Comparing Real Walking in Immersive Virtual Reality and in Physical World using Gait Analysis

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Abstract: One of the main goals of immersive virtual reality is to allow people to walk in virtual environments in an ecological way. Several techniques have been developed in the literature: the use of devices such as omni-directional treadmills, robotic tiles, stepping systems, sliding-based surfaces and human-sized hamster balls; or techniques such as the walking-in-place. Conversely, real walk requires the precise tracking of the user, performed on a large area, in order to allow him/her to explore the virtual environment without limitations. This can be achieved by using optical tracking systems, or low cost off-the shelf devices, such as the HTC-Vive tracking system. Here, we consider the latter solution and we aim to compare real walking in a virtual environment with respect to walking in a corresponding real world situation, with the long term goal of using it in rehabilitation and clinical setups. Moreover, we analyze the effect of having a virtual representation of the user's body inside the virtual environment. Several spatio-temporal gait parameters are analyzed, such as the total distance walked, the patterns of velocity in each considered path, the velocity peaks, the step count and step length. Differently from what can be typically found in the literature, in our preliminary results we did not find significant differences between real walk in virtual environments and in a real world situation. Also having the virtual representation of the body inside virtual reality does not affect the gait parameters. The implication of these results for future research, in particular with respect to the specific considered setup, are discussed.

1 INTRODUCTION

In this paper, we aim to compare real walking in a virtual environment (VE) with respect to walking in a corresponding real world situation, to investigate whether it is possible a natural walk in virtual reality (VR). Moreover we investigate the role of having a virtual body in walking tasks.

The problem of walking in immersive VR has been extensively addressed by researchers in the last years, due to its implication in the reduction of sickness, in the increase of the sense of presence and in the improvement of the overall user experience (Kim et al., 2017). Moreover, natural walking in immersive VR can improve the natural interaction of the users inside the VEs, since they can freely explore it.

In the literature (see (Nabiyouni and Bowman, 2016) for a taxonomy of walking-based locomotion techniques in VR), the problem of achieving unlimited area for locomotion in VR has been addressed by developing various devices such as omni-directional treadmills, robotic tiles, stepping systems, sliding-based surfaces and human-sized hamster balls. All these techniques employ stationary or moving surfaces to allow the user staying (almost) fixed in a limited physical space while walking in VR. To avoid the use of external devices, several systems use the walking-in-place technique. Also in this case, users can explore a VE larger than the physical environment. Nevertheless, all these techniques are quite far from providing the user an experience similar to the one experienced by real walking. The main problems hampering real walking in VR are related to the lack of systems capable to track the users' movements in a sufficiently large portion of space, and capable to transfer users' movements into VR. Nowadays, typical setups for implementing real walking are based on optical tracking systems, e.g. see (Nabiyouni et al., 2015; Janeh et al., 2017b).

The different solutions to allow people's locomotion in VR have been analyzed and compared in the literature. In (Nabiyouni et al., 2015), the authors compared a high-fidelity real walking with a low-fidelity gamepad technique and a medium-fidelity locomotion interface (the Virtusphere). 16 optitrack flex 3 cameras tracked the users movements at a 100

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Hz sampling frequency. As a result, in line with the McMahan hypothesis (McMahan et al., 2012), the use of the virtusphere (medium-fidelity) produced worst performance than those obtained using the gamepad (low-fidelity).

By considering real walking setups, one of the main issues is the fact that isometric mappings, i.e. replicating the exact amount of movement of the users' head inside the VE, are often misperceived by people walking in VR (Steinicke et al., 2010; Janeh et al., 2017b). In particular, people do not perceive distances in VR as in a corresponding real-world situation. To mitigate the issue, in (Steinicke et al., 2010), translation gains are introduced, though the results presented in (Janeh et al., 2017b) show that further investigations on this aspect are needed. Also the effect of having a virtual representation (i.e. an avatar) inside the VE has been addressed, with respect to depth perception. In (Valkov et al., 2016), the authors presented the results of an evaluation of the users distance perception with different avatar representations, by showing that the anthropometric fidelity of the avatar has stronger effect on the distance perception than a realistic representation.

