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Evaluation of a force plate system for measuring center of pressure in railroad ballast

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ABSTRACT

Traditional biomechanical analyses have focused primarily on the human gait across hard, flat surfaces and provide little information about human locomotion as a function of work environment or terrain. The purpose of this study was evaluation of a force plate system for measure of center of pressure (COP) in railroad ballast by comparing its accuracy across three surface conditions (hard surface, mainline ballast and walking ballast) with two configurations (level and 7° cross-slope). Custom walkways and an isolation fixture were developed to rigidly attach a force plate beneath ballast surfaces to collect the COP. The difference in COP location ($\Delta COPx$, y, z) between the force plate system and a calibration system (motion capture derived) were compared using repeated-measures analysis of variance. Results indicate that the effects of surface condition and configuration were not significant for $\Delta COPx$, y, z and no differences were found among the three surface conditions during pairwise comparison, though $\Delta COPx$, y, z were different between the center and corners of the force plate in ballasts for both level and cross-slope configurations. The system presented in this study demonstrates the feasibility of measuring the COP by using an isolation-fixture force plate to expand the scope of biomechanical studies on ballast surfaces that are level or cross-slope.

1. Introduction

The biomechanics of human gait have been studied extensively in the past decade with most gait analysis conducted on level, hard surfaces including indoor tracks and treadmills [1–4]. However, work environments may include a variety of terrain and walking conditions. Recently, research has extended our understanding of human locomotion on other surface conditions, like sand, grass and rock [5–11], and configurations, like inclines/declines [12–14] and cross-slope [15–17]. A few studies investigated the energy costs and kinematics when walking on sand or grass, but not kinetics due to the challenges of validating the accuracy and reliability of force plate measurement on these altered conditions [5–7]. Other research investigated lower limb biomechanics when walking on sloped surfaces at various gradients; validation of tilted force plate systems has also been performed [13,15,16]. These studies indicated that significant differences exist in ground reaction force, kinematics and kinetics while walking on sloped conditions compared to level conditions, and further our understanding of gait adaptation on non-level surfaces.

Several studies looked into the gait characteristics during locomotion on ballast (crush rock aggregate) and a cross-slope condition [10,11,18], which is the occupational environment for many workers employed in the rail industry. The two primary ballast types were defined as walking ballast (WB, diameter 9.53–31.75 mm), generally located in railroad yards, and mainline ballast (MB, diameter 19.05–63.5 mm), generally located on main track lines. Andres et al. [10] reported that walking on cross-slope MB significantly increased the rear foot range of motion compared to walking on either WB or no ballast (NB). Merryweather et al. [18] found that a significant increase in knee flexion and foot clearance was required to prevent trip potentials while walking on ballast compared to hard surfaces in level and cross-slope situations. Wade and Redfern [19] investigated a method to measure ground reaction force using a force plate embedded beneath 63.5-mm and 101.6-mm of ballast. This method suggested that measuring reaction force with ballast applied to the top surface of the force plate was

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feasible in level conditions. However, the approach might be inappropriate for measurements with greater ballast depths, where the effects of force dissipation would most likely increase, especially along the edge of the force plate. It is unclear whether or not their setup would be appropriate for cross-slope conditions. A following study conducted by Wade et al. [11] utilized this force plate system to study gait biomechanics on ballast and reported that joint moment ranges were smaller, but the muscle co-contraction levels were greater on ballast compared with NB in level condition.

The purpose of this study was to evaluate a custom, slope-adjustable walkway system with an isolation fixture for the force plate to determine the center of pressure (COP). In order to validate this walkway system, a calibration system, including a rigid mechanical device and associated software, was utilized to determine the COP. This walkway system is proposed to expand the capabilities to study biomechanics, including gait for various activities on railroad ballast.

2. Methods

Two custom walkways were designed and constructed of engineering I-beams to provide the ability to test multiple experimental conditions including varying walking surfaces and cross-slopes. It was of particular interest to study two types of ballast (WB and MB) and two configurations (level and cross-slope of 7°) to resemble the typical environments encountered by railroad employees working in the railyard or on the mainline [10]. Each walkway was 23 cm deep and provided a working surface 76-cm wide by 7.3-m long with an embedded force plate (model OR6-5-1000, AMTI, Watertown, MA) to record reaction force and the COP. Ten adjustable jacks were placed on each walkway so one side of the walkway could be elevated to generate the cross-slope condition (Fig. 1a–c). WB and MB were filled 20-cm depth in two walkways similar to the previous study, and then compacted by ballast tamper (similar to Model MRC 1100 P, FCS Rail Inc., Italy) to produce consolidation and reduce shifting to resemble ballast in normal railroad conditions other than freshly laid or disturbed ballast [10,20].

