Assisted walking-in-place: Introducing assisted motion to walking-by-cycling in embodied virtual reality

Yann Moullec, Mélanie Cogné, Justine Saint-Aubert, Anatole Lécuyer

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Fig. 1: We introduce assisted motion to walking-by-cycling using a motorized bike (left). The user embodies an avatar which is viewed in first-person perspective (right). The bike drives the user's legs in a cycling motion, which makes the avatar walk in synchrony (middle) without requiring effort from the user.

Abstract—In this paper, we investigate the use of a motorized bike to support the walk of a self-avatar in virtual reality (VR). While existing walking-in-place (WIP) techniques render compelling walking experiences, they can be judged repetitive and strenuous. Our approach consists in assisting a WIP technique so that the user does not have to actively move in order to reduce effort and fatigue. We chose to assist a technique called walking-by-cycling, which consists in mapping the cycling motion of a bike onto the walking of the user's self-avatar, by using a motorized bike. We expected that our approach could provide participants with a compelling walking experience while reducing the effort required to navigate. We conducted a within-subjects study where we compared "assisted walking-by-cycling" to a traditional active walking-by-cycling implementation, and to a standard condition where the user is static. In the study, we measured embodiment, including ownership and agency, walking sensation, perceived effort and fatigue. Results showed that assisted walking-by-cycling induced more ownership, agency, and walking sensation than the static simulation. Additionally, assisted walking-by-cycling induced levels of ownership and walking sensation similar to that of active walking-by-cycling, but it induced less perceived effort. Taken together, this work promotes the use of assisted walking-by-cycling in situations where users cannot or do not want to exert much effort while walking in embodied VR such as for injured or disabled users, for prolonged uses, medical rehabilitation, or virtual visits.

Index Terms—Embodiment, virtual walk, avatar, perceived effort

1 Introduction

Virtual locomotion is one of the most fundamental tasks to achieve in virtual reality (VR). The most natural locomotion technique in VR remains real walking, where users physically walk in their real environment in order to navigate. However, this technique requires a large interaction space, which makes it difficult to implement in small VR setups. Other techniques have been suggested to mitigate this issue, some of which require real walking movements and contain users to limited spaces using redirection techniques [42] or devices such as treadmills [18], others explore motion-based metaphors that can be performed while staying stationary [20, 48]. Typically, walking-in-place (WIP) techniques consist in performing stationary walking-like motions to navigate in the virtual environment [20, 48, 58]. For instance, raising knees [58] or cycling [20] have been proposed as WIP motions.

Due to the repetitive nature of the gait cycle, WIP techniques can be judged strenuous [5, 13, 49, 56, 60, 66]. We proposed to assist a WIP technique so that the user does not have to actively move in order to reduce effort and fatigue. We chose to assist a technique called walking-by-cycling [20], which consists in mapping the cycling motion of the user to the walking animation and displacement of the self-avatar, because it is relatively straightforward to automate with a motorized bike. Based on previous work, we expected that this "assisted walking-by-cycling" could render a compelling walking experience, similar to active walking-by-cycling in terms of ownership, and provide a higher walking sensation than when making no movement. We conducted a user study to compare assisted walking-by-cycling to active walking-by-cycling and absence of motion in terms of walking sensation, embodiment, perceived effort and fatigue.

In brief, our main contributions can be summarized as follows:

- Introducing assisted motion to walking-by-cycling in order to relieve users from exerting too much effort while maintaining a compelling walking experience.
- Conducting a study which showed that assisted walking-by-

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cycling induced levels of ownership and walking sensation similar to that of active walking-by-cycling, but it induced less perceived effort, and that assisted walking-by-cycling induced more ownership, agency, and walking sensation than a static simulation.

2 Related work

In this section, we discuss past work related to walking in virtual reality (VR). It is split into three subsections. subsection 2.1 gives an overview of stationary locomotion techniques in VR and present past work which aimed at reducing fatigue and effort induced by such techniques. subsection 2.2 and subsection 2.3 respectively focus on the contribution of active and passive body movements on enhancing walk-related sensations and embodiment.

2.1 Low-effort and compelling stationary locomotion techniques in VR

Boletsis proposed a classification of locomotion techniques in VR [4]. He distinguishes locomotion techniques that use artificial user interfaces, e.g. controllers, and those using physical user motion. These techniques allow for either continuous or discontinuous motion in virtual environments, and they require different sizes of interaction space. In this subsection, we give an overview of physical and continuous techniques implemented to provide stationary locomotion in VR, and present past work which aimed at reducing fatigue and effort induced by such techniques.

In order to navigate in virtual environments while staying stationary, researchers have developed various devices that allow users to perform real walking movements [18, 29, 30, 57]. For instance, treadmills-like devices allow users to perform real in-place walking movements in one [18] or two directions [29, 57]. More complex robotic systems can render walking experiences on uneven terrain [30].

However, many locomotion techniques do not use real walking movements but rather some kind of motion-based metaphor. These metaphors may involve various body parts. Whole-body leaning metaphors have been explored [24, 37, 40]. For instance, NaviChair, MuvMan and Swivel Chair are chair-like devices that measure user leaning to navigate in virtual environments [37]. Other leaning-based devices used pressure sensing boards to sense user leaning [24, 40]. Locomotion techniques based on head movements have also been proposed like head shaking [60] and head-directed navigation [10, 37]. Techniques based on upper body movements like arm swinging [49], hand flapping, or arm-controlled flying [5] have been proposed. Finally, many lower body movements have been explored. Typically, WIP techniques consist in mapping lower body movements like tapping heels [48], stepping [5], raising knees [5, 48, 58], wiping [48] or cycling [8, 9, 14, 15, 20, 25, 26] to virtual locomotion.

Comparative studies on VR locomotion have shown that physical user interfaces induce higher fatigue and effort than artificial interfaces like gamepads, controllers, or joysticks [5,10,13,47,49,56,60,66]. This was shown for physical interfaces involving various body parts such as hands [5, 10], arms [13, 49], head [60, 66], hips [49], for device-based interfaces like the VirtuSphere [47] and the stepper machine [5], for real walking [49] and for WIP [49, 56]. Since they do not engage the user's body, artificial user interfaces are less tiring but also lack to render a compelling walking experience. To solve this problem, a variety of body motions such as the adaptation of WIP to fingers [36] have been proposed [22, 33, 36, 48, 49, 65, 66], with variable impact in terms of fatigue and closeness to real walking. Bruno et al. have also proposed adding speed gains to WIP, which makes the techniques less fatiguing compared to classical WIP [7].

