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Short communication

# Ground reaction forces and impulses during a transient turning maneuver

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ABSTRACT

Understanding the kinetic strategies of turning as expressed in ground reaction forces (GRFs) and impulses (GRIs) is necessary to design therapies and technologies to enable patients with ambulatory difficulties perform daily activities. Previous studies have reported data only for one step of the turn and expressed the data in terms of a global reference frame making it difficult to understand how the forces act on the body to cause a change in heading and orientation during a turn. This study is the first to report GRF and GRI data for three steps of a turn and express that data in terms of a body reference frame. Motion and GRF data were collected from 10 subjects walking at self-selected speeds along a straight path and performing 90° left and right turns. During the left turn, turn initiation and apex steps were collected. During the right turn, turn termination steps were collected. GRF data were rotated to a reference frame whose origin was the body center of mass (COM) and aligned to the COM trajectory and then integrated to find the GRIs. In the medial–lateral direction, straight steps were characterized by a brief medial impulse at heel strike followed by a prolonged lateral impulse. Turn initiation and termination steps were both characterized by medial impulses spanning the entire stance phase while apex steps were characterized by a large lateral impulse. In the anterior–posterior direction, initiation steps had larger braking and smaller propulsive impulses than straight steps. Apex steps had larger propulsive impulses than straight steps, and termination steps had smaller braking and larger propulsive impulses than straight steps.

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## 1. Introduction

Turning has been shown to make up a considerable amount of the steps taken during activities of daily living (Glaister et al., 2007a) and to be a difficult challenge for patients with Parkinson's disease (Stack and Ashburn, 1999) and the elderly (Cumming and Klineberg, 1994). To create effective strategies to enable patients with ambulatory difficulties perform daily activities more safely, it is important to investigate the biomechanical strategies used during turning maneuvers.

To change the body center of mass (COM) trajectory and the orientation of the trunk during a turn, the body must modulate horizontal ground reaction forces (GRFs) and impulses (GRIs). While several studies have reported investigations of GRFs and GRIs during 45° (Houck, 2003; Xu et al., 2004), 60° (Patla et al., 1991) and 90° turns (Xu et al., 2004; Taylor et al., 2005), several factors regarding these studies make drawing conclusions about the biomechanical strategies of turning difficult. Firstly, turning has been shown to be a multi-step mechanism (Glaister et al., 2007a) but the previous works have only reported data for one step of the turn. Secondly and more importantly, the previous studies on turning presented data in terms of global rather than body coordinate systems. Since the body rotates relative to a global coordinate system during a turn, it is difficult to understand how the GRFs and GRIs act on the body without expressing them in terms of a body reference frame. Therefore, the purpose of this study was to investigate the horizontal GRFs and GRIs while navigating a 90° hallway corner for three steps of a turn expressed in a body reference frame.

## 2. Methods

Ten able-bodied subjects (6 male, 4 female, age range 24–47 years) gave their informed consent to participate in these Institutional Review Board-approved experiments. Thirty-five reflective spherical markers were placed on the subjects

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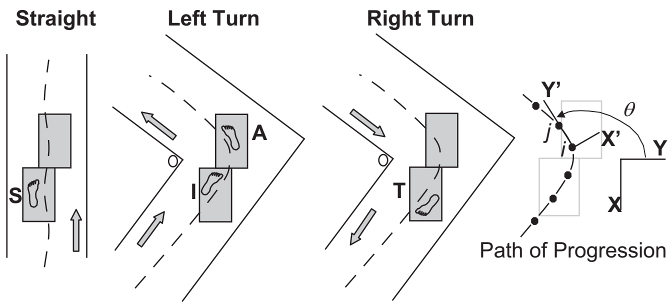


**Fig. 1.** Experimental protocol and reference frame definition. Subjects performed straight walking trials to collect straight steps (S), left-turn walking trials to collect turn Initiation (I) and apex steps (A), and right-turn walking trials to collect turn termination steps (T). The method to define the body reference frame is thoroughly detailed in Glaister et al. (2007b). The global reference frame is defined by $X$ and $Y$ while the body reference frame is defined by $X'$ and $Y'$. $\theta$ is the angle between the two reference frames. Gray arrows represent the direction walked during each trial type. Dashed lines represent the path of progression.

and anthropometric measurements were taken in accordance with Vicon's Plug-In-Gait model (Vicon Peak, Lake Forest, CA, USA). Motion was captured using a 12 camera Vicon 612 system (Vicon Peak) sampling at 250 Hz. GRFs were collected with two Bertec 4060-NC force plates (Bertec Corporation, Columbus, OH, USA) at 1500 Hz. Raw marker trajectories were filtered with a Woltring quintic spline algorithm with an MSE value of 20. Each subject's COM was calculated with Plug-In-Gait based on marker placements and anthropomorphic data (Dempster, 1955).

