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Biomechanical evaluation of virtual reality-based turning on a self-paced linear treadmill

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ABSTRACT

Background: Patients with brain injuries such as Parkinson's disease or stroke exhibit abnormal gait characteristics especially during gait transitions such as step initiation and turning. Since such transitions could precipitate falls and resultant injuries, evaluation and rehabilitation of non-steady state gait in those patients are important. Whereas body weight supported treadmill training (BWSTT) provides a safe and controlled environment for gait training, it is unable to adequately train for gait transitions since the typical linear treadmill does not allow for changes in walking direction and natural fluctuations in speed.
Research question: This paper verifies if the suggested virtual reality (VR) based walking interface combined with the unidirectional treadmill can stimulate the user to initiate turning gait.
Methods: To validate whether initiation of turning was successfully achieved with the proposed walking system, we developed the VR-based walking interface combined with the self-paced treadmill and compared kinematics, kinetics, and muscle activation levels during the VR-based turning and overground (OG) turning as well as between straight walking and turning within conditions.
Results: Despite walking on a linear treadmill, subjects showed significant increases in head rotation, pelvic rotation, right hip abduction, left hip adduction, foot progression, medial-lateral ground reaction forces, right medial hamstring activation level, and changes in step width during the VR turn compared to straight walking.
Significance: The developed VR-based turning interface can provide a safe and controlled environment for assessment of turning in healthy controls and may have a potential for assessment and training in patients with neurological disorders.

1. Introduction

Recent studies on gait disorders in patients with Parkinson's disease (PD) and stroke have found that patients have difficulties during gait transitions such as step initiation, termination, and turning. They often exhibit increased tremor, hesitation, a loss of stability, or even falls. This phenomenon is termed freezing of gait (FOG) [1–3] known to be caused by problems in the basal ganglia circuit [1,4–6].

Since daily gait consists of both steady state walking and transitions such as accelerations, decelerations, and directional changes [7,8], it is important to include these in gait assessment and rehabilitation. Patients with brain injuries have fall rates of 40–70 % [9] during such gait transitions. Moreover, falls often cause other secondary complications or injuries.

BWSTT with a commercial linear treadmill has been widely used for gait rehabilitation, but it is currently limited in its ecological validity because it essentially provides stepping practice in a single direction. Since directional changes have also been shown to elicit FOG in PD [10,11] we undertook the challenge of trying to simulate this in our VR-based linear treadmill setup.

Previous studies reported the effect of VR on human gait by observing kinematic and kinetic changes in VR versus real environments. Specifically for turning, some researchers found that directional changes in the VR corridor could evoke head rotation and actual

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turning in overground [12,13] or on omnidirectional treadmills [14,15]; however it has not yet been shown whether VR with the linear treadmill could evoke turning mechanisms similar to OG turning.

This study aimed to verify whether it is possible to initiate turning on a VR-based self-paced linear treadmill. We analyzed biomechanical data from the following conditions: 1) VR-evoked turning on a self-paced linear treadmill, 2) straight walking on the same treadmill, 3) OG turning, and 4) OG straight walking. We compared the two turning conditions and we compared each turning condition to their respective straight walking condition. Analysis of turning biomechanics on the VR treadmill system could determine whether the proposed VR system can evoke similar turning mechanisms as in OG walking.

2. Materials and methods

Ten healthy young adults (age: mean 25.0 years, range 22.1–35.1 years; 5 males, 5 females) participated in the study. All subjects signed informed consent forms prior to participation, and the study was approved by the institution's Internal Review Board at the National Institutes of Health. We did not specifically instruct them how to turn on the treadmill in response to the VR cues, so we could evaluate whether the VR interface would intuitively stimulate the intention of natural turning mechanics.

To develop the VR-based turning interface, we combined the VR projection system and the self-paced walking treadmill (Fig. 1). Turning and self-paced walking were implemented by displaying a 90-degree direction change in the VR corridor and enabling the belt speed to be controlled by the intention to change direction and speed detected from movements of user's body parts. To assess the realism of a VR-based treadmill interface, biomechanical parameters were analyzed for VR turning versus VR straight walking, VR turning and OG turning, and OG turning versus OG straight walking. The head rotation angle as an intention of turning, changes in joint movements, ground reaction forces, muscle activity, and step length and width were measured. VR and OG turning experiments were conducted using the VR corridor on a linear treadmill and an L-shaped corner on a prescribed OG path, respectively. Due to space limitations in the laboratory, OG turns in only one direction (left turns) were performed and only the left VR turns were used in the comparisons.