In this work, we explore another lead to mitigate effort and fatigue during VR locomotion while maintaining a good physical engagement of the user by assisting a WIP motion.

2.2 Influence of active and passive movements on walk-related sensations

Walk-related sensations include various sensations like vection, walking sensation, walking naturalness or realism. They relate to the similarity of the virtual walk with a real walking experience. Vection, or the sensation of self-motion [51], is part of walking sensation since walking is a locomotion method. Walking sensation, naturalness and realism are used interchangeably. Similar to previous work [2, 19, 45], we favor the term walking sensation. These sensations have been shown to be influenced by motor, proprioceptive, and vestibular cues caused by movements and posture in VR [2, 37, 40, 56] and outside VR [27, 28, 54, 62, 64]. Both active body movements [37, 40, 51, 56, 60] and passive body movements [2, 27, 28, 51, 54, 62, 64], where users are moved by a device or a third party, have been investigated in the literature.

As shown in subsection 2.1, active movements have been leveraged as user interfaces for VR locomotion. Nilsson et al. have proposed a classification for natural locomotion techniques in VR [50]. According to these authors, techniques that render a walking experience with most fidelity are the ones reproducing real walking movements like treadmills [18] or redirected walking [42]. Stationary motion-based metaphors [49, 56, 60] like WIP can also be relatively natural walking metaphors, although less natural than real walking [63]. Real walking was indeed reported to be more natural than virtual head-directed flying and WIP [63]. However, motion-based metaphors are often judged more natural than traditional input systems. For instance, Shake-your-head, a WIP technique where head oscillations are used to move forward, was judged more realistic than keyboard and joystick in terms of walking sensation when users were seated [60], and Triggerwalking, which consists in continuously mapping a trigger press to virtual camera oscillations and forward motion was judged more natural than joystick [56]. Arm swinging has been shown to be as natural as WIP movements [49], showing that upper body movements could perform as well as lower body movements in terms of naturalness. Motion-based metaphors were also shown to affect vection [40]. Standing leaning-based locomotion was shown to induce significantly more vection than joystick locomotion in VR [40], while seated leaning-based locomotion showed mixed results [37, 41]. Overall, active body movements can induce walk-related sensations similar to those induced by real walking, although real walking is more natural.

The effect of passive movements on walk-related sensations have mostly been investigated outside VR [27, 28, 54, 62, 64]. They include seated whole-body motion like lift, roll [28, 54, 62], and pitch [54, 62], which were shown to induce a sensation of walking [28, 54, 62]. Turning sensations on curvilinear paths have also been induced using seated whole-body motion [62]. Passive limb movements in seated users such as arm-swinging [54], heels vertical movement, and feet longitudinal movement [27, 64] have also been shown to induce a sensation of walking [54, 64]. In VR, similar results were attained using lift and yaw seated whole-body motion [2]. Interestingly, during curvilinear motion simulation in non-immersive VR, while both active and passive leaning induced more vection than joystick locomotion, passive leaning induced more vection than active [51]. These studies show that walk-related sensations can be induced even when users are passively moved.

Even without movements from users, walking sensations have been induced by the observation of VR walking simulations [38, 45, 53]. In such simulations, it was shown that body posture has an influence on walking sensations [53]. During the observation of a virtual avatar walking in first-person perspective, sensation of walking was reported to be higher while standing than in a semi-sitting position called the Fowler's position, and standing and seating did not differ significantly [53].

In summary, past work showed that both active and passive movements could be leveraged to induce walk-related sensations. Up to now, active and passive movements have been compared only once in a study on vection and leaning [51]. Thus, by comparing the impact of active and assisted – or passive – walking-by-cycling, and being static, our work contributes to better understanding what induces a walking sensation in VR.

2.3 Influence of active and passive movements on embodiment

The sense of embodiment towards a virtual body or body part in VR is usually decomposed into three inter-dependent components: self-location (the feeling of being co-located with the virtual body), agency (the feeling of controlling the virtual body), and body ownership (the feeling of self-attribution of a virtual body) [34]. The sense of embodiment has been reported to be induced and influenced by visuo-motor synchrony, the consistency between the movements of the user and the perceived movements of the embodied body [23,39].

Visuo-motor synchrony can be attained using both active body movements and passive body movements, where users are moved by a device or a third party, which cause different levels of ownership and agency [1,6,16,31,32,44,61]. Dummer et al. have shown that visuo-motor synchrony with active movements induced higher self-report self-location and ownership than with passive movements in a Rubber Hand Illusion (RHI) setup, while overall RHI effect did not differ significantly [16]. In other studies using RHI setups, active and passive movements were reported to induce similar levels of ownership [6,31,32], measured by self-report and proprioceptive drift – an objective measure of ownership [31]. However, either visuo-motor synchrony with passive movements did not induce any agency [31,32], or it induced a lower agency than with active movements [6]. The same observations were made in a setup involving video feedback of the participant's hand [44]. These findings were recently reproduced in a VR first-person perspective Virtual Hand Illusion (VHI) setup: active movements did not induce more ownership than passive movements but it induced more agency [1]. Control over the movements during visuo-motor synchrony was also reported to influence the nature of the illusion [61]. In the setup, which involved a projection of the participant's real hand, proprioceptive drifts localized to the stimulated finger were reported for passive movements while proprioceptive drifts spread across the whole hand were reported for active movements. These studies show that visuo-motor synchrony with passive movements induces similar levels of ownership but cancels or decreases agency compared to visuo-motor synchrony with active movements.

Surprisingly, Kokkinara et al. reported that first-person perspective observation of a walking avatar in VR induced more agency than third-person perspective while participants did not have any control over their avatar's walking [38]. Their proposed explanation relied on prospective models of agency, which have highlighted the role of intention in agency [12]. They argued that, while no explicit instruction was given to have intention over the walking, the observation of the avatar's legs in first-person perspective combined with the usual experience of walking could have initiated an action representation for the planning of the next movement. This action representation would have created an intention over the walking which would have contributed to the illusory agency. In another embodied VR study, even if embodiment was not measured, it was shown that viewing a full-body avatar in first-person perspective induced more walking sensation and sensation of striking the ground than viewing only hands and feet or viewing no avatar [45]. Thus, embodiment seems important in order to induce compelling walking sensations in VR walking simulations.

