CyberWalk: Enabling Unconstrained Omnidirectional Walking through Virtual Environments

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Despite many recent developments in virtual reality, an effective locomotion interface which allows for normal walking through large virtual environments was until recently still lacking. Here, we describe the new CyberWalk omnidirectional treadmill system, which makes it possible for users to walk endlessly in any direction, while never leaving the confines of the limited walking surface. The treadmill system improves on previous designs, both in its mechanical features and in the control system employed to keep users close to the center of the treadmill. As a result, users are able to start walking, vary their walking speed and direction, and stop walking as they would on a normal, stationary surface. The treadmill system was validated in two experiments, in which both the walking behavior and the performance in a basic spatial updating task were compared to that during normal overground walking. The results suggest that walking on the CyberWalk treadmill is very close to normal walking, especially after some initial familiarization. Moreover, we did not find a detrimental effect of treadmill walking in the spatial updating task. The CyberWalk system constitutes a significant step forward to bringing the real world into the laboratory or workplace.

Categories and Subject Descriptors: J.4 [**Computer Applications**]: Social and Behavioral Sciences—*Psychology*

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1. INTRODUCTION

In recent years, virtual reality (VR) has seen significant advances in the quality of 3D graphics, visual displays [Edgar 2007; Patterson et al. 2006], 3D audio [Kapralos et al. 2008], and haptic interfaces [Fritschi et al. 2008; Iwata 2008; Laycock and Day 2003]. For navigation through virtual environments (VEs), high-fidelity driving [Kemeny and Panerai 2003; Kemeny 2009] and flight simulators have been developed, as well as multipurpose simulators [Teufel et al. 2007; Valente Pais et al. 2009]. Thanks to these developments, VR is now an essential tool in such diverse areas as skill training (for instance in the medical domain [Vidal et al. 2006; Aggarwal and Darzi 2009; Seymour 2008; Mohan and Proctor 2006] and in aircraft pilot training), rehabilitation [Erren-Wolters et al. 2007; Holden 2005], and neuroscience [Bülthoff and van Veen 2001; Sanchez-Vives and Slater 2005; Tarr and Warren 2002], as well as in the treatment of anxiety disorders [Gregg and Tarrier 2007; Choy et al. 2007; Powers and Emmelkamp 2008], and of other psychological problems [Riva 2005]. Moreover, it finds increasing application in domains such as education [Torres 2008], gaming [Rizzo et al. 2006], industrial prototyping, and architecture. However, one area where, until recently, only few successful VR interfaces have been developed is that of active locomotion through large VEs.

In daily life, our most intuitive way to navigate through the world is on foot. In fact, throughout the largest part of our evolutionary history as modern humans, walking has been the only mode of transportation for our ancestors [Weaver and Klein 2006]. Most current VR setups, however, do not offer the possibility of walking through VEs, or do so only in a very restrictive manner. In most cases, users simply navigate through the VE using keyboard, mouse, joystick, or similar input devices. This creates a sensory conflict, where the user is physically not moving, but receives visual input congruous with self-motion. Behavioral studies suggest that this sensory conflict may impede the formation of an accurate spatial representation of the environment and impair navigation performance [Ruddle and Lessels 2006; Chance et al. 1998; Bakker et al. 1999]. In addition, this conflict is thought to increase the risk of simulator sickness [Bertin et al. 2005; Macefield 2009; Jones et al. 2004].

In order to allow for natural walking through large-scale VEs, we need an omnidirectional locomotion interface. Although several clever solutions have been developed to enable omnidirectional walking through large-scale VEs (see the supplemental materials), to the best of our knowledge a device that makes truly unconstrained omnidirectional walking possible still does not exist. In the CyberWalk research project, we set out to develop an omnidirectional treadmill system that allows for exactly that. Our main goal was to achieve walking that would be as natural as possible. This puts several constraints and requirements on the treadmill system in terms of its size, possible speeds and accelerations, and on the control of treadmill velocity. Here, we describe the design of our system, highlighting the novel features and the ways in which it is optimized for natural walking (Section 2). In Section 3 we outline the treadmill velocity control system, based on the position and walking velocity of the user. We performed several behavioral experiments, which allowed us to test the effectiveness of our new device and compare walking behavior on the treadmill to normal walking (Section 4). Finally, in Section 5 we discuss our findings, as well as possible improvements on and applications of the CyberWalk treadmill.

2. DESCRIPTION OF THE OMNIDIRECTIONAL CYBERWALK TREADMILL SYSTEM

Our CyberWalk treadmill is based on a torus design similar to Iwata's treadmill [Iwata and Yoko 1999; Iwata 1999]. However, we developed and implemented several new design solutions to overcome some of the shortcomings in Iwata's original design. Several of these solutions have been patented [Schwaiger et al. 2008b, 2008a]. The CyberWalk system was developed with the following design requirements in mind. First, it should support normal walking speeds, allowing users to walk the way they would on a normal stationary surface. Second, it should be able to change its speed and direction quickly enough to compensate for any changes in walking velocity within the normal range of walking behavior in order to keep the user within the confines of the walking surface at all times. At the same time, however, it should be large enough to limit these accelerations to levels which, ideally, will not be noticeable to the user, and in any case do not make the user unstable. Third, the system should be safe to use, even for users with no previous experience of walking on it.

Apart from these three main requirements, some other features were also desired in order to make immersive walking in VR possible. The walking surface should consist of one continuous surface, without noticeable gaps, and it should feel as stiff as a normal stationary walking surface. Vibrations in the platform and auditory noise should be restricted to a minimum. And, finally, the system should be easy to integrate with other VR equipment, such as tracking systems, visualization, and audio systems.

2.1 Required Speed, Acceleration, and Size

The normal walking cycle can be divided into an acceleration phase, a deceleration phase, and a steady-state or rhythmic phase [Kaufman and Sutherland 2006]. During these respective phases, the walking speed as perceived by the walking person depends on sensory feedback from several senses. During steady-state walking, the perceived walking speed is dominated by vision, in particular by the optic pattern generated on the retina [Gibson 1950; 1966; Koenderink and Doorn 1987; Lappe et al. 1999; Warren and Hannon 1988], as well as by the relative motion with respect to objects in the surrounding environment. In this phase, vestibular input is not very strong, and is thought to play only a minor role in the perception of walking speed [Mittelstaedt and Mittelstaedt 2001; Glasauer et al. 1994]. During the acceleration and deceleration phases, however, the vestibular system provides the brain with critical information concerning the changes in walking speed. This inertial input was shown to be important for the perception of walking speed and for maintaining postural stability [Mittelstaedt and Mittelstaedt 2001; Jahn et al. 2000; Fitzpatrick et al. 2006]. When simulating normal walking on a treadmill, it is therefore important to retain these inertial cues during acceleration and deceleration phases. This can be done in two ways. The first solution is to apply an external force to the body of the user by means of a mechanical tether, in order to simulate accelerations and decelerations, even though the user hardly moves out of place. Although this principle has been shown to work, adequate application of the forces to the body of the user is difficult [Christensen et al. 2000; Hollerbach et al. 2000; Checcacci et al. 2003]. Moreover, generalization of this system to a truly omnidirectional locomotion interface is not straightforward, because the actuation of the tether has to be constructed in such a way that it does not interfere with omnidirectional walking. Therefore, we decided to take a different approach. On the CyberWalk treadmill, changes in walking speed are not immediately fully compensated for by the treadmill, but only gradually. When the user starts to walk from a standstill, the treadmill gradually increases its speed, but at a lower rate than the acceleration of the user. Consequently, the user initially walks out of the center of the platform and is then only slowly brought back. Similarly, when the user stops walking or changes the walking direction, the treadmill responds gradually, allowing for the normal inertial input to the vestibular system. This system has been shown to work very well for controlling treadmill speed on a large linear treadmill [Souman et al. 2010].

