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Kinematic adaptations of the hindfoot, forefoot, and hallux during cross-slope walking

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ABSTRACT

Despite cross-slope surfaces being a regular feature of our environment, little is known about segmental adaptations required to maintain both balance and forward locomotion. The purpose of this study was to determine kinematic adaptations of the foot segments in relation to transverse (cross-sloped) walking surfaces. Ten young adult males walked barefoot along an inclinable walkway (level, 0° and cross-slope, 10°). Kinematic adaptations of hindfoot with respect to tibia (HF/TB), forefoot with respect to hindfoot (FF/HF), and hallux with respect to forefoot (HX/FF) in level walking (LW), inclined walking up-slope (IWU), i.e., the foot at the higher elevation, and inclined walking down-slope (IWD), i.e., the foot at the lower elevation, were measured. Multivariate analysis of variance (MANOVA) for repeated measures was used to analyze the data. In the sagittal plane, the relative FF/HF and HX/FF plantar/dorsiflexion angles differed across conditions ($p = 0.024$ and $p = 0.026$, respectively). More importantly, numerous frontal plane alterations occurred. For the HF/TB angle, inversion of IWU and eversion of IWD was seen at heel-strike ($p < 0.001$). This pattern reversed with IWU showing eversion and IWD inversion in early stance ($p = 0.024$). For the FF/HF angle, significant differences were observed in mid-stance with IWD revealing inversion while IWU was everted ($p < 0.004$). At toe-off, the pattern switched to eversion of IWD and inversion of IWU ($p = 0.032$). The information obtained from this study enhances our understanding of the kinematics of the human foot in stance during level and cross-slope walking.

1. Introduction

Biomechanics research related to gait has focused largely on level walking, with less attention paid to cross-slope inclined surfaces, i.e., a surface sloped perpendicularly with respect to the direction of movement [1–3]. In the urban setting, sidewalks and roadways are commonly tilted to permit water drainage. The recommended range for cross-slope inclination is 0.5–2.3° [4]; however, irregular terrain may increase this range of values up to 6° [5]. Greater slopes may well exceed these guidelines based on local topography. For example, in many steeply inclined streets it is common to encounter a cross-walk with a transverse slope of 10°. Despite the prevalence of cross-slopes in our environment, little knowledge of segmental adaptations necessary to maintain both balance and forward locomotion exists. Sidewalks and roadways with irregular or prolonged cross-slopes may impede gait and present a circumstance for an increased risk of fall and lower extremity injuries.

Cross-slope locomotion is analogous to a leg-length discrepancy adaption, in which the up- and down-slope limbs must perform a functional over flexion and extension, respectively, to keep the body vertical [6]. Dixon and Pearsall [7] recently reported substantial left to right asymmetrical changes in the kinematics and kinetics of the lower limb joints during cross-slope (6°) walking. For instance, they reported a decreased inversion of the up-slope ankle and increased inversion of the down-slope ankle on the cross-slope walking surface. The coronal plane kinematics of cross-slope walking could place the ankles at risk for both medial (up-slope) and lateral (down-slope) ankle complex ligament injury [8]. While for young adults cross-slopes 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.) [9].

In many gait studies, the biomechanical models usually represent the foot as a single rigid segment, permitting only aggregate foot angles to be determined [7,10,11]; as such, within foot bend and torsion are obscured. This modeling representation has been noted to be insufficient to assess foot pathologies [12] or form specific treatments [13]. The human foot is an intricate, multi-joint mechanism, which is fundamental for the interaction between the lower limb and ground during locomotion [14].

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Table 1
Kinematic abbreviations and sign conventions used for the foot segment angles: hindfoot with respect to tibia (HF/TB), forefoot with respect to hindfoot (FF/HF), and hallux with respect to forefoot (HX/FF).