Overall, past work suggests that visuo-motor synchrony with active movements benefits agency but not ownership, which is similar for passive movements. Even without movements by users, an illusory sense of agency was reported during the observation of a virtual walk in embodied VR which seems to highlight walking simulations as a special case with regards to agency. Our study compares the impact of active movements, passive movements, and no movements on embodiment during an embodied VR walking simulation. This contributes to better understanding how passive movements affect the sense of embodiment in a VR walking simulation where past work focused on RHI and VHI setups. This study also extends previous work that highlighted the illusory sense of agency induced by the static observation of a virtual walk by comparing it to simulations with passive and active movements.

3 User Study

We compared the impact of assisted walking-by-cycling, active walking-by-cycling and absence of motion during a walking simulation in a user study. We evaluated embodiment and walking sensation in a within-subjects study with three conditions: *assisted*, *active* and *static* condition. The order of the conditions was counterbalanced using Latin square ordering.

Fig. 2: First-person view of the virtual scene: speed gauge on the left, first-person avatar at the bottom, clear shadow in the middle

3.1 Overview

In the experiment, seated participants observed a walking simulation that took place on a straight forest path in first-person perspective (see Figure 1 and Figure 2). Each walking simulation lasted 4 minutes. Depending on the condition, participants performed various motions:

- Condition *assisted*: assisted walking-by-cycling, where the user's legs were driven by a motorized bike in a cycling motion,
- Condition *active*: active walking-by-cycling, where the user performed the cycling motion,
- Condition *static*: the user did not move.

The procedure described in this article was approved by the ethical committee from the Inria Rennes research center.

3.2 Hypotheses

Our hypotheses for the study were the following. As explained in subsection 3.3, we used the virtual embodiment questionnaire by Roth and Latoschik [52] to measure embodiment. For each of the three sub-categories of the embodiment questionnaire, which are, ownership, agency, and change in the perceived body schema, or change, previous work led us to make three hypotheses. First, strong evidence suggests that assisted – or passive – motion induces similar levels of ownership than active motion but cancels or significantly reduces agency [1,6,31,32,44,61]. As for condition *static*, despite reports of an illusory sense of agency induced in first-person perspective by the observation of a virtual walk [38], we hypothesized that both agency and ownership would be significantly lower than both the *active* and *assisted* conditions since visuo-motor synchrony is much less involved in condition *static* and visuo-motor synchrony highly contributes to agency [11,17,23,34,55] and ownership [21,23,34,39]. Indeed, in condition *static*, only head motion is mapped onto the avatar, and this is the case in all conditions. Thus, the hypotheses for ownership and agency were:

- **H1**: Ownership is greater in conditions *active* and *assisted* than *static*.
- **H2**: Agency is greater in condition *active* than *assisted*, and greater in conditions *active* and *assisted* than *static*.

Change relates to the perception of a change in one's own body schema (change in weight, height, width, and change in general) which is especially important when considering the Protheus effect [52]. It is not correlated with agency nor ownership, but it is correlated with presence and immersion, and it is positively affected by immersion with an HMD in first-person perspective [52]. WIP [3,63] and more importantly cycling-in-place [20] have been reported to induce more presence than traditional joystick [3,20] or head-directed flying [63] techniques. Other studies did not report a higher presence for WIP than keyboard control [49], joystick [56], or teleportation [56]. Based on these mixed results, we expected the *active* and *assisted* conditions to induce higher levels of change than *static*. However, previous work does not allow us to have clear expectations about a difference between the *active* and *assisted* conditions. Thus, we made the following hypothesis for change:

- **H3**: Change in the perceived body schema is greater in conditions *active* and *assisted* than *static*.

Based on the literature on walking sensation [2, 51, 56, 60] (see subsection 2.2), we expected that performing a cycling motion would positively impact walking sensation. Thus, we hypothesized that walking sensation would be higher in conditions *active* and *assisted* than *static*. As for comparing active and passive motion, previous work only shows that passive leaning may induce more vection than active leaning [51]. However, we hypothesized that being active while cycling would probably be closer to real walking than being passive. This led us to make the following hypothesis:

- **H4**: Walking sensation is greater in condition *active* than *assisted*, and greater in conditions *active* and *assisted* than *static*.

For fatigue and perceived effort, we expected that having to actively perform a cycling motion would be more tiring than being passively moved or being static. Thus, we hypothesized that fatigue and perceived effort would be higher in condition *active* than *static* and *assisted*. In addition, passive motion may cause an illusion of making an effort and thus condition *assisted* could induce more perceived effort than *static*. Thus, the hypotheses on perceived fatigue and effort were:

- **H5**: Fatigue is greater in condition *active* than in conditions *assisted* and *static*.
- **H6**: Perceived effort is greater in condition *active* than *assisted*, and greater in conditions *active* and *assisted* than *static*.

3.3 Measures

Per-condition questionnaires included the virtual embodiment questionnaire designed by Roth and Latoschik [52] and the Virtual Reality Sickness Questionnaire (VRSQ) [35]. The three sub-categories of the virtual embodiment questionnaire – ownership, agency, and change – yield a 1 to 7 score [52] while the VRSQ yields a 0 to 100 score. The virtual embodiment questionnaire was chosen so that agency and ownership could be measured and analyzed separately, in accordance with our distinct hypotheses. Self-location is not the focus of this study and it correlates with ownership [31, 34], it was thus not measured to avoid having too many questions. Additional items valued on a 7-point Likert scale were included to characterize the users' walking sensation and perceived effort or perceived exertion: *I felt like I was walking* ; *I had the sensation of making an effort* (1 = Strongly disagree, 7 = Strongly agree). Perceived fatigue was also assessed using the Rating-of-Fatigue scale [46] (0-10 scale).

