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The Integrated Virtual Environment Rehabilitation Treadmill System

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Abstract

Slow gait speed and interlimb asymmetry are prevalent in a variety of disorders. Current approaches to locomotor retraining emphasize the need for appropriate feedback during intensive, task-specific practice. This paper describes the design and feasibility testing of the integrated virtual environment rehabilitation treadmill (IVERT) system intended to provide real-time, intuitive feedback regarding gait speed and asymmetry during training. The IVERT system integrates an instrumented, split-belt treadmill with a front-projection, immersive virtual environment. The novel adaptive control system uses only ground reaction force data from the treadmill to continuously update the speeds of the two treadmill belts independently, as well as to control the speed and heading in the virtual environment in real time. Feedback regarding gait asymmetry is presented 1) visually as walking a curved trajectory through the virtual environment and 2) proprioceptively in the form of different belt speeds on the split-belt treadmill. A feasibility study involving five individuals with asymmetric gait found that these individuals could effectively control the speed of locomotion and perceive gait asymmetry during the training session. Although minimal changes in overground gait symmetry were observed immediately following a single training session, further studies should be done to determine the IVERT's potential as a tool for rehabilitation of asymmetric gait by providing patients with congruent visual and proprioceptive feedback.

Index Terms

Adaptive systems; biomechanics; gait symmetry; locomotion rehabilitation; motor learning; self-paced treadmill; virtual environment

I. Introduction

Reduced gait speed and interlimb asymmetry are pervasive among individuals undergoing gait rehabilitation for neurologic or musculoskeletal disorders, including stroke, cerebral palsy, total joint arthroplasty, lower extremity amputations, and traumatic brain injury. In particular, individuals post-stroke demonstrate slow, asymmetric gait for years following the stroke [1]. Although walking on a standard treadmill involves greater symmetry than walking overground [2], [3], the completion of treadmill-based locomotor training for individuals post-stroke does not improve interlimb symmetry [4]–[6]. The goal of the present work was to develop and test a coupled virtual environment (VE) and treadmill system that can improve locomotor training by providing congruent visual and proprioceptive feedback regarding gait speed and asymmetry on a step-by-step basis. Here we demonstrate the system's feasibility as a rehabilitation tool for individuals with neurologic disorders.

A limitation of conventional locomotor training is that walking on a treadmill eliminates optic flow. Optic flow is the visual motion sensed by the eyes as the body moves through the environment, which is important for controlling gait speed [7], [8] and stride length [8], [9]. Incorporating a VE into treadmill training restores the optic flow of forward motion and may increase immersion and motivation [10], making visual information regarding movement relevant and important for improving walking patterns [7]. For individuals recovering from stroke, treadmill training with an integrated VE system has increased gait speed [11], endurance, and community participation [12]. However, it is critical for optic flow to match proprioceptive feedback from the limbs [8]. Any incongruence between leg velocity and optic-flow velocity will alter gait characteristics to reduce the mismatch between competing visual and proprioceptive feedback [8].

It is well known that movement patterns can be modified using visual or proprioceptive inputs (e.g., with prism glasses, virtual environments, posturography platforms, split-belt treadmills). Recent evidence suggests that walking on a split-belt treadmill with limbs moving at different speeds has the capacity to create adaptive changes in limb asymmetries [13]. Auditory feedback has also shown some success in altering interlimb asymmetry [14], however, the combination of visual and proprioceptive stimuli may represent a more powerful form of feedback for improving locomotor symmetry than sound. We believe that the use of visual and proprioceptive feedback regarding relevant measures of gait asymmetry (propulsive force, step length, stance time) will focus the patient's attention to enhance motor learning [13]–[15].

Our system, the integrated virtual environment rehabilitation treadmill (IVERT), couples an immersive VE with an instrumented split-belt treadmill. It provides the patient with appropriate and congruent visual and proprioceptive stimuli from the VE and treadmill belt speeds, respectively. A key feature of the IVERT system is a novel adaptive treadmill speed control algorithm, which dynamically controls the speed of the treadmill belts based on characteristics of the patient's gait. The patient's gait speed is estimated from ground reaction force (GRF) measurements, and the treadmill belt speeds are then adjusted to match the patient's pace and to keep the patient centered on the treadmill. Importantly, the speed of the patient's viewpoint motion in the VE is matched to the speed of the treadmill, so the patient receives visual feedback of gait speed. Finally, the IVERT system can simulate the experience of walking a curved path, visually and proprioceptively, by curving the trajectory in the VE, rotating the virtual viewpoint, and producing different speeds with the left and right treadmill belts. The magnitude and direction of curvature is determined by the patient's inter-limb asymmetry, allowing simulated path curvature to be used as real-time feedback for gait asymmetry.

