Lower limb biomechanical analysis of unanticipated step on a bump

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Summary

Though previous studies have investigated walking over different ground conditions, it remains unclear how humans quickly adapt to unexpected variations in terrain. This work aims to investigate lower limb biomechanics when stepping on an unanticipated bump. Human subjects walked over a small, unanticipated bump of variable size, and contacted that bump with either their toe or their heel over five experimental conditions. Stepping on the bump with the heel, both plantarflexor torque and positive ankle work were less than level ground walking. Stepping on the bump with the toe, plantarflexion torque was higher than level ground walking. Higher co-contraction was reported from hip joint muscles for all conditions with a bump, which may be a contributor to the source of higher energy expenditure when walking over uneven terrain. Insights from studies such as this may guide the development of adaptive controllers for wearable robots intended for use in unstructured environments.

Introduction

Previous studies have investigated the biomechanics of the lower limb on different terrains, such as sand (Davies and Mackinnon, 2006), ballast (Wade et al., 2010; Gates et al., 2012) or grass (Davies and Mackinnon, 2006). Adaptations associated with walking on uneven terrain included higher muscle activation and variability, and higher generation of joint work, resulting in higher energy expenditure (Voloshina et al., 2013). Nevertheless, it is still unclear how humans quickly adapt to unexpected variations in terrain. These variations include everyday objects such as grass, rocks, branches and potholes.

Therefore, the aim of the present study was to investigate lower limb joint mechanics while performing an unanticipated step on an irregular surface, in this case a small bump. We hypothesized that lower limb joint mechanics would be different depending on which part of the foot initially contacted the bump.

Methods

Nine healthy male adults (age 29.1 ± 4.8 yrs; mass 76.8 ± 10.2 kg; height 176.3 ± 4.7 cm; mean ± SD) were asked to walk at their preferred walking speed along a straight walkway during five different conditions. Four conditions involved unanticipated bumps of two different height and one level walking condition served as a baseline (*FLAT*). In the four conditions with bumps, participants stepped on different sized bumps with their right toe (*HITO*, *LOTO)* or with their right heel (*HIHE*, *LOHE*). Participants were instructed to look straight and wore a pair of specialized glasses that obstructed their view of the exact bump location before stepping on it.

The bumps were placed on a force platform (OR-6, AMTI, 1000 Hz) embedded into the ground to measure ground reaction forces and calculate inverse dynamics. Lower limb kinematics and muscle activation (EMG) on eight lower limb muscles were also collected by motion capture (Vicon, 120 Hz) and surface electromyography (Telemyo, Noraxon, 1500 Hz) (**Fig. 1**). Positive work was calculated as the time integral of positive power, and co-contraction indexes (CCI; Chambers and Cham, 2007) were calculated between antagonistic muscle pairs for stance phase.

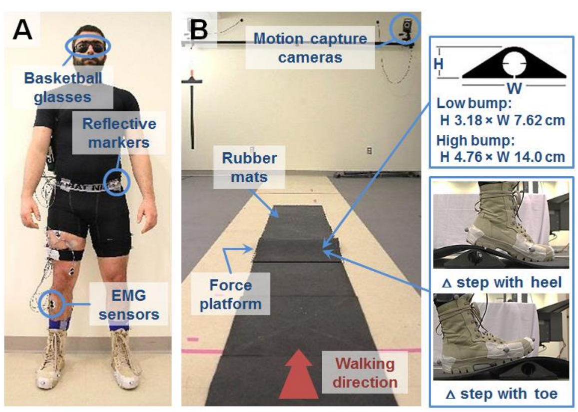

Figure 1. **(A)** Instrumented participant; **(B)** Experimental setup. The pictures on the far right show different experimental conditions: the bump dimensions on low and high conditions (top) and the foot positions on heel and toe conditions (bottom).