A general questionnaire was added after the last condition. Participants had to rank the three conditions according to their personal preference. They were also asked to assess their confusion with regards to walking-by-cycling: *It was confusing to control a walking motion in the virtual environment with a cycling motion* (7-point Likert scale). A final section allowed users to make general comments about the different conditions and the experiment altogether.

In addition to these self-report measures, users' pedaling speed and head-mounted display (HMD) orientation were recorded. Pedaling speed was recorded for the *assisted* and *active* conditions to make sure that the walking speed was consistent between conditions. Pedaling speed data is the record of completion time for all pedaling cycles. HMD orientation was recorded to account for the amount of time the users watched their legs during each condition. HMD orientation data is the record of the angle between the HMD's forward direction and the down direction at each frame, associated to the duration of the frames.

3.4 Experimental apparatus

An HTC Vive Pro HMD provided visual and audio cues from the virtual environment (see Figure 5). The HMD's orientation was mapped onto the orientation of the 3D view and the orientation of the avatar's head in the virtual environment. Computer specifications were the following: Intel Core i7-11800 CPU, 16GB RAM, NVIDIA GeForce RTX 3070 Laptop GPU. Participants' motion was tracked by a Vive tracker placed on each of the bikes' right pedal and participants used a Vive controller to trigger events in the scene (see Figure 5). The virtual scene was rendered using the Unity3D game engine. To animate the avatars, we used a standard walking animation from Mixamo. Different avatars were designed using MakeHuman. Variants included two genders, three levels of corpulence and three races. Additional customization included skin tone (light, brown or black), haircut and hair color. Avatars' local scale in the scene was adapted by the experimenter to approximately match participants' height.

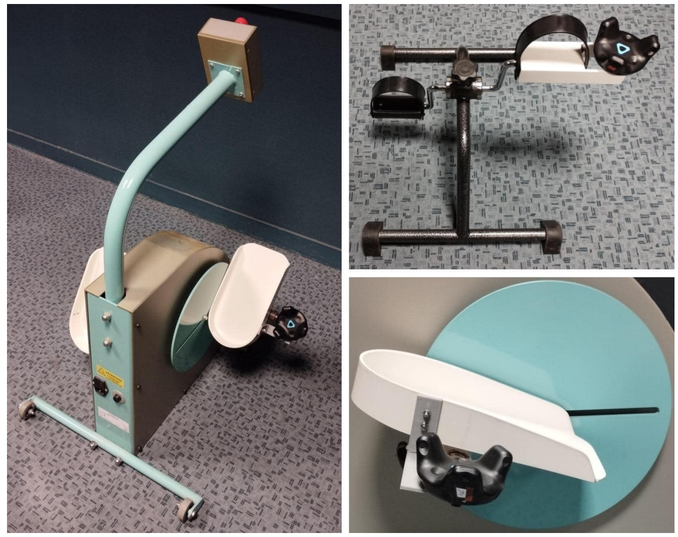

Fig. 3: Motorized bike (left), Standard bike (top-right), Vive tracker attached to the motorized bike (bottom-right)

To assist users in performing walking-by-cycling, we used a cycloergometer, which is a medical motorized bike (see Figure 3, left). This device is entirely automated and applying pressure on the pedals does not make them move. Just like traditional walking-by-cycling, the cycling motion was synchronized with the walking simulation. The motorized bike was not directly controlled by the VR application, but was activated by the experimenter. To perform the active cycling motion, a small steel bike was used (see Figure 3, top-right). On the bike, the pedaling resistance was tuned so that the force required to pedal was comfortable and that the bike provided some level of support to the users' feet. In condition *static*, no bike was used and the participants' feet rested on the ground. The process used to extract the angle of rotation of each bike and to control the walking animation are respectively presented in subsubsection 3.4.1 and subsubsection 3.4.2.

Differences between the two bikes were compensated as much as possible to avoid postural biases between conditions *assisted* and *active*. The small bike's radius of rotation measured to $10cm$ and could not be changed On the motorized bike, it was set to $11cm$ which was the closest option to the other bike. The two bikes also differ in terms of the height of the axis of rotation. The height difference of $9cm$ was compensated by raising the chair in front of the motorized bike by $9cm$ (see Figure 5). The difference between the bikes' pedal shapes was judged as not important since the position of the feet with respect to the pedals' local rotation axis was similar.

3.4.1 Extracting the cycling motion

The cycling motion was extracted using Vive trackers. 3D-printed tracker supports were designed to attach a tracker on the right pedal of each bike (see Figure 3, top-right and bottom-right). The supports were designed to place the trackers as close to the pedals' local rotation axis as possible so they performed a circular motion no matter how the

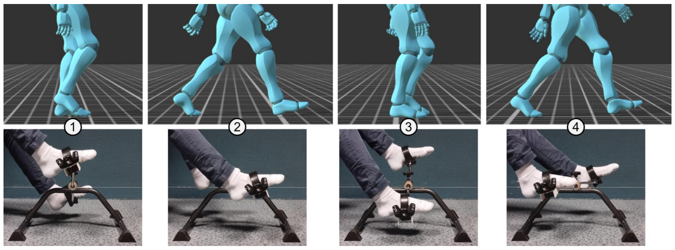

Fig. 4: Correspondence between the pose in the avatar's gait cycle and the pedals' position

Fig. 5: Experimental setup for conditions *static* (left), *active* (middle), and *assisted* (right)

pedals rotated locally. For the small bike, a slight correction along the tracker's forward axis was applied to get a proper circular motion.

During the calibration process, the application saved the position and orientation of the circles around which each tracker rotated. This process consisted in reading the position of three points on each circle, and computing each circle's center and normal direction from the points. The values were stored using Unity's *PlayerPrefs* storage system so they persist between simulations. Unity's *SignedAngle* function is used to compute the angle of rotation between a "zero" vector and the vector from the center to the tracker's position, using the rotation axis as a reference. To make the system more robust, both the vector from center to tracker and the zero vector are first projected onto the rotation plane before computing the angle of rotation. This yields a -180 to 180 angle in degrees.