Subjects walked at their self-selected speeds for straight walking trials and two types of turning trials (Fig. 1). During left-turn trials, turn initiation (I) and apex (A) steps were collected. During right-turn trials, turn termination (T) steps were collected. The hallway was 42 in wide in accordance with Americans with Disabilities Act requirements and common architectural dimensions. The outlines of the hallway were marked on the floor with tape and a 5-ft-tall pole was placed at the inner apex to prevent subjects from crossing through the corner. For the turning trials in this study, the outside foot was constrained to the apex step while the inside foot was constrained to the initiation and termination steps. Five trials of each step type were collected for each subject. All 50 trials for each step type were included in mean calculations for statistical comparisons.

A reference frame local to the body was created with an origin at the COM. The body reference frame was aligned to the COM trajectory using a two-point finite difference method (Glaister et al., 2007b). The angle between the body and global reference frames was calculated and used to rotate GRFs measured globally to the body reference frame. The anterior–posterior and medial–lateral GRFs were then integrated to find the braking, propulsive, medial and lateral shear GRIs. Braking and propulsive impulses were defined as those that acted opposite and in the direction of forward progression, respectively. Medial and lateral impulses were defined as those that acted to push the body away and towards the contralateral limb, respectively. The reference frame rotation and GRI calculations were accomplished using Matlab (Mathworks, Natick, MA, USA). Each GRI was compared for each step using a repeated measures ANOVA with a Scheffe's post-hoc test and statistical significance was set to $p<0.05$ using StatView (SAS Institute, Inc., Cary, NC, USA).

## 3. Results

The GRFs and GRIs for each step are presented (Fig. 2) as are a visual interpretation of the results (Fig. 3). Statistical significance is noted (Fig. 2).

During straight walking, a brief impulse in the medial direction existed ($4.1\pm2.0$ Newton-% stance phase/kg body mass) followed by a prolonged impulse in the lateral direction ($33.9\pm11.9$ N-%SP/kg). From early to mid-stance, a braking impulse existed ($55.4\pm10.5$ N-%SP/kg) which later switched to a propulsive impulse ($52.0\pm8.1$ N-%SP/kg).

The GRIs differed from straight walking during turning. During the initiation step, a lateral impulse ($0.3\pm0.5$ N-%SP/kg) was absent and replaced by a medial impulse ($53.3\pm24.6$ N-%SP/kg) extending throughout stance phase. The braking impulse ($61.5\pm10.6$ N-%SP/kg) was larger and the propulsive impulse ($41.0\pm8.2$ N-%SP/kg) smaller than straight walking. During the apex step, the medial impulse ($0.3\pm0.3$ N-%SP/kg) was absent replaced by a very large lateral impulse ($153.5\pm31.1$ N-%SP/kg). The braking impulse ($59.5\pm13.9$ N-%SP/kg) was similar to straight steps, but the propulsive impulse ($68.3\pm12.2$ N-%SP/kg) was significantly larger. The termination step was similar to the initiation step in that the lateral impulse ($0.6\pm1.9$ N-%SP/kg) was absent and instead a medial impulse ($50.3\pm20.1$ N-%SP/kg) existed throughout stance phase. The termination step had a braking impulse ($36.8\pm8.6$ N-%SP/kg) that was smaller than both straight steps and the other turning steps, and it had a propulsive impulse ($58.8\pm12.1$ N-%SP/kg) that was larger than straight and initiation steps, but smaller than the apex step.

## 4. Discussion

This study compared the horizontal GRFs and GRIs for straight walking and three turning steps in a body reference frame. The data from this study differs from previous studies due to differences in experimental protocol, but also due to the inclusion of a body reference frame in this study. The effect of a body reference frame can be seen by comparing the anterior–posterior GRFs in the three previous studies that investigated the apex step; the propulsive forces of late stance were shown to decrease with increasing turning angle. They were largest in 45° turns (Houck, 2003), smaller in 60° turns (Patla et al., 1991), and nonexistent in 90° turns (Taylor et al., 2005). In contrast, the results of this study showed a large propulsive force for steps at the apex of a 90° turn. This discrepancy is likely related to the choice of a reference frame. The benefit of using a body as opposed to a global reference frame is that the GRFs and GRIs will be expressed in an anatomical perspective showing how they act on the body to cause changes in COM trajectory and trunk orientation during a turn.

