Tapping-In-Place: Increasing the Naturalness of Immersive Walking-In-Place Locomotion Through Novel Gestural Input

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Abstract

Walking-In-Place (WIP) techniques provide one possible solution to the problem emerging when an immersive virtual environment (IVE) offers a larger freedom of movement than the physical environment where the interaction is taking place. Such techniques are particularly useful when the spatial constraints are very prominent. However, many previous WIP techniques rely on the same gesture for input – a stepping gesture resembling the one performed when walking up a flight of stairs. It seems possible that this gesture may be perceived as more physically straining than real walking which may lead to a less natural walking experience. In this paper we present two novel forms of gestural input for WIP locomotion and describe a within subjects study comparing these to the traditional stepping gesture. The two gestures proposed are: a wiping gesture where the user alternately bends each knee, moving one lower leg backwards, and a tapping gesture where the user in turn lifts each heel without breaking contact with the ground. Visual feedback was delivered through a head-mounted display and auditory feedback was provided by means of a 24-channel surround sound system. The gestures were evaluated in terms of perceived naturalness, presence, and real world positional drift. The tapping gesture was significantly more natural than the wiping gesture and was experienced as significantly less strenuous than the other two techniques. Finally, the tapping gesture resulted in significantly less positional drift.

Index Terms: H.5.1 [Information Interfaces and Presentation]: Multimedia Information Systems—Artificial, augmented, and virtual realities H.5.2 [Information Interfaces and Presentation]: Interfaces—Input devices and strategies I.3.6 [Computer Graphics]: Methodology and Techniques—Interaction techniques I.3.7 [Computer Graphics]: Three-Dimenshional Graphics and Realism—Virtual Reality;

1 Introduction

A particularly problematic obstacle facing developers of immersive virtual environments (IVEs) is what might be referred to as the problem of incompatible spaces. A virtual space may be virtually infinite in size. Thus, the user should be able to move freely to the extent that the virtual topography and architecture allow it. However, in the real world the user's movement is confined to a limited physical space. As long as the virtual space is smaller than, or the same size as, the physical space we may regard the two spaces as compatible. However, if the virtual environment offers a larger freedom of movement than the physical environment the incompatibility emerges. At best the incompatibility may be detrimental to the user experience. The user may inadvertently probe the boundaries of the system which in turn may hamper the illusion of presence – often defined as the sensation of "being there" in the virtual environment [31]. At worst the incompatibility can be dangerous, since immersed users may be unaware of real world obstacles.

Within the academic community numerous different solutions to the problem of incompatible spaces have been proposed in relation to interactive walking simulation. These can be grouped into at least three categories:

1. *Mechanical repositioning:* Elaborate mechanical setups facilitating relatively natural walking without changing the user's position relative to the physical environment [7, 11, 12, 13, 18].

2. *Redirected walking:* A collection of techniques which makes it possible to discretely or continuously reorient or reposition the user through overt or subtle manipulation of the stimuli used to represent the virtual world [6, 8, 10, 19, 30, 32].

3. *Walking-In-Place (WIP) techniques:* Alternative interaction strategies enabling users to move within the virtual environment by performing body movements resembling real world walking while remaining stationary [9, 24, 29, 37, 38].

All three may serve as potential solutions to the problem of incompatible spaces in their own right. With that being said, they are not equally viable if applied outside a laboratory setting where the spatial and technological constraints are even more prominent, i.e., in the household of an average consumer. Such consumer IVEs are far from commonplace, but recent technological developments such as the Microsoft Kinect[1] and the Oculus Rift[2] usher in a future where IVEs no longer have to be confined to the laboratories of public and private institutions. However, the limited space available to many consumers effectively renders redirection techniques ineffective since these are contingent upon some degree of movement on behalf of the user. Similarly, current mechanical setups, such as omnidirectional treadmills, cannot be considered a feasible alternative within a foreseeable future [2]. For the moment this leaves WIP techniques as the most promising of the three approaches.

While WIP techniques in their current forms cannot compete with real walking in terms of simplicity, straightforwardness, naturalness [37], studies do suggest that they may elicit a stronger sensation of presence than techniques where users push a button to propel themselves forward [29]. Particularly, the convenience and cost-effectiveness have been highlighted as factors making the lower level of control and naturalness worthwhile tradeoffs [9]. Slater,

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Usoh and Steed [28] describe that a primary advantages of their original walking-in-place technique [26] is that the gestural input generates proprioceptive feedback similar, albeit not identical to, the one resulting from real walking. In turn this entails a higher degree of correspondence between the proprioception and stimuli in other modalities suggesting exocentric motion perception. Moreover, Williams and colleagues [39] found that walking in place on the Wii was as effective as physically walking in a simple spatial orienting task. These potential advantages suggest the need for finding the best possible WIP technique.