We were motivated to represent gait asymmetry as walking a curved trajectory because during hemiparetic, asymmetric walking the paretic leg behaves similarly to the "inner leg" while walking a curved trajectory, in that the inner leg takes shorter steps compared to the outer leg [22], [23]. Likewise, walking on a split-belt treadmill with the belts running at different speeds has been compared to walking a curved trajectory because the leg on the slower belt takes shorter steps [24]. Drawing upon the similarities between pathological gait asymmetry and the natural asymmetry of healthy persons walking a curved path, we present a virtual locomotion trajectory that is curved proportional to the patient's gait asymmetry. Thus, patients can readily form an association between their asymmetry and the visual feedback provided by the curved path so that feedback is appropriate, natural, and intuitive. We report here on the design of the IVERT system and the results of a feasibility study involving patients with hemiparesis from a variety of central nervous system pathologies, all of which yield slow, asymmetric walking.

II. Methods

A. IVERT System

Participants received feedback from the IVERT system (see Fig. 1) while walking on a split-belt instrumented treadmill (Bertec Corp., Worthington, OH). Force sensors mounted below the parallel treadmill belts (170 × 40 cm each) measure the ground reaction forces and moments at 960 Hz via a Vicon system (Vicon MX+, Vicon Nexus 1.4, Vicon/Peak, Los Angeles, CA). These data are communicated to the control application computer (Dell XPS, Round Rock, TX) using VRPN [20], an open-source device-management and networking software layer designed for virtual-reality applications (see Fig. 2). The IVERT control algorithms determine the left and right treadmill belt speeds and the path the participant traverses through the VE. The participant's viewpoint in the VE moves at a speed that matches the treadmill's speed, which the participant actively controls.

1) User Control of Treadmill Speed—The IVERT control algorithm estimates the participant's gait speed in real-time from GRF and center-of-pressure (COP) measurements to produce treadmill belt speeds that match the participant's current gait speed, giving the participant active, real-time unencumbered control of the treadmill's speed. Gait speed is calculated as the product of cadence and step length at the beginning and end of each stance phase (four times per gait cycle). Stance phase is the period when the vertical GRF exceeds a threshold of 10% body weight. Step length is computed as the anterior–posterior distance between the COPs on the two force platforms at each heel strike. Estimates of acceleration are obtained by integration of the anterior–posterior GRF during the stance phase of each limb. A Kalman filter, with a two-state model (gait speed and acceleration), is used to combine these estimates. The process-noise model, Q(Delta;t, η), is a function of the sampling interval and a single parameter, η, that is determined by optimization as part of filter design (as in [21]). The variance of the measurement error for cadence and step length estimates are obtained from data gathered from control subjects walking at a variety of fixed speeds. The variance of the measurement error for acceleration is based on the variance of anterior–posterior force for a standing person of average weight. The Kalman model's three parameters (two measurement variances and one process noise parameter) are set a priori and need not be adjusted on a per-user basis.

To keep the participant centered on the treadmill, the control system uses a feedback controller based on the current estimated gait speed and the anterior–posterior position of the participant's center of mass (COM). The COM is determined from the COP on the two belts during each double-support and mid-stance period. Based on the anterior–posterior position of the COM relative to the center of the treadmill, an offset is added to or subtracted from the estimated gait speed to gradually move the participant toward the center of the treadmill.

2) Virtual Environment—While walking on the treadmill, participants view a virtual environment (VE) written using the Gamebryo graphics engine (Emergent Game Technologies, Inc., Calabasas, CA) that depicts a park with rolling hills, trees, rocks, and a trail lined with fence-posts. Though the treadmill remains level, the participant's virtual viewpoint translates up and down, remaining a fixed height above the virtual ground, as they go up and down hills. The height of the participant's eyes is measured prior to walking to provide accurate vertical position of the virtual viewpoint. The VE model, is 300×300 m in size, and repeats in all directions, making it effectively infinite in extent.

