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RUNNING ON UNEVEN TERRAIN: CHANGES IN BIOMECHANICS AND ENERGETICS

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INTRODUCTION

Animals and humans navigate uneven terrain in their everyday lives and yet the majority of gait research is conducted on smooth, level ground. As a result, changes in biomechanics and energetics during locomotion on uneven terrain have scarcely been quantified. We previously found that during walking on uneven ground, larger hip joint work is a major contributor to increased energy expenditure [1]. However, studies have suggested that a running gait is self-stabilizing, similar to a simple spring-mass model [2]. In particular, adjustments of the angle of attack and leg stiffness are likely used as stabilization techniques during running [2,3]. In this study, we aim to provide insight into the changes in running biomechanics that may lead to increased metabolic cost on uneven terrain and to determine if humans adjust similarly during walking and running on uneven surfaces.

METHODS

We constructed an uneven terrain surface by attaching wooden blocks of three different heights (2.54cm variability) to an exercise treadmill belt. Individual blocks were oriented lengthwise across the belt and arranged in a pattern to form square stepping areas of varying heights (after [4]). The short dimension of the blocks permitted the belt to curve around the treadmill rollers and allowed us to collect kinematic, metabolic and electromyography (EMG) data simultaneously during continuous running (Figure 1). The uneven terrain treadmill was placed on top of in-ground force plates, which also allowed us to collect ground reaction force (GRF) data for inverse dynamics calculations of joint torques and powers. We used a separate in-ground force treadmill to collect data during running on the even surface. Five young healthy subjects participated in the study. The running speed on both surfaces was 2.3 m/s, to allow for safe navigation of the uneven terrain.

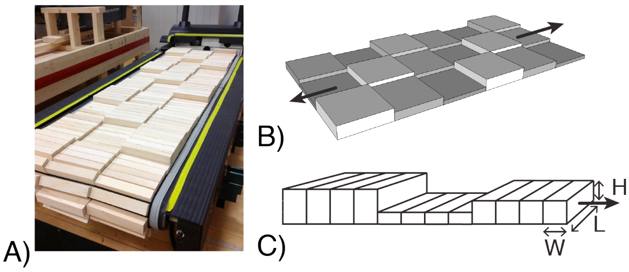

Figure 1. A) Treadmill with uneven terrain surface attached. B) Schematic of the uneven surface layout, consisting of three alternating heights (arrows indicate treadmill's long axis). C) Close-up representation of the individual blocks comprising each stepping area.

We defined the effective leg length to be the direct-most distance from the greater trochanter to the 5th metatarsal markers of the stance foot, normalized to subject leg length. We calculated the effective leg stiffness as the ratio of the peak vertical GRF to the vertical displacement of the effective leg length at the instant of maximum limb compression.

RESULTS AND DISCUSSION

We found a 5% increase (from 9.96 to 10.5 W/kg; average standing metabolic rate: 1.49 W/kg) in net metabolic rate for running on the uneven surface when compared to running on the even surface. Mean step width, normalized to subject leg length (mean: 0.962 m), increased by 9%, while step length remained unchanged. There was also a statistically significant 30% increase in step width variability during running on the uneven surface. Step period did not change significantly between the two conditions (Table 1).

Peak vertical GRFs appear to remain the same during running on the even and uneven surfaces, although there is a significant 20% increase in peak ground contact force (p <0.01). The vertical GRFs are also more variable on uneven terrain when compared to smooth terrain. Net normalized vertical displacement decreases by approximately 24% (Figure 2A). This is consistent with the finding that the mean maximum leg stiffness increases 12.3kN/m to 16.9kN/m ($p < 0.01$).