Several researchers addressed the problem of understanding whether low-cost and off-the-shelf solutions can be valid for scientific purposes, and whether these setups, designed for entertainment purposes, cause undesired effects on the users. As an example, in (Chessa et al., 2016b), the authors investigated the quality of a commercial low-cost VR headset, the Oculus Rift DK2, with respect to the sense of presence (Slater et al., 1994) and the cybersickness. More recently, in (Niehorster et al., 2017), an analysis of the precision and accuracy of the HTC-Vive VR headset is presented. The authors conclude that such a system is maybe affected by some errors due to the fact that a tilting of the reference plane can occur, especially when the sensors loose the tracking. Nevertheless, the quantitative error measures they reported are not significant with respect to the application described in this paper.

We should also take into account that, in the literature, several studies show the relationship among walking in VR and gait instability. In (Hollman et al., 2007), the authors analyzed ten healthy volunteers walking on an instrumented treadmill in a VR environment and a non-VR environment. They showed that subjects walked in the VR environment with increased magnitudes and rates of weight acceptance force and with increased rates of push-off force. The gait deviations reflect a compensatory response to visual stimulation that occurs in the VR environment, suggesting that walking in a VR environment may induce gait instability in healthy subjects. Previoulsy, in (Mohler et al., 2007), the authors showed that gait parameters within a head-mounted display (HMD) VE are different than those in the real world. A person wearing a HMD and backpack walks slower, and takes a shorter stride length than they do in a comparable real world condition. Though comparing walking in VE with respect to walking in real conditions, all these previous works did not consider natural walking, but they addressed the problem by using treadmills. This is probably due to technological constraints, since the possibility of implementing low cost natural walking (yet in a limited space) is a quite recent achievement. A recent paper (Janeh et al., 2017a) consider real walking in immersive VE with an HTC Vive HMD, by comparing the behaviour of adults and younger people. The authors showed that older adults walked very similarly in the real and VE in the pace and phasic domains, which differs from the results found in younger adults. In contrast, the results indicated a different base of support for both groups while walking within a VE and the real world. They also considered non-isometric mappings, and they found in both younger and older adults an increased divergence of gait parameters in all domains correlating with the up- or down-scaled velocity of visual self-motion feedback.

In this paper, we decided to implement and analyze walking by using first-person perspective (i.e. direct mapping between the head position of the user and the virtual camera inside the VE). In particular, we considered a commercial low-cost solution that we used both for the VR setup (i.e. for the tracking of the users' movements, and thus for the implementation of real walking) and also for the gait analyzes. The main goal is to achieve natural walking in a simple setup, affordable by everyone, with the long term aim of using it in rehabilitation and clinical setups. A precise biomechanical analysis of the locomotion in our setup is out of the scope of this paper, and it will be considered in a future work. Indeed, the rationale underlying our contribution is the validation of a low-cost setup, based on the HTC-Vive device, designed for a future clinical use. As an example, individuals with neurodegenerative diseases such as Parkinsons disease, Multiple Sclerosis, dementia syndromes due to the deficits of motor and cognitive functions, typically present gait dysfunctions. Virtual Reality represents an attractive option to investigate, in a controlled way, the locomotor difficulties by replicating the real-life situations when dramatic and potentially dangerous gait problems occur (e.g., walking through a crowded space, crossing the street at the green light or entering an elevator before the door closes). In particular, there is a great need of a refinement of VR to represent more closely the real-life situations when gait problems occur for a better understanding of this phenomenon and for new and personalized treatments. Our aim is to have an affordable VR system with performances that are well suited to specific clinical protocols based on real walking.

Here, in order to understand how people perceive depth in VR, and the behaviour of walking in an immersive VE, we considered three different conditions: (i) real walking in a VE, without a representation of own body inside VR; (ii) real walking in a VE, with a virtual representation of own body inside VR (in particular an avatar of the users' legs); (iii) walking in a real-world situation, consistent with the VE.

The main original contributions of this paper are:

- the quantitative evaluation of real walking in VR, by analyzing gait parameters. In particular, we will compute and compare the total distance walked by the users, the number of steps to cover a given part of the path, maximum peak velocity, step size, by considering the three described conditions. Moreover, we analyze the velocity profile of walking. It is worth noting that we do not take into consideration translation gains techniques, such as the one proposed by (Steinicke et al., 2010; Janeh et al., 2017b);
- a comparison between the behavior of users who have not a virtual representation of themselves inside the VE with respect to users who can see an avatar replicating their movements inside the VE (Chessa et al., 2016a; Valkov et al., 2016).