Dual Quadro FX 1800 video cards (nVidia, Santa Clara, CA) drive the VE display on three short-throw projectors (WT610, NEC, Itasca, IL) mounted in front of a three-panel display surface. The three images (each 1280×1024 pixels) combine to form a single image approximately 4.5 × 1.2 m in size, with a 175° horizontal and 60° vertical field of view. The front and side screens are located approximately 1.2 and 0.9 m, respectively, from the participant's eyes when the participant is centered on the treadmill.

B. Asymmetry Feedback

While participants are walking, the IVERT system computes gait asymmetry on a step-by-step basis and presents feedback to the participant 1) visually, as virtual path curvature in the VE and 2) proprioceptively, as different treadmill belt speeds. Because patients exhibit different forms of asymmetry (e.g., temporal, spatial, propulsive), the gait characteristic used to determine path curvature may be chosen to fit the patient's needs. IVERT currently supports asymmetry (side-to-side ratio) of stance time, step length, and propulsive force as feedback parameters. Propulsive force is computed as the integral of the anterior–posterior

GRF between mid-stance and toe-off. Mid-stance begins when the anterior–posterior GRF becomes positive.

1) Virtual Path Curvature—IVERT presents visual feedback of asymmetry by curving the virtual locomotion path in the VE. The curvature of the virtual locomotion path is varied continuously according to the participant's current asymmetry. The path curvature, κ, is determined by either propulsion, stance time, or step length as follows:

$$\kappa = -c \cdot \log_2 \left(\frac{PF_{\text{right}}}{PF_{\text{left}}}\right)$$
$$\kappa = +c \cdot \log_2 \left(\frac{ST_{\text{right}}}{ST_{\text{left}}}\right)$$
$$\kappa = -c \cdot \log_2 \left(\frac{SL_{\text{right}}}{SL_{\text{left}}}\right)$$

where PF_{right} and PF_{left} are the integrals of propulsive force, ST_{right} and ST_{left} are the stance times, SL_{right} and SL_{left} and are the step lengths for the most recent step on each side. A scale factor c can be increased to progress training so that a small amount of asymmetry will yield a larger curvature. A higher value of c magnifies gait asymmetry to allow the participant to more easily observe the effects of gait changes, however c must not be set so high that the rate of rotation of the virtual viewpoint exceeds comfortable limits. The value of c may be adjusted manually for the individual, or computed based on pre-trial measurements of the participant's asymmetry. In this study we used a value of $c = 0.30$ but this value was increased to 0.40 for the participants with less severe asymmetry.

A Kalman filter is used to improve the reliability of path curvature estimates and to ignore misregistered steps (e.g., due to cross-over between belts). Path curvature is updated twice per gait cycle: at the end of each stance phase (for propulsion or stance-time feedback) or at the beginning of each stance phase (for step length feedback). To prevent abrupt changes in virtual path curvature, a low-pass filter (1 Hz cutoff) is applied and the result is resampled to a rate of 60 Hz (making the sample period 16.6 ms or approximately 1% of the gait cycle for a person walking at a rate of 75 steps/min).

2) Belt Speed Difference—Participants are also provided with proprioceptive feedback in the form of different treadmill belt speeds. The estimated gait speed, described above, forms the treadmill's base speed v_{base}, which is the average speed of the two treadmill belts. Based on the direction and degree of asymmetry in the participant's gait, one belt will move faster than v_{base} and one belt will move slower than v_{base}

$$\begin{aligned} v_{\text{diff}} &= w \cdot \kappa \cdot v_{\text{base}} \\ v_{\text{left}} &= v_{\text{base}} + \frac{v_{diff}}{2} \\ v_{\text{right}} &= v_{\text{base}} - \frac{v_{\text{diff}}}{2} \end{aligned}$$

where κ is the virtual path curvature (a function of the participant's asymmetry) and w is a scale factor that controls the magnitude of the proprioceptive feedback. Thus, the sensitivity of proprioceptive and visual feedback are controlled independently. All participants here used $w = 0.25$.

C. Participants and Training Protocol

Five participants with central nervous system pathology resulting in hemiparesis used the IVERT system to improve gait symmetry. We recruited two individuals with chronic stroke (male, 57 years old, 32 months post-stroke; male, 53 years old, 48 months post-stroke), two adults with hemiparetic cerebral palsy (male, 53 years old; female, 57 years old), and one adult (male, 45 years old) with hemiplegia resulting from a hemi-craniectomy intended to treat an oligodendroglioma in the right parietal lobe. All participants could walk without assistance, although one individual with stroke routinely used a cane and an ankle-foot orthosis.