3.4.2 Mapping the cycling motion to the virtual walking

Similarly to past work from the literature which mapped a cycling motion to a walking animation [20], the angle of rotation of the bike was used to control the time of a prerecorded walking animation. One pedaling cycle corresponded to one gait cycle following the schema depicted in Figure 4. However, contrary to past work [20], gait length was not adapted as a function of walking speed. This choice was made to simplify the control law for forward speed in the virtual scene: with our system, pedaling twice as fast makes users move twice as fast, whereas making larger steps would make the speed even greater. Also, this ensures that for a given angle, only one avatar pose corresponds, which may help users getting used to the walking metaphor. Control of the walking animation was done using Unity's "Motion Time" system, which gives control over the time of animation with scripts instead of mapping application time to animation time. This way, each frame, the bike's angle of rotation was directly mapped to the 0 to 1 value controlling the avatar's walking pose: $motionTime = (angle + 180)/360$. Unfortunately, the Motion Time system does not support the application of animation root motion. Thus, root motion was computed each frame from the difference between previous and actual angle of rotation: $root \mathrel{+}= \Delta angle \times speed/\omega$. The variables $speed$ and ω were respectively the walking and the rotation speed when not using Motion Time (expressed resp. in m/s and deg/s). Both were measured on the walking animation clip.

3.4.3 Walking speed and walking sensation

Step frequency was constant across participants and conditions and equal to 50 gait cycles per minute. This implies that in condition *assisted*, rotation speed was constant and equal to $50rpm$ and that in condition *active*, participants were instructed to maintain a speed of $50rpm$. They were helped doing so using a speed gauge present in all conditions (see Figure 2). Absolute forward speed varied between participants since avatar height, and thus absolute step length, was adapted to match participants. For instance, a 1.6-meter tall avatar moved at a speed of $0.93m.s^{-1}$. We did not have smaller avatars make larger steps relative to their height since it would have made their gait unnatural. We favored constant step frequency over constant forward speed because a variable step frequency would imply having participants pedal faster than others, which would have impacted fatigue and perceived effort, where different speeds should mainly have impacted vection, which was not the focus of the study.

Sensory cues were presented to participants in order to increase walking sensation. They included footstep sounds, played each time the avatar's feet struck the ground, and slight camera oscillations. Both have been reported to increase walking sensation [19, 43]. Camera oscillations were set to 15% of animation amplitude, which resulted in lateral and vertical sinusoidal oscillations of 0.5 cm and 0.7 cm of amplitude respectively for a 1.75-meter-tall avatar. To allow indirect observation of the avatar, a low-angle directional light source projected a clear shadow in front of the avatar (see Figure 2). In the experimental protocol, participants were also instructed to look down at their virtual body several times during each walking simulation (see subsection 3.5), which should also increase walking sensation [45].

3.5 Protocol

At the beginning of the experiment, participants were explained the procedure and signed a consent form if they agreed to the terms of participation. Participants then sat on a chair, installed the HMD and the first condition was launched by the experimenter. Before each walking simulation, participants observed their avatar in a mirror for 30 seconds in order to familiarize themselves with the virtual body and environment. For each condition, participants had to press the trigger on the Vive controller to start walking. This caused a countdown of 5 seconds before the walking simulation started. In condition *assisted*, this time allowed the experimenter to turn on the motorized bike. When the finish line was reached by the avatar, participants' field of view slightly faded to indicate that the task was complete. Participants were then required to press the trigger again to stop walking and end the simulation with a complete fade-out.

Several instructions were given to participants. They were explained the trigger mechanism to start and end the simulation. For condition *static*, they were told not to move their legs. For condition *assisted*, they were told that they did not need to move their legs since they would be moved by the motorized bike. For condition *active*, as explained in subsubsection 3.4.3, participants were instructed to actively cycle while maintaining a speed of $50rpm$. Like in Kokkinara et al.'s study [38], participants were reminded to watch their virtual body. During the simulation, white spheres appeared 12 times at random times in front of them. Each time this occurred, they were instructed to look down at their avatar for a few seconds. This was done so that participants were conscious of having a virtual body and that they could directly observe its walking motion.

Between each condition, participants took off the HMD, a laptop was handed to them and they filled in the questionnaire corresponding to the condition. The first questionnaire contained additional demographic data: gender, age and familiarity with VR. The last questionnaire contained the additional items related to the complete experiment (see

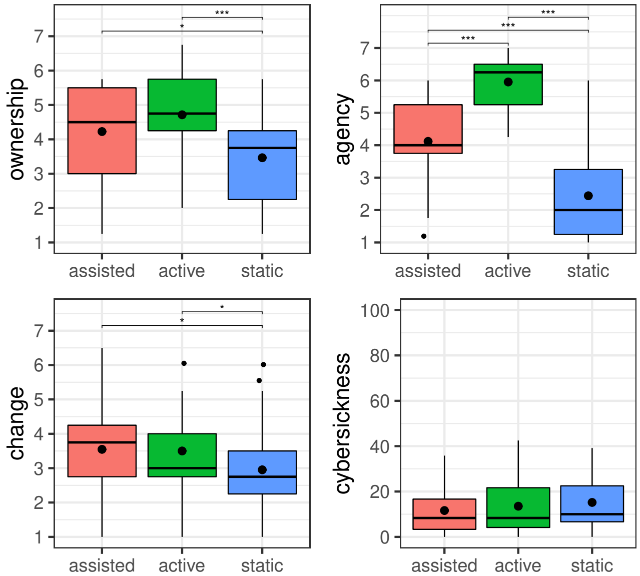

Fig. 6: Box plots for the sub-components of embodiment (ownership, agency, change) and cybersickness for each condition. Large black dots represent the means, and brackets indicate post-hoc significance levels. Higher is better for embodiment, lower is better for cybersickness.