Foot segment angles	Sagittal	Frontal	Transverse
HF/TB	Plantarflexion (PF): −	Eversion (Eve): −	Abduction (Abd): −
	Dorsiflexion (DF): +	Inversion (Inv): +	Adduction (Add): +
FF/HF	Plantarflexion (PF): −	Eversion (Eve): −	Abduction (Abd): −
	Dorsiflexion (DF): +	Inversion (Inv): +	Adduction (Add): +
HX/FF[a]	Flexion (Flx): −	–	–
	Extension (Ext): +		

[a] Sagittal plane only.

In response, recent studies have begun to model the foot as a multi-segment structure to allow more detailed analysis of foot kinematics during level walking [15–19]. One such facsimile is the Oxford foot model proposed by Carson et al. [15] that uses skin mounted markers to define the foot segments, and unlike other models, is not dependent on X-ray calibration [18]. In addition, this particular model has demonstrated robust repeatability, with an overall inter-segment angle standard deviation of less than $\pm 1^\circ$ throughout a gait cycle [15,20].

Given the above preface, multi-segment foot models may be used to quantify in greater detail the foot's adaptations to a cross-slope surface during walking. It is hypothesized that the relative segmental foot motions of hindfoot, forefoot, and hallux segments will vary significantly between level and cross-slope walking as well as show substantial asymmetrical differences between the up-slope and down-slope feet, especially in the frontal plane. Therefore, the objective of this study was to determine kinematic adaptations of foot segments in relation to cross-sloped walking surfaces. Understanding of the relative motions of the foot segments could help in the design of a variety of prostheses and walking aids.

2. Method

Ten healthy adult males with no previous orthopedic ailment participated. They had an average age of 24.8 ($\pm$8.4) years, height of 175.6 ($\pm$7.1) cm, and mass of 68.8 ($\pm$8.6) kg. All subjects signed a consent form approved by the McGill University Research Ethics Board Office.

Participants were fitted with 39 reflective markers placed over bony landmarks of the lower limbs according to the Oxford foot model [15]. In this model, the foot consists of hindfoot, forefoot, and hallux segments, while the tibia is represented as a single rigid body. A transversely inclinable walkway of entire length 7 m and width 1.22 m with an embedded force plate (AMTI, model OR6-5-1000, Watertown, MA, USA) was used. The force plate was located in the middle of the walkway such that the participants performed at least three steps on the ramp before hitting the force plate. The force plate was secured into the walkway via a number of bolts and stabilized by several sub-platform braces. To avoid slippage, the walkway and force plate were covered with Mondotrack (Mondo America Inc., Laval, QC, Canada).

Participants were familiarized to the walkway area and then performed a minimum of ten self-selected speed barefoot walking trials at each of the flat (0°) and up- and down-slope (10°) conditions, respectively. Six trials per condition with complete data sets were selected. The average speed was calculated to be of 1.43 ± 0.26 m/s on each condition ($p > 0.198$). Since the right foot was considered only, for the inclined conditions the participants walked in both directions such that the right foot was in up-slope and down-slope positions, respectively. A trial was excluded if the foot did not land completely on the force plate or if the subject targeted the platform.

Kinematic data were collected at 240 Hz using an eight camera Vicon™ system (Vicon, Los Angeles, USA). The data were filtered with a fourth-order zero-phase lag Butterworth filter having a cutoff frequency of 8 Hz. Force plate data were acquired at 960 Hz and filtered using a fourth-order low-pass Butterworth filter with a 20 Hz cutoff frequency. The force plate was zeroed prior to collection on the cross-slope condition to remove the effect of its weight on the output channels.