The paper is organized as follows: in Section 2 we describe the setup, the experimental protocol and the gait parameters we consider and analyze; in Section 3 we present and discuss the outcome of the experiments; finally in Section 4 we discuss the possible implications of the obtained results and how to further analyze and improve our setup.

2 MATERIALS AND METHODS

2.1 Participants

Eighteen healthy volunteer subjects (10 female and 8 male, median ages 24, range 19-33) participated in this study and completed the experiment. The participants are students or members of our University. All subjects gave written informed consent in accordance with the Declaration of Helsinki. They wore the HTC-Vive head-mounted-display for about 15 minutes during the experiment and all of them were naive

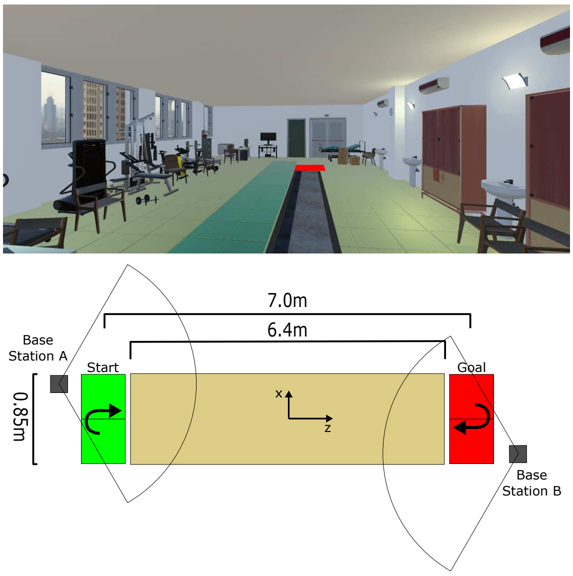

Figure 1: Schematic setup of experiment. (Top) The participants view by wearing the HMD. (Bottom) A sketch of the setup representing the position of the base stations, inversion zones and walkway with the dimensions. The reference system is centered on walkway.

to the experimental conditions, wearing their normal clothes. The total time per participant, including pre-questionnaires, instructions, experiment and post-questionnaires, was 30 minutes.

2.2 Experimental Setup

The experiment has been performed in a laboratory room with a walking free space of $8m \times 2m$ in size. During the experiment, the room was darkened in order to reduce the participant's perception of the real world while immersed in the VE and not to have any lights that can disturb HTC-Vive infrared-cameras.

The setup has been developed by using Unity 3D: models and animations are taken from free libraries publicly available on the web (e.g., Sketchfab, Turbosquid, Mixamo), and then fitted to our needs. We exactly replicated in VR an existing room and walkway used for biomechanical experimental sessions. In order to allow the subjects to identify real walking space inside the VE, we added a virtual walkway ($6.4m \times 0.85m$). At the end of the walkway two inversion zones (zone 1 and zone 2) highlight where subjects have to make a 180 deg turn and start walking in the opposite direction (Figure 1). Green colored zone represents the start, red colored the end.

The participants wore an HTC-Vive HMD for the stimulus presentation, which is equipped with a AMOLED display with resolution of 1080×1200 pixels per eye, a refresh rate of 90 Hz and an approximate 110° diagonal Field of View (FOV). The system is equipped with two base stations that are able to detect and track the 3D positions of the headset and of the two Vive controllers, by using infra-red light. A VR-ready laptop, equipped with an Intel processor with Core i5 3.5GHz, 8 GB of RAM and Nvidia GeForce 1060 (6GB VRAM) Graphics Cards, has been used for rendering, system control and recording.

The base stations were positioned face to face at a distance of 8 meters and at a height of 2 meters from the floor (see Figure 1) and connected by the provided sync cable. It is worth noting that this distance is different from the one recommended by HTC, and that in (Niehorster et al., 2017) the authors reported some measurements errors when the setup looses the tracking due to a distance between the base stations bigger than the recommended one. Nevertheless, we decided to implement this solution in order to be compliant with the real room and setup (specifically the size of the walkway) at the Hospital, where we are going to continue our experimental validation. Moreover, we previously verified that our setup is not affected by tracking issues. In particular, the headset and the controllers are always visible to the base stations, which provide continuous measurements.

