How humans run on rough terrains

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1 Introduction

Humans have evolved to run adeptly on natural terrains [1], yet there are few studies on how they maintain stability on undulating terrains. Studies of running on flat ground and step-like terrains (i.e. terrains which vary in height, but not slope) suggest that changing step width [2], increasing swing-leg retraction rate [3], and increasing energy dissipation [4] are some means by which humans may maintain stability. A mathematical study of running dynamics on terrains with slope and height variations finds an additional stabilizing factor, namely minimizing tangential collisions with the ground [5]. We perform human-subject experiments on undulating rough terrains with both slope and height variations to characterize the strategies used by humans to maintain stability.

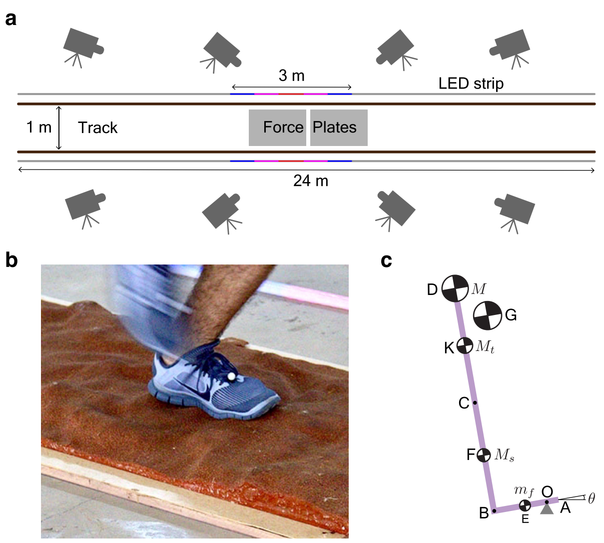

Figure 1: **a**, Schematic of the running track, camera placement, force plate positions and the light strip with a 3 m moving, illuminated section. **b**, A close up of a patch of uneven II with the foot of a runner pictured for scale. **c**, A three link model of the foot (A-B), shank (B-C) and thigh (C-D) that moves with uniform velocity and no spin before colliding with the ground at an angle θ. Leg lengths and masses obtained from measurements and [6].

2 Methods

Nine consenting volunteers (1 woman, 23-45 yrs, 66.1 ± 8.5 kg, leg length 0.89 ± 0.04 m), ran back-and-forth for 8–10 min on 3 different tracks (flat, uneven I, uneven II; peak-to-valley height difference of 18 ± 6 mm and 28 ± 11 mm, respectively, and similar peak-to-peak horizontal seperation). Speed was controlled by lights moving at 3 m/s on both sides of the track (Fig. 1a,b). We recorded kinematics of the hip and foot using an 8-camera motion capture system (Vicon Inc.), and ground reaction forces at the middle of the track using two force plates (AMTI Inc.). Breath-by-breath respirometry data were recorded using a mobile gas analyzer (Oxycon Mobile, CareFusion Inc.).

Steady-state oxygen consumption rates were averaged and normalized by the runner's mass and speed after subtracting the baseline recorded during quiet standing and excluding the transients during first 3 minutes. Mid-stance was defined as when the heel marker's forward velocity was at a minimum and it's height was below 15 mm of the marker's height when the subject was standing. Center of mass (CoM) trajectory during stance was found using the average of the hip markers and fitted with a regression line in the horizontal plane. Twice the distance of nearest approach of the foot at mid-stance from this line is defined as the step width. Forward foot speed at landing was calculated by taking the derivative of a cubic spline fitted to the heel marker's trajectory just before touchdown.

The dimensionless parameter $\hat{\varepsilon}_t$ quantifies the momentum lost due to the forward collision,

$$\hat{\varepsilon}_t = 1 - \left(\max_T \int_0^T F_y \, dt \right) / (m v_y), \qquad (1)$$

where F_y is the fore-aft ground reaction force, and mv_y is the forward momentum of the runner just prior to collision.

To identify the effect of foot speed and joint compliance in modulating the fore-aft collisional impulse, we model the runner in the sagittal plane as a leg comprised of three rigid rods connected by hinge joints that are either infinitely compliant or rigid and the rest of the body's mass located at the hip (Fig. 1c). Using recorded kinematic data and the collision equations we determine the fraction of forward momentum retained over stance for the model runner in the two stiffness extremes under the assumption of an instantaneous, inelastic collision.

Mean/median and standard deviations/interquartile ranges of energetic, kinematic, and kinetic variables within a single trial were estimated across terrain conditions and statistical comparisons were performed using a linear mixed-model (LMM) in R. Terrain is a fixed factor and subject a random factor with repeated measures. The significance threshold was 0.05. Post-hoc comparisons were performed when the LMM was significant.