Even though exceptions do exist [14, 34, 35], many WIP techniques seemingly rely on the same gesture for instigating forward viewpoint displacement, namely, leg movements resembling those performed when ascending a flight of stairs. It would seem that this gesture may be more physically straining than real walking. In this paper we describe a study performed with the intention of determining how this gesture measures up against two novel forms of gestural input in terms of naturalness, presence and real world positional drift. The evaluation was essentially motivated by the hypotheses that a better match between the perceived physical effort of walking in place and real walking would lead to an experience of more natural WIP locomotion. The paper is structured as follows: In section 2 we present previous attempts at facilitating virtual travel using WIP techniques. In section 3 we discuss the discrepancies between the biomechanics of real walking and the gesture most commonly used for WIP locomotion and then we introduce two alternatives to this gesture. Section 4 details the study performed with the intention of evaluating how the two alternative gestures measure up against the prevalent one and each other. Section 5 summarizes the results which are discussed further in Section 6. Finally, Section 7 summarizes and concludes upon the presented study before outlining potential future work.

2 Related Work

To our knowledge, no previous attempts at comparing gestural input for WIP locomotion have been performed. However, several different WIP techniques have been implemented. On the most general level it is possible to distinguish between techniques relying on manipulation of a physical interface for step detection and techniques dependent on various forms of motion tracking to determine whether the user is walking or not. Physical interfaces do in principle also perform primitive gesture tracking in the sense that the manipulation of the physical interface is equated with a given gesture being performed. However, proper tracking systems rely on continuous detection of positions or velocities of given body parts.

Secondly, it is possible to classify WIP techniques according to whether the mapping between the performed gesture and the virtual locomotion is direct or indirect [9]. In case of the former there is a direct correspondence between the motion of the tracked body part and the viewpoint displacement, and in the latter case no such relationship exists. Notably that does not mean that indirect approaches necessarily entails discontinuous viewpoint displacement since a continuous velocity may be determined from discrete phenomena, such as the step frequency.

2.1 Physical Interfaces

Almost without exception, the WIP techniques relying on physical interfaces employ a indirect mapping between the stepping gesture and the viewpoint's displacement. Many of these use the forces exerted when a foot comes into contact with the ground to detect that a step has been taken. Since this impact is a discrete event, it is impossible to directly map the continuous movement of the legs to the translation of the viewpoint.

One such interface is the Walking Pad [3, 4] which detects the user's steps through 60 iron switch sensors embedded on a 45cm x 45cm plexiglass surface. Moreover, processing of the binary values provided by the switches makes it possible to determine the orientation of the user's feet when these touch the ground and based on this information the walking direction is determined.

Similarly Bouguila and collegues [5] describe a platform which facilitates foot based locomotion through four embedded load sensors. Notably this interface differs in that it can reorient users towards a visual display since the platform also serves as a mechanical turntable. Additionally, this device is capable of simulating surface inclines and declines via three air cylinders mounted underneath the turntable.

It is interesting to note that a commercially available physical interface already have been used to facilitate WIP locomotion, namely, Nintendo's Wii Balance Board.[3] Williams, Bailey, Narasimham, Li, and Bodenheimer [39] combine the balance board, which is embedded with four pressure sensors, with an orientation sensor. Their WIP-Wii algorithm detects how rapidly the user applies weight to each corner of the board and translates the viewpoint accordingly. The orientation sensor is used to determine the direction of heading.

The Wizdish [34] presents an example where there is a direct mapping between virtual locomotion and interaction with a physical interface. Strictly speaking the Wizdish is not a physical interface since it relies on a motion capture system for detecting the user's movement. However, the interaction is contingent upon the gesture being performed via the Wizdish itself. The surface of the Wizdish is concave and almost spherical. Users wearing a pair of low friction shoes are able to take steps by simultaneously sliding one foot forward and the other backward without breaking contact with the surface of the dish. The magnitude of the walking motion is then based on the forward motion of the feet. Notably this is one of the examples of a WIP technique which does not rely on "stair ascending" gesture.

2.2 Motion Tracking

Slater and colleagues [26] describe one of the earliest implementations of a WIP techniques, originally dubbed the Virtual Treadmill [29]. This technique does not explicitly rely on tracking of leg movements. Instead it detects whether users are walking in place via a neural network recognizing patterns in the tracked head movement. Feasel, Whitton, and Wendt [9] describe that the viewpoint displacement used for the original virtual treadmill was discrete rather than continuous. When the neural network registered a step, the viewpoint abruptly jumped a full step length forwards. Moreover, this algorithm may have been perceived as somewhat unnatural since movement was not instigated until four steps in place were detected and it would similarly not terminate the movement unless no steps had been detected for two full cycles.

Another implementation which also relies on head movement is the so-called Shake-Your-Head technique proposed by Terziman et al. [35]. However, rather than detecting the head movements resulting from walking in place, this technique relies on more explicit head gestures such as lateral head oscillation for walking and lateral head movement for jumping. An interesting implications of this is that the technique also can be used by seated users.

Zielinski, McMahan, and Brady [41] present a WIP technique that uses a camera to track the shadows cast by the users' feet onto the floor of an under-floor projection system within a six-sided CAVE. In addition to enabling forwards movement, it also includes to possibility of sidestepping. While the gesture used for forward locomotion seemingly correspond to the one commonly used for WIP techniques, sidestepping is achieved through a pinch gesture similar to the one used touch screen devices.