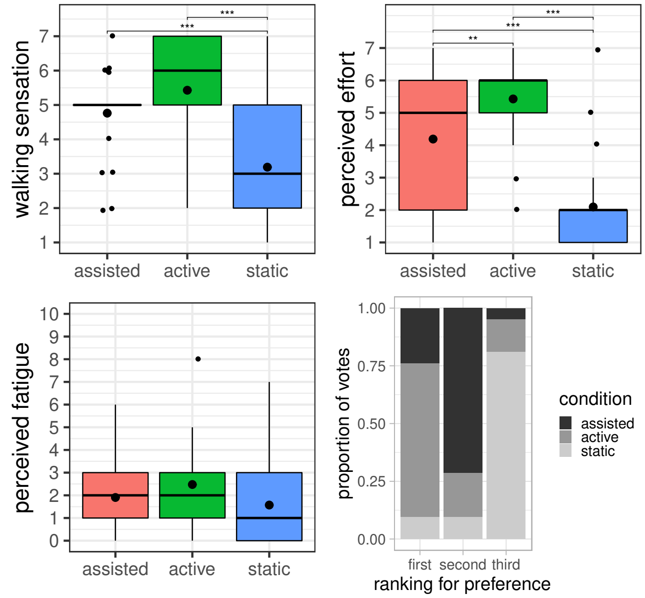

Fig. 7: Box plots for walking sensation, perceived effort and fatigue for each condition. Large black dots represent the means, and brackets indicate post-hoc significance levels. Preference score for each condition. Higher is better for walking sensation, lower is better for perceived effort and fatigue.

subsection 3.3). Overall, the experiment lasted about 40 minutes, including less than 15 minutes in VR.

3.6 Participants

A total of 21 volunteers were included in this study (15 male, 5 female, 1 did not specify, mean age = 24.6, SD = 5.99 years). They were moderately familiar with VR: six had never used it before, nine had used it a few times, and six used it often. They were not told the purpose of the experiment, had normal or correct to normal vision, and were not compensated for their participation in the experiment. Participants were researchers from the Inria Rennes research center and students from Rennes University recruited through grouped emails. In addition to the 21 participants, two volunteers could not finish the experiment due to too much discomfort, one of which during the *assisted* condition, the other during the *active* condition. Their incomplete data was excluded from the statistical analysis.

4 Results

This section reports the results of the user study comparing assisted walking-by-cycling (condition *assisted*), a traditional active walking-by-cycling implementation (condition *active*), and a condition where the user is static (condition *static*). Each condition was evaluated in terms of embodiment (subsection 4.1), walking sensation (subsection 4.2), perceived effort and fatigue (subsection 4.3).

Since we conducted a within-subjects user study with Latin square ordering, independent variables are the 3-level within-subjects factor *condition*, and the 3-level between-subjects factor *order*, the order in which each participant tried the conditions. For each of the dependent variables, we performed a two-way mixed-model ANOVA with *condition* as the within-subjects variable and *order* as the between-subjects variable. Each ANOVA corresponds to one of the hypotheses specified in subsection 3.2. When the Shapiro-Wilk normality test did not validate the normality assumption, we used the Aligned Rank Transform (ART) model before performing the ANOVA. Post-hoc tests were performed using the Estimated Marginal Means (emmeans) method with Bonferroni correction.

4.1 Embodiment

The results for the three sub-components of embodiment – ownership, agency, and change – are reported on Figure 6.

The ART ANOVA conducted for ownership showed a significant effect of condition ($F_{2,36} = 8.62,\ p < 0.001,\ \eta_p^2 = 0.324$). Post-hoc tests showed that condition *static* ($M = 3.46,\ SD = 1.34$) induces less ownership than conditions *active* ($M = 4.71,\ SD = 1.27,\ p < 0.001$) and *assisted* ($M = 4.23,\ SD = 1.42,\ p = 0.032$).

For agency, the ANOVA showed a significant effect of condition ($F_{1.91,34.45} = 40.49,\ p < 0.001,\ \eta_p^2 = 0.692$). Post-hoc tests showed that condition *static* ($M = 2.44, SD = 1.53$) induced less agency than conditions *active* ($M = 5.95, SD = 0.84,\ p < 0.001$) and *assisted* ($M = 4.12,\ SD = 1.28,\ p < 0.001$), and that condition *active* induced more agency than condition *assisted* ($p < 0.001$).

As for change, the ANOVA showed a significant effect of condition ($F_{1.88,33.89} = 4.95,\ p = 0.043,\ \eta_p^2 = 0.216$). Post-hoc tests showed that condition *static* ($M = 2.95,\ SD = 1.44$) induced less change than conditions *active* ($M = 3.5,\ SD = 1.22,\ p = 0.040$), and *assisted* ($M = 3.55,\ SD = 1.37,\ p = 0.023$).

4.2 Walking sensation

The ANOVA for walking sensation showed an effect of condition ($F_{1.41,25.33} = 18.75,\ p < 0.001,\ \eta_p^2 = 0.510$). Post-hoc tests showed that condition *static* ($M = 3.19,\ SD = 1.72$) induced less walking sensation than conditions *active* ($M = 5.43,\ SD = 1.47,\ p < 0.001$), and *assisted* ($M = 4.76,\ SD = 1.3,\ p < 0.001$). Overall, participants did not think it was too confusing to control a walking animation with a cycling motion ($M = 3.52,\ SD = 1.69$ on a 7-point Likert scale).

In addition to self-report walking sensation, two related objective measures were recorded: cycling speed for the *assisted* and *active* conditions and HMD orientation for all conditions. Indeed, since cycling speed was tied to walking speed, it may have influence walking sensation, and avatar observation was shown to influence walking sensation [45].

After trimming the first and last 10 seconds of each of the participant's recording for cycling speed, the average speed over the 4 minutes of walking simulation was computed. Results showed that participant's average speed was close to $50rpm$ in the *assisted* ($M = 49.9rpm,\ SD = 0.5rpm$) and *active* conditions ($M = 50.3rpm,\ SD = 3.66rpm$). The ART ANOVA performed on the results for the *active* and *assisted* conditions showed no effect of condition ($F_{1,18} = 1.22,\ p = 0.283$).

We defined the time each participant looked down at their avatar as the time the angle between HMD's forward direction and the down direction was less than 45°. Results showed a relatively consistent although highly variable avatar watch time: $M = 66.3s$, $SD = 28.8s$ for *assisted*, $M = 60.3s$, $SD = 28.6s$ for *active*, and $M = 53.8s$, $SD = 24.4s$ for *static*. The ANOVA performed on these results revealed no effect of condition ($F_{1.44,25.95} = 5.22$, $p = .061$).