We have decided to use the HTC-Vive controllers, not for tracking the users' hands and for interacting with objects in the scene, as they have been developed for, but for detecting and tracking the position of the users' legs. For this reasons, each participant performed the entire experiment with the HTC-Vive wireless controllers tied to the lateral compartment of the left and right legs, directly over the muscle peroneus longus. The controllers were used to record both 3D leg positions during the walk and for rendering leg models replicating the users' participant movements in the VE.

2.3 Experimental Protocol

In order to assess cybersickness issues, all the participants filled out the Simulator Sickness Questionnaire (SSQ) (S. Kennedy et al., 1993) immediately before and after the experiment. The questionnaire consists of 16 questions corresponding to symptoms that are rated by participants in terms of severity on a Likert scale from 1 (none) to 4 (severe). These symptoms include nausea, burping, sweating, fatigue and vertigo. Furthermore, the Slater-Usoh-Steed presence questionnaire (SUS PQ) (Slater et al., 1998; Slater, 1999) was filled out after the experiment.

Each participant was asked to walk at their normal pace along the virtual (or real) walkway, without stepping out, and moving between the two zones with the purpose to reach red zone (the goal) in each trial. The two zones alternatively switch their color whenever the subject reaches the red zone, moving the goal to the other side of the walkway. Therefore, subjects turned on themselves and kept walking in the opposite direction. This was repeated 8 times for each condition. The experiment included 3 conditions, thus 24 total trials :

1. VR_{avatar}: Real walking in the VE along the walkway for 8 trials, where the participants see the rendering of the leg models inside of VE. We measured the leg length of each participant to rescale proportionately his/her virtual model, visible during this configuration.
2. VR: Real walking in the VE along the walkway for 8 trials, where we disable the leg models rendering, thus no visual feedback of the user's body is present.
3. Real: Real walk without HMD for 8 trials, on a real-world path identical to the one inside the VE.

The "Real" condition has been always presented as the last in the experiment, while "VR_{avatar}" and "VR" conditions have been permuted.

We recorded the 3D positions of the HMD and of the two controllers fixed on the users' legs.

2.4 Gait Quantities Estimation

From the raw 3D positions of the HMD (i.e. of the users' head) and of the two controllers (thus indicating the position of the users' leg) we have computed the following quantities:

- *Walked Distance*: the distance between the subject's position of two successive inversion points (see Fig. 2, black lines)
- *Stride length*: it is the distance between successive points of heel contact of the same foot. Since the HTC-Vive controllers were attached on the middle portion of the legs we measured the instant of heel strike looking at the horizontal controller displacement (HCD) along the z axis. We computed HCD from the difference $zleg_{left} - zleg_{right}$. Heel strikes for the left foot occur at roughly the same instant as the HCD reaches a maximum (or a minimum for the right foot) (see Fig. 2, red lines, black dots). We computed the stride length as the difference between the controller positions at the instants of two successive peaks of the HCD curve.
- *Step length*: it is the traveled distance from one HTC-Vive controller (swing leg) with respect to