Each individual participated in a single session of training with the IVERT system. The session consisted of 20–40 min of treadmill walking while receiving visual and proprioceptive feedback about gait symmetry. All participants wore a safety harness attached to an overhead support that slides along a track, allowing participants to move forward or backward on the treadmill freely.

Participants began the IVERT training session with several minutes of acclimation to the adaptive treadmill speed control system. Participants practiced until they could demonstrate the ability to independently start, stop, accelerate, and decelerate the treadmill using the GRF-based control system. Although the VE display was visible during the acclimation period, path curvature was disabled and belts were operated at the same speed. Once the participant was comfortable with the system, feedback was enabled (virtual path curvature and differential belt speeds), and the participant began a series of trials. Each trial lasted 5–10 min, depending on the participant's level of fatigue, and each participant performed four trials (with the exception of Participant 4, who stopped after three trials). Path curvature and belt speed difference were controlled by propulsive asymmetry in the first two trials and by stance time asymmetry in the final one or two trials. Between trials, participants were given several minutes rest.

Participants were instructed to walk at a comfortable pace and to keep the locomotion path through the virtual environment as straight as possible. Although they were told that gait symmetry controlled path curvature, they were given no specific instruction about which gait characteristics to modify. Our goal was to encourage participants to actively engage in the learning process, experimenting with different means of modifying their gait while receiving real-time performance feedback.

D. Outcome Measures

Immediately before and after the IVERT training session, participants walked overground on a GAITRite mat (CIR Systems, Havertown, PA). Each participant completed three trials at their self-selected comfortable gait speed and three trials at the fastest possible walking speed. For the self-selected speed, participants were instructed to walk at their normal, comfortable pace; for the fast speed, participants were instructed to walk as fast as they safely could. Partial steps (e.g., beginning or end of the walkway) and marks from assistive devices were removed automatically using the GAITRite software or manually by the investigators. The editing process left an average of 18 ± 6 steps per subject for the self-selected condition, and 13 ± 2 steps per subject for the fast walking speed condition. Gait velocity, stance time, single support time, and step length were computed for each limb using the GaitRite analysis software. Asymmetry was calculated as the ratio of paretic-to nonparetic-side measures. A value of 1.0 indicates perfect symmetry; we consider values less than 0.9 or greater than 1.1 to be asymmetric [1]. We performed a Wilcoxon matched-pair signed-rank test ($\alpha = 0.05$) to compare overground symmetry before and after training for stance time, single support time, and step length at both the self-selected and fast speeds.

During the IVERT training session, time-stamped force and COP data were captured from the treadmill's force plates and recorded using VRPN. These data were used to assess within-session changes in temporospatial and propulsive asymmetry. Specifically, a Wilcoxon rank sum test ($\alpha = 0.05$) was used to compare the average symmetry from the first minute of walking to the last minute of walking. An additional comparison was made between the average symmetry during the first minute of walking and the average symmetry during the minute of walking with the greatest amount of symmetry (e.g., "best" minute).

We recorded comments the participants made during walking trials. Between trials and at the end of the session we asked participants about usability (how hard was it to learn to use the system, what was easy, what was hard, what they liked and did not like about the experience) and what modifications they made to their walking in order to straighten their virtual path.

III. Results

None of the participants had prior experience using the treadmill system, yet participants quickly became comfortable with walking on the IVERT system and were able to maintain a stable speed. Fig. 3 shows some representative examples of treadmill belt speeds during the first 5 min of walking on the treadmill with adaptive speed control. Most participants' initial treadmill speed during the first 5 min was comparable to their overground gait speed. For each participant, overground (OG) gait speed and average treadmill (TM) speed during the first 5 min were as follows: P1 (OG: 1.02 m/s; TM: 1.16 m/s), P2 (OG: 0.51 m/s; TM: 0.45 m/s), P3 (OG: 1.00 m/s; TM: 0.61 m/s), P4 (OG: 0.67 m/s; TM: 0.77 m/s), and P5 (OG: 1.01 m/s; TM: 1.15 m/s). In a typical session, the average belt speed difference was approximately 0.05 m/s but would occasionally increase to 0.10 m/s or more.

