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The influence of deformation height on estimating the center of pressure during level and cross-slope walking on sand

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ABSTRACT

Force plates are frequently used to collect the ground reaction forces (GRF) and center of pressure (COP) during gait. The calculated COP is affected by the material type and thickness covering the top surface. If the surface is deformable, these effects can be significant. The purpose of this study is to simulate and evaluate the effects of deformation height when calculating the COP in a deformable surface during gait. The GRF and COP data during normal gait were collected from 20 healthy adult males on sand in two conditions (level and cross-slope of 10°). The COP differences in the anteroposterior (AP) and mediolateral (ML) directions were modeled for constant deformation heights (10–50 mm, 10 mm increments). The results showed the magnitude of COP changes in the AP and ML directions were different in both level and cross-slope conditions. A significantly larger COP_{ML} difference was shown for the cross-slope condition than level condition for the same deformation height. The COP was more sensitive to the deformation height for the downhill limb than uphill limb in the cross-slope condition. The results of this study suggest that the maximum allowable deformation height before a correction for surface deformation is needed is 20 mm for level condition and 10 mm for cross-slope condition, where 3 mm difference in COP is considered as the tolerance limit. Surface deformations beyond these thresholds may lead to an inaccurate interpretation and evaluation of joint kinetics during gait on deformable surfaces.

1. Introduction

Force plates are key instruments in biomechanics research to provide the ground reaction force (GRF) and the center of pressure (COP) information. The COP is the single point of origin of the ground reaction force vector on a force plate's surface that is used for inverse dynamics. However, it is not directly determined from the force plate and is usually calculated from the analog signals using several parameters which characterize the force plate. When a floor covering exists above the top surface of a force plate, the thickness of the covering effects the calculated COP. However, this parameter may not always be constant and continuously changes during gait on deformable surfaces like sand. Although human locomotion on smooth, hard level surfaces is well described, there is a paucity of studies investigating gait on other surfaces, such as found in outdoor environments including construction work, military activities and railroad work. These often include walking over inconsistent and deformable surfaces like sand or gravel and cross-slope (transversely inclined) conditions. Some previous research has focused on the energy cost of human locomotion on different terrains but did not describe the COP [1–3]. Lejeune et al. investigated the mechanics and energetics of human locomotion on sand [4]. The studies performed by Kim and Yoo analyzed upper and lower limb biomechanics when carrying a military backpack while walking on cross-slope sand surfaces [5,6]. Other studies have focused on the effects of walking on gravel, like railroad ballast. Wade et al. compared the difference of joint kinetics when subjects walked on smooth and ballast surfaces [7]. Merryweather investigated the lower limb biomechanics when walking on cross-slope and level railroad ballast with 10 subjects [8]. A follow-up study using the same data by Xu discussed the effect of cross-slope and ballast surface for the knee contact force during gait [9]. In these studies, the calculated COP from a force plate only accounted for the initial sand or ballast depth. Any

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height change as a result of sand or ballast displacement during contact was neglected or not considered. The COP is a key parameter used for evaluation of joint moments, muscle forces and joint loading during walking; therefore, differences in actual and computed COP on deformable surface could result in erroneous conclusions.

Since the location of the COP affects the estimation of joint kinetics including muscle and joint forces [10–13], and studies of movements on various deformable terrains continue to increase, this research provides valuable guidelines for when it might be acceptable to neglect the effect of a deformable surface on COP. The effect of surface deformation on determining the COP needs to be evaluated to prevent misrepresentation of the results of joint biomechanics of gait on deformable surfaces.

The purpose of this study is to simulate and evaluate the differences in calculating the COP during gait on a deformable surface. Specifically, we would like to know the magnitude of this difference as it relates to the deformation height and whether this is the same for different surface conditions (level and cross-slope), and for different directions (anteroposterior (AP) and mediolateral (ML)).

2. Methods

2.1. Experimental set-up

Twenty healthy male adults (age 24.9 ± 3.5 years; height 1.76 ± 0.04 m; weight 77.2 ± 5.7 kg) volunteered for this study. Participants were carefully selected from a healthy young population who were not currently experiencing injury or pain in the lower extremities that may affect normal gait. All participants reviewed and signed an informed consent document approved by the University of Utah Institutional Review Board. Two adjustable walkways (7.3 m long, 0.76 m wide and 0.23 m deep) and custom isolation fixtures were constructed (Fig. 1) to perform this work. One walkway was covered with 3/4 in. reinforced plywood with two embedded force plates (OR6-5-1000 and OR6-7, AMTI, Watertown, MA) to replicate a hard surface environment. The other track was filled with sand to simulate a common deformable surface environment. Two force plates were embedded 20 cm beneath the sand surface in this track with the isolation fixtures. The isolation fixture consisted of two welded steel rectangles concentrically aligned with 6.4 mm clearance between walls. The outer frame was securely attached to the base of each track, and the inner frame securely fit on the force plate by use of four alignment tabs. The alignment tabs ensured all shear forces were transmitted to the surface of the force plate. Previous studies