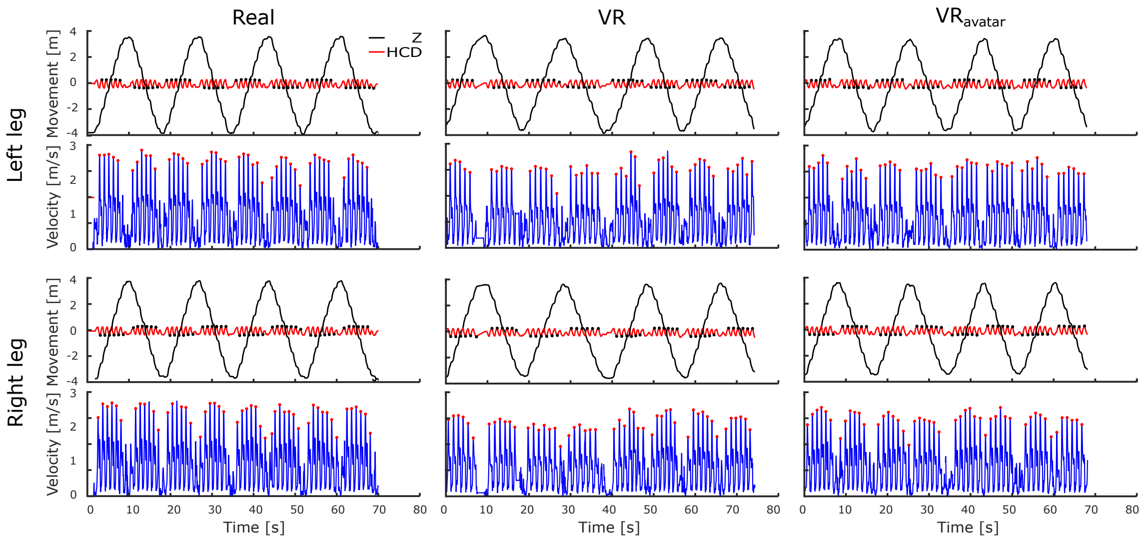

Figure 2: Example of data from one participant. Each column show data for one of the three conditions. First and second rows show data for the left leg. The third and fourth show data for the right leg. In each subpanel black lines represent the time course of the z-position, red lines the horizontal controller displacement (HCD) and blu lines represent the modulus of the velocity profile. Black dots mark the maximum and minimum of the HCD curve used to identify the heel contact time points. Red dots mark the peak swing velocity.

the other (stance leg) between the heel strike occurrences of each foot. In healthy subjects this parameter result about half stride length. We computed the step length as the difference between the swing controller position at its heel strike (maximum of the HCD curve) and the distance between the controller position at its heel strike (previous minimum of the HCD curve).

- *Step count*: it is defined by the number of steps taken to cover the entire path, for each trial.
- *Cadence*: it is the number of steps per unit time measured in steps/minute. We divided the step count by the time interval between the first and the last step in each trial and normalized with respect to one minute.
- *Peak Velocity*: it is the maximum value of the velocity. It is measured in meters per second. We computed peak velocity by looking at the peaks of the derivative of the controller positions (see Fig. 2, blue lines, red dots)
- *Velocity profile*: it is a window of $1.2s$ centered on the *peak velocity*.

To perform all the statistical analysis for the aforementioned parameters, we computed the average values across trial (for the walked distance) and across step (for the other parameters) for each subject and for each condition (Real, VR, VR_{avatar}).

3 RESULTS

3.1 Biomechanics of Walking

As we have discussed in Section 2, here we analyze the biomechanics of walking through spatio-temporal parameters to evaluate motor performances in three different conditions compared to each other: real walking (Real), virtual walking (VR) and virtual walking with users body representation in VE (VR_{avatar}). Statistical analysis was performed with Wilcoxon rank sum test at the 5% significance level.

Figure 3 summarizes the mean values and standard deviations of the considered biomechanical quantities, averaged across participants for the three conditions.

We first analyze all the trajectories (all the trials, for each subject) in each considered condition (Real, VR and VR_{avatar}), thus computing the total distance traveled in each trial. Each participant was asked to walk to reach the inversion zones for both the real condition and two virtual conditions. Our results show that participants travel in the correct way the distances presented to them in all conditions, as shows in Figure 3, and statistical analysis produces no significant differences among real and virtual conditions (p= 0.0718 and p=0.2473 respectively for Real vs. VR and Real vs. VR_{avatar}). Therefore, we can have a first indication that there is no difference between real and virtual behaviors, in opposition to previous perceptual studies that reported understimation