Qualitatively, we noticed a general tendency for participants to increase symmetry during the IVERT training sessions. While gait symmetry was not statistically different between the first and last minute of each trial ($p = 0.109$), we observed that in 79% of the trials, the minute with the greatest amount of temporospatial or propulsive symmetry occurred within the final 2 min of walking. The first minute of walking was therefore significantly more asymmetric than the "best minute" of each trial ($p = 0.009$). Fig. 4 shows the propulsive force from each limb of two participants during the course of several trials in which propulsive force asymmetry was used to control path curvature. The solid curve indicates the smoothed time series, low-pass filtered with a cutoff frequency of 0.5 Hz. While the step-by-step propulsive forces appeared to become more symmetric during the training period in these two participants, they used different strategies to increase symmetry.

Participant 3, for instance, increased propulsive force from the paretic limb during the course of the training session [Fig. 4(e) and (g)]. Specifically, we visually observed an increase in paretic side propulsion within each trial and a higher overall level of propulsion in the second trial compared to the first. In contrast, Participant 1 showed a different pattern of adaptation, with propulsion on the paretic side remaining roughly constant while nonparetic propulsion was decreased to achieve symmetry [Fig. 4(a)].

The overground gait asymmetry for stance time for the five participants at self-selected and fast walking speeds are displayed in Fig. 5. Overall, very minimal changes to overground symmetry were observed immediately after IVERT training. No significant differences were found at the $\alpha = 0.05$ level. At the self-selected walking speed, stance time ($p = 0.68$), single support time ($p = 0.23$), and step length asymmetries ($p = 03.5$) remained unaltered immediately after a single session of IVERT training. Likewise, no differences were observed at the fast speed ($p = 0.14$ for stance time asymmetry, $p = 0.08$ for single support time asymmetry, $p = 0.50$ for step length asymmetry).

1) Participant Comments—Several participants said the task was more exhausting mentally than physically. These participants said that they were most focused on what they needed to do in order to maintain a straight path. Other comments related to the visual environment. Some mentioned that appreciated have a concrete goal: keeping the VE from rotating, walking on the road, or walking towards a specific landmark (e.g., tree or rock). One participant noted that she was motivated to walk straight by her desire to eliminate unintended turning. Most comments related to the visual feedback, while only two of the participants reported that they noticed the difference in speeds between the two belts.

IV. Discussion

The IVERT system is intended to provide appropriate and congruent visual and proprioceptive feedback to serve as a tool for rehabilitating asymmetric gait in individuals with hemiparesis. Our feasibility study demonstrates that individuals with hemiparesis can successfully acclimate to the system and perceive the feedback regarding asymmetry. Substantial improvements in overground walking symmetry were not observed in the majority of subjects after just one training session. Further work will be needed to assess the capabilities of this system in creating long-term changes in overground gait through repeated use.

Our approach differs from the work of others in several respects. The adaptive treadmill control algorithm described here uses only GRF as inputs. In contrast, other self-paced motorized treadmills have required flexible tethers to monitor the anterior/posterior position of the participant on the treadmill [7], [10] or rigid mechanical tethers to monitor the forces exerted about the COM during treadmill walking [19], [25]. Monitoring the COM, however, assumes that leg movements are symmetrical, because the independent contributions of each side are not incorporated into the computation of the speed of the treadmill belts. Due to the marked gait asymmetries present post-stroke [26], [27], independent measurements from each side are required for accurate proprioceptive feedback of limb movement. Independent control of treadmill belt speeds by each limb has been accomplished previously by monitoring the electrical current required to drive the treadmill's motors [24]. Compared to this method, the force-instrumented treadmill provides a richer data source that enables us to implement a more sophisticated algorithm, using precise measurements of the timing, position, and propulsive force of each step to determine the treadmill belt speeds.

The adaptive speed control is coupled with an immersive VE to provide a realistic optic flow and sense of motion through the VE as well as to enhance participant motivation. Although others have successfully coupled VEs with treadmill control [9], [10], [28], the IVERT system's ability to control locomotion speed and heading through the VE without the use of hand-held controls or devices attached to the body [19], [25] provides patients with a more natural and unencumbered interface. We believe that the participants' relative lack of awareness of the belt speed difference is due to one or more of these factors: the matched visual and proprioceptive cues simulate path curvature effectively enough that the belt speed difference seems natural, participants were too immersed in the VE to notice, or the relative magnitude of the difference was too small to be detected.

