KINEMATIC ADAPTATIONS OF THE FOORFOOT AND HINDFOOT DURING CROSS-SLOPE WALKING

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INTRODUCTION

Biomechanics research in gait has focused largely on level walking, with less attention paid to transversely inclined (cross-sloped) surfaces [1–3]. Despite cross-slopes being a regular feature of our environment, little is known about specific inter-segmental foot adaptations necessary to maintain both balance and forward locomotion.

Substantial left to right asymmetrical changes in the kinematics and kinetics of the hip, knee and ankle joints have been recently reported [4], even with modest cross-slopes angles. While for young adults cross-slope may not be a significant challenge, the asymmetrical demands of cross-slope walking could pose great functional muscular-skeletal and balance obstacles for special populations (elderly, amputees, *etc*). From the above study, it is hypothesized that forefoot-hindfoot (FF-HF) kinematics also will be different between level and cross-slope walking.

METHODS

Ten healthy adult males with no previous orthopedic ailment participated in the study. Participants were fitted with 39 reflective markers placed over bony landmarks according to the Oxford Foot Model [5] (Figure 1). A 7m inclinable walkway with an embedded force plate (AMTI, model OR6-5-1000, Watertown, MA, USA) was used. Participants were habituated to the walkway area and then performed a minimum of six self-selected speed walking trials on the flat (0º) and inclined (10º) conditions. Kinematic adaptations of FF-HF were compared between level walking (LW), up-slope inclined walking (IWU), and down-slope inclined walking (IWD) for the right foot only. Kinematic data were collected at 240 Hz using an eight camera Vicon™ system (Vicon, Los Angele, USA). The data were filtered with a fourth-order zero-phase lag Butterworth filter having a cutoff frequency of 8 Hz in MatLab® (v2008b, The Mathworks Inc., Natick, MA, USA).

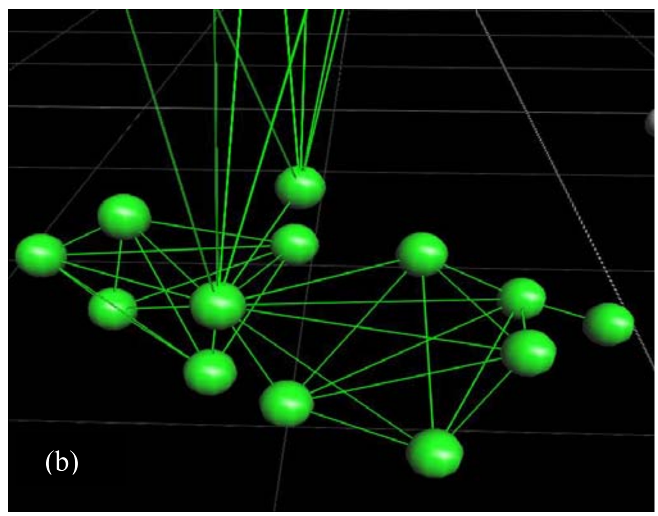

Figure 1: Anterior view (a) of marker placement based on Oxford Foot Model. Lateral view (b) of right foot rendered in Vicon environment.

For statistical analysis of the motion patterns of the FF and HF, the stance phase was evaluated at three events determined from the vertical ground reaction force (GRF). The events were taken at the first and second maximum GRF values (MaxFz1 and MaxFz2, respectively) and at the minimum GRF between them (MinFz). The three-dimensional (3D) kinematics of FF-HF were analyzed using a between subject MANOVA for repeated measures using SPSS™ (SPSS for Windows, version 16.0). This was followed by a Bonferroni post-hoc test if a statistical difference was observed ($\alpha = 0.05$).

RESULTS AND DISCUSSION

The abduction/adduction of FF with respect to HF was significantly different at MaxFz2 and MinFz ($p < 0.001$ and $p = 0.005$, respectively) (Figure 2). For MaxFz2, post-hoc analysis revealed differences between LW and both slope conditions (IWU, $p = 0.043$; IWD, $p = 0.004$), and between IWU and IWD ($p = 0.000$). For MinFz, differences were observed between IWD and the two other conditions (IWU, $p = 0.006$; LW, $p = 0.041$).

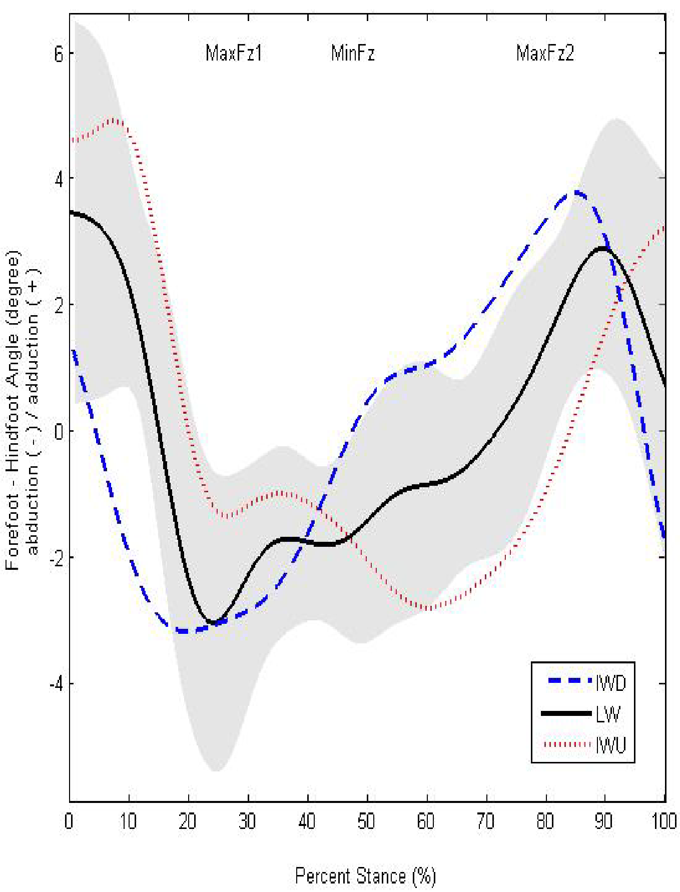

Figure 2: Overall mean trials of forefoot-hindfoot abduction/adduction in flat and inclined conditions. Gray area indicates the standard deviation of level walking trials.

FF-HF kinematics during level walking has been reported in previous studies [6]. This study shows that compared to horizontal walking, cross-slope walking requires adaptations of the FF-HF. In general, results suggest that subjects modified their transverse plane kinematics in order to minimize and conform to the ground height difference between the LW, IWU and IWD foot induced by the cross-slope.

CONCLUSIONS

The mechanisms by which the body enables cross-slope walking, specifically in order to prevent slipping, can be seen in the alteration of the FF-HF kinematics. Variations in the relative motions of the foot segments need to be considered in the design of lower limb prostheses and in orthopaedic and neurological rehabilitation.

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