Biomechanical analysis and inertial sensing of ankle joint while stepping on an unanticipated bump

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***Abstract*— Walking on uneven terrain with a wearable assistive robot requires the controller to adapt to rapid changes in human's biomechanics. To do so, the changes due to terrain should be measured using wearable sensors. We investigated human ankle joint mechanics when stepping on different small, unanticipated bumps with either the forefoot or the rearfoot. It was shown that kinematics and kinetics change significantly depending on how humans step on a bump, and that changes in kinematics could be measured by IMUs. This result could be used to inform the design of adaptive controllers for wearable robots that provide optimal assistance to the ankle joint when walking on uneven terrain.**

I. Introduction

LOWER extremity wearable robots have been developed to help able-bodied individuals to walk or carry loads, and several recent studies have shown reductions in energy expenditure in lab-based tests [1]-[3]. For practical use outside of lab, it is crucial that these devices quickly adapt to variable terrain. Previous studies have shown that humans adapt their kinematics and kinetics to irregular surfaces such as wooden blocks [4] or ballast [5]. If designed purely for walking on flat surfaces, assistance from wearable devices may become less optimal or even obstructive to natural motion. However, it is still unclear how humans change their kinematics and kinetics when stepping on irregular surfaces, and how wearable sensors can measure the changes.

In line with this, the aim of our study was (i) to investigate ankle joint kinematics and kinetics while performing a step on an irregular surface and (ii) to check if the kinematic variations can be sufficiently captured by inertial measurement units (IMUs) mounted on the body. IMUs have been used for gait analysis in the detection of gait events (e.g. heel-strike and toe-off) [6], [7] and joint angle measurement [8], but most studies have been conducted only on treadmills or flat ground, and the feasibility of IMU sensing to capture the kinematic changes on irregular surface has not been thoroughly studied. To address this topic, an experimental study was conducted in which subjects walked on simplified irregular surfaces, in this case a small bump, and ankle joint mechanics as well as the measurements from body-mounted IMUs were investigated.

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II. Methods

Nine healthy male adults (age 29.1 ± 4.8 y; mass 76.8 ± 10.2 kg; height 176.3 ± 4.7 cm; mean ± SD) participated in this study. Participants were asked to walk on a straight flat walkway during five different conditions: four conditions involving bumps of two different heights (Fig. 1) and one condition without bumps (*FLAT*). In the conditions with bumps, participants stepped on bumps of different sizes with their right rearfoot (*High-RF, Low-RF*) or with their right forefoot (*High-FF, Low-FF*). Participants were asked to look straight in order not to know the exact bump location before stepping on it.

IMU (VN-100, VectorNav) consisting of gyroscopes, accelerometers, and magnetometers (all 3-axes) were placed at the dorsum of the foot and the front of the shank (Fig. 1). Angular velocity and orientation (Euler angles calculated by IMU's onboard extended Kalman Filter) were collected at a frequency of 200 Hz. Ankle joint angle was calculated by subtracting the sagittal angles of the two IMUs.

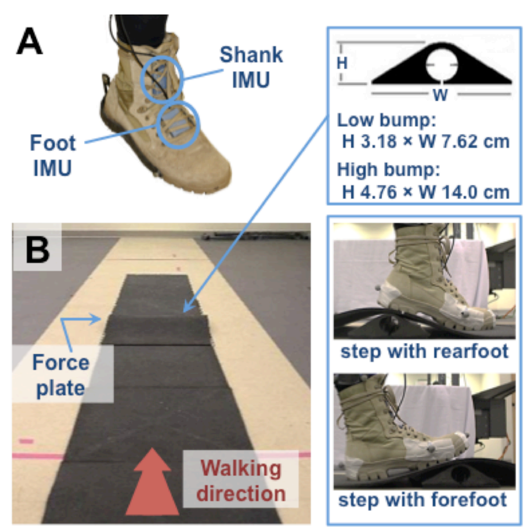

Fig. 1. **(A)** Placement of IMU on foot and shank. **(B)** Experimental setup, dimension of bumps used for experiment (right top) and foot positions on each condition.

Ground-truth lower limb kinematics was collected by an optical motion capture system (Vicon; 120 Hz), and ground reaction forces on the stride of interest were collected with a force plate (OR-6, AMTI; 1000 Hz) to calculate reference joint torques using inverse dynamics. Positive work was calculated as the time integral of positive power. Muscle activation on eight lower limb muscles (biceps femoris, rectus femoris, vastus medialis and lateralis, tibialis anterior, soleus, gastrocnemius lateral and medial) was also collected by surface electromyography (Telemyo, Noraxon; 1500Hz).