An important feature of the IVERT system is that the gait parameter used to control curvature feedback can be chosen to fit the dominant type of the patient's asymmetry. Although we have focused here on just two control parameters (stance time and propulsive force), we have the capability to choose from other parameters of gait. For example, a patient who exhibits substantial temporal asymmetry might be provided with feedback based on single support time or stance time, while a patient with spatial asymmetry might be provided with feedback based on step length. The ability to customize the IVERT system for each individual patient provides a promising alternative to "one size fits all" approaches.

As individuals adjust gait symmetry during training, they receive immediate feedback. We propose that this process of active learning by experimentation and feedback may be more effective than methods that rely upon inconsistent, qualitative feedback from a therapist. Other training paradigms have used a split-belt treadmill with the belts running at different fixed speeds to restore symmetry in individuals post-stroke [13]. The improvement in symmetry through motor-adaptation becomes evident as an after-effect, which washes out quickly once belt speeds are returned to the same speed [13], and translates only briefly to overground walking [29].

Others have shown small transfers of gait symmetry from treadmill to overground walking by eliciting after-effects from neural adaptation [29], [30]. Given the fact that we did not perturb walking in a similarly dramatic way, it would be surprising if gait patterns were substantially altered by the single session. To alter walking behavior in the long term, through repeated training sessions, we believe that the IVERT system can help make patients aware of their gait patterns and encourage patients to work actively to adjust their patterns using accurate and relevant feedback.

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Biographies

Jeff Feasel received the B.S. degree in computer science from the University of Buffalo, Buffalo, NY, and the M.S. degree from the University of North Carolina at Chapel Hill, where he is currently a graduate student in the Department of Computer Science.

His current work is in developing treadmill-based virtual locomotion interfaces for training and clinical applications. Previous work has involved the development of sensors, human interface devices, 3D interaction techniques, and automated evaluation of training performance. He has developed several novel locomotion interfaces, including walking-in-place, joystick, and treadmill-based locomotion. He works with the Effective Virtual Environments research group at UNC Chapel Hill and collaborates with the Interdisciplinary Human Movement Sciences Laboratory.

Mary C. Whitton (SM'09) is a research Associate Professor of Computer Science at the University of North Carolina at Chapel Hill. She co-leads the Effective Virtual Environments research group that investigates what makes virtual environment systems effective and develops techniques to make them more effective for applications such as simulation, training, and rehabilitation. Before joining UNC in 1994, she was co-founder of two companies that produced high-end hardware for graphics, imaging, and visualization.

Ms. Whitton is a member of ACM and ACM SIGGRAPH. She has held leadership roles in ACM SIGGRAPH including serving as President from 1993 to 1995.

Laura Kassler (S'09) received an undergraduate degree from High Point University, High Point, NC, and the M.S. degree from Wake Forest University, Winston-Salem, NC. She did additional graduate work at The University of North Carolina at Chapel Hill, working with the Effective Virtual Environments research group and collaborating with UNC's Interdisciplinary Human Movement Sciences Laboratory

She is currently working as an Instructor at Alamance Community College.

Frederick P. Brooks, Jr. (LF'97) was an architect of IBM's Stretch and Harvest supercomputers in the 1950s. In the 1960s, he was Corporate Project Manager for development of IBM's System/360 computer family hardware, and the OS/360 software. He founded the UNC Department of Computer Science in 1964 and chaired it for 20 years. His current research is in interactive graphics and virtual environments. His best-known books are The Mythical Man-Month (1975,1995), Computer Architecture (with G.A. Blaauw, 1997), and The Design of Design (2010).

Dr. Brooks received the National Medal of Technology and ACM's Turing Award.

Michael D. Lewek received the B.S. degree in exercise science from Ithaca College, and the MPT and Ph.D. (biomechanics and movement science) degrees from the University of Delaware. He worked as a post-doctoral fellow at the Rehabilitation Institute of Chicago from 2004 to 2006.

Since 2007, he has been on faculty at the University of North Carolina at Chapel Hill. His research interests focus on locomotion, with an emphasis on mechanisms of and interventions for ameliorating gait dysfunction in individuals with neurological disorders.

Fig. 1.
IVERT system's treadmill and virtual environment.