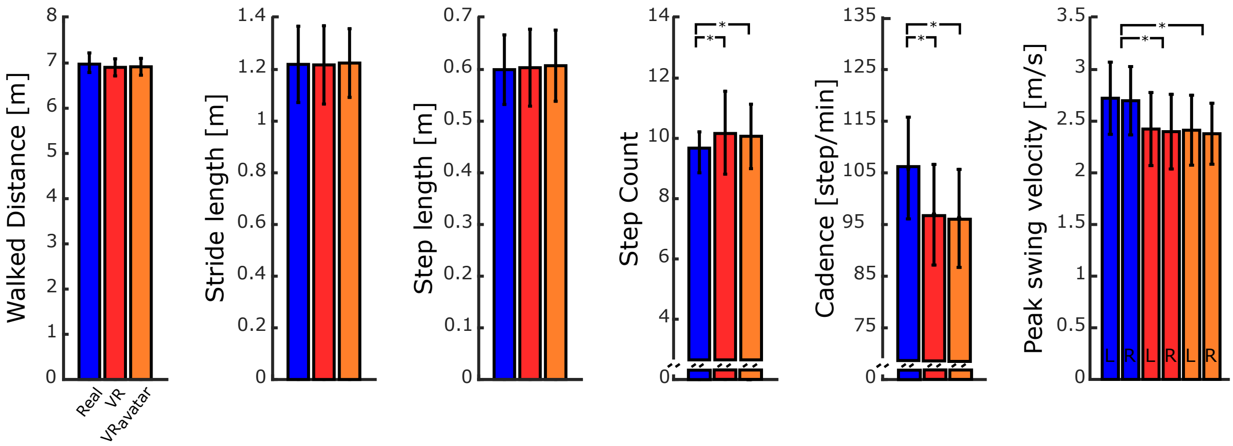

Figure 3: Mean and standard deviation in each condition of walking for spatio-temporal parameters. On step count, cadence and peak velocity significant differences between Real and two virtual conditions are highlighted.

and depth compression in a VE (Valkov et al., 2016; Janeh et al., 2017b). It is worth noting that the contribution of having a virtual representation of the users' legs does not emerge, probably due to the fact that no depth compression occurs also in the standard VR setup without avatar.

To obtain a finer analysis at the level of the single stride/step we first analyzed the *stride length*. From the analysis no significant effect of immersive walking in VE emerged (p=0.788 and p=0.6464 respectively for Real vs. VR and for Real vs. VR_{avatar}).

The same result arises from the estimation of the *step length*. It is worth to note that these values are consistent with the *stride length*, which is about double in healthy subjects. As for *stride length*, the Wilcoxon rank sum test produces no significant differences (p=0.987, p=0.861 for Real vs. VR and Real vs. VR_{avatar}).

On the contrary, the *step count* shows significant differences between real and virtual conditions. The obtained values show that in a VE people tend to make a slightly greater number of steps. Mean *step count* value for Real condition (9.45± 0.68 step) is significantly smaller than mean *step count* values for the two virtual conditions (VR: 10.48± 1.24, p=0.01; VR_{avatar}: 10.5± 1.01, p=0.002).

Cadence is defined as the number of steps per unit time (steps/minute). The obtained values for *cadence* are linked to the previously computed *step count* value, indeed we still have significant differences between real and virtual conditions (p= 0.0018 for Real vs. VR and p=0.0023 for Real vs. VR_{avatar}).

We also analyzed velocity, to assess and to compare the *peak velocity* during the swing phase for each foot. Mean peak values show a difference ($p < 0.05$ for Real vs. VR and Real vs. VR_{avatar}, computed for left and right leg) between real and virtual conditions, with greater velocity during real walk (2.72± 0.35 m/s for left leg and 2.7±0.33 for the right leg) compared to walking in VE (VR: 2.42 ± 0.36 m/s and 2.39 ± 0.36 m/s respectively for left and right leg, VR_{avatar}: 2.41±0.34 and 2.38±0.29 respectively for left and right leg). This result is in agreement with results in the literature that reported an evident reduction of velocity in VE with respect to a real world situation (Nabiyouni et al., 2015).

It is worth noting that in our setup the Real condition was always presented at the end of the experiment. This can have an influence in the presented results, we should further analyze.

Despite this significant difference in peak velocity, it is evident (as shown in Figure 2) that there is a velocity pattern that is repeated in similar way in all the three conditions. Since the values between left and right leg are very similar, we used the average values for the following analysis. Therefore, the analysis of the average velocity profile (across trial and subjects) for each condition, allowed us to assess whether there is an actual correspondence and overlapping between real and virtual conditions. This is qualitatively illustrated in Figure 4(left), in which the average profiles for all conditions are shown with their associated standard deviations. The similarity among the conditions is even more evident if we look at the normalized profiles with respect to maximum value for each condition. Indeed, Figure 4 shows how such profiles are extremely repeatable. The statistical analysis of the average quadratic error between the mean profiles in the three conditions, all normalized as mentioned above, does not appear to be a significant difference (p= 0.231 e p=0.112 Real vs. VR and Real vs. VR_{avatar}). Such a result could be the confirmation that we have achieved a natural walk behaviour in virtual environments.