In order to allow the user to receive adequate inertial input, the walking surface has to be large enough to accommodate several steps without large changes in treadmill speed. From pilot studies on a linear treadmill, we determined that the minimum size of the walking surface that would accommodate this control scheme was at least 6×6m [Souman et al. 2010]. However, financial and mechanical considerations made us limit the eventual size to 4×4m. This size allows for changes in treadmill speed that are low enough to maintain the postural stability of the user, but makes it unavoidable that these accelerations will sometimes be noticeable to the user. In terms of speed, the treadmill has to

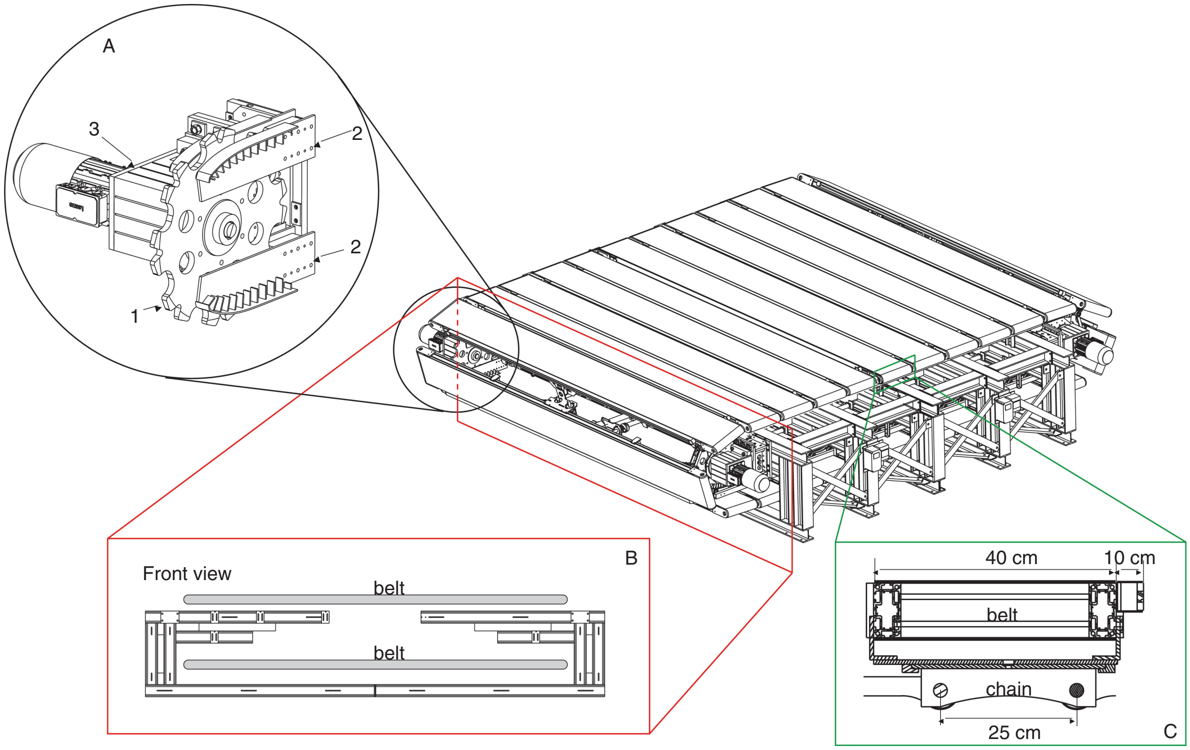

Fig. 1. The CyberWalk omnidirectional treadmill. A: one of the sprocket wheels (1) with clothoid guiding rails (2), and drive with gearbox (3). B: front view of the supporting structure, with cantilever beams. C: cross-section of an individual belt, with the larger (40cm) and smaller (10cm) belt segments.

accommodate the range of normal walking speeds, up to 2m/s. In order to keep the user within the walking surface, accelerations up to 1m/s^2 should be possible [Souman et al. 2010; Brenière and Do 1991].

2.2 Basic Design

The CyberWalk treadmill consists of 25 segmented belts 5m-long and 0.5m-wide, which are mounted on two large chains in the shape of a torus (Figure 1). The belts constitute one direction of motion, while the chains form the perpendicular direction. The chains are capable of speeds up to 2m/s, while the belts can run at 3m/s. In practice, speed in both directions is limited to 1.4m/s, to reduce wear and tear. The maximum accelerations are 0.5m/s^2 in the main chain direction and 0.75m/s^2 in the belt direction. The footprint of the platform is 6.5×6.5m, with a height of 1.45m. The total treadmill system weights about 12000Kg, with a moving mass of approximately 7500Kg. A smaller version of the treadmill has been described in Schwaiger et al. [2007].

To prevent the different belt segments from slapping together when they go round from bottom to top or vice versa, the chain is guided on rollers over a special guiding rail. Where the rollers leave the linear rail on the top side of the platform, they are guided onto a circular rail of radius R by using a joining clothoid profile, where the curvature changes linearly from zero to $1/R$. This eliminates the step in rotational speed, which Iwata's Torus treadmill suffered from [Iwata and Yoko 1999; Iwata 1999]. At the lower side, a similar reverse circular-clothoid profile guides the chain back to a linear rail (see Figure 1, A). The chains are driven by four powerful motors (10kW each), placed at the corners of the platform (Figure 1). The two motors pulling the chains in the same direction are equipped with incremental encoders. Their controllers are frequency coupled, using a master-slave architecture to ensure exact synchronization. The two motors on the other end generate a slight counter momentum, keeping tension on the part of the chain which is on top. This way, the two chains always run at the same speed, and jerkless reversals of motion direction are possible.

Each belt segment has its own smaller motor (1.5kW), consisting of an asynchronous drive with a planetary gearbox. The drives are controlled by frequency converters with sensorless vector control to provide a constant speed independent of belt load. To be able to drive the belts and still have a nearly gapless walking surface, each belt is divided into two parts (40cm and 10cm wide, respectively). In addition, the narrower part is less high, making it possible to install the mounting clamp of the main chain, support rollers and belt actuation (see Figure 1, C). Both belt parts are driven by the same roll drive, ensuring synchronous motion. This construction allows for a walking surface with gaps between the different belts which do not exceed a few mm. The belts only run when they are on top. As soon as the chains transport them to the lower side of the platform, the belts are switched off to prevent excessive wear and tear on the belts when they are in a nonhorizontal orientation. To this end, each belt segment is equipped with a bar code, which is read by a single bar code reader as the belts move past. From the bar code information, the low-level control system determines which belts should be switched on or off.

Since the main chain rotates endlessly, it is a challenging problem as to how to feed the energy and the data bus to the belt segments. This is solved by a combination of a linear guide and rotational feedthrough. Inside the platform, a linear rail with a carriage and trailing cable system has been mounted. An electric rotational feedthrough is placed on the carriage. It can transduce five lines with 230V and 40A of alternating current, as well as four shielded lines for the data bus. The system is actuated by an elastic belt which connects the rotating part to one belt segment. The motion of the belt segment tows the energy supply. Power and data transmission are fed through from one belt to the next.

As noted above, the platform is a large and heavy device. Overall weight has been minimized by using lightweight materials such as aluminium where possible. To keep the mass of the device as low as possible, while at the same time guaranteeing structural stability and stiffness, the supporting framework consists of two cantilever beams, with a gap in the center (Figure 1, B). The gap provides space for the power supply to move with one of the belts, as described above.