4.3 Perceived effort and fatigue

The ANOVA for perceived effort showed an effect of condition ($F_{1.91,34.37} = 38.26$, $p < 0.001$, $\eta_p^2 = 0.680$). Post-hoc tests showed that condition *static* ($M = 2.10$, $SD = 1.55$) induced less perceived effort than condition *active* ($M = 5.43$, $SD = 1.29$, $p < 0.001$), and *assisted* ($M = 4.19$, $SD = 1.89$, $p < 0.001$), and that condition *active* induced more perceived effort than condition *assisted* ($p < 0.008$). As for fatigue, the ART ANOVA almost showed effect of condition ($F_{2,36} = 3.19$, $p = 0.053$). Scores for fatigue show some trend towards more fatigue induced by the *active* condition ($M = 2.48$, $SD = 1.91$) compared to the *assisted* ($M = 1.90$, $SD = 1.67$) and *static* ($M = 1.57$, $SD = 1.96$) conditions, and more fatigue induced by *assisted* than *static*.

4.4 Cybersickness and preference

The results for cybersickness are reported on Figure 6. Across the three conditions, cybersickness was relatively low: $M = 13.5$, $SD = 11.5$, and the ART ANOVA did not show a significant effect of condition ($F_{2,36} = 1.26$, $p = 0.296$). The mean and standard deviation are $M = 15.2$, $SD = 12.7$ for condition *static*, $M = 13.5$, $SD = 11.8$ for condition *active*, and $M = 11.6$, $SD = 10.1$ for condition *assisted*.

Participants preference scores are reported on Figure 7. Two thirds of them preferred the *active* condition, about 24% preferred the *assisted* condition, and 9% preferred the *static* condition. The *assisted* condition came second for 71% of them, and condition *static* came last for 81%. This shows a clear preference for the *active* and *assisted* conditions over the *static*, and some preference of the *active* over the *assisted*. We performed a Friedman test with a Kendall effect size on preference results. It showed a significant effect of condition ($p < 0.001$, $W = 0.41$). Wilcoxon signed-rank tests with Bonferroni correction showed that condition *static* was significantly less preferred than condition *active* ($p = 0.007$) and *assisted* ($p = 0.003$), with no significant difference between *active* and *assisted* ($p = 0.561$).

5 Discussion

In this section, we discuss the results with regards to the hypotheses that we made in subsection 3.2. We compare the results to the literature and give perspectives for future work.

5.1 Effect of assisted motion on embodiment

The study showed that condition *assisted* induced a level of ownership similar to that of *active* while inducing less agency, and that both *assisted* and *active* induced more ownership and agency than *static*. This supports **H1** and **H2** and is consistent with previous work on the influence of active and passive movements on embodiment. The study confirms that previous results on ownership and agency that have been attained in very controlled rubber hand illusion and virtual hand illusion setups [1, 6, 31, 32, 44, 61] (see subsection 2.3) can be reproduced in a more ecological simulation that is an embodied walking simulation.

The study showed that condition *assisted* induced a level of change similar to that of *active*, and that both *assisted* and *active* induced more change than *static*, which supports **H3**. In addition with the results on ownership and agency, this shows that adding synchronized motion – whether active or assisted – to a static simulation contributes to increasing all three sub-components of embodiment.

The results of the study concerning agency also bring new information on the illusory sense of agency induced by the first-person perspective observation of a virtual walk identified by Kokkinara et al. [38]. The *static* condition corresponds to their first-person condition with camera oscillations, or head swaying. Agency is slightly lower in our study ($M = 2.44$) than in theirs ($M \approx 3.5$). Various differences between the studies may explain these results. We assessed agency with four items where they only used one, and there may have been differences among the populations. Finally, the fact of comparing this simulation to different conditions in both within-subjects designs may have influenced participants' answers. The study shows that adding assisted cycling motion to such stimulation can increase agency, even with no actual control over the cycling motion. In the study, camera oscillations were present in all conditions in order to increase the sensation of walking. However, Kokkinara et al. reported much higher levels of agency without oscillations in first-person perspective. Further work could investigate whether the same difference in agency between the three conditions are induced without camera oscillations. Indeed, since participants were really moving during the *active* and *assisted* conditions, oscillations may have had more impact in the *static* condition and impaired agency more than in the two others.

In their study, Kokkinara et al. also measured ownership [38]. Their results on ownership differ from our results ($M = 3.46$ in our study against $M \approx 5$ in theirs). The same differences between the two studies than for agency may explain this difference.

5.2 Walking sensation: similar performance of assisted and active walking-by-cycling

Even if control over the walking motion could seem to be an important component of walking experience, the *assisted* condition induced a walking sensation similar to that of *active*, and significantly more walking sensation than *static*. This partially supports **H4**, in which condition *active* was expected to induce more walking sensation than *assisted*. A previous study on vection and leaning for VR locomotion showed that passive leaning induced more vection than active [51]. Our study provides a new comparison between active and passive motion with regards to walking sensation for embodied VR locomotion. Future research needs to be conducted to better characterize the effect of assisted motion and assisted WIP on walk-related sensations, like vection, during VR locomotion. The results for walking sensation in the *static* condition ($M = 3.19$) however show a major difference with previous work investigating first-person walking with camera oscillations [38] ($M \approx 5.5$). While the questions used to assess walking sensation were the same in both studies, other explanations may be included (population and within-subjects design, see subsection 5.1). Other work reported a lower walking sensation in a first-person walking simulation with camera oscillations [45] ($M \approx 35\%$ on a 100-point visual analogue scale), but comparison seems difficult due to the different scale. In this study, we did not evaluate vection specifically but walking sensation in general in order to limit the number of questions and because it was not the focus of the study. This should be addressed in future evaluations of our approach.

Results for cycling speed showed that the motorized bike was reliable and that participants followed the speed instructions well. This should have prevented walking speed differences from having too much influence on walking sensation. Since viewing a full body avatar was shown to enhance walking sensation [45], we made the participants look at their avatar frequently during each simulation (see subsection 3.5), and we measured their HMD orientation throughout the simulations. Results showed that the time each participant looked down at their avatar was consistent across conditions which ensured the validity of the results for walking sensation.