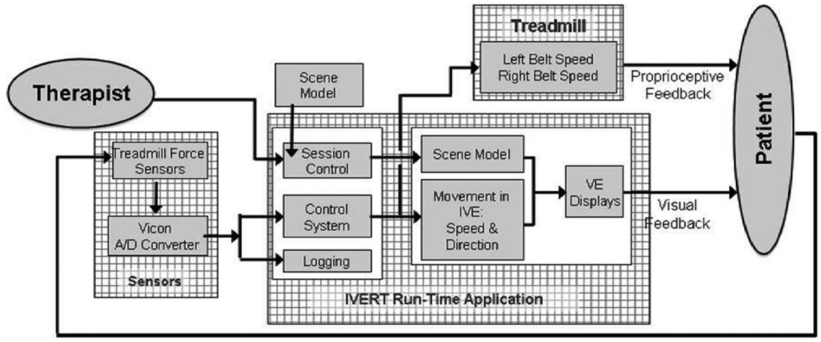

Fig. 2.
Block diagram of the IVERT system.

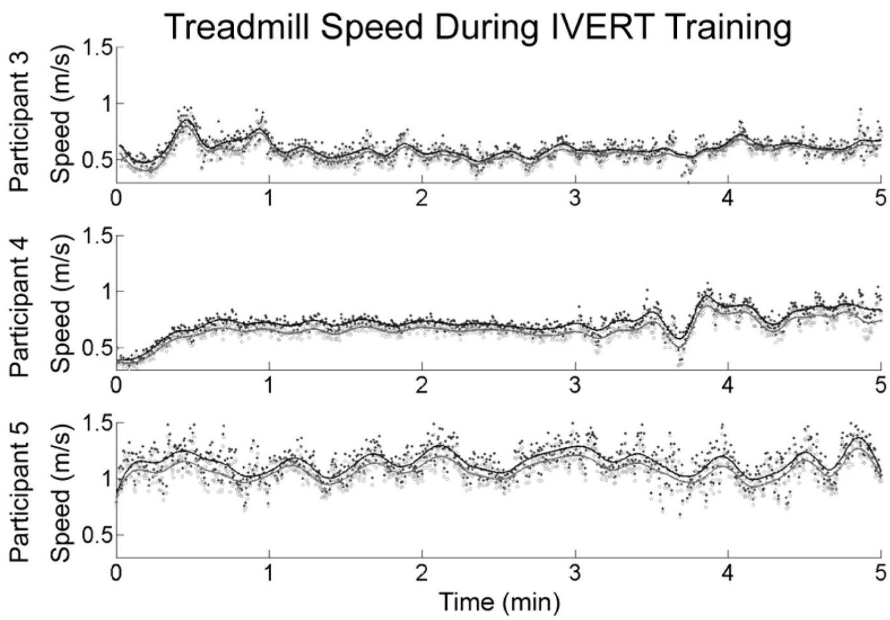

Fig. 3.

Representative examples of treadmill speed displayed over the first 5 min of walking with adaptive treadmill speed control. The speeds of the two belts differ based on the participants' current asymmetry. Gray and black circles indicate treadmill belt speeds for each step of the paretic and nonparetic side, respectively. The solid curves show the smoothed time-series (paretic side gray, nonparetic side black).