The treadmill is embedded in a raised floor, which only leaves the 4×4m walking surface visible (Figure 2). The gap between floor and walking surface is made as small as possible (ca. 1cm), to prevent users from getting stuck in it with their feet. Users wear a safety harness connected to the ceiling, to prevent them from falling and getting their hands into this gap. In addition, the harness prevents users from reaching the edge of the platform with their feet. It does not offer any support while walking, allowing for normal walking. For safety, users are observed by an experienced operator at all times. Both the operator and the user have immediate access to an emergency button, which stops treadmill actuation instantly. The entire system, including the emergency function, is battery-buffered, providing controlled shutdown even in the case of power failure. The kinetic energy of the moving mass is used to decelerate the entire system in an emergency stop.

3. TREADMILL VELOCITY CONTROL

The high-level treadmill control system determines how the treadmill responds to changes in walking speed and direction of the user (see Figure 3). It is designed in such a way that it allows the user to execute natural walking movements in any direction. It tries to keep the user as close to the center of

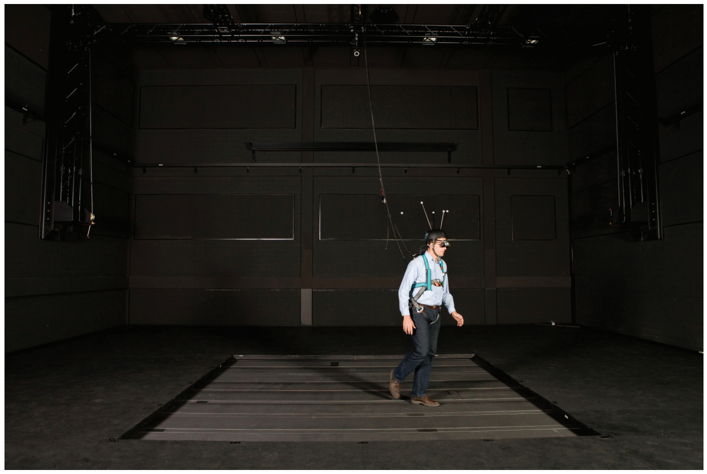

Fig. 2. The CyberWalk treadmill built into a raised floor. The user wears a head-mounted display for visualization and a helmet with infrared-reflecting markers for tracking purposes. The safety harness prevents the user from walking off the treadmill and from reaching the treadmill surface with his hands.

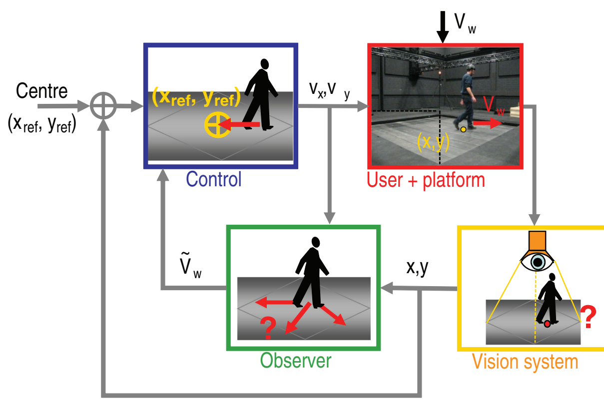

Fig. 3. Higher level control system. The treadmill system aims to keep the user in the center of the treadmill (x_{ref}, y_{ref}). To this end, the walking velocity (v_w) of the user is estimated by a linear Observer system, which uses the treadmill velocity and user position as inputs.

the platform as possible, while at the same time taking perceptual bounds for speed and acceleration of the moving surface into account. In this section, we briefly illustrate the modeling assumptions and control design adopted to solve the treadmill control problem. For a full description of the control design, see De Luca et al. [2009]. A perceptual evaluation of a one-dimensional implementation of the same system has been described previously [Souman et al. 2010].

3.1 Treadmill Model

Both treadmill directions (x and y) are actuated independently by servo-controllers which accept high-level velocity reference commands and provide low-level torque output. However, the control law has been designed at the acceleration level, with the velocity control inputs computed by numerical integration. Acceleration control is better suited to take the limitations of both the platform and the human user into account, while ensuring a smoothly changing velocity input to the platform.

The interaction between the walker and the platform can be modeled by the following second-order linear system

$$\begin{aligned} \dot{x}_i &= v_i, \\ \dot{v}_i &= a_{ci} + a_{wi}, \end{aligned} \qquad i = 1, 2 \tag{1}$$

where x_i is the (measurable) position of the walker and v_i is the speed of the user, both relative to a stationary frame of reference; a_{ci} denotes the acceleration of the platform, while a_{wi} represents the user's (intentional) acceleration. Indices $i = 1, 2$ represent the two planar directions $x_1 = x$ and $x_2 = y$ on the platform surface, with $x_1 = x_2 = 0$ denoting the platform center. Position information is provided by an optical tracking system, which tracks the position and the orientation of the head of the user. This data is not only used for treadmill control, but also for visualization. The orientation θ_w (around the vertical axis) of the user cannot be modified by the platform motion, and is thus not included in the kinematic model (1). We did, however, use the orientation of the user to improve the control behavior (see Section 3.3).

3.2 Control Design

The simplest way to stabilize system (1) and keep the user at a desired position x_{ref} would be to use a control law of the form:

$$a_c = -a_w - k_v v + k_p(x_{ref} - x), \tag{2}$$

in each of the two planar directions, with gains $k_p > 0$ and $k_v > 0$ (the directional index $i = 1, 2$ was dropped for simplicity). However, this requires knowledge of the immeasurable quantities v and a_w, which describe the *a priori* unknown intentional motion of the user. This problem can be solved by replacing v and a_w in Eq. (2) by proper estimates $\hat{v}$ and $\hat{a}_w$, that is, by taking

$$a_c = -\hat{a}_w - k_v \hat{v} + k_p(x_{ref} - x). \tag{3}$$

The voluntary acceleration a_w of the user (an external disturbance for the control system) is estimated by the disturbance observer,

$$\begin{aligned} \dot{\xi}_1 &= \xi_2 + k_1(x - \xi_1) \\ \dot{\xi}_2 &= a_c + k_2(x - \xi_1) \\ \hat{a}_w &= k_2(x - \xi_1), \end{aligned} \tag{4}$$

where gains $k_1 > 0$, $k_2 > 0$, and (ξ_1, ξ_2) is the observer state. Transforming these equations in the Laplace domain, we obtain

$$\hat{A}_w(s) = \frac{k_2}{s^2 + k_1 s + k_2} A_w(s) = F_1(s) A_w(s). \tag{5}$$

This shows that the estimation $\hat{a}_w$ is a stable, low-pass filtered version of the unknown quantity a_w.

Similarly, a separate estimation of the user's absolute velocity v (an unmeasurable state of the system) is provided in the so-called "dirty derivative" form of the position measure by the linear observer,

$$\begin{aligned} \dot{\xi}_3 &= k_3(x - \xi_3) \\ \hat{v} &= k_3(x - \xi_3), \end{aligned} \tag{6}$$

with gain $k_3 > 0$ and state ξ_3. In the Laplace domain, this yields

$$\hat{V}(s) = \frac{k_3 s}{s + k_3} X(s) = \frac{k_3}{s + k_3} V(s). \tag{7}$$

Note that the dynamics of the two estimations $\hat{v}$ and $\hat{a}_w$ are completely independent. Moreover, after short transients, the two estimates in Eqs. (4) and (6) converge to their true values when the user is moving at constant acceleration and, respectively, at constant velocity. Having a good estimation $\hat{v}$ of the user's velocity with respect to a stationary reference makes it possible to estimate a user's voluntary walking velocity v_w as

$$\hat{v}_w = \hat{v} - v_c, \tag{8}$$

where v_c is the velocity of the controlled platform. This variable can be either numerically integrated from (3), or measured from the low-level platform controller; we used the latter method. The estimated walking velocity $\hat{v}_w$ may be used to update the visualization of the virtual scene.

