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Corner height influences center of mass kinematics and path trajectory during turning

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ABSTRACT

Despite the prevalence of directional changes during every-day gait, relatively little is known about turning compared to straight gait. While the center of mass (COM) movement during straight gait is well characterized, the COM trajectory and the factors that influence it are less established for turning. This study investigated the influence of a corner's height on the COM trajectory as participants walked around the corner. Ten participants (25.3 ± 3.74 years) performed both 90° step and spin turns to the left at self-selected slow, normal, and fast speeds while walking inside a marked path. A pylon was placed on the inside corner of the path. Four different pylon heights were used to correspond to heights of everyday objects: 0 cm (no object), 63 cm (box, crate), 104 cm (desk, table, counter), 167 cm (shelf, cabinet). Obstacle height was found to significantly affect the COM trajectory. Taller obstacles resulted in more distance between the corner and the COM, and between the corner and the COP. Taller obstacles also were associated with greater curvature in the COM trajectory, indicating a smaller turning radius despite the constant 90° corner. Taller obstacles correlated to an increased required coefficient of friction (RCOF) due to the smaller turning radii. Taller obstacles also tended towards greater mediolateral (ML) COM-COP angles, contrary to the initial hypothesis. Additionally, the COM was found to remain outside the base of support (BOS) for the entire first half of stance phase for all conditions indicating a high risk of falls resulting from slips.

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1. Introduction

Human gait has been a widely researched area especially concerning slips, trips, and falls. However, the majority of research has examined straight gait. Turning and non-straight steps make up approximately 35–45% of all steps (Glaister et al., 2007a) yet have received little attention compared to straight gait. An individual's whole-body center-of-mass (COM) trajectory has been well characterized during straight gait (Gard et al., 2004; Granata and Lockhart, 2008; Lee and Farley, 1998; Lee and Chou, 2006; Lockhart et al., 2003; MacKinnon and Winter, 1993; Orendurff et al., 2004) but is less understood during turning.

Turning is distinctly different than straight walking (Glaister et al., 2008; Hicheur and Berthoz, 2005). Turning requires a much larger required coefficient of friction (RCOF) to prevent slips (Fino and Lockhart, 2014) and has a higher incidence of falls resulting from slips (Yamaguchi et al., 2012a) than straight walking due to the lateral displacement of the COM relative to the base of support (BOS). Larger turning radii affect the orientation of the head and trunk (Sreenivasa et al., 2008), increase the COM displacement outside the BOS (Hollands et al., 2001), and decrease the walking velocity (Dias et al., 2013). Increasing the walking speed has a similar relationship, increasing the COM displacement outside the BOS (Orendurff et al., 2006).

To date, no study has examined how the geometry of an object affects the COM while turning. During turning, individuals lean in towards the apex to compensate for the centripetal force (Courtine and Schieppati, 2003). While the degree to which individuals lean depends on speed (Orendurff et al., 2006) and turning radius (Hollands et al., 2001), the response is unknown if this lean is obstructed by an obstacle. Previous studies have used objects to demark a corner (Grasso et al., 1998) or prevent participants from crossing through a corner (Glaister et al., 2008; Glaister et al., 2007b), but there is currently no knowledge concerning how the object's shape or size influences the participants' kinematics. Our earlier analysis reported no effect of obstacle height on RCOF during the push-off phase of gait (Fino and Lockhart, 2014) but did not examine other phases of the turn nor reported COM trajectories. Given that most turns in a crowded environment are to avoid obstacles (Glaister et al., 2007a), it is worth investigating

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whether the geometry of those obstacles impacts the resulting maneuvers and influences fall risk. While important for researchers wishing to examine turning gait, this knowledge may also be useful in designing pedestrian environments by providing guidelines for the size of barricades, posts, tables, and walls in order to maximize pedestrian flow and reduce the chances of slips and falls.

This study observed the effect of objects' heights on the COM trajectory at slow, normal, and fast walking speeds during a 90° turn. We hypothesized that taller obstacles would restrict the mediolateral (ML) component of the COM-COP angle, θ_{ML}. Additionally, taller obstacles were expected to result in wider turns, larger path curvatures, and greater clearance between the obstacle and the COM or COP. The RCOF at weight acceptance was hypothesized to increase with obstacle height and speed. The COM and COP clearance and θ_{ML} were expected to increase with speed (Fino and Lockhart, 2014; Orendurff et al., 2006) and be greater for step turns compared to spin turns (Taylor et al., 2005).

2. Methods

2.1. Participants

Seven males and three females, 18–45 years of age (mean 25.3 ± 3.74 years), were recruited from Virginia Tech and the surrounding community for the study. Participants were informed of the protocol and gave written informed consent prior to the experiment. Participants were excluded if they had any history of balance disorders, dizziness, musculoskeletal injury within the past year affecting normal gait, any neurological disorders, one or more concussions within the past year, and / or significant visual impairment. The complete protocol was approved by the Institutional Review Board at Virginia Tech.