3 Results and discussion

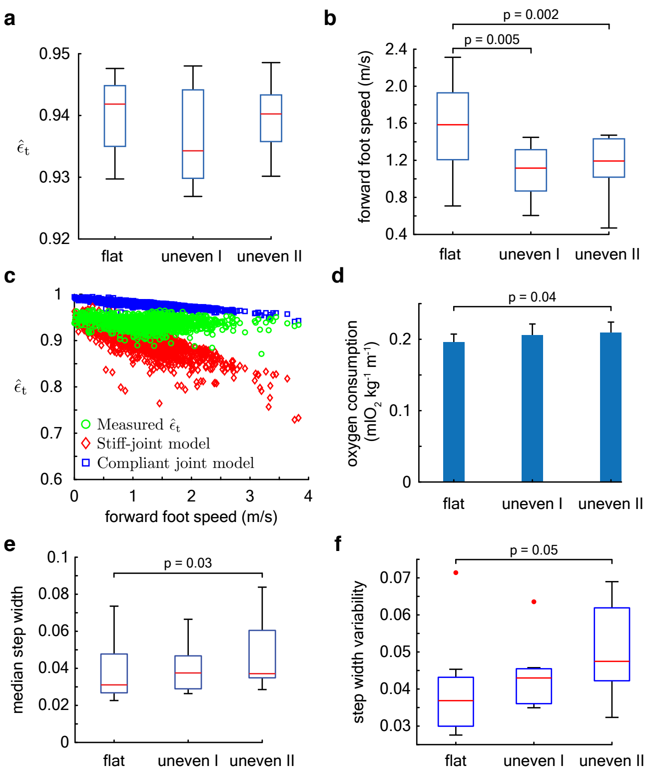

Figure 2: a, Box plots of $\hat{\varepsilon}_t$ for all subjects on the three terrains. **b**, Box plots of forward foot speed at landing for all subjects on the three terrains. **c**, Dependence of forward foot speed landing for the measured $\hat{\varepsilon}_t$ (green circles), calculated $\hat{\varepsilon}_t$ values using the collision model for a compliant leg (blue squares) and rigid leg (red diamonds) for every recorded step across subjects and terrain types. **d**, Mean oxygen consumption across all subjects on each terrain. Whiskers represent standard deviation. **e**, Box plots of median step width (normalized to leg length). **f**, Box plots of interquartile range of step width. Red lines denote the median, boxes represent the interquartile range, whiskers extend to 1.5 times the quartile range, and data outside this range are denoted by red dots.

Subjects maintained mean $\hat{\varepsilon}_t = 0.94$ on all terrains with no significant difference across terrain types (Fig. 2a). The standard deviation of $\hat{\varepsilon}_t \approx 10^{-2}$, suggests that it is a tightly controlled parameter.

Mean forward foot speed at landing was terrain-dependent ($p = 0.001$), and lower by (0.37 ± 0.10) m/s (mean $\pm$ S.E. of mean, $p = 0.005$) on uneven I compared to flat ground, and by (0.40 ± 0.10) m/s ($p = 0.002$) on uneven II compared to flat ground (Fig. 2b). Measured $\hat{\varepsilon}_t$ values closely track calculated $\hat{\varepsilon}_t$ values from the compliant joint model which show weak dependence on forward foot speed at landing compared to $\hat{\varepsilon}_t$ values from the stiff joint model (Fig. 2c). Thus we propose that compliant leg joints at landing are primarily responsible for maintaining low forward collisions.

Mean energy consumption, quantified as oxygen consumed/unit distance/unit mass, was terrain dependent ($p = 0.04$, Fig. 2d). It increased by 6.8%±2.5% ($p = 0.04$) on uneven II compared to flat ground. Median step width was terrain dependent ($p = 0.03$, Fig. 2e), with step width on flat ground significantly lower than uneven II by (0.004 ± 0.001) (mean $\pm$ S.E. of mean, $p = 0.03$). Similarly, step width variability was also terrain dependent ($p = 0.05$, Fig. 2f) with the interquartile range of step width on uneven II greater than that on level ground by (0.005 ± 0.002) (mean $\pm$ S.E. of mean, $p = 0.04$).

4 Conclusions

Our results suggest that reducing tangential collision impulses plays an important role in stabilizing running on flat and rough terrains. Low tangential collision impulses were maintained due to compliant leg joints at touchdown. We also find that energy consumption for running on rough terrain increases by $\approx 7\%$ compared to flat ground (similar to [4]). This is associated with a slight increase in median step width and step width variability of ≈ 5 mm, and an increase in leg retraction rate on rough terrains compared to flat.

5 Acknowledgments

Funding from Human Frontier Science Program and Wellcome Trust/DBT alliance.

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