5.3 Assisted walking-by-cycling requires less effort

The results for perceived effort support **H6**, which is that condition *active* induces more perceived effort than *assisted* and *assisted* more than *static*. As for fatigue, although the means seem to show the same trend, no significant effect of condition was shown by the statistical analysis, which does not support **H5**. This inconsistency between the two variables may be explained by their nature: where perceived effort relates to an instantaneous feeling, fatigue accumulates over time when making an effort. A 4-minute trial may not have been long enough to induce important levels of fatigue, hence the small, non-significant, difference between the conditions. In their feedback, one participant reported that condition *assisted* would probably be more convenient for longer uses than condition *active*. Another reported that since walking is not a very strenuous activity, making little effort did not impair the sensation of walking, which is confirmed by the results for walking sensation. Overall, this suggests that assisted walking-by-cycling could probably prove useful for long uses or for users that cannot or do not want to exert effort while walking in VR. This should be properly evaluated in future work.

Additionally, in condition *assisted*, results for perceived effort show a high variability. This may be attributed to different receptions of the simulation or different interpretations of the question, like for walking sensation in condition *static*. Another possible explanation is that some participants may not have been completely relaxed when moved by the bike. Before the simulation started, they were told that they would be passively moved and that they did not need to perform the motion. Future work on the evaluation of this technique should verify that their legs were completely relaxed by measuring the pressure on the pedals or muscle activity in the legs.

5.4 Low levels of cybersickness

The results showed that the level of cybersickness was low and was not influenced by the conditions. However, two volunteers had to stop the experiment before the end because they felt sick, and feedback from the others showed some negative effects of the different conditions. Sick volunteers recovered completely after a few minutes. The first excluded participant felt sick during the *assisted* condition, after trying the *active* condition. They explained they were sick because the passive motion was disturbing, which made them panic due to slight emetophobia (fear of vomiting). While the other participants did not mention being sick during the *assisted* condition, one mentioned that they felt uncomfortable being forced to move. The second excluded participant, prone to motion sickness, felt sick during the *active* condition after trying the two others and feeling relatively comfortable. This participant reported that they felt sick because it was difficult to maintain a constant rotation speed, which led to irregular vection. This could be solved by having more resistance and inertia in the pedals, but it would probably lead to more fatigue. Among the participants who reached the end of the experiment, eight explained that it was difficult to maintain a constant speed during the *active* condition, and two of them reported that the resulting irregular vection caused cybersickness. However, six other participants reported that the *static* condition induced the most cybersickness because of the vestibular mismatch between real and virtual motion, and one of these six felt that moving their limbs attenuated this feeling. Participants' feedback seems to reflect the scores for each condition which was highest for condition *static*, intermediate for *active*, and lowest for *assisted*, although they do not differ significantly. Overall, sources for cybersickness seem to depend on individuals' sensitivity and it remains relatively low. Although cybersickness is lowest in condition *assisted*, longer exposure time may result in higher scores and yield significant differences between the conditions. This should be tested in future work in order to confirm the viability of our approach.

5.5 Perspectives and future work

The results of the study can be summarized as follows: assisted walking-by-cycling induced similar ownership, change, and walking sensation compared to active walking-by-cycling, while inducing less perceived effort but also less agency. Both non-static conditions induced more ownership, agency, change, walking, and perceived effort, and were enjoyed more than the *static* condition. Cybersickness and fatigue did not significantly differ between conditions and remained relatively low.

Overall, the results show that assisting a WIP motion, walking-by-cycling in this study, in embodied VR provides a good level of ownership and walking sensation while reducing perceived effort. In the future, devices that assist other WIP motions like heel tapping, knee raising, or knee bending and that use other positions could be designed and evaluated.

Since change was shown to be highly correlated with presence [52], the results of the study regarding change encourage us to evaluate whether they translate to presence as well. This would be an interesting finding since, as explained in subsection 3.2, previous studies comparing WIP techniques to more static approaches like joystick have reported mixed results on presence [3, 20, 49, 56, 59, 63]. In future evaluations of assisted walking-by-cycling, presence could be measured to investigate whether it is in fact higher than in static simulations.

Limitations of assisted walking-by-cycling include the fact that it prevents users from physically turning to navigate, and from performing other interactions with their legs, such as jumping or crouching, and it demands additional hardware compared to other WIP techniques. In addition, in order to integrate assisted walking-by-cycling to VR applications with embodied locomotion, the users should be given more control over the cycling motion by allowing them to start, stop, change speed, and turn. In the study, no real control was given to participants over the cycling motion. Rather, the motorized bike was turned on and off by the experimenter when participants pressed the trigger on their controller. This absence of real control was designed to ensure that participants walked at the required speed. Since participants were not aware of the experimenter's role in the initiation of the cycling motion, this process still probably induced some sense of control. Indeed, the *assisted* condition induced a relatively high level of agency ($M = 4.12$), which shows at least that it did not impair agency too much. Giving real and more complete control over the cycling motion to users could improve agency even more by adding intention to the passive motion. This could be done by installing pressure sensors on the pedals, which would allow users to control the motorized bike using admittance control, and would probably result in a more natural interaction. Hybrid systems that mix assisted and active walking-by-cycling could also be designed. This could be done by having different modes of locomotion that could be switched with controllers. The motorized bike could also be leveraged to render terrains of different textures and slopes by modifying the control law for assisted walking-by-cycling or the pedaling resistance for active. These are promising leads to explore in future research with the aim of providing effortless and compelling walking techniques in embodied VR.

6 Conclusion

In this paper we explored the effects of introducing assisted motion to a WIP technique called walking-by-cycling in embodied VR. This consisted of using a motorized bike that drove the user's legs in a cycling motion, which was then mapped onto the walking of their self-avatar. In a user study, we compared "assisted walking-by-cycling" to a traditional active implementation, in which users performed the cycling motion without assistance, and to a static walking simulation. We assessed the effects of these different techniques on the sub-components of embodiment, walking sensation, perceived effort and fatigue. Overall, the results of the study showed that both walking-by-cycling simulations provided more compelling walking simulations than the static simulation. They also showed that assisted walking-by-cycling induced similar ownership and walking sensation than active walking-by-cycling, while inducing less perceived effort but also less agency. Taken together, this work promotes the use of assisted walking-by-cycling when users cannot or do not want to make much effort while walking in embodied VR. Our results pave the way to providing effortless and compelling walking techniques in embodied VR. Our approach could benefit injured or disabled people, or be used in many applications such as prolonged VR simulations, medical rehabilitation, or virtual visits.

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