Competing Foot-to-Ground Clearance Costs during Walking with Added Foot Load

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Summary

Humans weigh multiple factors to walk without falling, including swinging their foot at a height that avoids tripping or excessive lifting. The addition of load at the foot may affect these two competing costs. We tested whether added foot load would lower foot-to-ground clearance during swing to alleviate the increased cost of lifting additional mass. Healthy, young adults walked at 1.25 ms^{-1} with loads from 0 kg to 2.0 kg per foot. We found no significant changes in ground clearance despite an increase in net metabolic cost. Hence, the other factors, such as the increased risk of tripping, may outweigh the energetic savings from lowering the loaded foot.

Introduction

Humans prefer to walk with a non-zero foot-to-ground clearance during leg swing. While lifting the foot costs energy, hitting the ground during swing is also costly. The trade-off between the two coupled with the uncertainty of hitting the ground yields a non-zero clearance [1]. It is unclear if the addition of mass at the foot would shift the preferred ground clearance. Added load at the foot is more costly than at more proximal locations [2], a penalty that could be relieved by lowering the foot. We investigated the effect of added mass on the two competing costs of ground clearance. Despite the risk of ground contact, we hypothesized that ground clearance would be lowered with added mass to avoid the penalty of maintaining a constant height with a heavier load.

Methods

Healthy, young adults (N=7, 3 female, 4 male, age 20 to 25 years, mass 67.7$\pm$13.1 kg, height 1.70$\pm$0.10 m) walked on a treadmill at 1.25 ms^{-1} with added loads on their feet. In randomized order, we tested one unloaded trial (0 kg) and the addition of 0.5 kg, 1 kg, 1.5 kg, and 2 kg per foot. Using data from motion capture (Qualysis AB, Gotenburg, Sweden), foot-to-ground clearance was determined as the minimum vertical distance during swing of the average between the first and fifth metatarsal markers (Figure 1 Top). Energetic expenditure was assessed with indirect calorimetry (COSMED Kb5, Rome, Italy) and standard conversion factors [3]. To obtain steady-state values, only metabolic data taken during the final two minutes of each six-minute trial was used for analysis. A four-minute quiet standing trial was also obtained. All participants provided informed consent.

We performed a linear regression between added mass and foot-to-ground clearance and net metabolic rate. Fits were performed with a single trend (significant if $p<0.05$) and individual offsets for each participant. Using base units of body mass M, standing leg length L, and gravitational acceleration g, ground clearance was normalized by L (mean 0.9157) and power by $Mg^{1.5}L^{0.5}$ (mean 1994 W).

Results and Discussion

Net metabolic rate increased with added mass, but foot-to-ground clearance did not (Figure 1). Net metabolic rate increased at a rate of 0.017 (0.504 W/kg, p=1.3e-6; R^2 = 0.89). However, foot-to-ground clearance did not vary significantly (4.50e-4 n.d., 6.25e-6 m/kg, p = 0.48, R^2 = 0.95).

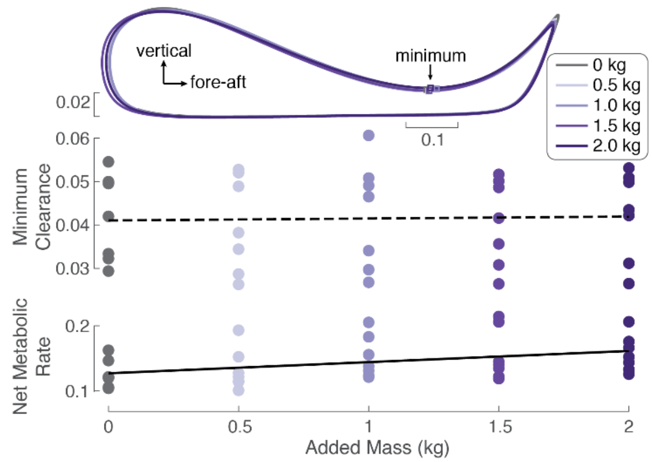

Figure 1: (Top) Mean toe trajectories. (Middle) Mean minimum clearance and (Bottom) net metabolic rate as a function of added mass per foot from each participant (circles) and linear fits (trend significant if solid; non-significant if dashed). Units: n.d.

Contrary to our hypothesis, participants did not choose to modify their ground clearance in response to added weight. At the highest load, lowering clearance by 32% is similar to carrying 0.1 kg less on each foot [1]. Perhaps the risk of hitting the ground is too high, but it is also plausible that heavier masses are required to modify ground clearance.

Conclusions

The energetic consequence of lifting a distally added mass (e.g. heavy shoes, ankle exoskeletons or protheses) could be offset by reducing clearance. However, at weights up to 6% of body mass, this metabolic penalty is borne without the potential savings of lowering the swing foot.

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References

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