The motion tracking based solutions described so far employ discrete mapping between the WIP gesture and the forward movement of the viewpoint. However, systems using direct mappings have

[3]www.nintendo.com/wii/enhance/#/accessories

been proposed. Feasel, Whitton, and Wendt [9] describe a technique refereed to as Low-Latency, Continuous-Motion Walking-in-Place (LLCM-WIP). This technique controls the viewpoint displacement based on the speed of the user's vertical heel movement and promises low starting and stopping latency, smooth motion between steps, within-step control of the speed, and turning on the spot without erroneous forward movement.

Wendt, Whitton, and Brooks' Gait-Understanding-Driven Walking-In-Place (GUD WIP) [38] similarly takes the vertical speed of the heel as an input. However, it sets itself apart from its predecessors in that it is informed by gait principles and thereby produces walking speeds that correspond better with those of real walking.

Moreover, it is worth noting that WIP locomotion also has been achieved using commercially available motion tracking systems such as the Microsoft Kinect which can be used for WIP locomotion in combination with the Flexible Action and Articulated Skeleton Toolkit (FAAST) [33]. Interestingly, Kim, Gracanin, and Quek [14] have proposed the technique Sensor-Fusion Walking-In-Place (SF-WIP), which relies on the acceleration and magnetic sensors embedded within two smart phones in combination with a magnet to produce WIP locomotion from any walking like movement performed by stationary users.

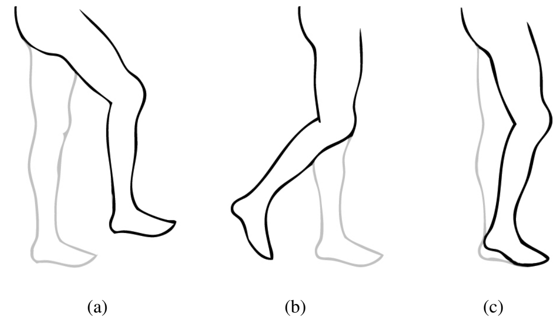


Figure 1: The three gestures used for the study at the point corresponding to midswing of a normal gait cycle. (a) Marching: The user alternately lifts each foot off the ground by raising the thighs in front of the body. (b) Wiping: The user in turn bends each the knee while keeping the upper leg relatively steady which results in backwards movement of the feet. (c) Tapping: The user alternately lifts each heel of the ground while keeping the toes in contact with the ground.

3 Gestural Input for WIP Locomotion

As suggested, it would appear that many of the WIP techniques reviewed in section 2 rely on the same gesture for input. The user alternately lifts each leg as if climbing a flight of stairs or marching on the spot. Henceforth we refer to this gesture as *Marching*. While this gesture does bear semblance with normal walking the two differ in more than one regard.

3.1 Biomechanics at a Glance

We are generally able to describe the act of walking through repeated gait cycles – the period from initial contact of one foot until the same foot makes contact again. The gait cycle is normally divided into the two phases: the stance phase (loading response, midstance, terminal stace, and preswing) and the swing phase (initial swing, midswing, and terminal swing) [22].

The act of walking is sometimes described as controlled falling [15]. Dynamic stability is achieved through a combination of support forces, momentum and inertial forces, and energy is conserved by taking advantage of the forward kinetic energy and the gravitational potential energy of the center of body mass. According to [1] it seems that the most important factor in the gait cycle is hip moment. During the initial phase this moment is primarily provided by the quadriceps muscle group (located on the anterior of the thigh), whereas the terminal phase is dominated by the hamstring group (located on the posterior of the thigh) [1].

As previously suggested, a main advantage of the Marching gesture is that it provides proprioceptive feedback similar, but not identical to, to one produced during real walking [28]. However, like any gesture serving as a proxy for its real word counterpart the feedback is not identical. Most notably, the marcher does not swing the legs, but rather lifts them as if ascending a flight of stairs. A related area in which the two differ appear to be energy consumption. Unlike the case of real walking, gravity and forward momentum cannot be used to reduce the work performed by the muscles during walking in place. This presumably results in an even larger activation of the quadriceps muscle group during the initial "swing" phase.

3.2 Alternative Gestures

Labouring under the assumption that the Marching gesture indeed is more physically straining than real walking, it seems plausible that WIP locomotion might be perceived as more natural if it relied on gestures activating different muscle groups or demanding less muscle activity. Currently we have conceived of two such alternative forms of gestural input for WIP locomotion:

3.2.1 Wiping Gesture

The first of the two gestures resembles the movement performed when wiping one's feet on a doormat. The user alternately bends each leg backwards in order to produce movement. Thus, the initial swing is replaced by the user bending one knee and moving the leg backwards, while the terminal swing is replaced by the user lowering the leg again. This is believed to activate the hamstring muscle group which is normally activated during the last part of the gait cycle. While this gesture does involve some of the muscle activation of real walking it seems possible that it may be perceived as equally as physically straining as the Marching gesture. Throughout the following we refer to this gesture as *Wiping*.