Analyses of turning are complicated because in addition to changes in trajectory and orientation, the body also changes velocity (Hase and Stein, 1998, 1999). Therefore, some of the differences seen between GRIs in this study could be related to velocity changes as opposed to trajectory and orientation changes. Nonetheless, some insights can be gained by comparing this study to others investigating constant velocity circular walking and velocity changes during straight walking.

During constant velocity circular walking, it has been shown that the medial–lateral GRIs were a highly significant effect compared to straight walking with the impulses acting to shift the body towards the center of the circle (Orendurff et al., 2006). Similarly, the medial–lateral impulses during turning steps in this study differed significantly from straight walking, acting away from the direction of the turn. The lateral impulses were twice as large for the apex step compared to the other steps studied and likely contributed to the change in COM trajectory since trajectory changes would require larger impulses than those needed to cause a change in trunk rotation. However, the medial–lateral impulses during the turning steps may contribute in a lesser manner to changes in trunk orientation as well.

In an investigation of the kinetic mechanisms governing velocity changes during straight walking, deceleration was characterized by a larger braking impulse and a reduced propulsive impulse (Orendurff et al., 2008). A similar pattern was observed during turn initiation steps suggesting that the anterior–posterior impulses during the initiation step may act to decelerate the body going into the turn. Reciprocally, acceleration was characterized by a reduced braking impulse and a larger propulsive impulse (Orendurff et al., 2008). Likewise, the termination step exhibited a similar pattern suggesting that the anterior–posterior impulses during this step may act to accelerate the body coming out of a turn.