3.3 Control Tuning

Users are most sensitive to changes in platform speed when they are standing still [Souman et al. 2010]. Consequently, the most difficult situation for unobtrusive platform control is when the user abruptly stops walking. In this case, the treadmill has to decelerate sufficiently fast to keep the user within the boundaries of the platform and then bring the user back to its center. However, it should not stop too quickly because this would destabilize the user. To understand this, consider the analogy of a person walking forward in a moving train. As long as the train is moving at a constant speed, accelerations and decelerations during walking are unproblematic. However, if the train stops at the same moment that the person stops walking, the person's momentum would catapult him/her forward. Abrupt changes in treadmill velocity would have the same effect and, besides endangering the user (by the risk of falling), would disrupt the immersiveness of the VR. Therefore, changes in treadmill speed should be kept as small as possible. Depending on how fast the user is walking before stopping and what his/her position on the platform is, these two constraints of keeping the person within the walking area and reducing changes in treadmill speed may be incompatible. One way to lessen this problem is to "virtually" increase the size of the treadmill by changing the reference position x_{ref}, depending on the walking velocity of the user. Instead of keeping x_{ref} (the position to which the system aims to bring the user back to) always at the center of the platform, this reference position is shifted towards the platform boundary in the direction of user velocity. Such behavior can be implemented by defining

$$x_{ref} = k_{ref} \arctan \hat{v}_w, \tag{9}$$

where the *arctan*() function serves to saturate the shift of the reference position, and the gain k_{ref} determines the limits of this saturation.

While walking, the user is much more stable along the walking direction (X_w) than in the orthogonal, lateral direction (Y_w). Therefore, larger changes in treadmill speed can be commanded in the walking direction without disrupting VR immersiveness. To take advantage of this, we designed the control law (3) in the coordinate frame (X_w, Y_w) attached to the user. This coordinate frame is rotated by angle θ_w relative to that of the platform (this angle represents the orientation of the user relative to the platform and is provided by the tracking system). The control gains in the X_w direction may be higher than those in the Y_w direction, causing the platform to change its speed more quickly in the X_w direction. Before commanding the desired velocity to the platform, the acceleration commands resulting from (3) must be rotated back to the coordinate frame (X, Y) attached to the platform. From an implementation point of view, this is equivalent to computing (3) with variable (i.e., θ_w-dependent) position and velocity control gains along the (X, Y) directions. For instance, we use the position gain matrix,

$$K_p(\theta_w) = R(\theta_w) K_{p_w} R^T(\theta_w),$$

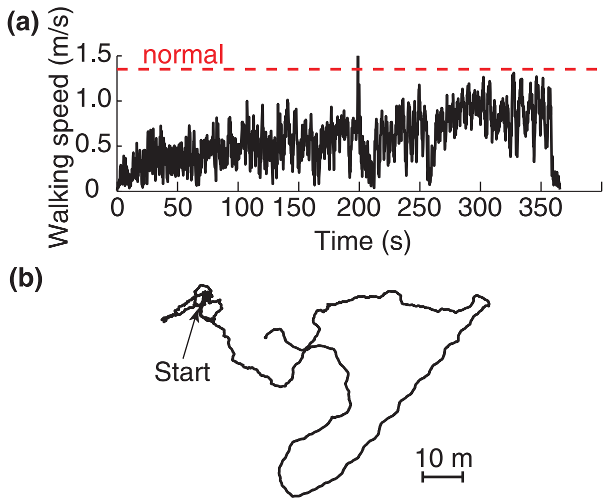

Fig. 4. Example data from a naïve user in the Virtual Pompeii scenario. (a) Walking speed over time. The dashed horizontal line indicates average normal speed (about 1.35m/s). (b) Trajectory walked.

with

$$R(\theta_w) = \begin{bmatrix} \cos\theta_w & -\sin\theta_w \\ \sin\theta_w & \cos\theta_w \end{bmatrix},$$

where $K_{p_w} = \mathrm{diag}\{k_{p_{x_w}}, k_{p_{y_w}}\}$ is the chosen diagonal and constant position gain matrix in the frame (X_w, Y_w) attached to the user. The velocity gains k_v are transformed in a similar way.

A formal proof of closed-loop stability, and additional discussion of the experimental validation of the proposed control law can be found in De Luca et al. [2009].

4. BEHAVIORAL EVALUATION

In the first few weeks of operation, close to a hundred people walked on the treadmill. In the demonstration scenario, a virtual model of the ancient city of Pompeii before the Vesuvius eruption in 79 AD was used. Users could explore the streets and enter houses. The model was based on actual archeological data and created by our CyberWalk partner of the Computer Vision Laboratory at the ETH in Zürich, using the CityEngine software package (Procedural, Zürich, Switzerland) [Müller et al. 2006]. The first observation we made was that walking behavior varied considerably between users. Some persons started to walk at a fast pace right from the beginning. Others were much more apprehensive, and only walked very tentatively. Most users started walking at a much slower speed than normal, and then gradually increased their speed when they started to get used to the device and to gain trust in it. An example of typical walking speed profile and trajectory is shown in Figure 4.

In order to evaluate the effectiveness of the new treadmill setup, we performed two behavioral experiments. The task of the participants was to walk on a circular path with normal walking speed. In addition, the first experiment required them to judge what angle the arc they walked subtended. Walking in a small circle, with a radius comparable to the size of the platform, presents a real challenge to an omnidirectional walking system, since the treadmill has to constantly change its velocity in order to keep the user on the platform. Comparing walking behavior on the treadmill with normal overground walking will show to what extent we succeeded in simulating real, natural walking in VR with our treadmill setup.

In many VR setups, a desktop interface is used to move through the VE, for instance with a mouse, joystick, or keyboard. Hence, information about the layout of the environment comes mainly from visual input. Physical walking through an environment is thought to provide additional information about its layout and to help in spatial navigation and cognition [Ruddle and Lessels 2006; Chance et al. 1998; Usoh et al. 1999]. If our treadmill setup is successful in simulating normal walking, these benefits of actual walking in spatial updating tasks should also be present when participants walk on the treadmill. To test this, participants in the first experiment were asked to not only walk along a circle, but also to judge how far they walked. This is a difficult task, which has been shown to be affected by the availability of attentional resources [Takei et al. 1997, 1996]. Hence, if treadmill walking distorts the perceptual cues that come from normal walking, or is more attentionally demanding, performance on this spatial updating task should deteriorate. Spatial updating performance (either during normal overground walking or during treadmill walking) was compared to that in a condition where participants did not walk, but navigated with a joystick. In this condition, only visual information concerning the traveled angle was available. Hence, comparison of the spatial judgments in this condition to those in the treadmill and normal walking conditions will show to what extent actual walking is important for spatial updating.

4.1 Experiment 1: Walking an Arc of a Circle by a Specified Angle

4.1.1 *Methods: Participants.* Twelve students from the Eberhard Karls University in Tübingen served as paid participants (age range 21 to 27; 7 females). They all had normal vision and none of them reported any locomotor or vestibular problems. Participants gave their written informed consent, after being instructed about the experiment and the treadmill. None of them had walked on the treadmill before.

Stimuli and apparatus. The experiment was carried out in large hall (12×12 m walking area), equipped with a 16-camera Vicon MX13 optical tracking system (Vicon, Oxford, United Kingdom). The treadmill is located in this tracking hall, built into a raised floor (see Figure 2). For the normal walking condition, the treadmill was covered with wooden boards with a thick rubber coating, creating one continuous walking area. The position and orientation of the participant's head were tracked with the Vicon system at 120Hz. To this end, the participant wore a helmet with infrared reflecting markers. The tracking data were used to update the visualization and to control the treadmill velocity. In the no-walking condition, the participant was seated and tracking data was not used to update the visualization.