2.2. Experimental procedure

The full procedure and overheard view of the set-up was reported by Fino and Lockhart (2014). Briefly, participants walked along a 0.75 m wide marked path with a 90° turn. The path was straight for 3.5 m followed by a 90° left turn into a 2.5 m straight segment. The beginning and end of the path were marked with start and stop lines, respectively. A 10 cm diameter pylon was placed on the inside of the 90° corner as the obstacle. Four different pylon heights were used corresponding to heights of everyday objects: 0 cm (no object), 63 cm (box, crate), 104 cm (desk, table, counter), and 167 cm (shelf, cabinet). The floor surface was covered in a Micropore tape (3 M, St. Paul, MN 55144-1000, USA) to prevent slipping while turning the corner, especially at fast speeds. Prior testing revealed gait adjustments and slips when performing the task. The tape successfully increased the available friction of the floor allowing the participants' natural actions to be observed without any adaptations (Fino and Lockhart, 2014). Participants wore their own athletic shoes throughout the experiment.

Three-dimensional kinematics were measured using a six-camera Pro-Reflex motion analysis system (Qualisys Track Manager version 1.6.0.163, Qualisys AB, Gothenburg, Sweden) and 35 infrared-reflective markers placed bilaterally over the first, second, and fifth metatarsal heads, medial and lateral malleolus, calcaneus, medial and lateral femoral condyle, anterior superior iliac spine, trochanter, iliac crest, clavicle (adjacent to the suprasternale), acromioclavicular (AC) joint, lateral humeral condyle, ulnar stylus, third metacarpal head, ear, and top of head. A marker was also placed on top of the corner pylon directly over the inside corner of the path. Two force plates (AMTI # BP6001200100, AMTI Force and Motion, Watertown, MA 02472, USA) (Bertec #K80102, Type 45550-08, Bertec Corporation, OH 43212, USA) were embedded into the walkway at the corner. All data was sampled at 100 Hz.

Participants were instructed to walk normally within the path, to avoid hitting the pylon, and to continue until they reached the stop line. The participants were instructed to walk at one of three speeds: normal (NW), slower than their normal pace (SW), and "as fast as possible without running or jogging" (FW). Warm-up trials were used to adjust the subjects starting position to ensure their turning limb landed on the corner force plate. The participants performed three straight gait trials followed by 24 turning trials for each speed. The turning trials were divided into four blocks, one for each obstacle height. For each obstacle height, participants performed three step turns and three spin turns, where a step turn was defined as a turn away from the stance limb and a spin turn is defined as a turn toward the same side as the stance limb (Taylor et al., 2005). To eliminate order effects, speed, obstacle height, and strategy order was rotated for each participant (Fino and Lockhart, 2014).

2.3. Data analysis

Data from all ten participants were analyzed. Trials in which the participant stepped multiple times on the force plate or only partially stepped on the force plate were excluded from the analysis. A total of 291 of the 720 trials were excluded for this reason (148 slow trials, 84 normal, and 59 fast). The 3-dimensional marker data and the force plate data were filtered using a 5 Hz 2^{nd} order low-pass Butterworth filter. During the second half of the turning stance phase, several kinematic markers were obstructed from the cameras' views. Therefore, kinematic data from only the first half of each stance phase was analyzed. All analysis was performed using MATLAB (MATLAB and Statistics Toolbox Release 2013b, The MathWorks, Inc., Natick, Massachusetts, USA).

2.3.1. COM clearance and COP distance

The COM was calculated using individual body segments' masses and center of mass locations from the reflective markers at the segment endpoints (De Leva, 1996). The COM clearance was calculated as the distance in the horizontal plane from the COM to the corner pylon as shown in Fig. 1. Due to the different pylon heights, a vertical projection of the corner pylon was extended upward to the COM height. The ground reactive forces (GRF) were recorded by the force plate and used to calculate the COP according to the force plate manufacturer (Bertec Corporation, OH 43212,

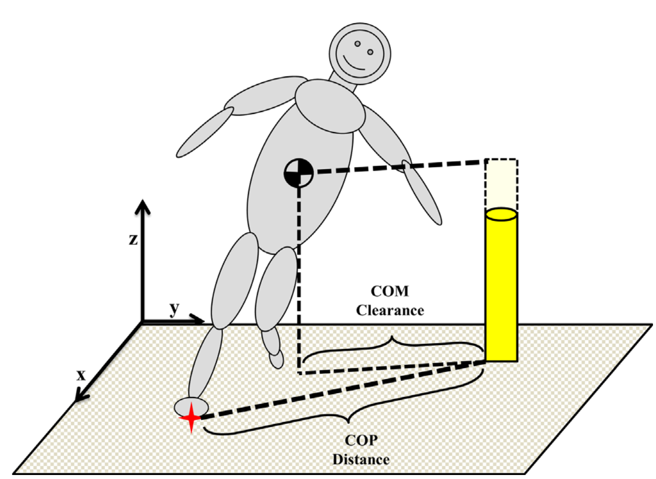

Fig. 1. Depiction of COM clearance and COP distance calculations. The COM clearance was the planar distance from the whole-body COM to the pylon (yellow) or pylon projection in the COM horizontal plane. The COP (red star) distance was the horizontal distance from the COP to the base of the pylon.