3.2.2 Tapping Gesture

The second alternative is a gesture where movement is generated by tapping each heel against the ground. The initial swing is now replaced by the user lifting one heel off the ground without breaking contact with the toes and the terminal swing corresponds to lowering the heel again. We refer to this gesture as *Tapping*. As with the Marching gesture, the intention is for Tapping to provide proprioceptive feedback similar, but not identical to, the one experienced during real walking. Moreover, Tapping is also believed to activate the quadriceps muscle group during the initial swing phase, as is the case with real walking [1]. However, Tapping and Marching differ since the former requires less muscles activity. Thus, the correspondence between the energy consumption of Tapping and real walking is believed to be higher than that of Marching and real walking. Figure 1 illustrates the three gestures at the point which would correspond to midswing of a gait cycle.

4 Study Design

The evaluation was performed with the intention of determining how the two novel forms of gestural input for WIP locomotion would compare to the prevailing gesture and each other in terms of perceived naturalness. We performed a comparative study using a within-subjects design including three conditions – one corresponding to each of the three gestures, Marching, Wiping, and Tapping. The order of the conditions was randomized so as to control potential order effects.

(a) (b)

Figure 2: (a) A top-down view of the environment. The path the participants walked along has been highlighted with red. (b) A screen shot of the environment as it looks from the user's point of view.

4.1 Participants and Procedure

A total of 27 participants (19 males, 8 females) took part in the experiment. They were between the ages of 19-43 years (M=29.8 years, SD=7.1) and were recruited via a mailing list comprising volunteers from Aalborg University Copenhagen and subscribers to the Danish periodical Ingeniøren (The Engineer). No compensation was offered for participation. All participants reported having normal or corrected-to-normal vision and hearing. None of them had previously tried virtual travel by means of a WIP technique. Initially the three gestures were demonstrated and the participants were informed of the general purpose of the experiment. Moreover it was made clear that within the context of the current experiment a natural walking experience would be one that felt like real walking. Before each trial the system was calibrated by asking the participants to perform the particular gesture until they felt comfortable doing so. In addition to calibrating the system for the individual gestures, this process also ensured that the participants understood the gestures and felt comfortable performing them. During the walk the experimenter observed the participants to make sure that they performed the gestures correctly. Once the walk was over, the participants were asked to fill out an electronic questionnaire. The three walks took in average 52.9 seconds to complete (SD = 12.4).

4.2 Task and Environment

In all three conditions the participants were asked to perform a simple locomotion task, namely, walking from one point to another by following a clearly visible path. This relatively straightforward task was favoured over more complex ones, such as precision or way finding task, since we wanted the walking experience to take a natural scenario as its point of departure. For the same reasons we chose a scenic, albeit not particularly grand, countryside environment as a setting for the walk. The path was 400 meters long.

The participants were instructed to walk at a steady pace they found comfortable; to stay on the path, if possible; and to refrain from stopping or walking in the opposite direction. We purposely avoided using a straight path since we wanted to ensure that the participants were forced to turn to both sides during the walk. The path and environment were identical for all three conditions. A top-down view of the path and a screenshot of the environment as it looks from the user's point of view are shown in Figure 2.

4.3 Setup

The IVE was simulated using an adapted version of the multimodal architecture described by Nordahl et al. [21], which originally was developed for the purpose of simulating walking-based interactions through visual, auditory and haptic stimuli [36].

4.3.1 Hardware

The movement of the user – the walking gestures and the head motion – was acquired by tracking the position and orientation of three markers – one placed on the head mounted display (HMD) and one placed on each of the user's ankles. The markers were tracked by means of a 16 cameras Optitrack motion capture system[4]. The 16 cameras were placed along the circumference of a circle with a diameter of 7 meters. 12 of the cameras were placed at a height of approximately 2.9 meters and the remaining 4 were placed about 1.8 meters from the ground. Placement of the markers on the ankles was chosen since the Tapping gesture only involved subtle movement of the heels. It was therefore regarded as beneficial to place the marker as close to the heel as possible. Moreover it is worth noting that placement of the markers on the front side of the lower leg would have led to some degree of occlusion during the Wiping gesture. Visual stimuli was delivered through a nVisor SX head-mounted display, with a resolution of 1280x1024 in each eye and a diagonal field of view of 60 degrees. A 24-channel surround sound system was used to deliver auditory stimuli. The system consisted of two RME Fireface 800 interfaces and one RME ADI-8 DS converter. 16 Dynaudio Bm5A mk II active monitors were evenly distributed at ear height along the circumference of the circle defined by the motion capture system, and an additional 8 Dynaudio Bm5A mk I speakers were distributed around the circle on the floor.

4.3.2 Software

The virtual environment stimuli and the motion tracking algorithm were produced in the multiplatform game development environment Unity3D[5] which facilitates stereoscopic viewing by the placement of two cameras within one environment. The soundscape accompanying the visuals was composed of ambient sounds, such as the sound of wind blowing and water flowing, and was delivered using the realtime synthesis engine Max/MSP.[6] A schematic drawing of the system used used for the current study can be seen on Figure 3.

