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Ground reaction forces and lower-limb joint kinetics of turning gait in typically developing children

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ABSTRACT

Turning is a common locomotor task essential to daily activity; however, very little is known about the forces and moments responsible for the kinematic adaptations occurring relative to straight-line gait in typically developing children. Thus, the aims of this study were to analyse ground reaction forces (GRFs), ground reaction free vertical torque (T_Z), and the lower-limb joint kinetics of 90° outside (step) and inside (spin) limb turns. Step, spin, and straight walking trials from fifty-four typically developing children were analysed. All children were fit with the Plug-in Gait and Oxford Foot Model marker sets while walking over force plates embedded in the walkway. Net internal joint moments and power were computed via a standard inverse dynamics approach. All dependent variables were statistically analysed over the entire curves using the mean difference 95% bootstrap confidence band approach. GRFs were directed medially for step turns and laterally for spin turns during the turning phase. Directions were reversed and magnitudes decreased during the approach phase. Step turns showed reduced ankle power generation, while spin turns showed large T_Z. Both strategies required large knee and hip coronal and transverse plane moments during swing. These kinetic differences highlight adaptations required to maintain stability and reorient the body towards the new walking direction during turning. From a clinical perspective, turning gait may better reveal weaknesses and motor control deficits than straight walking in pathological populations, such as children with cerebral palsy, and could potentially be implemented in standard gait analysis sessions.

1. Introduction

Turning is an essential component of gait (Glaister et al., 2007a) and is accomplished using primarily the inside (spin turn) or outside (step turn) leg (Hase and Stein, 1999; Patla et al., 1991; Taylor et al., 2005). Turning gait can be subdivided into initiation (approach), apex (turn), and termination (depart) phases (Glaister et al., 2008). During daily activities, the majority of turns rotate the body between 76° and 120° (Sedgman et al., 1994), leading many to study 90° turns in particular.

In adults, kinematic changes occur during 90° turning gait compared to straight-line walking. Presumably, these adaptations are driven by altered muscular patterns required to redirect the body centre of mass (COM) towards the new direction, as demonstrated by changes in ground reaction forces (GRFs), ground reaction free vertical torque (T_Z), and lower-limb joint moments and powers (Glaister et al., 2008; Hasan et al., 1991; Strike and Taylor, 2009; Taylor et al., 2005; Xu et al., 2006). To date, however, it remains unclear if similar adaptations occur in children, given their immature locomotor systems. Recent work from our group has demonstrated spatio-temporal and lower-limb joint kinematic adaptations during 90° turning gait (Dixon et al., 2013b), but the forces and moments responsible for these changes still require investigation.

Therefore, the aims of this study were to compare GRFs, T_Z, joint moments, and joint power during 90° turning gait (step and spin) and in straight-line walking in typically developing (TD) children. We hypothesised that (1) medio-lateral GRF would increase for turning compared to straight walking given the required direction change (Glaister et al., 2008; Segal et al., 2011), (2) T_Z would increase during spin turns as the foot rotates about the ground (Hasan et al., 1991), (3) joint moments at the ankle, knee, and hip, mainly in the coronal and transverse planes, would be modified to control turning gait kinematics (Taylor et al., 2005; Xu et al., 2006), and (4) peak ankle power generation would be decreased for turning compared to straight walking due to the decreased need for forward acceleration (Taylor et al., 2005).

Taken in combination with the results from our previous study (Dixon et al., 2013b), this investigation will lead to a broader

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understanding of turning biomechanics in TD children and could be used to assess turning gait adaptations in children with a range of gait disorders including those with cerebral palsy.

