Energetic tradeoffs of foot-to-ground clearance during swing phase of walking.

Amy R. Wu and Arthur D. Kuo
University of Michigan, Ann Arbor, USA
amyrwu@umich.edu, artkuo@umich.edu

1 Introduction

Control of foot clearance to the ground is needed to avoid stumbling or tripping from unexpected ground contact. Humans walking on uneven surfaces, for example, exhibit greater leg lifting than on flat surfaces to avoid obstacles [1] and also expend more energy [2]. This suggests a preferred clearance height from a tradeoff between energetic cost of leg lift versus risk of inadvertent ground contact during swing. It may be more costly to provide greater clearance, but it may also be costly to momentarily scuff the foot on the ground, for example due to the drag force produced. Since much of gait appears to be energetically optimal, the preferred clearance height may closely match with the lowest metabolic cost. Lifting the legs higher should be metabolically costly due to greater joint work. Scuffing should also require more effort, for example due to the increased work to overcome frictional drag at ground contact. We expect both deviations from nominal to increase metabolic cost.

2 Methods

We compared the energetic costs of walking at different foot clearance heights from 8 young, healthy adults. Subjects walked with their preferred clearance and also with three levels of leg lifting, measured through maximum toe height from the treadmill surface, and three levels of scuffing, measured through scuff impulse, the integral of drag (backward) ground reaction force generated over the swing phase. One subject scuffed during heel strike instead of swing, and therefore his scuff data was not included. Each subject walked for approximately 6 minutes at a constant speed of 1.25 m/s. We measured metabolic energy expenditure and gait kinematics and kinetics.

3 Results

We achieved three different levels of scuff impulse and toe clearance heights. The lowest measured metabolic cost coincided with the subjects' preferred clearance height and increased approximately linearly with more leg lift or scuff impulse. During swing, imparting more drag of 1.5 N for 1 second costs about the same as lifting the legs 0.1 m higher.

Changes in step parameters contributed towards the increase in energetic cost for leg lift but not for scuffing. Subjects exhibited longer step length, step width, and step period and shorter double support duration with increased leg lift. However, only minor adjustments were made in step width to accommodate for scuffing.

Leg lifting also affected center of mass (COM) work while scuffing did not. Positive COM work increased at a rate of 8.5 J per 0.1 m of leg lift and negative work at a rate of 11 J per 0.1 m. However, walking with scuffing was not significantly different from normal walking.

The energetic cost of leg lifting could be explained in part by changes in step parameters and COM work. However, it is still unclear what governs the costs for scuffing. We used inverse dynamics to study joint work during swing phase. With higher leg lifting, positive and negative knee and hip work increased. With greater scuffing, significant changes included increased positive knee and hip work and greater negative hip work. The increase in negative joint work could be due to swing leg retraction after scuff but prior to heel contact. If the swing foot is moving faster than normal after the scuff, more negative work could be needed to slow foot speed prior to heel strike.

4 Discussion

Control of foot clearance is vital to fall avoidance, and humans appear to compromise between costs such as leg lift work and to overcome friction at foot-to-ground contact during swing. Both are energetically costlier than preferred walking due to increased positive joint work. Thus foot-to-ground clearance may contribute towards greater effort required to walk on uneven terrain and for patients with gait abnormalities, such as drop-foot, and amputees without proprioceptive awareness of their prosthetic foot clearance. Our results also indicate that more economical walking could hypothetically be achieved with stepping stones to allow for foot clearance or with shoe soles that provide frictionless interaction with the ground during swing but not stance.

References

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