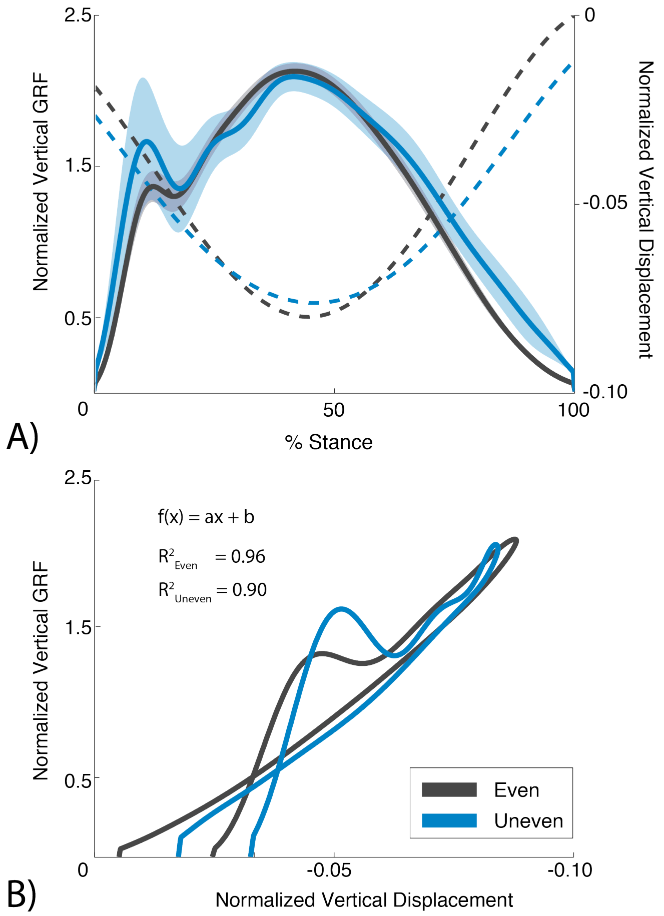

Figure 2. A) Average vertical GRF across subjects for even and uneven running conditions, normalized to subject weight. Shaded regions indicate mean standard deviations. Dotted lines indicate average vertical displacement, normalized to subject leg length. B) Force-displacement curves showing change in leg stiffness for two conditions.

In our previous study we quantified the changes in energetics during walking on a surface with similar height variability when compared to walking on a smooth surface. We found that the increase in metabolic cost was close to 28% on uneven terrain, while we only see a 5% increase during running. This supports the suggestion that running is 'self-stabilizing' through changes in the angle of attack and leg stiffness [2]. In particular, changes in leg stiffness may be the result of greater muscle activation, which would lead to higher energy expenditure. In addition, a larger ground contact force suggests that the subjects stiffen their ankle through increased muscle co-activation before initial ground contact, possibly due to an inaccurate internal model of the ground surface. Increased mean step width and step width variabilities could also be contributing factors to increased energetic cost. Further data analysis will examine leg stiffness during 'up' and 'down' steps on the uneven terrain, changes in muscle co-activation and changes in joint work as potential contributors to increased metabolic cost of running on uneven terrain.

CONCLUSIONS

To identify biomechanical correlates responsible for increased energy expenditure while running on uneven terrain when compared to smooth terrain, we constructed an uneven terrain treadmill that allowed us to record biomechanical, electromyographic, and metabolic energetics data from human subjects for prolonged periods of time. We found that, on average, subjects increased their leg stiffness during ground contact when running on uneven terrain when compared to running on smooth terrain. This suggests that increased muscle activity is a major contributor to larger energy usage, although further analysis still needs to be done.

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Table 1. Step parameters for two terrain conditions. All parameters except step period are normalized to subject leg length (mean: 0.962 m). Shown are averages (and standard deviations, s.d.) across subjects. Step variability is defined as the standard deviation of step distances over a trial, reported as an average (and s.d.) across subjects. Asterisks signify a statistically significant difference between the Even and Uneven conditions (α = 0.05)

	Even		*Uneven*		*p − value*	
	Mean(s.d)	*Step.var.(s.d)*	*Mean(s.d)*	*Step.var.(s.d)*	*Mean*	*Step.var.*
Width	0.124 (0.023)	0.020 (0.002)	0.135* (0.024)	0.026* (0.002)	0.047	0.035
Length	0.891 (0.048)	0.041 (0.008)	0.891 (0.043)	0.049 (0.013)	0.957	0.082
Height	~	0.004 (0.002)	~	0.008* (0.003)	~	0.002
StepPeriod(s)	0.712 (0.080)	0.068 (0.110)	0.687 (0.051)	0.164 (0.064)	0.423	0.069