Turning in the VR was controlled by head rotation and the VR was synchronized to move at the same speed as the treadmill. The VR created with 3D rendering software (Unity Technologies, US) consisted of a 42-meter hallway with three 90-degree turns (right, left, and left, consecutively). An integral of the head rotation angle was used to indicate turning intention when calculating the rotation angle of the VR corridor (Fig. 2). To prevent the VR (Φ_{VR}) from rotating back to the orientation prior to the turn as the head rotates back in line with the pelvis, the head rotation angle (θ_{head}) was integrated as follows:

$$\Phi_{VR} = K_{head} \int \theta_{head}\, dt \quad (1)$$

where K_{head} represents a constant gain value of 3.65 that adjusts the amount of VR rotation angle per head rotation angle.

To improve the realism of VR and help users perform self-paced gait on the treadmill, the speed of the treadmill belt was adjusted to accomplish the user's intended speed. For self-paced walking, the motion capture system (Vicon Motion Systems, US) tracked the real-time velocities of the pelvis and feet and a custom control algorithm [16–18] estimated a target speed of the belt (Fig. 2). The speed of the treadmill was then controlled to track the estimated target speed in real-time. Conceptually, the self-paced treadmill control reacts quickly to speed up or slow down based on the movement of the pelvis and feet.

OG straight walking and left OG turning were achieved by walking along the L-shaped path starting at the top of the L (Fig. 1). A portable screen was placed vertically on the inside corner of the L-shaped path to serve as the wall. The left turn had a 6 m long straight section followed by 4 m section after the turn.

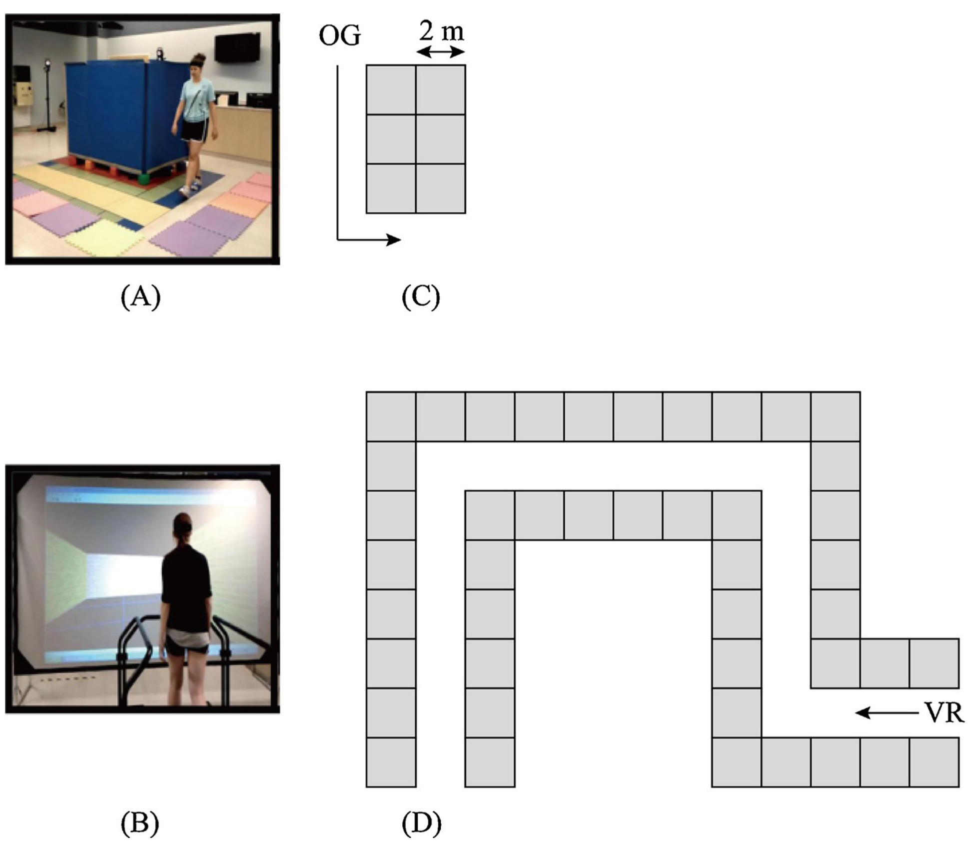

Fig. 1. Experimental setup (left) for (A) the overground and (B) treadmill turning with VR system (down) with maps (C and D) that used for each test.