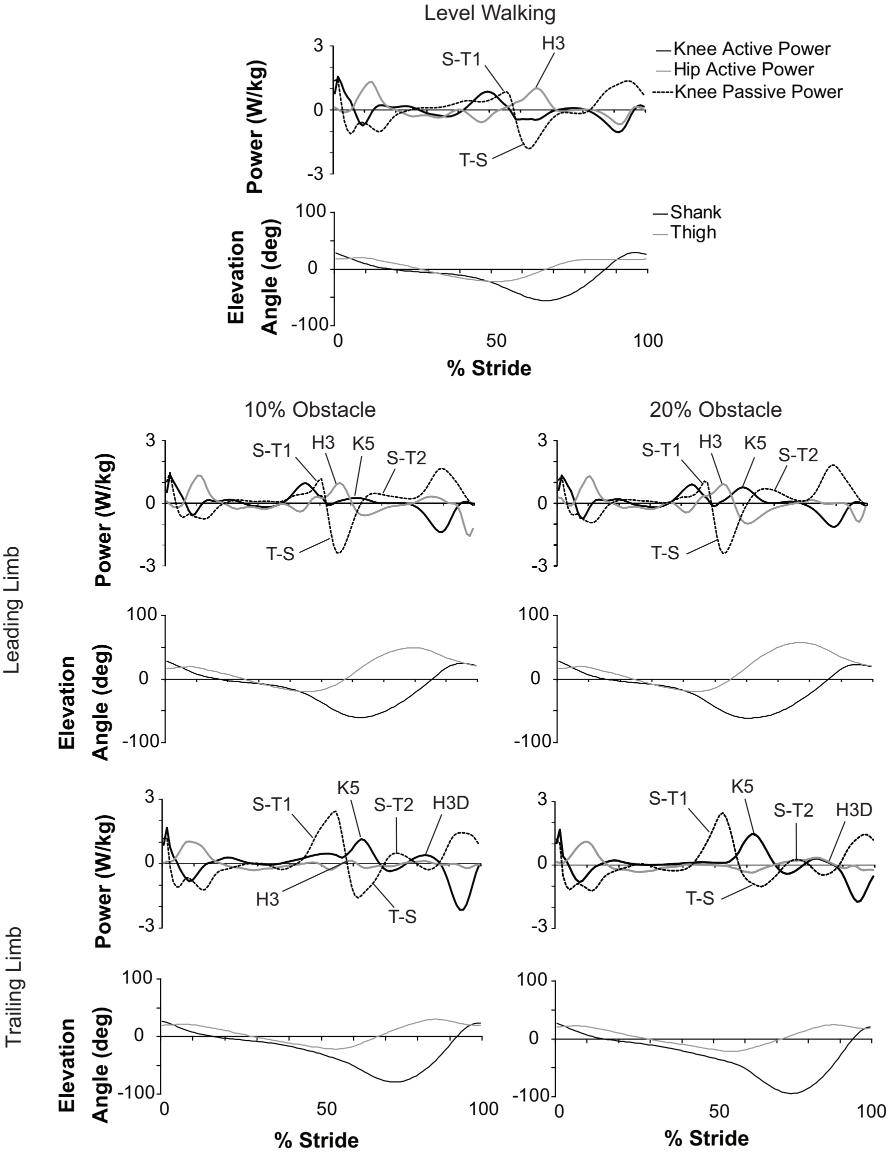

Fig. 1. Average mechanical power and segment elevation angle trajectories from a representative participant. For power, targeted bursts (K5, H3, H3D, S-T1, T-S and S-T2) are labeled. For muscle powers, negative is absorption and positive is generation. For passive power at the knee, the distal end of the thigh was used, so positive indicates transfer from shank to thigh while negative the opposite.