The same algorithm was used to produce forward viewpoint displacement from all three gestures. Each of the two markers placed on the user's ankles yield a three-dimensional position and orientation which were used to control the forwards movement of the viewpoint within Unity3D. In connection with WIP locomotion, the velocity of forward movement is often defined by estimating the stepping frequency of the user. However, a different solution was employed since the three gestures may involve markedly different stepping frequencies. The velocity of the viewpoint transformation can generally be described in terms of the following equation:

$$viewpoint\,velocity = normal\,velocity \times scale\,factor \qquad (1)$$

Since height is positively correlated with step length [38], the normal velocity was defined in terms of the user's height – acquired during the calibration of the system – as follows:

$$normal\,velocity = \frac{user\,height}{C} \qquad (2)$$

The constant C was established through informal evaluations of the perceived walking speed achieved by varying the divisor. A suitable value was found to be $C = 0.45$. It is worth noting that this caused the algorithm to produce walking speeds closer to those of a fast runner. That these were perceived as more natural can presumably be ascribed to the fact that motion perception is influenced by peripheral vision when speed judgements rely on optic flow [23]. In this case the field of view was restricted by the HMD. The user influenced the virtual velocity through vertical movement of the feet in the case of all three gestures. The vertical components (y) of the position data were used to define the scale factor and thereby influence the viewpoint velocity. However, since the vertical positions

[4] www.naturalpoint.com/optitrack
[5] www.unity3d.com
[6] www.cycling74.com

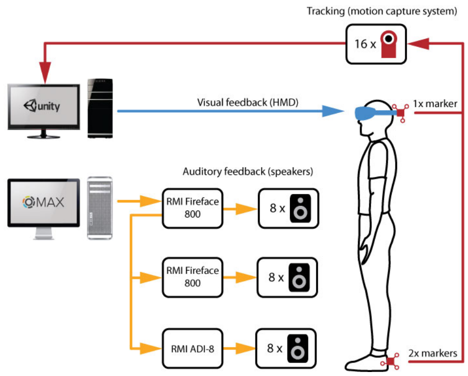


Figure 3: Schematic drawing of setup used for the study.

vary considerably from gesture to gesture the scale factor is defined as follows:

$$scale\,factor = \frac{highest\,recent\,foot\,position}{expected\,step\,height} \tag{3}$$

The highest recent foot position was defined as the highest value of y within the last 0.5 seconds and the expected step height was the mean step height obtained during pretest calibration. Thus, regardless of what gesture was being performed, if the marker was at the same height as it was during the calibration, the normal velocity would not be scaled. If the user stood still the normal velocity would be multiplied by zero. The scale factor value was clamped between 0 and 1.75 entailing that highest possible velocity was a 75% increase of the normal walking speed. Since the task performed by the participants involved continuous motion from start to end starting and stopping latencies were not formally measured. However, it would take about half a step cycle before the user reaches the normal velocity and stopping latencies of at least 0.5 seconds were to be expected given the definition of the highest recent foot position.

Finally it is worth noting that the viewpoint was not transformed forward along the gaze direction of the user. Instead the orientation of the two markers mounted on the ankles are used to approximate the direction of the feet. Thus, it is possible to produce an estimate of the body orientation, which in turn defines the direction of heading, by averaging the two vectors corresponding to the forward orientation of the markers.

4.4 Measures

While the primary purpose of the study was to determine how the three gestures would compare in terms of naturalness, we decided to include two additional measures, namely the sense of presence and the amount of real world positional drift occurring during the walk. Naturalness and presence was assessed by means of a questionnaire and positional drift was evaluated based on behavioural data.

4.5 Subjective Measures of Naturalness and Presence

The experienced degree of naturalness was assessed by four questionnaire items requiring the participants to rate their level of agreement with particular statements on a scale from '1' to '7' ('1' signified strong disagreement and '7' signified strong agreement). The four items related to the following topics:

Naturalness: As in other questionnaires related to the experience of IVEs [16, 17, 29, 40] we included one questionnaire item explicitly asking the participants to rate how natural they found the experience of walking in the IVE was.

Physical strain: It seems highly likely that a WIP gesture will be experienced as more natural, if it requires a similar degree of muscle activity as real walking. Thus, we included an item asking the participants indicate whether the given gesture was more physically strenuous than the action it was serving as a proxy for.

Self-motion compellingness: Since natural walking involves exocentric motion perception, we added an item asking the participants to rate whether they indeed felt as if they were moving during the virtual walk.

Acclimatisation: In order to determine how quickly interaction via the gestures became second nature, the questionnaire contained an item asking the participants to rate how quickly they forgot that they were not really walking.