The dependent variables were the kinematic adaptations of hindfoot with respect to tibia (HF/TB), forefoot with respect to hindfoot (FF/HF), and hallux with respect to forefoot (HX/FF) (only in the sagittal plane) during level walking (LW), inclined walking up-slope (IWU), and down-slope (IWD). The inter-segment foot angles calculated according to the method proposed by Grood and Suntay [21] were obtained from the Vicon™ Oxford foot model outputs. The averages of computed angles were used to generate offsets for joint angles during each condition for each subject. Kinematic abbreviations and sign conventions used for the foot inter-segment angles are presented in Table 1. For statistical analysis of the motion patterns of the HF/TB, FF/HF, and HX/FF, the stance phase was evaluated at five events present in normative vertical ground reaction force (GRF) data [22]. The events were taken at heel-strike (HS), first and second maximum GRF values representing weight acceptance (MaxFz1) and propulsion (MaxFz2) respectively, during mid-stance characterized as the minimum GRF between them (MinFz), and at toe-off (TO).

The three-dimensional intra-foot segments angles of the right HF/TB, FF/HF, and HX/FF were taken for each event and averaged across all the trials per condition within subjects. These angles were analyzed using a between subject repeated measures MANOVA. This was followed by a Bonferroni post hoc test if a statistical main effect for conditions was observed ($\alpha = 0.05$).

3. Results

Intra-segment angles of the right hindfoot, forefoot, and hallux plotted against percent of stance for the LW, IWU, and IWD conditions showed distinct patterns of motion (Fig. 1). For the HF/TB angles, the eversion/inversion of the hindfoot with respect to tibia was significantly different at HS, MaxFz1, and MaxFz2 ($p < 0.05$), as presented in Table 2. Pairwise comparisons revealed significant differences at HS between IWD and the two other conditions (LW, $p = 0.029$; IWU, $p < 0.001$). The hindfoot everted with respect to tibia in IWD while it was inverted during LW and IWU at HS. For MaxFz1 and MaxFz2, post hoc analysis showed differences between IWU and IWD ($p = 0.024$ and $p = 0.032$, respectively). While the hindfoot was everted with respect to tibia at MaxFz1 during IWU, it showed an inversion in IWD. Significantly greater eversion was noted during IWD compared to IWU at MaxFz2.

Table 3 presents the FF/HF angles during the LW, IWU, and IWD conditions. The PF/DF of the forefoot with respect to hindfoot was significantly different at TO. Pairwise comparisons revealed the forefoot plantarflexion with respect to hindfoot in IWD is

Table 2
Means (SD) of the hindfoot with respect to tibia angles (°) across the five intervals of stance phase in level walking (LW), inclined walking up-slope (IWU), and down-slope (IWD).

Plane	Event	LW	IWU	IWD
Sagittal	HS	1.85 (3.16)	1.62 (3.63)	3.34 (3.51)
	MaxFz1	−4.61 (2.83)	−4.72 (2.56)	−3.77 (1.82)
	MinFz	0.37 (2.86)	1.22 (0.81)	0.93 (0.52)
	MaxFz2	2.92 (1.77)	4.27 (1.21)	2.71 (1.87)
	TO	−5.73 (3.12)	−4.49 (3.51)	−6.54 (2.81)
Frontal	HS	2.22 (2.64)	5.19 (1.74)	−1.41 (3.30)[a,b]
	MaxFz1	1.32 (2.37)	−1.02 (3.0)	3.47 (3.80)[b]
	MinFz	−0.98 (1.91)	−2.26 (1.11)	−1.97 (1.57)
	MaxFz2	−1.41 (1.21)	−0.59 (1.98)	−2.91 (1.76)[b]
	TO	7.32 (3.89)	9.38 (3.66)	5.35 (6.02)
Transverse	HS	2.97 (1.51)	3.57 (2.47)	2.89 (3.27)
	MaxFz1	−5.34 (2.43)	−5.72 (0.86)	−6.88 (3.12)
	MinFz	−1.38 (1.95)	−1.17 (1.34)	−0.80 (1.68)
	MaxFz2	1.30 (3.03)	3.28 (0.87)	2.66 (2.18)
	TO	6.10 (4.37)	7.38 (3.70)	5.88 (4.44)

[a] LW vs. other conditions ($p < 0.05$).
[b] IWU vs. IWD ($p < 0.05$).