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# Examining anticipatory turn signaling in typically developing 4- and 5-year-old children for applications in active orthotic devices

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ABSTRACT

To develop active pediatric orthotics, it is important to accurately predict alterations to a straight path, such as turns. In this study we examine anticipatory signals prior to a pre-defined turn in seven healthy children. Subjects walked along a predefined 4.25 m straight path and then made either a 40-degree turn left or right, or continued straight based on a pre-set color panel at the endpoint. The forward center of mass (COM) velocity for the stride prior to the turn region was 1.16 ± 0.22 m/s (no significant difference was seen with respect to turn direction, $p > 0.05$). In the stride prior to landing in the turn region, subjects showed a significant difference in the mediolateral COM velocity with respect to the turn direction ($p = 0.003$ for 30% and $p < 0.0005$ for 40–100% of the gait cycle). No significant differences were observed in the sagittal plane kinematics of the hip, knee, or ankle during the preparatory stride with respect to turn direction ($p > 0.05$) when compared at 10% gait increments. However, significant differences were observed in pelvic rotation for 10–30% ($p < 0.05$) and 70–100% ($p < 0.0005$) of the gait cycle. The subjects were inconsistent in strategy used to perform a turn. In trials to the left and right, 66% and 56% of the trials were step turns, respectively. The varying turn strategy may be a function of limited instructions provided to the child, or ongoing development in the children's COM control. Yet even with the varying strategies, there exist anticipatory signals that can be used to design real-time controllers for assistive devices with readily available sensor systems.

## 1. Introduction

Technology development is ongoing in the field of adaptive orthotics that assist with daily tasks [1–5]. To develop active orthotics, it is important to accurately predict alterations to a straight path, such as turns, since the active orthosis may need to provide a different level of assistance. However, many gait studies focus primarily on adults during straight-path gait, with only a handful examining turning [6–10]. Since children and adults have different anthropometric scalings [11] and use different biomechanical strategies [12,13], devices designed for adults will not necessarily work for children without modification of the design and control algorithms. To develop active pediatric assistive orthotics with appropriate control systems, attention must be given to children's typical kinematics and anticipatory strategies. Applying anticipatory turning signals to the control of an orthotic device, pediatric or adult, is novel as these devices typically focus on control for straight-path gait [1–4].

While signals that anticipate a turn in children have not been previously studied, gait initiation has been shown to have anticipatory signals. For example during gait initiation, in children as young as 2.5 years old, the center of foot pressure moves backward and toward the stepping foot, which results in the forward and lateral shift of the center of mass (COM) position towards the stance leg. However, these trends are not consistent until children are 4–6 years old [14,15]. Determining changes in COM position by examining the velocity in the mediolateral (ML) and anteroposterior (AP) directions may allow for development of software that predicts gait initiation using postural data.

At its most basic level, turning requires body reorientation in the direction of intended travel [6]. Turns occur in a top-down sequence for adults, from the head to the torso, pelvis, and feet [6,8–10]. By examining trunk motion in adults, Patla et al. [6] suggest the COM motion anticipates a turn. Hollands et al. [8] further show that when examining the full body kinematics, COM translation was achieved through use of foot placement and hip motion. Since anticipatory signals are observed in gait initiation for children, and adults show COM anticipation prior to a turn, we

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hypothesize that there are anticipatory signals in children approaching a turn. In this work, we examine those signals that can be measured using sensors which could be embedded within a future orthotic device. In recent years, low power wireless communication and inertial sensing technologies have rapidly matured and enable real-time body motion measurement from sensors that can be embedded within an assistive device. Inertial measurement units (IMUs) provide information on rigid body translational acceleration and rotational velocity using three-dimensional accelerometers and gyroscopes, respectively. Using appropriate algorithms, such as Kalman filtering, the orientation of the rigid body can be determined [16,17]. Thus, for a joint of interest, an IMU can be placed on the rigid bodies surrounding the joint, permitting the calculation of the joint angle. While the IMU provides a reasonable estimate of rigid body orientation, it provides a poor estimate of rigid body translation. As global COM position would be difficult to determine using IMUs in an eventual clinical device, we examined COM velocity as an indicator of COM motion, as this measurement can be readily obtained using IMUs [16]. Specifically, we examined ML COM velocity as this direction describes the shift of the body from right to left in the coronal plane. If this ML COM velocity is non-zero over a time period, the parameter provides information on the evolving ML COM position.

In this study we examine anticipation to a pre-defined turn in 4- and 5-year-old children with the intention of using this information, in the future, to design an active orthosis. We hypothesize that in the stride prior to the turn, (1) there will be a shift in the subject's ML COM velocity that anticipates a change in body direction towards the target and that (2) lower-extremity kinematics provide sufficient information to determine a change in direction. To incorporate COM velocity into a device, an IMU would be required near the COM of the body, while to incorporate joint angles, IMUs would need to be placed on the limb segments.

## 2. Methods

### 2.1. Participants

Seven healthy children (4 girls and 3 boys, aged 4.86 ± 0.32 years, mass 18.1 ± 2.3 kg, height 108.1 ± 5.6 cm) participated in this pilot study after parental consent. Procedures were approved by Children's Hospital Boston's Clinical Investigation Committee. Participants were recruited if they were (a) between 14.5 and 22.7 kg and 96.5 and 119.4 cm tall, (b) able to walk without assistance, and (c) able to follow instructions in English. The acceptable mass and height ranges were based on the 30th percentile 4-year-old to the 70th percentile 5-year-old as given by standard pediatric charts. Subjects were excluded if they had a known health condition that could affect their balance or locomotion, or if they had a visual handicap that would prevent them from seeing the turn direction.