2. Methods

2.1. Subjects

Fifty-four TD children having performed straight and 90° turning tasks (left and right), recruited to construct our laboratory reference database, were considered for this study. All children were free of gait abnormalities and performed barefoot trials while fitted with retro-reflective markers according to the Plug-in Gait (PiG) (Kadaba et al., 1990) and Oxford Foot Model (OFM) (Stebbins et al., 2006) marker sets. Although kinematic analysis of a similar dataset resulted in 17 subjects having performed both turning conditions (Dixon et al., 2013b), few did so while correctly contacting the force plates. Limiting the analysis to these subjects would have been overly restrictive; instead, all subjects performing both straight walking trials and at least a single turning trial with clean force plate hits were considered (Table 1). Ethics approval was obtained from the local ethics committee and prior to the analysis session, informed assent/consent was granted.

2.2. Data collection and processing

Marker data were collected at 100 Hz via a 12-camera Vicon MX system (Vicon, Oxford, UK). Concurrently, two force plates (Advanced Mechanical Technology, Inc., Watertown, USA) collected GRF data at 1000 Hz. Knee flexion/extension axis was optimised to reduce cross-talk between the sagittal and coronal plane measurements (Baker et al., 1999). Marker data were filtered using the Woltring algorithm (Woltring, 1986) and knee and hip net internal joint moments and power were computed in Vicon Nexus (v.1.7 Vicon, Oxford, UK). Data were then exported to Matlab (v2011b, The Mathworks Inc., Natick, USA) for further analysis.

Table 1
Summary of group anthropometrics.

Condition	*n*	Age (yrs)	Weight (kg)	Height (m)	Sex
Straight	48	10.6 ± 2.9	39.6 ± 14.3	1.5 ± 0.2	22 F, 26 M
Spin apex	37	10.5 ± 2.9	39.1 ± 14.4	1.5 ± 0.2	15 F, 22 M
Spin approach	39	10.9 ± 2.9	40.5 ± 14.9	1.5 ± 0.2	18 F, 21 M
Step apex	16	11.3 ± 2.9	42.3 ± 14.7	1.5 ± 0.2	8 F, 8 M
Step approach	21	11.6 ± 3.0	43.7 ± 13.2	1.5 ± 0.2	9 F, 12 M

Mean (SD) anthropometric values for each group. All subjects performed straight walking trials. Numbers of female (F) and male (M) subjects also listed.

Centre of pressure (COP) and T_Z were obtained from the force plate data according to Kwon (1998). Specifically, T_Z was computed as:

$$T_Z = M_z - (x - x_0)F_x + (y - y_0)F_y \quad (1)$$

where M_z is the moment about the vertical axis of the force plate; x and y are the horizontal components of the COP; x_0 and y_0 are the horizontal components of the true origin of the force plate; F_x and F_y are the horizontal components of the GRF.

GRF, COP, and T_Z data were then filtered using a fourth order zero-lag Butterworth filter (18 Hz cut-off frequency) and down-sampled to match the kinematics. These data, along with anthropometric quantities, were input into standard inverse dynamics equations applied to the OFM to compute ankle (hindfoot with respect to tibia), three-dimensional net internal joint moments and power (Dixon et al., 2012). Unlike Dixon et al. (2012), who reported ankle moments when only the OFM forefoot segment made ground contact, here ankle moments were calculated for the entire gait cycle. Finally, joint kinetic data were filtered using a fourth order zero-lag Butterworth filter (10 Hz cut-off frequency). Turning style was determined by identifying the limb for which the single-limb support phase was responsible for the greatest amount of pelvic rotation. Thus, if more pelvic rotation occurred over the inside leg, the turn was identified as a spin turn, otherwise it was labelled a step turn (Dixon et al., 2013b).

To allow for anatomically meaningful analysis of GRFs, components were aligned with the turning direction (Glaister et al., 2007b) estimated via the horizontal projection of the anterior pelvic vector into the global system. The polarity of the medio-lateral component of the GRF (F_{ML}) and T_Z were reversed for trials where the left foot made contact with the force plate to maintain a common right foot reference system. Data for the left and right turns were pooled. Kinematic changes during turning gait have been previously identified between the second foot-strike (FS2) and the fourth foot-off (FO4) (Dixon et al., 2013b), representing approximately 162% of a gait cycle (Fig. 1). To capture the majority of this cycle for kinetics, data for the ipsilateral limb were partitioned from FO1 to FS3, from FS3 to FO3, and from FO3 to FS5, while data for the contralateral side were partitioned from FS2 to FO2 and from FO2 to FS4. Thus, force plate data were obtained for the approach (2nd) and turn (3rd) steps only (Fig. 1).