Visual stimuli were presented in a head-mounted display (eMagin Z800 3DVisor, eMagin, Bellevue (WA), USA; resolution 800×600 pixels, refresh rate 60Hz, 32×24 deg field of view). The HMD was built into goggles, preventing the participant from seeing anything else but the image on the displays. To suppress auditory cues to direction from the treadmill and from environmental sounds, participants wore ear plugs and a pair of noise-canceling headphones. White noise was played over the headphones, masking any remaining environmental sounds. Responses were given via a gamepad, which participants held in their hands throughout the experiment.

Participants were guided on a circular path by a virtual purple icosahedron (diameter 10cm), which served as a visual target and moved above a ground plane with a random texture (Figure 5(a)). The target icosahedron always moved on a circle with a radius of 4m. The speed of the target was determined by the walking speed of the participant. The target was always positioned 50cm in front of the position on the circle closest to the position of the participant. Hence, if the participant did not follow the target, it would get smaller in the display and disappear to the side until the participant walked back to the circle again. In the condition where participants did not walk, the virtual scene camera

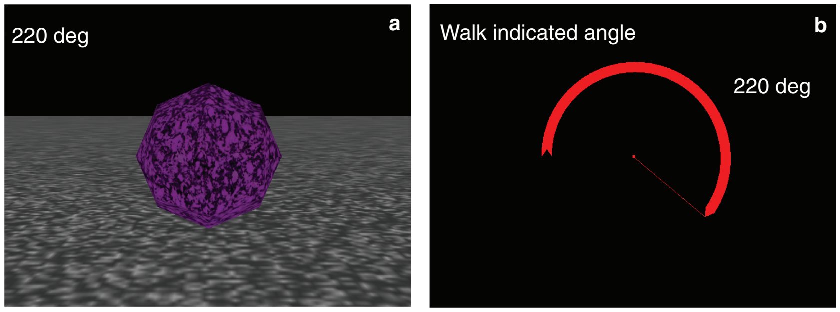

Fig. 5. Visual stimulus in the evaluation experiments. (a) Purple target sphere, presented above a randomly textured ground plane. The sphere always moved on a circle. (b) Instruction screen, showing how far the participant should move in the next trial (Experiment 1).

always followed the visual target on a circle, while the participant controlled the speed of the target by pressing a joystick on the gamepad (the speed was constrained to be in the range of normal walking speeds, between 0 and 1.5m/s). In this condition, only optic flow information from the ground plane was available for making angle judgments.

Design and procedure. Participants were instructed to follow the visual target as well as they could at a comfortable walking speed. Before each trial, they would see the angle that they had to walk represented in the display, both visually and as a number of degrees (Figure 5(b)). After a button press, the visual target appeared and the participant started walking (or moving with the joystick in the no-walking condition), until he or she felt that an arc subtending the desired angle had been walked. During the trial, this angle was indicated in degrees at the top left of the display (see Figure 5a). Once the participant judged that the specified angle had been reached, he/she stopped walking and proceeded to the next trial by button press. Walking direction alternated from trial to trial.

The angles that participants were required to walk varied between 180 deg and 360 deg, in steps of 10 deg. The radius of the circle was always 4m, which was the biggest circle that could be reliably tracked by the Vicon system in the tracking hall. Angles were presented in random order. Each angle was tested twice, in two different sessions. The first session in each condition was considered to be training and was used to test how treadmill walking changed with experience. If walking behavior would stabilize by the end of the first session, the spatial judgments from the second session could then be used to compare performance in the different conditions.

All participants performed all three conditions (no-walking, treadmill walking, normal walking). These were tested on different days. The order of conditions was counterbalanced across participants. Participants did not receive any feedback concerning their performance during the experiment.

Analysis of walking behavior. Walking behavior was tested with the following parameters: average walking speed, step length and step frequency during each trial, the variability of the radius at which participants walked in each trial and the regularity of steps and strides. Instantaneous walking speed was determined from the sum of stored treadmill speed and differentiated position data of the head from the tracking system. Walking speed data were low pass filtered using a third order Butterworth filter with 3Hz cutoff. Since instantaneous walking speed was still quite noisy, even after filtering the data, the median was used to compute the average speed in each trial. To measure the extent to which participants succeeded in following the target circle, the distance to the midpoint of the circle on which the visual target moved, was computed for each sample of the tracking data. For each trial, the standard deviation of these distances in all samples was used as a measure of the extent to which

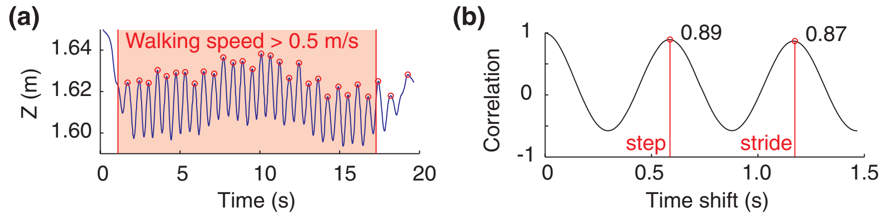

Fig. 6. Computation of walking parameters from vertical head position. (a) Example profile of vertical head position over time. The shaded region indicates where walking speed was above 0.5m/s. Red open circles indicate detected peaks in the head position used to compute the step frequency and step length. (b) Example autocorrelation function computed from the profile in (a). The first peak indicates how regular the walking is between successive steps, the second peak between different strides (steps with the same leg).

participants succeeded in following the circular path of the target. A perfectly circular path would result in a standard deviation of zero. If participants veered from the circle, the standard deviation of the radius at all samples would increase with the extent of the deviation.

The other parameters were computed from the filtered vertical position of the head (third-order Butterworth filter with 3Hz cutoff). The characteristic head-bobbing movements during walking can be used to extract various walking parameters [Terrier and Schutz 2003; 2005]. Because the estimated values for these parameters become unreliable for very slow walking, this analysis was limited to the longest period of each trial in which walking speed was continuously above 0.5m/s. If this produced a period of less than 6 successive steps, the trial was discarded from further analysis. This was true for 23.3% of the trials in the first treadmill session, 7.6% in the second, and of 5.2% and 3.8% of the trials in the two normal walking sessions, respectively.

From the intervals between successive head bobs, the median step frequency was computed. Combining the location of head bobs with position data produced the median step length. We also estimated the regularity of the walking behaviour across different steps. To this end, the autocorrelation of the vertical position of the head was computed (see Figure 6b). The first two peaks in the autocorrelation function indicate the correlation between the vertical motion profile of the head between two consecutive steps (with different legs), and that between a step and the next step with the same leg (or stride). These two regularity parameters are often computed from acceleration data [Kavanagh and Menz 2008; Moe-Nissen and Helbostad 2004]. However, we applied this analysis directly to the position data from our tracking system. Testing with a subset of the data showed that this produced very similar results.

4.1.2 *Results. Walking behavior.* Figure 7(a) shows the average walking speed in the treadmill and normal walking conditions. Overall, participants walked slower on the treadmill than on normal ground ($F(1, 11) = 8.914,\ p = 0.012$). Walking speed increased in both conditions over the course of the trials ($F(18, 198) = 25.162,\ p < 0.001$), causing the average walking speed to be higher in the second session than in the first ($F(1, 11) = 74.535,\ p < 0.001$). The increase in walking speed mainly took place in the first session, resulting in a significant interaction effect of session and trial number ($F(18, 198) = 11.606,\ p < 0.001$). It is important to note that when using the mean to compute the average walking speed, rather than the median, the differences between the two conditions all disappear. The mean walking speed on the treadmill was on the same level as on normal ground. However, given the noisiness of the data, we feel that the median gives a better representation of the average.