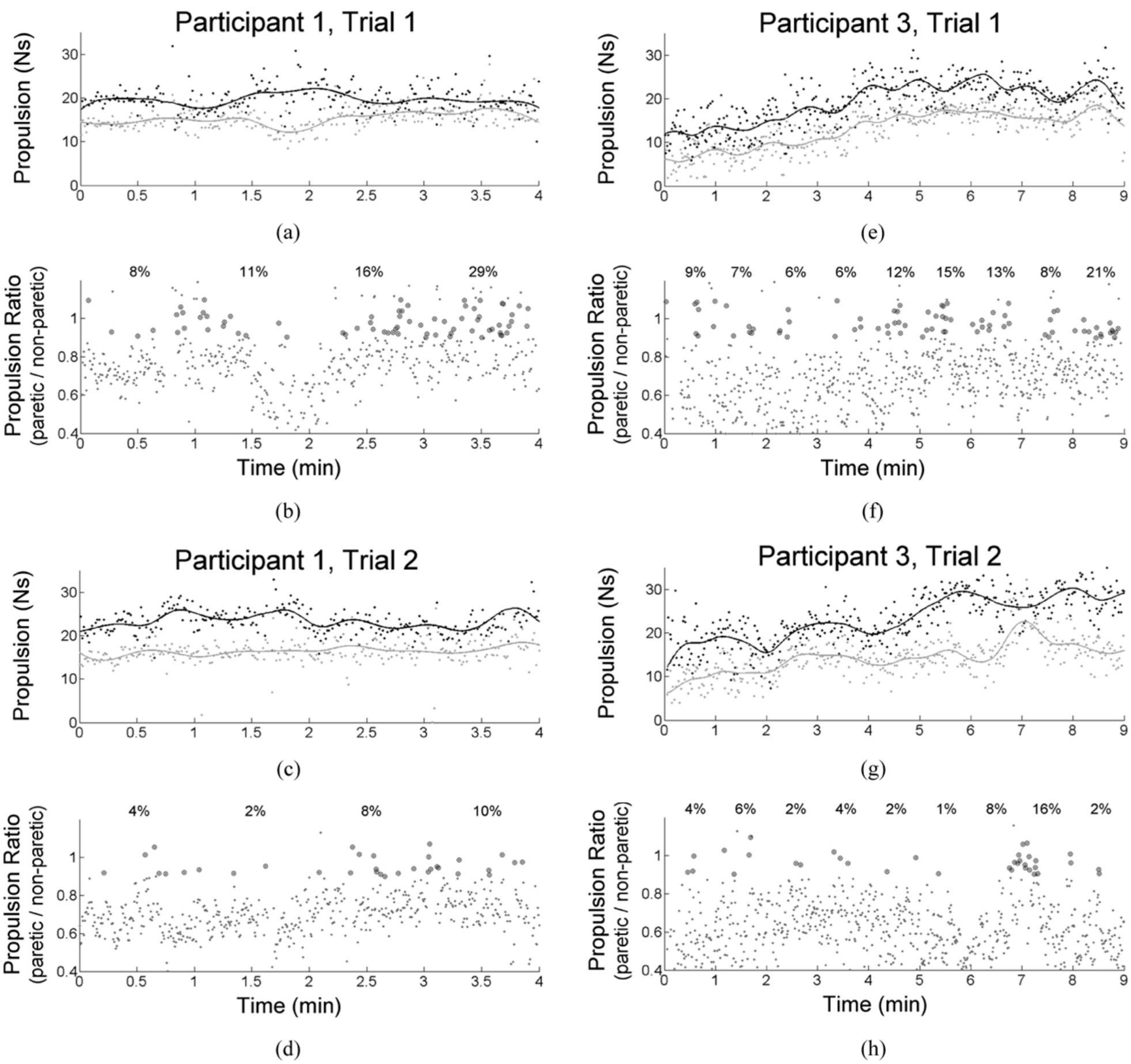

Fig. 4.

(a), (c), (e), (g): Representative examples of propulsive force for each limb as a function of time. Each point represents the integral of anterior–posterior force between mid-stance and toe-off. The solid curve indicates the smoothed time-series. The nonparetic side is shown in black; the paretic side in gray. (b), (d), (f), (h): The ratio of propulsive force (paretic/ nonparetic) from the most recent step of each limb. Points within 10% of symmetrical (0.90–1.10) are highlighted. The percentage of steps within 0.90–1.10 during each 1-min interval is shown at the top of the graph.

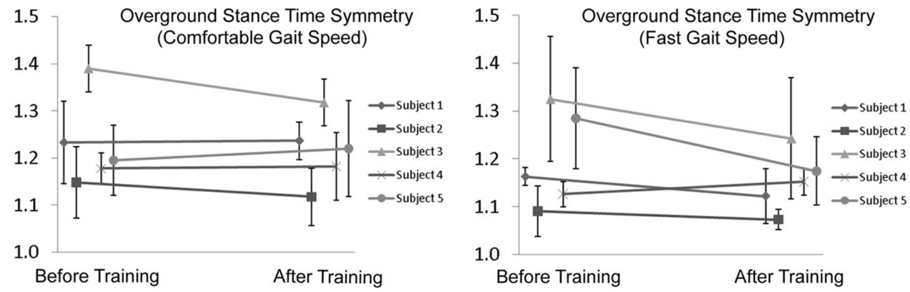

Fig. 5.

Individual measures of stance time symmetry in overground gait before and after training with the IVERT system. Symmetry was measured at a self-selected, comfortable gait speed and at a fast gait speed.