III. RESULTS

The ankle angle during stance phase varied greatly over the five experimental conditions (Fig. 2A). Ankle torque plantarflexion onset was found to happen significantly later in the gait cycle for *High-RF* (31.0 ± 3.6%) and *Low-RF* (27.0 ± 3.5%) and earlier for *High-FF* (9.3 ± 2.6%) and *Low-FF* (13.2 ± 2.1%), compared to *FLAT* (19.7 ± 2.3%; all $p < 0.01$ by paired t-test) (Fig. 2B). Similarly, onset of positive joint power was found to happen later for *High-RF* (57.4 ± 2.0%) and *Low-RF* (56.1 ± 2.0%) and earlier for *High-FF* (49.4 ± 3.7%) compared to *FLAT* (52.2 ± 1.9%; all $p < 0.01$) (Fig. 2C). Ankle positive work was lower in both *High-RF* (0.17 ± 0.03 J kg^{-1}) and *Low-RF* (0.20 ± 0.04 J kg^{-1}) compared with *FLAT* (0.26 ± 0.03 J kg^{-1}; both $p < 0.002$). Mean muscle activation of lateral gastrocnemius and soleus was higher in *High-FF* compared with *FLAT* (52% and 29% respectively, both $p < 0.01$) (Fig. 2D).

IMU-based joint angles showed average root mean square error of 3.2° (*High-RF*: 3.1°, *Low-RF*: 3.2°, *FLAT*: 2.8°, *Low-FF*: 3.3°, *High-FF*: 3.5°) compared to ground-truth (dashed lines in Fig. 2A).

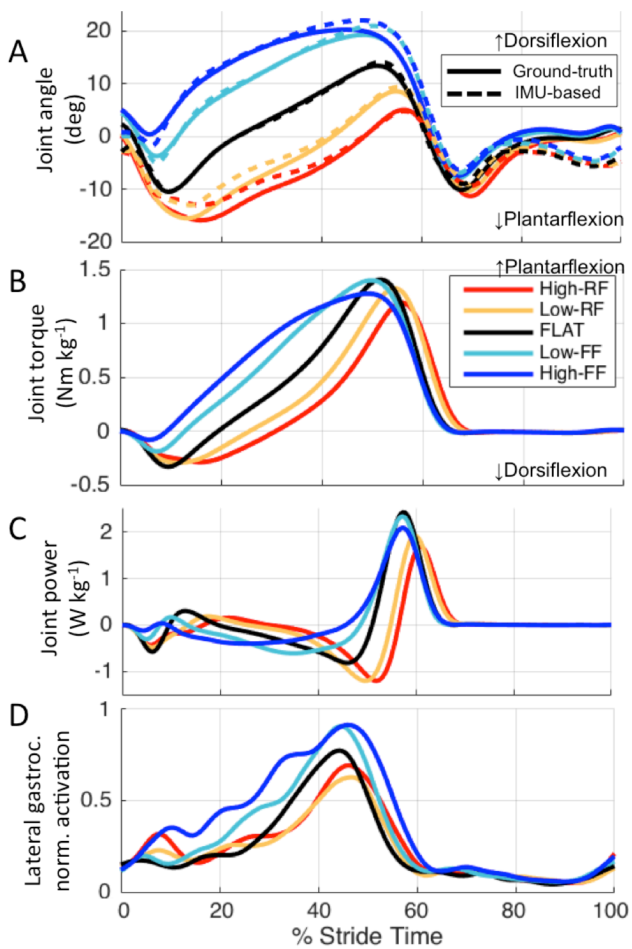

Fig. 2. Averaged ankle joint kinematics and kinetics over the five experimental conditions: (**A**) Joint angle. Ground-truth measured by optical system (solid) and IMU-based (dashed). (**B**) Joint torque. (**C**) Joint power. Joint torque and joint power are normalized to the subject's body weight. (**D**) Normalized muscle activation of lateral gastrocnemius, a plantarflexor muscle.

IV. DISCUSSION & CONCLUSION

The present findings suggest that humans adapt differently when stepping on an unanticipated bump, depending on which part of the foot contacts the bump. There were clear changes in the kinematics and kinetics across the different conditions as measured using motion capture and a force plate. It can be noted that the joint torque profile varied significantly over the five experimental conditions, as it is one of the most important measures for designing and controlling wearable devices assisting locomotion. In addition, it was shown that body-mounted IMUs have a potential to capture the changes in kinematics on uneven terrain. These results suggest the possibility of real-time wearable assistive devices that can adapt to irregular terrain by means of body-mounted IMU sensors. Future work will include applying these findings to the soft exosuits [2], [3], making it highly adaptable to various ground conditions.

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