The lower walking speed on the treadmill was largely caused by shorter steps ($F(1, 11) = 50.876\ p < 0.001$; see Figure 7(b)). Like walking speed, step size increased during the first session (main effect of

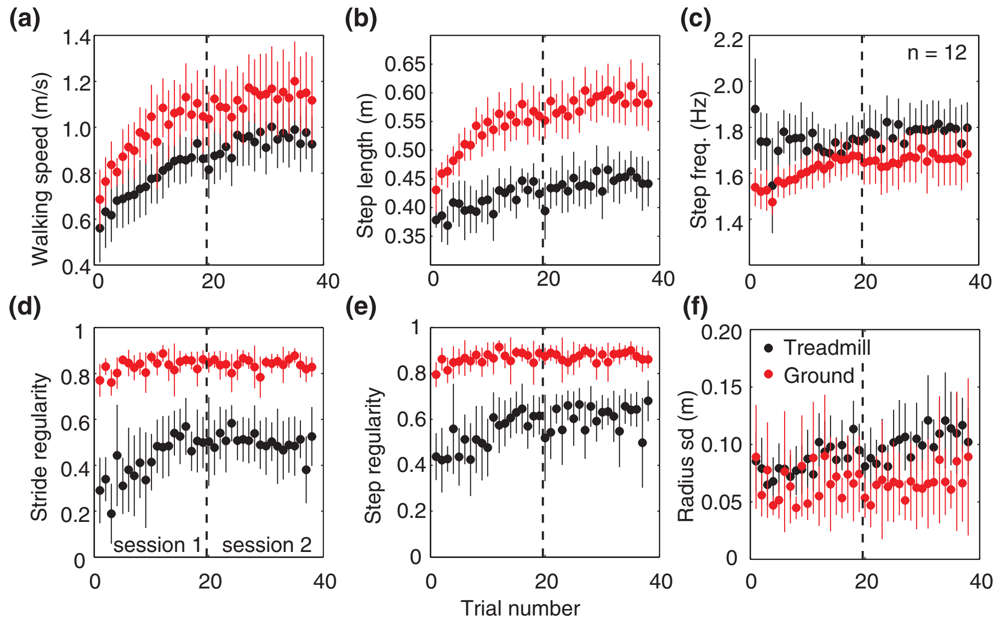

Fig. 7. Walking parameters for treadmill walking (black) and normal walking (red) in Experiment 1. Data was recorded in two successive sessions of 19 trials each. Error bars show 95% confidence intervals of the mean across 12 participants.

session: $F(1, 11) = 125.906$, $p < 0.001$; main effect trial number: $F(18, 198) = 20.366$, $p < 0.001$; interaction trial × session: $F(18, 198) = 6.066$, $p < 0.001$), but more so during normal walking (interaction trial × condition: $F(18, 198) = 2.513$, $p = 0.001$; trial × session × condition: $F(18, 198) = 2.261$, $p = 0.003$). Step frequency (Figure 7(c)) was higher for treadmill walking than normal walking ($F(1, 11) = 22.5$, $p = 0.001$). Overall, step frequency increased with trial number ($F(18, 198) = 3.452$, $p < 0.001$), causing the step frequency to be higher in the second session ($F(1, 11) = 8.036$, $p = 0.016$). However, this was mainly due to an increasing step frequency in the normal walking condition, not in the treadmill condition (indicated by the condition × trial ($F(18, 198) = 2.643$, $p = 0.001$), session × trial ($F(18, 198) = 2.368$, $p = 0.002$) and condition × session × trial ($F(18, 198) = 2.970$, $p < 0.001$) interactions).

The regularity of both steps (with contralateral leg; Figure 7(e)) and strides (with ipsilateral leg; Figure 7(d)) was higher for normal walking than for treadmill walking ($F(1, 11) = 175.645$, $p < 0.001$, and $F(1, 11) = 198.062$, $p < 0.001$, respectively). In the treadmill condition, however, the regularities increased during the first session, whereas this was hardly the case in the normal walking condition (interaction condition × session × trial: $F(18, 198) = 2.572$, $p = 0.001$, and $F(18, 198) = 3.793$, $p < 0.001$, respectively; this is also reflected in significant interactions of condition × session ($F(1, 11) = 8.706$, $p = 0.013$, and $F(1, 11) = 9.691$, $p = 0.010$), session × trial ($F(18, 198) = 2.458$, $p = 0.001$, and $F(18, 198) = 4.636$, $p < 0.001$), and condition × trial (only for step regularity: $F(18, 198) = 1.898$, $p = 0.018$).

The variability in the radius at which participants walked, finally, was slightly higher in the treadmill condition ($F(1, 11) = 6.956$, $p = 0.023$; see Figure 7(f)), indicating that participants had a harder time in this condition to follow the visual target on a circular path. However, this difference changed in the course of the experiment (indicated by interactions condition × session, $F(1, 11) = 6.464$, $p = 0.027$, and condition × trial, $F(18, 198) = 2.282$, $p = 0.003$).

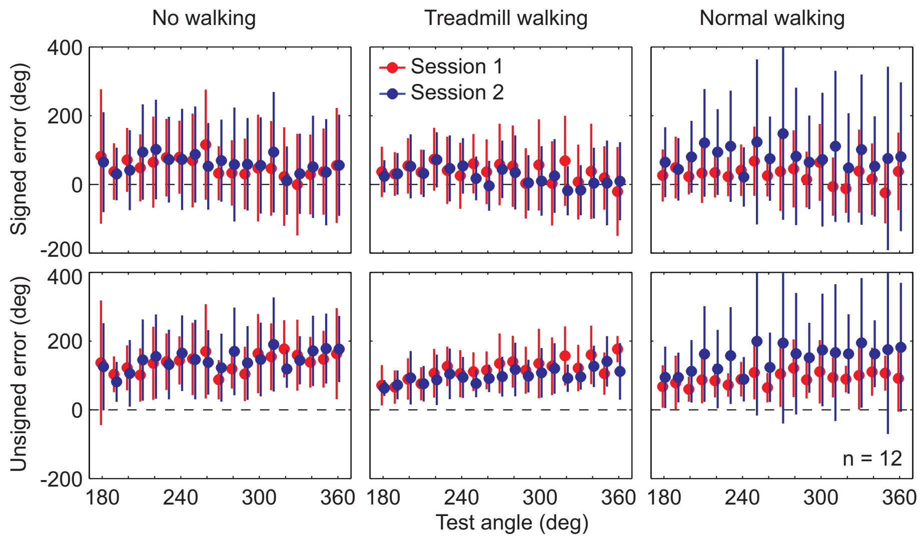

Fig. 8. Average signed (top row) and unsigned errors (bottom row) in Experiment 1. Errors show the difference between the angle walked by the participants and the angle they were instructed to walk. Data from the first session in each condition is shown in red, with those from the second session in blue. Error bars as in Figure 7.

Spatial updating task. Performance in the spatial updating task was expressed in the error made by the participants (the difference between how far participants actually walked and the test angle they were instructed to walk). Figure 8 shows both the signed (top row) and unsigned (bottom row) errors. On average, the signed errors were positive, suggesting that the participants underestimated how far they had walked, and consequently walked too far. However, the variability between participants was quite large, with some participants systematically undershooting and others overshooting. There was remarkably little difference between performance in the first session, which was considered to be a practice run, and the second one. We only analyzed data from the second session, when walking parameters had stabilized. Signed response errors did not differ significantly between the three conditions ($F(2, 22) = 0.583$), nor did they differ for different angles ($F(18, 198) = 1.257,\ p = 0.220$). There was no interaction effect ($F(36, 396) = 0.808$). Although the responses overshot the desired angles, this difference was not significant ($F(1, 11) = 1.202,\ p = 0.296$, for the overall average). The unsigned errors showed a small effect of test angle ($F(18, 198) = 2.148,\ p = 0.006$), which was due to an increase in the unsigned error with angle ($F(1, 198) = 11.047,\ p = 0.007$ for the linear contrast). Unsigned errors did not differ significantly between the three conditions, nor was there a significant interaction effect (both $F's < 1$).