Results

Though all lower limb joints showed changes in kinematic and kinetics, differences in the ankle were the most pronounced. The ankle angle during stance phase varied greatly over the five experimental conditions (**Fig. 2A**). As shown in **Fig. 2B**, the onset timings for plantarflexor torque significantly differed from baseline in every condition. This makes the average plantarflexion torque during the stance phase lower for the heel conditions (*HIHE*: 0.27 ± 0.10, *LOHE*: 0.36 ± 0.09 Nm kg^{-1}) and higher for the toe conditions (*HITO*: 0.63 ± 0.20 Nm kg^{-1}, *LOTO*: 0.59 ± 0.10), compared to *FLAT* (0.48 ± 0.07 Nm kg^{-1}). Similarly, onset timings for positive ankle power during push-off varied over conditions, resulting in significantly lower positive work for the heel conditions (*HIHE*: 0.17 ± 0.03, *LOHE*: 0.20 ± 0.04 J kg^{-1}) compared to *FLAT* condition (0.26 ± 0.03 J kg^{-1}; both $p < 0.002$ by paired t-test) (**Fig. 2C**).

We found differences in muscle activation at the hip joint by investigating co-contraction (biceps femoris and rectus femoris, biceps femoris and vastus medialis, as well as biceps femoris and vastus lateralis). Higher co-contraction on average was reported for all of the bump conditions compared to baseline (*HIHE*: 29.3, *LOHE*: 24.9, *LOTO*: 17.9, *HITO*: 21.8, *FLAT*: 13.8; A higher value indicates higher co-contraction and muscle activation).

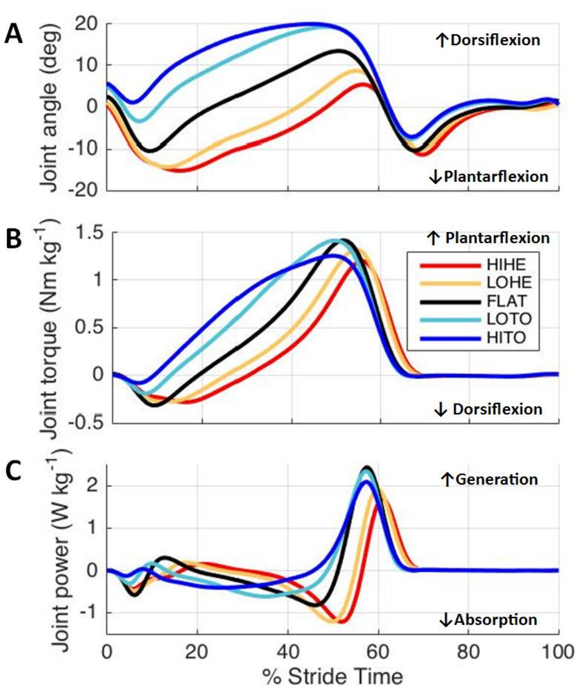

Figure 2. Averaged ankle joint kinematics and kinetics over the five experimental conditions: **(A)** joint angle, **(B)** joint torque, and **(C)** joint power. Joint torque and joint power are normalized to the subject's body weight.

Discussion

The present findings suggest that when stepping on an unanticipated bump, humans adapt differently depending on which part of the foot contacts the bump. Stepping with the heel, both plantarflexion torque and positive ankle work were less than level walking. Conversely, when stepping with the toe, plantarflexion torque was higher than the baseline. When the bump lies under the heel, the ankle is more plantarflexed and is not able to perform the same level of torque or work required for level walking.

Higher reported co-contraction at the hip during bump conditions might indicate that participants stiffen their hip joints to increase stability. Though a similar amount of total positive joint work was reported among conditions, higher co-contraction may cause higher energy expenditure when walking over uneven terrain (Voloshina et al., 2013).

Together with increasing the knowledge of lower limb mechanics in different walking conditions, these findings may be useful for development of assistive devices that augment human walking. Future work will apply these findings to the soft exosuit for walking assistance (Ding et al., 2016; Asbeck et al., 2015) making it more adaptable to various ground conditions.

Acknowledgement

This material is based upon the work supported by the DARPA, Warrior Web Program (Contract No. W911NF-14-C-0051), the National Science Foundation (Grant No. CNS-1446464), the Samsung Scholarship, the Funai Overseas Scholarship, and the São Paulo Research Foundation (FAPESP; Grant No. 2015/02116-1). This work was also partially funded by the Wyss Institute for Biologically Inspired Engineering and the John A. Paulson School of Engineering and Applied Sciences at Harvard University. The authors would like to thank Jozefien Speeckaert and Ignacio Galiana for their contribution to this work.

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