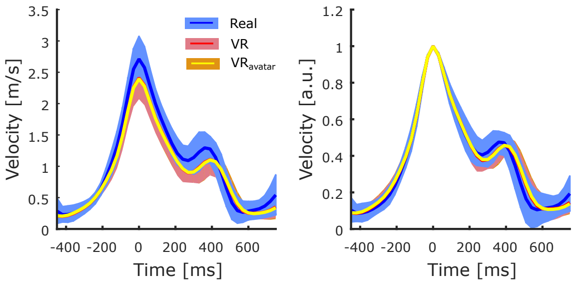

Figure 4: (left) Mean velocity profile and (right) normalized mean profile for Real, VR and VR$_{avatar}$ conditions.

We can also say that having a virtual representation of the users legs has not led to any change in any of the parameters compared. Nevertheless, it is worth noting that this result could be affected by the reduced field of view of HMD. This fact will be the focus of future analysis.

3.2 Self-reported Assessment through Questionnaires

The SSQ score averaged across all the participants is 10.39 $\pm$ 10.65 before the experiment, and 12.46 $\pm$13.87 after the experiment. The scores indicate overall low simulator sickness symptoms for walking with an HMD (p = 0.61). Moreover, the analysis of the sub-scores of the SSQ indicate that no specific domains of simulation-related sickness were changed by VR exposure: we measured a mean N (Nausea) score of 8.48$\pm$11.74, a mean O (Oculomotor) score of 11.79$\pm$11.4 and a mean D (Disorientation) score of 12.37$\pm$ 20.2. The mean SUS PQ score for the sense of feeling present in the VE was M = 2.8 $\pm$1.98, which indicates a moderate sense of presence.

4 CONCLUSION

In this paper, we have addressed an important problem related to interaction in immersive virtual reality: natural walking inside virtual environments. Researchers have addressed such a problem by developing systems and techniques that allow people to explore VE, though having a limited physical interaction spaces (i.e. by using treadmills, stepping systems, or walk-in-place techniques). Recently, new technologies allow people to precisely track the 3D position of the users and to translate such measures into position and orientation of the virtual cameras, thus replicating human movements inside the VR. This is typically achieved by using optical tracking systems (Janeh et al., 2017b). Here, we have presented a low-cost system that uses the HTC-Vive tracking system, only. Our aim was to evaluate human locomotion, from a biomechanical point of view, in order to assess whether such a system can be effectively used in clinical VR tasks involving walking. For this reason, we have created a virtual environment that replicates a specific setup used at Hospital, where people can walk and we have compared some gait quantities derived from the users' tracking, in order to understand whether differences occur between walking in the real world and in VR. We have also taken into account the presence of an avatar inside VR replicating the movements of the users' legs, to understand whether this affects locomotion.

Referring to the main paper's aims described in Section 1 we can devise the following conclusions and future works:

- The analysis of the considered gait parameters shows that there are no significant differences in the total distance the users walk, in the stride and step length. On the contrary, we noticed significant differences in the peak swing velocity, the step count and the cadence. This can be explained by the fact that subjects wore a cabled HMD for the virtual conditions, and this could be a possible factor that introduces differences in the walking behavior with respect to a real world situation. Moreover, most of the subjects have never experienced walking in immersive VR before, thus we should further analyze whether these differences disappear after a longer training session. The velocity profiles of each walking averaged across participants do not show significant differences among the three conditions, thus showing that people walk in a similar way in the three scenarios.
- The obtained results can be affected by the fact that we have used a low-cost setup to track users' movements. From the literature (Niehorster et al., 2017), we know that the considered setup is characterized by a good accuracy but in some situations it can be affected by errors. In particular, shifts in the reference measurement system can occur when working far from the theoretical limit of use of the HTC-Vive, as in our case. A future work will be a comparison with a optical tracking system, in order to verify whether the same results are obtained also by using a different tracking system, and to further assess the reliability of our low-cost system.
- All the results show that no differences occur between the situation in which the user can see an avatar of his/her legs, and the one in which no visual feedback about his/her own body is pre-

sented. This is partially in contrast with the results obtained by (Valkov et al., 2016), we plan to further analyze the contribution of having a visual feedback of the users' own body inside VR, by considering more complex tasks involving locomotion, e.g. walking on different surfaces and in presence of obstacles.