4.1.3 *Discussion. Walking behavior.* Walking in a small circle is one of the most demanding tests for an omnidirectional treadmill setup. Since the CyberWalk treadmill is not able to rotate the walking surface around the vertical axis, the circles walked by our participants had to be compensated for by continuous changes to the speed of the treadmill in both axes (main chains and belts). Our participants had never walked on the treadmill before and it was evident that they had to get used to walking on it. This conforms to our informal observations during the first demonstrations on the treadmill. Walking performance stabilized after about 15 to 20 trials (corresponding to roughly the same amount of time in minutes). Surprisingly, it took participants about the same amount of time to reach stable walking performance in the normal walking condition. Part of the learning must, therefore, have been due to walking with the HMD and the inability to see the room [Hollman et al. 2007]. Nevertheless, participants walked considerably slower in the treadmill condition, which was mainly caused by a reduced step length. Similar effects were found on the regularity of walking behavior, both with the same leg (strides) and with the contralateral leg (steps). In agreement with previous studies, we found that step frequency was higher on the treadmill [Durgin et al. 2007; Murray et al. 1985; Stolze et al. 1997; Alton et al. 1998; Menegoni et al. 2009]. There may be two causes for the reduced step length on the treadmill. First, treadmill accelerations and decelerations were noticeable, and may sometimes have produced a slight feeling of instability in the user. Possibly, participants tried to compensate for this by taking smaller steps. Second, the safety harness worn by the user may have affected how they walked. Although the harness does not pull on the user when he/she is standing or walking in the center of the treadmill, it may do so when the user accelerates quickly and walks towards the edge of the treadmill. Informal testing suggests that walking becomes even more natural without the use of the harness, but of course this comes at the cost of increased safety risks, and is at present not feasible for general use.

Spatial updating. The distances walked in order to reproduce a certain angle of a circle were, in general, quite variable, both within and between participants. Although participants walked slower on the treadmill, spatial updating performance on the treadmill did not differ from that during normal overground walking. This suggests that the treadmill system allows for walking behavior that is sufficiently close to normal walking so as not to disturb spatial updating performance. Surprisingly, however, performance in the no-walking condition was also not worse than in the two walking conditions. Although visual rotation information has been found before to be sufficient for adequate spatial updating with detailed virtual scenes [Riecke et al. 2007], our scene only contained optic flow information and no localizable landmarks.

One explanation why performance was not worse in the no-walking condition may be that participants relied on elapsed time, rather than on traveled distance. Since the radius of the circle was always the same, angle and time were correlated for a given walking speed. If participants relied on time, then breaking this correlation by varying the radius should make body cues concerning the traveled angle more important and lead to better performance in the walking conditions than in the no-walking condition. We tested this in a control experiment, where the radius of the circle varied between 2.0m and 4.0m in 0.5m steps. Rather than trying to walk a specified angle, as in Experiment 1, participants now walked until they heard an auditory cue. This cue was presented at various angles ranging between 180 deg and 360 deg. They then had to report how far they thought they walked by means of the same visual display of a circle used in Experiment 1 (see Figure 5(b)). By lengthening or shortening the arrow with the gamepad joystick control, they indicated what angle they just walked. This way, we ensured that all participants walked the same angles, hoping to reduce variability in the data. Because the same angle with a smaller radius resulted in a smaller distance, and therefore required less time to walk, participants could no longer rely on time to give their estimate of the angle they walked. However, the results (with five participants) were very similar to those of Experiment 1. Participants generally underestimated the traveled angle and no systematic differences between the three conditions were observed. Consequently, participants were unlikely to have relied on time, rather than on angle.

Presently, we do not have an explanation for the lack of effect of actual walking in our spatial updating task. In one sense, our findings are congruent with the literature, in that a coherent picture of the importance of body cues is lacking. Visual cues seem to be sufficient for basic spatial updating tasks if the field of view is large and the visual image has a high level of detail [Riecke et al. 2007, 2002]. Physical rotations have been found to improve spatial updating in some studies [Bakker et al. 1999; Klatzky et al. 1998], but not in other, more complex tasks [Ruddle and Lessels 2006, 2009]. Actual walking, including both rotations and translations, is sometimes found to improve performance relative to physical rotations only [Chance et al. 1998; Ruddle and Lessels 2006, 2009], whereas other studies do not report such a benefit [Klatzky et al. 1998]. In contrast to most other studies, our experiment involved curved trajectories with a combination of simultaneous translation and rotation. Although adding translation to rotations does not affect the judgment of the angle of rotation with passive self-motion without vision [Ivanenko et al. 1997a, 1997b], it might be the case that the repetitive small rotations of the body which occur with active walking introduce noise into the integration of changes in walking direction over time. This might reduce the reliability of the body cues for rotation and explain why adding these cues did not result in improved spatial updating performance. It may also explain why humans are not very sensitive to the curvature of the path they are walking on [Kallie et al. 2007], and therefore often unknowingly deviate from their intended straight course [Souman et al. 2009].

4.2 Experiment 2: Walking Circles of Different Radii

In Experiment 1, participants walked in fairly small circles, with a radius of 4m. After a short familiarization period, walking behavior on the treadmill was quite normal, though somewhat slower and less regular than overground. In Experiment 2, we tested how walking behavior changes when the radius of the circles increases. In this case, the walking direction changes more slowly, which reduces the changes in treadmill velocity necessary to keep the user close to the center of the treadmill. If the differences in walking behavior in Experiment 1 were mainly due to instability caused by changes in treadmill velocity, walking speed and regularity should increase with larger circles. Unfortunately, the limited size of our tracking area did not allow us to measure walking behavior in the normal overground condition with larger circles. Therefore, treadmill results were compared to data from a study on walking behavior in natural circumstances, conducted with a combination of GPS and inertial tracking [Sreenivasa et al. 2010]. In Experiment 2, participants did not perform a spatial updating task, but only walked on a circular path at their preferred walking speed.

4.2.1 *Methods. Participants.* Five volunteering students and the first author participated in the experiment (age range 23 to 40; 1 female). All participants had normal or corrected-to-normal vision and none of them reported any locomotor or vestibular problems. They gave their written informed consent, after being instructed about the experiment and the treadmill. All of them had at least one hour of walking experience on the treadmill.

Design and procedure. As in Experiment 1, participants were instructed to follow the purple target at a comfortable walking speed as well as they could. They did not have to make any judgments of how far they walked. Participants walked in circles of 2, 4, 8, 16, or 32m radius. With the first 3 radii, they walked a complete circle, with 16m radius half a circle, and with 32m radius a quarter of a circle. Every radius was repeated 10 times, in random order. Since the circles with the larger radii (> 4m) did not fit in the tracking hall, participants only walked on the treadmill.