### 2.2. Experimental protocol

Participants were instructed to walk down a 4.25 m straight path and then make a 40-degree turn left/right, or continue straight based on a pre-set endpoint color panel (Fig. 1a). Due to limitations in the room, a second turn was incorporated into the path prior to the endpoint panels. The width of the designated path was 0.19 m. Participants were instructed to follow the direction of the path, but were not required to keep their feet within the path. The initial path length prior to the turn region was selected such that participants could have adequate time for gait initiation, followed by a steady state region prior to reaching the turn. Similar to Adolph et al. [18], we assumed that the first three steps are affected by gait initiation. Using the average kindergartner step length of 0.49 m [18], the path allows for approximately 8–9 steps prior to the turn region. Each endpoint consisted of a switchable colored wheel (black or yellow) behind a window, with a door underneath (Fig. 1b). Participants were instructed to follow the path to the yellow window, open the door, retrieve a token, and bring it back to the starting point. Participants completed 2 practice trials and 15 experimental trials at a self-selected walking speed. The experimental trials were randomized and consisted of 5 trials turning left, turning right, and continuing straight. If a child went to the incorrect endpoint, or prematurely stopped, the trial was repeated. No instruction was given regarding which foot participants should use to begin a trial or which foot should land in the turn region. Participants were offered an opportunity to take breaks between trials.

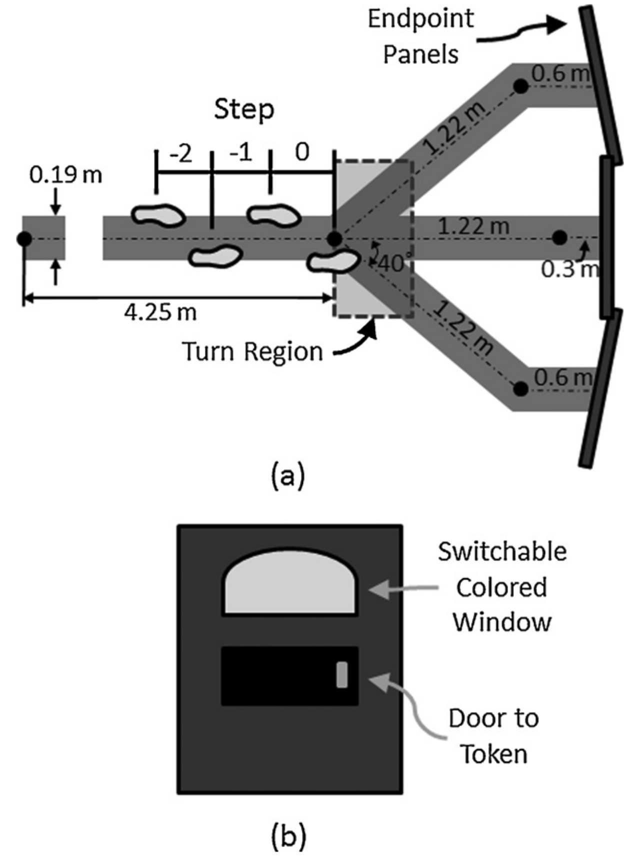

**Fig. 1.** (a) Schematic of the experimental setup. (b) Front view of an endpoint panel.

### 2.3. Data collection

Participant anthropometrics were measured for each subject, including total bodyweight and height, as well as body segment circumferences and lengths, for which key locations were defined by the Generator of Body Data (GEBOD) [19]. Three-dimensional motion data were captured at 120 Hz using eight Vicon MX-T40 cameras. Participants were provided with a sleeveless leotard, a snug-fit running cap, and shoes. Forty-eight reflective markers (diameter 9.5 mm) were attached to the participant using a modified Helen–Hayes marker set consisting of the following markers: forehead, top of head, back of head, over the ear, acromion process, sternum, bicep, lateral/medial humeral epicondyle, ulnar styloid process, radial styloid process, dorsal hand, anterior superior iliac spine, posterior superior iliac spine, anterior/posterior thigh, lateral/medial femoral condyle, anterior/posterior shank, lateral/medial malleolus, lateral/medial forefoot, toe, and heel. The markers located on the feet and head were placed on the shoes and cap, respectively. A camcorder, time-synced with the Vicon system, captured the steps surrounding the turn region (approximately 3–4 steps prior to the turn region and 2–3 steps after the turn region) so that foot landing in the turn region could be easily identified. While our design goal is to integrate IMUs into the device, we chose to evaluate the anticipatory signals using a Vicon system so that we could examine the full body kinematics. This allows us to minimize the number of IMUs required, while also decoupling the anticipatory control hypotheses from the determination of IMU placement, orientation, and calibration.

### 2.4. Data processing

Marker coordinates were exported to MATLAB v2009a (The Mathworks, Inc., Natick, MA) from Vicon Nexus v1.4 using the PECS interface and then filtered using a 6th-order low-pass Butterworth filter with a cut-off frequency of 10 Hz in the forward and reverse direction to achieve a zero-phase shift. Segment kinematics and body COM velocity were calculated using OpenSim v2.1 [20]. An OpenSim model, with 40 degrees-of-freedom, was scaled for individual body segments to match each subject. Based on the anthropometric measures, GEBOD was used to determine segment masses, inertias, and COM locations for all model segments for the individual subjects. The OpenSim model was then scaled and the inverse kinematics calculated for each trial. The final joint angles were filtered to remove high-frequency artifacts due to the inverse kinematics optimization process. A 6th-order low-pass Butterworth filter with a cut-off frequency of 10 Hz was again used in the forward and reverse direction. The COM velocities of the subject with respect