Events during force plate contact (FS2, FO2, FS3, and FO3) were identified using a 20 N cut-off, while the others (FO1, FS4, FO4, and FS5) were estimated using the marker coordinate algorithm of Zeni et al. (2008). After time normalisation, the ipsilateral and contralateral sides represented approximately 12–150% and 0–100% of the turning cycle, respectively. All quantities were normalised to body mass.

A representative trial for each subject and condition was obtained based on the minimum average root mean squared error of all dependant variables under study.

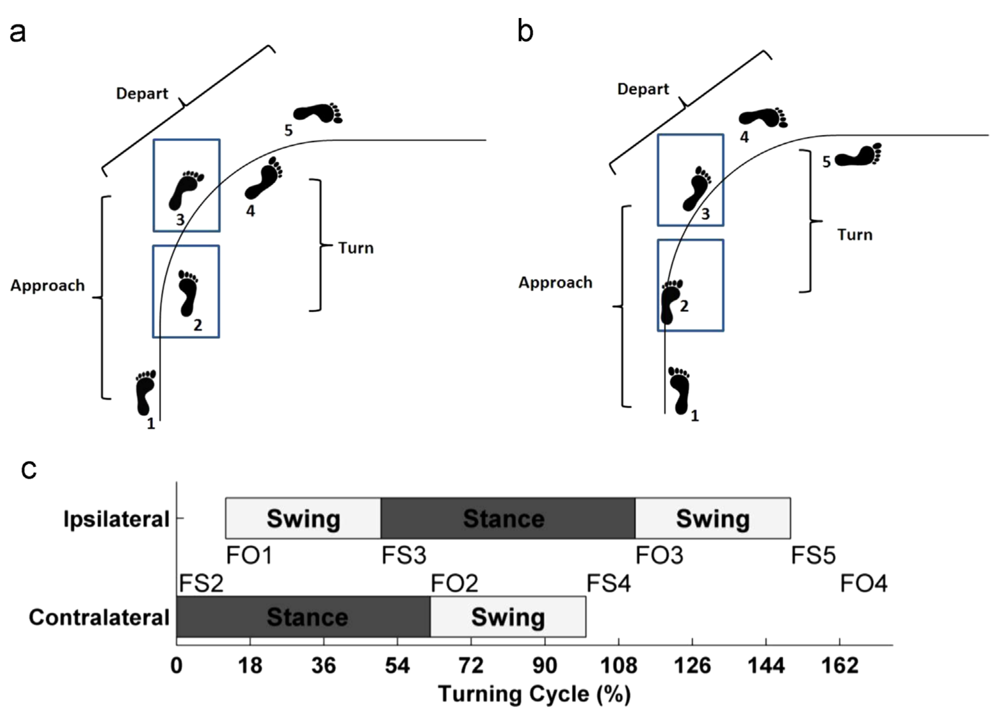

Fig. 1. Diagrammatic representation of turning techniques including foot-strike (FS) and foot off (FO) gait events: (a) a 90° step turn to the right (FS3 with left leg taken to be ipsilateral), (b) a 90° spin turn to the right (FS3 with right leg taken to be ipsilateral) and (c) turning events as a proportion of a complete turning cycle (162% gait cycle) (FS2 to FO4). FS2, FS3, and FS4 define the approach, turn, and depart phases of turning, respectively. For the ipsilateral limb, two swing and one stance phase are analysed (12–150%), while for the contralateral limb, a single stance and swing phase are studied (0–100%).