Moreover, the questionnaire included three items pertaining to the participants sensation of presence within the IVE, namely, the three items featured in the original version of the Slater-Usoh-Steed (SUS)questionnaire [26, 27]. These items assess the subjective sense of presence based on three factors: 1) The extent to which the participants had a sensation of "being there" in the IVE. 2) The extent to which the IVE becomes the dominant reality and is perceived as such. 3) The extent to which exposure to the IVE gave rise to a sense of viewing images as opposed to having visited a place. Like the remaining questionnaire these items were answered on rating scales ranging from '1' to '7' where a high rating would be indicative of presence.

Finally, an item in the questionnaire encouraged the participants to freely comment on their experience of the three conditions.

4.6 Behavioural measure of Unintended Positional Drift

During previous user studies, we have informally observed that many individuals wearing a HMD while walking in place, physically move in the same direction as they are headed within the virtual environment. We refer to this phenomenon as Unintended Positional Drift (UPD). If a WIP interaction technique is to be considered a meaningful solution to the problem of incompatible spaces, it is crucial that the user remains stationary. Thus, UPD should be considered crucial to the evaluation of any WIP technique intended for use in combination with a HMD. We employed three measures of UPD: *maximum drift* (the largest physical distance the user has been from the point where the locomotion started), *total drift* (the total physical distance covered by the user), and the *drift/travel ratio* (the ratio describing how far the user has drifted in the real world per travelled distance in the virtual world). In order to produce these measures we logged the participants real and virtual position twice a second. The logging was commenced and terminated once the participants crossed two previously defined points along the gravel path.

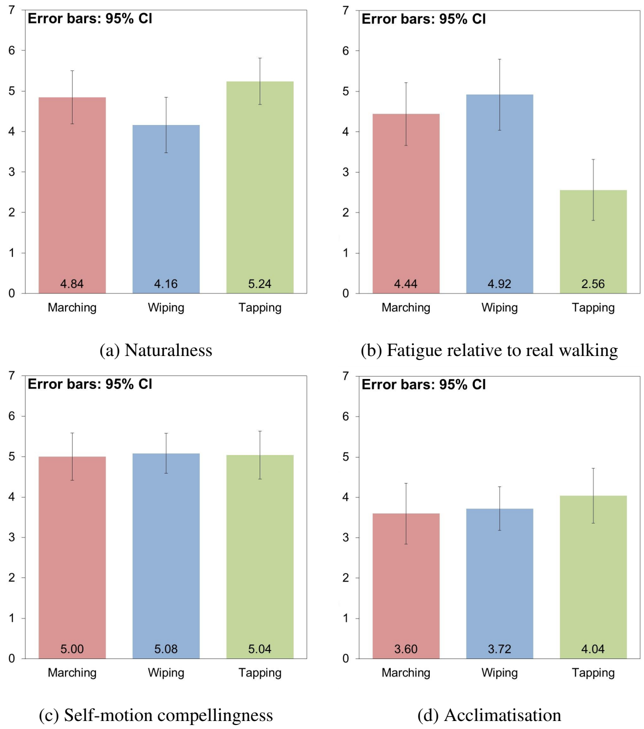
Finally, in order to get an measure of the velocity of the viewpoint transformation performance data related to completion time and travelled distance.

5 Results

An error related to the electronic questionnaire forced us to eliminate the questionnaire data from two participants. Moreover, an error during the logging of the real and virtual positions made it impossible to retrieve the data from three trials. Thus, the self-reported measures and the measures of UPD are based on 25 and 26 participants, respectively. Repeated-measures analyses of variance (ANOVAs) were used to compare the means obtained from all measures. All ANOVAs were performed using a significance level of .05. Significant measures were subsequently analysed by means of paired sample, two tailed t-tests using Bonferroni corrected alpha values of 0.017 per test. The p-values obtained from these post-hoc analyses are presented in Table 1.

5.1 Perceived Naturalness

The results obtained from the three questionnaire items related to perceived naturalness are shown in Figure 4. Significant differences were found in relation to the item asking explicitly about



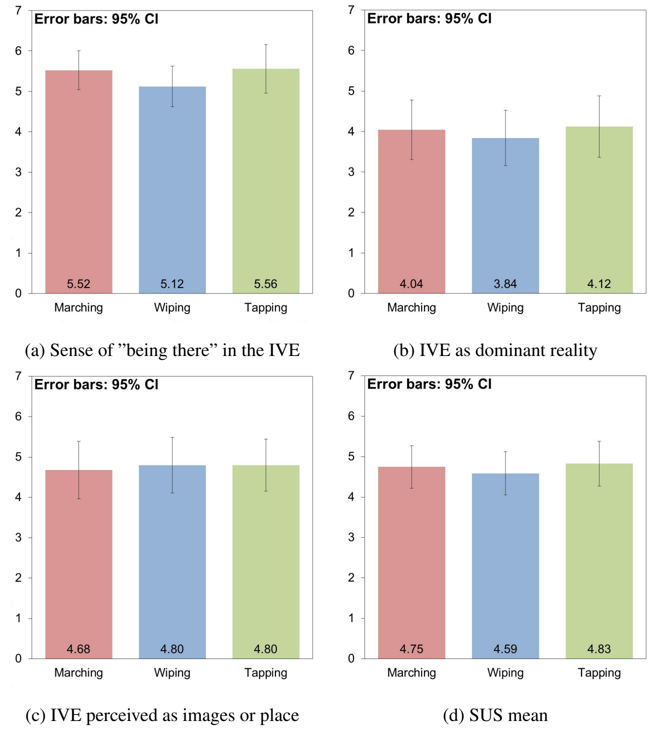
(a) Naturalness

(b) Fatigue relative to real walking

(c) Self-motion compellingness

(d) Acclimatisation

Figure 4: Results pertaining to the self-reported measures of perceived naturalness.