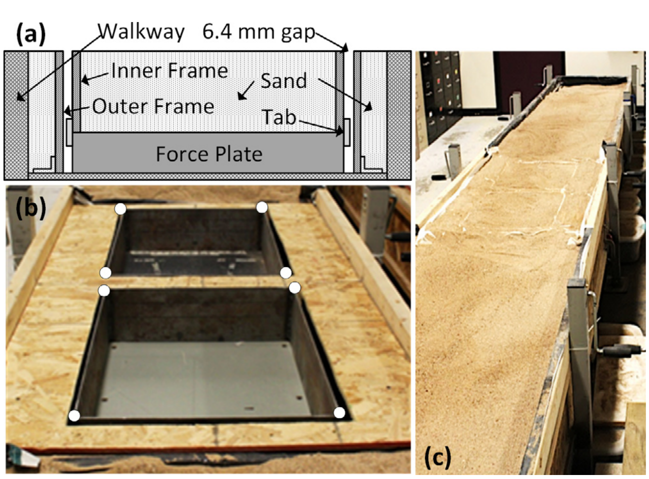

Fig. 1. The adjustable walkways and custom isolation fixture. (a) Schematic diagram of the isolation fixture; (b) the isolation fixture with markers on the inner frame; and (c) the adjustable walkways with embedded force plate.

confirmed that this force plate isolation technique could serve well to reduce the dissipation of force and accurately identify measured GRF on ballast and sand [5,8].

2.2. Data acquisition

Prior to data collection with participants, eight 10 mm diameter markers were carefully placed at the corners of the force plate using precision machined aluminum jig blocks. These markers where also placed on the inner rectangle of the isolation fixture for sand on both level and cross-slope conditions (Fig. 1). The marker location data were collected using a 16-camera motion capture system (NaturalPoint, Inc., Corvallis, USA) at 100 Hz for 5 s. These data were used to align the force platforms with the laboratory fixed coordinate system and serve as a reference truth for the height of the force plate surface compared with the walking surface (these were equal for the hard surface). Participants received a pair of BELLEVILLE 790G Gore-Tex boots to standardize footwear. The initial calibration trial was collected using the same motion capture system at 100 Hz with a modified Helen Hays marker set for five seconds when the participant stood on one force plate. For the dynamic trials, participants were asked to become accustomed to the walking surface by traversing the walkway, and an optimal starting range was identified to increase the likelihood of two sequential force plate contacts, which was critical for determining a successful trial. Three successful trials per participant at self-selected speed within the range of 1.20–1.40 m/s [14–16] on the tracks were collected for both level and cross-slope of 10° conditions over hard and sand surfaces. The walking direction was same for all trials to keep the left limb in the uphill for the cross-slope condition. Kinematic data were recorded at 100 Hz with digitally low-pass filtered at 6 Hz. The GRF and COP were collected at 2000 Hz with low-pass filtered at 20 Hz.

2.3. Data process

Major gait events (heel strike and toe off) were defined via force plate activation with a 20 N threshold to identify the stance phase of the gait cycle. The GRF and COP data during the stance phase were normalized by 101 data points. In order to evaluate the effect of deformation height for calculating the COP, the deformation height (t) was defined as the maximum vertical slippage depth of the sand surface in both level and cross-slope conditions (Fig. 2). This value was determined by calculating the difference between the height of heel marker on the shoe (h_1) obtained from the calibration trial and the height of heel marker above the reference plane (h_2) defined by the calibration markers on the inner frame (Fig. 2). This was done using MATLAB program (The Mathworks, Inc., Natick, MA). The results showed that the average deformation height during stance was 29 ± 8 mm and ranged from 11 to 41 mm on level condition. The deformation heights on the cross-slope condition were 36 ± 11 mm (14–60 mm) for the uphill limb and 49 ± 11 mm (18–62 mm) for the downhill limb. Therefore, the deformation heights from 10 to 50 mm, in 10 mm increments were chosen for simulation in the present study and analyzed for the total 120 trials with the sand surface (subject (20) × trial (3) × condition (2)).

The equations used to calculate the COP in the force plate coordinates were:

$$\mathrm{COP}_x = \frac{-(h-t) \times F_x - M_y}{F_z} \quad (1)$$

$$\mathrm{COP}_y = \frac{-(h-t) \times F_y - M_x}{F_z} \quad (2)$$

where COP_x and COP_y are the coordinates of COP in ML and AP directions, respectively. h is the original sand thickness above the