4.2.2 *Results and Discussion.* Figure 9 shows the different walking parameters as a function of radius. Walking speed ($F(4, 20) = 9.810$, $p < 0.001$), step length ($F(4, 20) = 79.446$, $p < 0.001$), stride regularity ($F(4, 20) = 14.257$, $p = 0.007$ after Greenhouse–Geisser correction for asphericity) and step regularity ($F(4, 20) = 15.042$, $p = 0.006$ after Greenhouse–Geisser correction for asphericity) all increased with the radius of the circle. Step frequency was not affected by radius ($F(4, 20) = 1.966$, $p = 0.139$), while the variability in the radius of the walked trajectories was lower for the larger radii

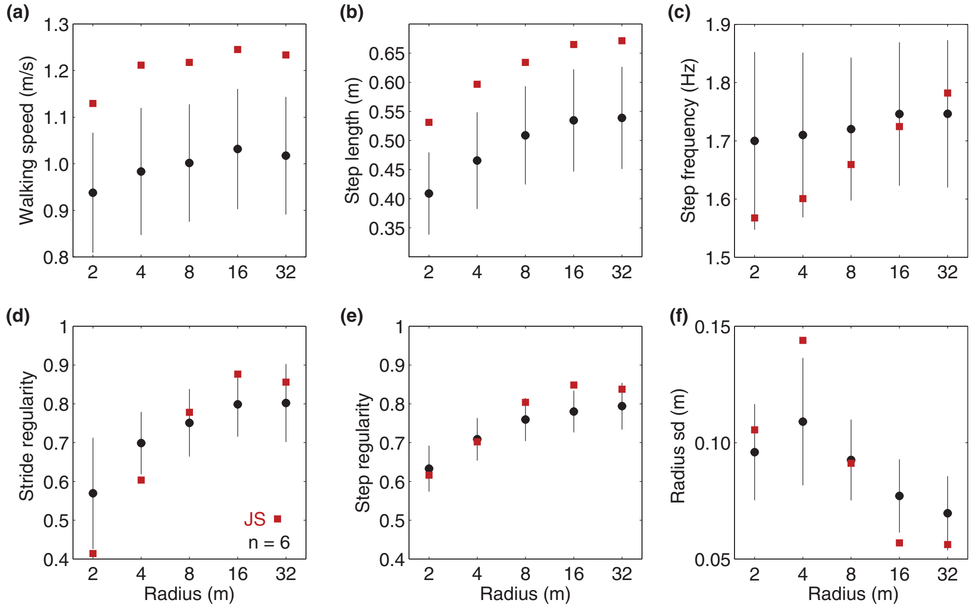

Fig. 9. Walking parameters in Experiment 2, as a function of circle radius. Error bars indicated the 95% confidence intervals of the mean across 6 participants. The red squares show the data of the first author, who was among the six participants, but had considerably more experience walking on the treadmill.

($F(4, 20) = 7.248,\ p = 0.001$). The values of the different walking parameters leveled off between radii of 8 and 16m. Figure 9 also shows the individual data points of participant JS, the first author. He had considerably more experience in walking on the treadmill than the other participants (dozens of hours). The data shows that walking speed and step length in particular were substantially higher for this participant than for the others.

In normal, overground walking, people walk slower in curves than on a straight path [Sreenivasa et al. 2010]. In particular, walking speed slows down for curves of large angles and small radii. Average walking speed for curves with a 16m radius has been found to be similar to that during straight walking (about 1.5m/s), decreasing to approximately 1.2m/s for curves of a 2m radius [Sreenivasa et al. 2010]. The effect of curve radius on walking speed may be the result of a more general motor control law [Hicheur et al. 2005; Vieilledent et al. 2001].

The results from Experiment 2 show a similar relationship between curve radius and walking speed. However, walking speed on the treadmill overall was lower than in normal walking. Partially, this may have been due to the fact that participants wore an HMD and walked in VR. Previous studies have found people to walk slower in VR than normally, even when not walking on a treadmill [Fink et al. 2007; Mohler et al. 2007]. However, the differences in walking behavior between our treadmill condition and the normal overground condition in Experiment 1 suggest that part of the reduction in walking speed was also due to the treadmill itself.

5. GENERAL DISCUSSION

The CyberWalk omnidirectional treadmill is a unique locomotion interface. As far as we know, it is the first truly omnidirectional treadmill of this size that allows for near-natural walking through arbitrarily large virtual environments. It still has its limitations, but at the moment it is the best solution in existence for making it possible to really walk in VR.

One of the main innovative features of the CyberWalk treadmill system is the control of treadmill velocity in response to changes in walking behavior. By making the treadmill respond gradually rather than immediately, the important inertial cues to acceleration and deceleration are retained. This fosters a real sense of walking, while at the same time retaining postural stability. When changes in walking speed and direction are small, this control scheme works very well. In fact, many first-time users are quite surprised to discover that they are walking in the center of the treadmill, rather than at the edge. They expect to walk off the treadmill at any moment, because they do not notice its recentering action. The only disadvantage of this control method is that it requires a relatively large walking surface, making the treadmill a large and complex machine. But although the treadmill is large and complex, it is designed according to fairly simple principles. Our improvements on Iwata's original torus design [Iwata and Yoko 1999; Iwata 1999], such as the clothoid profile of the chain guides, the cantilever construction, the nearly gapless surface (thanks to division of each belt into a large and a small belt segment), and the actuation of belts on the top of the treadmill only, have advanced the state-of-the-art in omnidirectional locomotion interfaces considerably, and can be implemented in any new system.

The CyberWalk treadmill system allows for normal walking through VR in many scenarios. Most users initially have to get used to it, partially because of initial uncertainty of what the machine will do, partially because the changes in treadmill velocity in response to sudden changes in walking velocity are still noticeable. After this initial adaptation phase, most users feel quite comfortable walking on the treadmill. In our evaluation experiments, we have subjected the treadmill system to the most severe test possible, walking in small circles. In this case, too, users had to adapt to treadmill behavior and reached steady walking performance after about 15 minutes. Although they were still not walking exactly as they did on normal ground, users were able to follow a circular path at a normal walking speed (albeit on the slower side). Further measurements suggest that users continue to improve their walking performance after this initial adaptation. For the most experienced user of the treadmill (the first author of this article), who has walked dozens of hours on the treadmill, walking speed and step length were clearly higher than for the other participants in Experiment 2 (see Figure 9), and were similar to the average overground walking speed and step length in Experiment 1 (see Figure 7).

People walk slower in VR than in real environments, even when not walking on a treadmill [Fink et al. 2007; Mohler et al. 2007]. The results of Experiment 2 show that in most common user scenarios, where users do not walk in tight circles, walking behavior on the treadmill approaches that of normal overground walking in VR (approximately 1.15–1.25m/s). Experiment 1 suggests that, although we did not find the benefit of walking per se in a basic spatial updating task, walking on the treadmill does not affect spatial updating negatively when compared to overground walking. The CyberWalk treadmill system will be used to further study the contribution of body cues and physical locomotion to the perception of self-motion and to spatial cognition. It allows us to study spatial cognition and navigation on a spatial scale that was not possible before. Rather than having to restrict walking to the size of a room, spatial behavior and cognition can be studied on the scale of buildings, streets, and even entire cities. Currently, experiments in virtual rooms [Ruddle et al. 2011], cities [Meilinger and Bülthoff 2010], and natural environments, which are all much larger than anything used in previous studies, are being conducted with use of the CyberWalk treadmill.

The current system still has room for improvement. After carrying out the evaluation experiments described above, we implemented a dead-zone in the center of the treadmill where changes in the position of the user are not used to control treadmill velocity if he/she is standing still. Since we use the head position of the user to control treadmill velocity, this makes it much more comfortable for users to look around in the VE while standing still. Using the position of the pelvis instead of that of the head for treadmill control is another improvement that will be implemented. In addition, we are investigating different solutions for the safety harness that keeps users from reaching the edge of the walking surface. Another way of improving the immersiveness of the system would be to combine it with so-called redirected walking techniques [Razzaque et al. 2001; Steinicke et al. 2008]. These commonly use a combination of translation and rotation gains between physical movements and their visual consequences in VR in order to enlarge the virtual environment which can be explored within a limited physical space. Adding these techniques to the treadmill system might be used to reduce the requirements for treadmill speed and acceleration.

Being able to physically walk through large VEs in an unrestricted manner opens up opportunities in various areas. Not only does it allow us to study spatial navigation and cognition in much more naturalistic environments [Bülthoff and van Veen 2001; Tarr and Warren 2002; Van Veen et al. 1998], it also provides new possibilities for rehabilitation training [Fung et al. 2004], for edutainment (gaming, virtual museums), design (architecture, industrial prototyping), and various other applications. The CyberWalk treadmill has brought us a significant step forward towards natural walking in large VEs.

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