(a) Sense of "being there" in the IVE

(b) IVE as dominant reality

(c) IVE perceived as images or place

(d) SUS mean

Figure 5: Results pertaining to the self-reported measure of presence.

how natural the walking experience was $(F(2,24) = 5.44, p < .01)$ and in relation to the item required the participants to rate whether the gesture had been more physically straining than real walking $(F(2,24) = 22.34, p < .01)$. In the former case the post-hoc analysis revealed a significant difference between the Wiping and Tapping gestures. In regards to physical strain, Tapping was significantly different from both Marching and Wiping. No significant differences were found between the means obtained from the items related to perceived self-motion compellingness and the item asking how quickly the participants forgot that they were not really walking.

5.2 Presence

The means pertaining to the three items featured in the SUS questionnaire are shown in Figure 5 along with the grand mean of the three items – the SUS mean. The comparison by means of the repeated-measures ANOVA revealed no significant differences.

Table 1: P-values obtained from paired sample, one tailed t-tests. Values indicating a significant difference are highlighted with bold ($\alpha = 0.017$). Marching = M, Wiping = W, and Tapping = T.

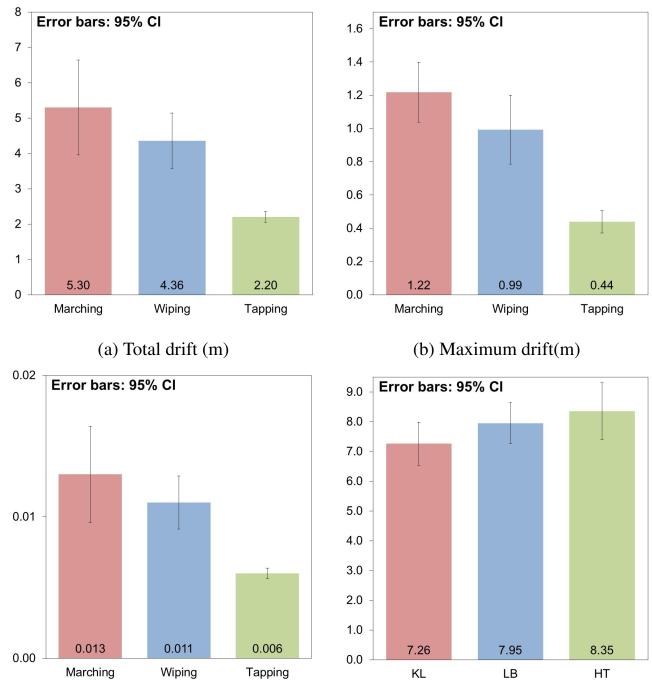
	M-W	M-T	W-T
Naturalness	0.051	0.179	**0.007**
Fatigue relative to real walking	0.247	<**0.001**	<**0.001**
Total drift	0.114	<**0.001**	<**0.001**
Maximum drift	0.048	<**0.001**	<**0.001**
Drift/travel ratio	0.103	<**0.001**	<**0.001**
Virtual velocity	0.083	<**0.008**	<0.409

5.3 Unintended Positional Drift

Figure 6 shows the results related to UPD. The comparison by means of repeated-measures ANOVAs yielded significant differences for all three measures of UPD: total drift $(F(2,25) = 19.79, p < .01)$, maximum drift $(F(2,25) = 39.04, p < .01)$, and drift/travel ratio $(F(2,25) = 20.42, p < .01)$. The post-hoc analyses indicated that Tapping was significantly different from both Marching and Wiping in regards to all measures, while the two in no cases differed significantly from each other. Finally it is worth noting that analysis of the performance data revealed that there was a significant difference in terms of the mean velocity of the viewpoint displacement across the three conditions $(F(2,25) = 3.55, p < .04)$.