REFERENCES

Chessa, M., Caroggio, L., Huang, H., and Solari, F. (2016a). Insert your own body in the oculus rift to improve proprioception. In *VISIGRAPP (4: VISAPP)*, pages 755–762.

Chessa, M., Maiello, G., Borsari, A., and Bex, P. J. (2016b). The perceptual quality of the oculus rift for immersive virtual reality. *Human–Computer Interaction*, pages 1–32.

Hollman, J. H., Brey, R. H., Bang, T. J., and Kaufman, K. R. (2007). Does walking in a virtual environment induce unstable gait?: An examination of vertical ground reaction forces. *Gait & Posture*, 26(2):289–294.

Janeh, O., Bruder, G., Steinicke, F., Gulberti, A., and Poetter-Nerger, M. (2017a). Analyses of gait parameters of younger & older adults during (non-) isometric virtual walking. *IEEE Transactions on Visualization and Computer Graphics*.

Janeh, O., Langbehn, E., Steinicke, F., Bruder, G., Gulberti, A., and Poetter-Nerger, M. (2017b). Walking in virtual reality: Effects of manipulated visual self-motion on walking biomechanics. *ACM Transactions on Applied Perception (TAP)*, 14(2):12.

Kim, A., Darakjian, N., and Finley, J. M. (2017). Walking in fully immersive virtual environments: an evaluation of potential adverse effects in older adults and individuals with parkinsons disease. *Journal of neuroengineering and rehabilitation*, 14(1):16.

McMahan, R. P., Bowman, D. A., Zielinski, D. J., and Brady, R. B. (2012). Evaluating display fidelity and interaction fidelity in a virtual reality game. *IEEE transactions on visualization and computer graphics*, 18(4):626–633.

Mohler, B. J., Campos, J. L., Weyel, M., and Bülthoff, H. H. (2007). Gait parameters while walking in a head-mounted display virtual environment and the real world. In *Proceedings of Eurographics*, pages 85–88.

Nabiyouni, M. and Bowman, D. A. (2016). A taxonomy for designing walking-based locomotion techniques for virtual reality. In *Proceedings of the 2016 ACM Companion on Interactive Surfaces and Spaces*, pages 115–121. ACM.

Nabiyouni, M., Saktheeswaran, A., Bowman, D. A., and Karanth, A. (2015). Comparing the performance of natural, semi-natural, and non-natural locomotion techniques in virtual reality. In *3D User Interfaces (3DUI), 2015 IEEE Symposium on*, pages 3–10. IEEE.

Niehorster, D. C., Li, L., and Lappe, M. (2017). The accuracy and precision of position and orientation tracking in the htc vive virtual reality system for scientific research. *i-Perception*, 8(3):2041669517708205.

S. Kennedy, R., E. Lane, N., Berbaum, K., and G. Lilienthal, M. (1993). Simulator sickness questionnaire: An enhanced method for quantifying simulator sickness. *The International Journal of Aviation Psychology*, 3:203–220.

Slater, M. (1999). Measuring presence: A response to the witmer and singer presence questionnaire. *Presence: Teleoper. Virtual Environ.*, 8(5):560–565.

Slater, M., McCarthy, J., and Maringelli, F. (1998). The influence of body movement on subjective presence in virtual environments. *Human Factors*, 40(3):469–477. PMID: 9849105.

Slater, M., Usoh, M., and Steed, A. (1994). Depth of presence in virtual environments. *Presence: Teleoper. Virtual Environ.*, 3(2):130–144.

Steinicke, F., Bruder, G., Jerald, J., Frenz, H., and Lappe, M. (2010). Estimation of detection thresholds for redirected walking techniques. *IEEE transactions on visualization and computer graphics*, 16(1):17–27.

Valkov, D., Martens, J., and Hinrichs, K. (2016). Evaluation of the effect of a virtual avatar's representation on distance perception in immersive virtual environments. In *Virtual Reality (VR), 2016 IEEE*, pages 305–306. IEEE.