Biomechanical and Energetic Consequences of Walking on Uneven Terrain

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Motivation:

Although animals and humans navigate complex terrain in their everyday lives, the biomechanical and energetic effects on legged locomotion from uneven terrain have scarcely been quantified [1]. Most gait research has examined locomotion on smooth, level surfaces. Identifying key gait parameters that permit agile locomotion across uneven surfaces could lead to clearer understanding of movement control in humans and animals, and could also have multiple clinical and robotic applications.

State of the Art:

Previous studies show that metabolic energy expenditure during locomotion is significantly affected by terrain compliance, such as sand or snow [2] [3] [4]. Soule et al. proposed a regression equation for predicting energetic cost while walking on various terrains classified using different terrain coefficients [5]. However, only a limited number of studies have addressed the biomechanical factors responsible for this increase in energy expenditure. Some have hypothesized that energy dissipation by the surface during stance explains why more energy is used during locomotion on compliant surfaces. For example, Lejeune et al. suggested that the metabolic energy increase caused by walking on sand is due to additional mechanical work that has to be done on the sand [4]. An earlier study also suggested that another effect of the sand surface is that it does not allow for smooth and continuous muscle activity, resulting in inefficient transformation of stored potential energy into kinetic energy [2]. Additional studies have shown significant changes in lower limb muscle activation when walking on compliant surfaces [6] [7]. These suggest that uneven surfaces may result in increased muscle co-activation and hence energy expenditure. The purpose of this study was to provide insight into the changes in walking biomechanics that lead to increased metabolic cost when walking on uneven terrain when compared to walking on level terrain.

Our Approach:

We have experimentally identified how gait parameters such as muscle co-activation, kinematic variability and energy expenditure are affected by instability from uneven terrain. To investigate these kinematic changes, we constructed an uneven-terrain treadmill, with terrain produced by securing wooden blocks of varying heights to the treadmill belt. The wooden blocks were of three different heights and could be arranged in multiple patterns, creating a fractal-like uneven surface. The blocks were cut such that they would curve around the treadmills ends as the belt moved over the rollers. We covered the blocks with a thin layer of cushioning foam, to decrease the discomfort of walking on the uneven terrain [Fig. 1A].

The uneven terrain treadmill allowed us to test the effects of uninterrupted walking on uneven surfaces within a laboratory setting. Subjects walked on the treadmill under three conditions: treadmill walking with blocks (uneven terrain); treadmill walking with only cushioning foam (control condition); and walking on the bare treadmill belt. During this time, we collected electromyography (EMG), kinematic and ergospirometry data. In addition to treadmill walking, subjects also walked overground on the same terrain conditions, as we collected kinetic data using in-ground force platforms. This allowed for inverse dynamics calculations of joint torques and powers.

Discussion:

The main focus of this study was to determine the biomechanical mechanisms responsible for increased metabolic energy expenditure during walking on uneven terrain when compared to walking on smooth terrain. In particular, we focused on the hypotheses that walking on uneven terrain would result in 1) higher co-activation of lower limb muscles, 2) greater positive mechanical work about the hip and knee joints and a decrease in positive mechanical work about the ankle joint, and 3) an increase in mean step width and step width variability when compared to walking on a level surface. This study has shown an approximate 30% increase in metabolic energy expenditure of walking on uneven terrain when compared to walking on a smooth surface. We examined several factors that could contribute to an increase in energy expenditure, of which changes in joint powers and work were particularly intriguing [Fig. 1B]. There was a significant increase in mechanical work done by the hip ($p<0.05$). Sawicki et al. have suggested that the hip joint may be less efficient than other lower limb joints due to its muscle-tendon architecture [8]. Given the increase in hip joint work, this is a potential contributor to increased metabolic cost. This raises the question of whether humans utilize a general biomechanical strategy to navigate uneven terrain. In addition, we ask if identifying these parameters and understanding their effects on energetics could potentially be useful for improving the stability of legged robots, or even have applications to clinical rehabilitation interventions.

Format: Talk

Keywords: Uneven terrain, gait dynamics, energy expenditure

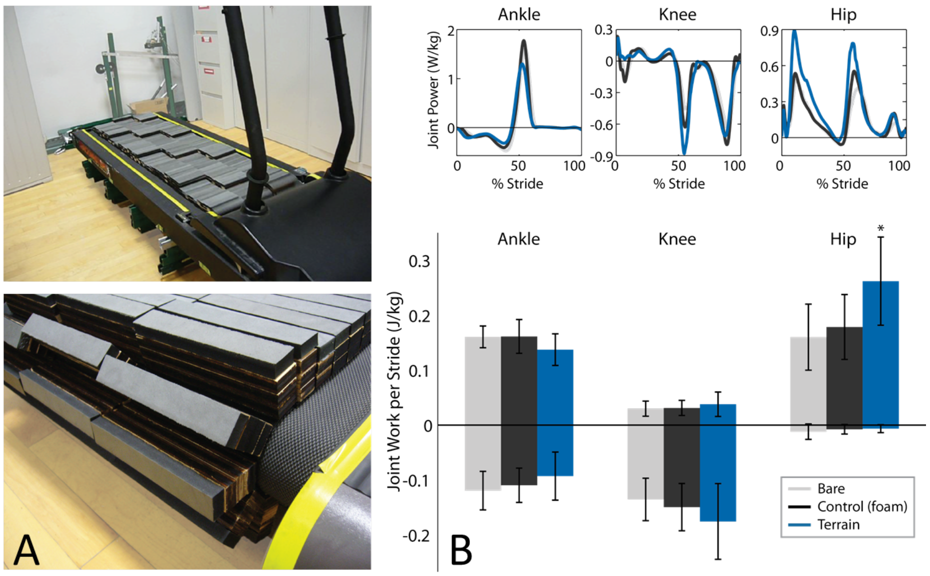

Figure 1. A) Top: uneven terrain treadmill; Bottom: Wooden blocks curving over the treadmill rollers. B) Top: Power (W/kg) and work (J/kg) for the ankle, knee and hip joints. Hip joint positive work during the terrain trial was significantly different from the control trial.

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