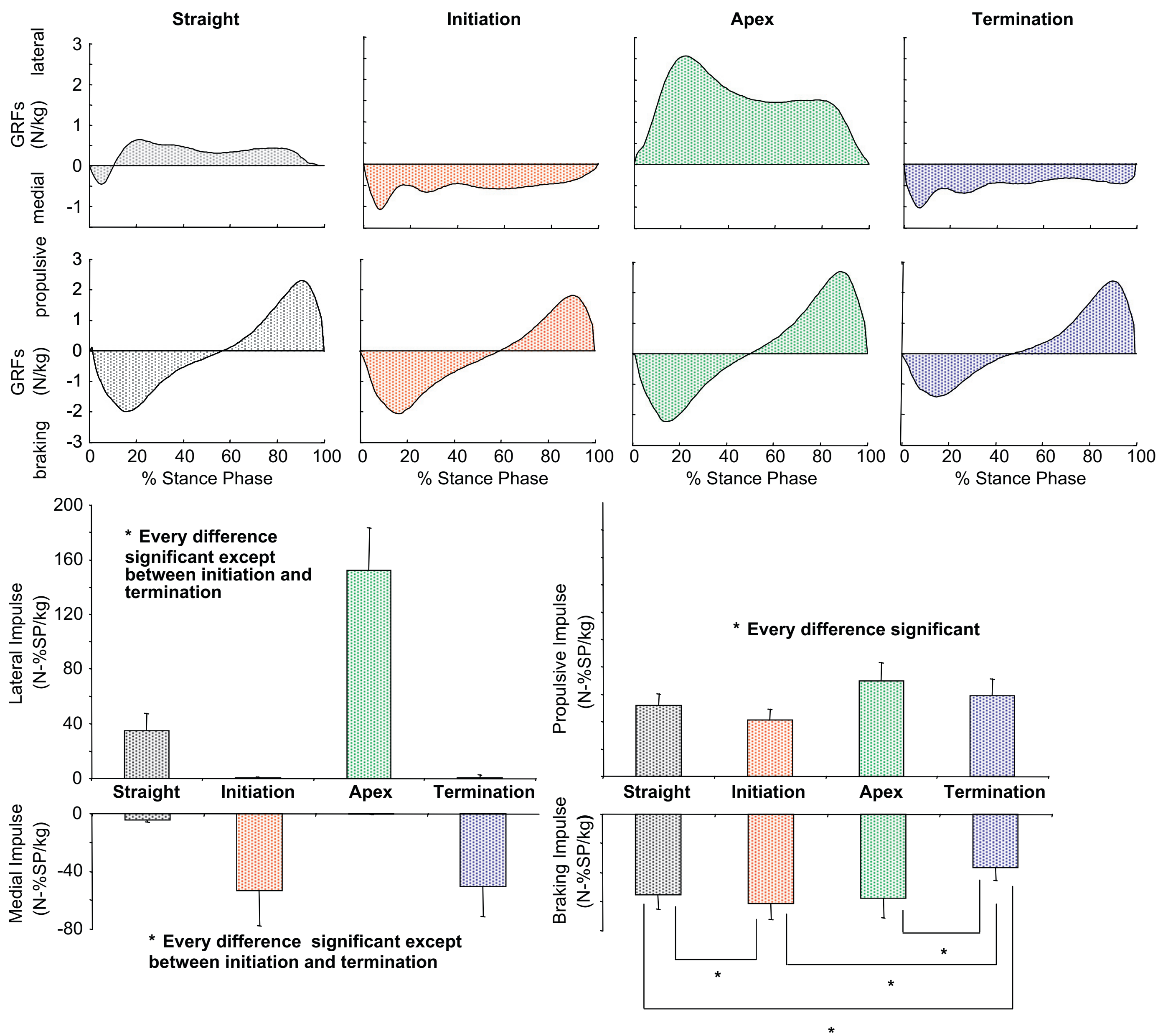


**Fig. 2.** Ground reaction forces and impulses for straight and turning steps. * indicates statistical significance at $p<0.05$.

In addition to speed changes, however, the braking and propulsive impulses may also contribute to body rotation. Jindrich et al. (2006), using data expressed in a global reference frame from Patla et al. (1991) and Houck (2003) suggested that the braking forces during the apex step act to prevent over rotation of the body. However, forces defined as braking in a global reference frame do not oppose the progression of the body throughout an entire turn. While it is entirely possible that braking forces prevent over rotation, this hypothesis should be tested with data expressed in a body reference frame.

## 5. Conclusion

This study is the first to present horizontal GRF and impulses expressed in a body reference frame for multiple steps of a turn. During the initiation step, a medial impulse existed throughout stance phase while the braking impulse was larger and the propulsive impulse was smaller than for straight walking. During the apex step, a very large lateral impulse existed throughout stance phase while the propulsive impulse was larger than for straight walking. During the termination step, a medial impulse existed throughout stance phase while the braking impulse was smaller and the propulsive impulse was larger than for straight steps. The results of this study provide insight into the biomechanical strategies governing turning maneuvers.

## Conflict of Interest

No conflict of interest, financial or otherwise, has influenced this work.

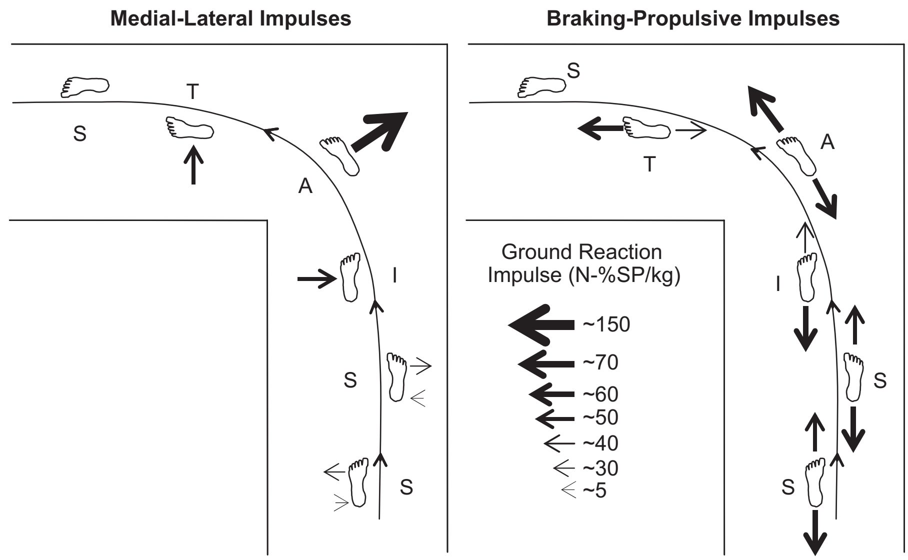


**Fig. 3.** Graphical depiction of the medial–lateral and braking–propulsive impulses for straight (S), initiation (I), apex (A) and termination (T) steps. Arrows are weighted based on the magnitude of the impulse.

## Acknowledgments

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