6 Discussion

The results obtained from the questionnaire item asking the participants to explicitly rate how natural they found the experience of walking, yielded some interesting information. The participants did in average find the Tapping gesture to be the most natural and the mean pertaining to this gesture was significantly higher than the one corresponding to the Wiping gesture. The Tapping gesture was also perceived as significantly less strenuous compared to Marching and Wiping, while the two did not differ significantly from one another. Judging from the mean rating themselves, it would seem that Tapping was the only of the three gestures that generally was not regarded as more physically demanding than real walking. With that being said, we cannot claim that we have confirmed the assumption that the Marching gesture is more physically straining than real walking since no physiological data related to muscle activity were collected. While the current study did not reveal such an effect, it seems plausible that the activation of the soleus muscles (the large muscles inside the calves) during Tapping might lead to fatigue during prolonged interaction. However, it would seem that the Tapping gesture is successful at partially im-



(a) Total drift (m)

(b) Maximum drift(m)

(c) Drift/travel ratio (m/m)

(d) Virtual velocity (m/s)

Figure 6: Results pertaining to the measures of Unintended Positional Drift (a, b, c) and the results related to virtual velocity (d).

itating both the proprioceptive feedback and the perceived degree of muscle activity associated with real walking. Here it is worth noting that a significant difference was found in regards to the virtual speed resulting from the three gestures. Marching resulted in a significantly lower speeds compared to Tapping. This may be viewed as a sign of fatigue during Marching since the inability to maintain high steps would result in reduced virtual speeds. With that being said, it cannot be ruled out that the differences in velocity might have influenced the participants ratings of naturalness and presence. The measure of self-motion compellingness did not reveal any significant differences between the three gestures suggesting that that all three in part elicited a compelling sensation of movement. Similarly, no differences were found between the means related to the question of how quickly the participants forgot that they were not really walking. Even though the setup used for the current study does not permit tracking of real walking over long distances, a comparison with such a condition could have provided insights regarded how natural the three gestures were compared to their real world counterpart. Moreover it would have been useful to include a more traditional form of virtual travel (e.g.joystick interaction) since this would have provided a known ground for comparison. The inclusion of these two conditions would similarly have been useful for the assessment of presence.

While the results from the SUS questionnaire did indicate that the participants may have experienced some degree of presence, no significant differences were found between the three gestures. It is possible that the gestures do not elicit different degrees of presence. After all, the three are very similar compared to the WIP technique and push button flight which did differ in terms of presence [29]. With that being said, it is also entirely possible that the employed measure of presence was not sensitive to the difference in presence, or reliably measured it for that matter. Indeed it has been questioned whether it is sufficient to rely on questionnaires as the sole measure of presence [25].

Finally the results pertaining to UPD were clear and consistent across the three measures. The Tapping gesture differed significantly from the two other gestures in terms of how far the participants in average moved, how far away the participants in average went from the starting point, and how far they in average moved per travelled meter in the IVE. While no significant differences were found between the two other groups, it is worth noting that Marching in average performed the worst in regards to all three measures. The reason why Tapping led to significantly less drift compared to the other two is most likely that the participants while walking straight did not break contact with the ground. Even though this may have prevented them from drifting, four participants explicitly mentioned that it made turning seem unnatural since they during this action were forced to break contact.

This necessarily leaves the question: should Tapping be considered the best alternative of the three. When it comes to reducing UPD the answer is yes, but in regards to naturalness it seems possible that a gesture mixing Marching and Tapping might be ideal. To be more exact, if the user performs the Tapping gesture without constantly keeping contact with the ground – in essence energy efficient Marching – then the user would receive the desired proprioceptive feedback and be able to turn in a more natural fashion. However, it has yet to be determined whether such energy efficient Marching is accompanied by large amounts of UPD. If it is, it seems possible that existing redirection techniques such as subtle reorientation of the user or overt delimitation of the physical space might be used to minimize the issue [20]. An interesting attribute of the Tapping gesture as well as energy efficient Marching, is that they in principle can be used as input for most of the WIP techniques described in section 2, if these were calibrated accordingly. The implementation used for the current study demonstrated that the Tapping gesture generates sufficient vertical foot movement to generate viewpoint displacement. Similarly vertical foot movement is needed for LLCM-WIP [9] and GUD WIP [38]. Moreover the SF-WIP [14] seems like a viable candidate for controlling virtual movement by means of Tapping or Wiping for that matter. The fact that the user does break contact with the heal when Tapping should the gesture detectable by physical interfaces such as the Walking Pad [3, 4] or the Wii Balance Board. Finally, it seems possible that Tapping will produce enough head movements in order to be used in combination with algorithms requiring such input [26, 35].

7 Conclusions and Future Work

In this paper we have described a study investigating how two novel forms of gestural input for WIP locomotion (Tapping and Wiping) compared to the most commonly used gesture (Marching) in terms of naturalness, presence and positional drift. The participants walked along a path in a virtual environment delivered via a HMD and a 24-channel surround sound system. The results indicate that the gesture Tapping is the most natural and best matches the perceived physical effort of real walking. This has led us to believe that Tapping, or variations of this gesture, might serve as ideal input for WIP techniques since the proprioceptive feedback and perceived physical strain appear similar to the ones experienced during real walking. Finally, no differences were found in terms of presence, but the Tapping gesture produced significantly less positional drift than both of the other gestures. While the current study yielded interesting information, future evaluations are necessary in order to optimize the gestural input for WIP locomotion. Particularly, it seems relevant to perform evaluations involving tasks that are sufficiently general in order to assess differences in usability and performance. Such tasks could include object avoidance and precision tasks, e.g., as starting and stopping efficacy. Moreover, it will be crucial to design tasks allowing for comparison with real walking and more conventional locomotion interfaces.

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