A custom isolation fixture was developed to isolate surrounding ballast from ballast directly in contact with the force plate. The isolation fixture consisted of two welded, concentrically aligned steel rectangle frames with 6.4-mm clearance between the inner and outer frame walls. The fixture was open from the top to bottom and ballast can be applied to the top surface of the force plate (Fig. 1d–f). The outer frame was securely attached to the base of each walkway and the inner frame securely fit on the force plate with four alignment tabs. The tabs served to "lock" the inner frame to the force plate to translate shear forces to the force plate from ballast.

Five digital video camcorders (PV-GS55, Panasonic Corporation of North America, Secaucus, NJ) were configured around the walkway setup to allow for a motion capture volume of 6.8 m^3. The laboratory coordinate system was oriented with *z*-axis upward, *x*-axis anterior/posterior, and *y*-axis medial/lateral. The force plate coordinate system was oriented with the *z*-axis directed downwards toward the surface of the force plate; these two coordinate systems were related using a transformation/rotation matrix.

The COPs derived from the force plate in the NB condition were calculated using Eqs. (1) and (2), where *x* and *y* were the coordinates of COP in the horizontal plane. *F*s and *M*s were the components of force and moment vectors as determined from the force plate. The values *a*, *b*, *c* are the configuration data of the true origin of the force plate which were determined by the manufacturer as part of the calibration procedure and supplied with the force platform. When ballast was placed on the force plate in the isolation fixture, the force plate origin relative to the contact surface plane was adjusted; therefore, the COPs were calculated using Eqs. (3) and (4), where *t* was the average ballast depth above the top surface of the force plate, which was 0.2 m in this study.

$$x = -\frac{M_y + cF_x}{F_z} + a \tag{1}$$

$$y = \frac{M_x - cF_y}{F_z} + b \tag{2}$$

$$x = -\frac{M_y + (c-t)F_x}{F_z} + a \tag{3}$$

$$y = \frac{M_x - (c-t)F_y}{F_z} + b \tag{4}$$

The calibration system included a rigid mechanical testing device (MTD) (Motion Lab Systems, Baton Rouge, LA) and associated software (CalTester, C-Motion Inc., Germantown, MD) that was used to validate the ability to accurately measure the COP in this custom, slope-adjustable walkway system. The MTD was designed with five reflective markers on wands attached to a calibration-testing rod with two conical tips, a test plate and a handle (Fig. 2a). The conical tips provided a way for direct force to be applied with a negligible applied moment or force couple [21,22]. The test plate was designed to rest on the surface of the force plate and had a machined conical impression in the center to constrain the conical tip and allow force to be applied near the corners of the force plate. The handle was a rigid bar with a machined conical impression for applying force to the MTD. The tip of the MTD rod location was determined by the motion capture component combined with the relative location information of reflective markers. For each trial, the test plate was placed at one of five locations on the force plate, including the four corners and the center.

A member of the research team placed the MTD on the base plate and applied a force (135 ± 27 N) through the rod by pressing down on the handle. While applying the force, the researcher pivoted the rod through a circular pattern along the vertical axis of the laboratory coordinate system according to the instructions provided by CalTester [21]. This procedure was followed at each location on the force plate for each surface condition and configuration.

Five trials were conducted at the four corners and the center of the force plate for each of six test conditions (NB level, NB cross-slope, MB level, MB cross-slope, WB level and WB cross-slope) for a total of 150 trials. Before conducting a trial, a known weight (44.5 N) was placed on the center and each of the corners for each condition/configuration to verify the force readings perpendicular to the plate surface, which was 44.022 ± 0.396 N and 43.932 ± 0.254 N in level and cross-slope conditions on average, respectively. Then, dynamic trials were performed with the MTD. Each dynamic trial consisted of a 15-s time period at each location. A member of the research team controlled the angle of the MTD while applying force. The video data and analog data were recorded simultaneously. Motion data were collected at 60 Hz using a motion capture system (Vicon Motion Systems, Centennial, CO) and then conditioned using a fourth order zero-lag Butterworth filter with a cutoff frequency of 6 Hz. Force plate data were recorded at 600 Hz. Data points where the applied vertical force was less than 20 N were excluded for analysis due to the sensitivity of calculated COP to small vertical forces (Eqs. (1) and (2)) [23,24].

For each trial, the data calculated using CalTester software provided the coincidence information between these two systems