On the usability of consumer locomotion techniques in serious games: Comparing arm swinging, treadmills and walk-in-place

On the Usability of Consumer Locomotion Techniques in Serious Games: Comparing Arm Swinging, Treadmills and Walk-in-Place

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***Abstract*—When we refer to locomotion in Virtual Reality (VR) we subtend a vast and variegated number of investigations, solutions and devices coming from both research and industry. Despite this richness, a consolidated methodology for evaluating the many locomotion techniques available is still lacking. The present paper extends a previous work in which authors performed a user study-based comparison between two common locomotion techniques, i.e., Arm Swinging, and an omni-directional treadmill with a containment ring. In the study, users were engaged in a realistic immersive VR scenario depicting a fire event in a road tunnel. Remaining adherent to the previously defined methodology, the current work widens the comparison to consider two other locomotion methods (keeping results obtained with the former technique above for reference purposes), namely, a different treadmill constraining the user through a top-mounted independent support structure, and Walk-in-Place, a technique which allows the user to move in the virtual environment by performing a natural marching gesture by exploiting two sensors placed on his or her legs.**

***Index Terms*—Virtual Reality, Human-Computer Interaction, locomotion, user experience, evaluation.**

I. Introduction

To date, locomotion in Virtual Reality (VR) can still be considered as an open problem to which researchers can provide an important contribution. In fact, modern VR Head-Mounted Displays (HMDs) are now all provided with a tracking system, whether *outside-in*, hence requiring external sensors (like with the HTC® Vive™, the Oculus® Rift, and the Valve® Index, etc.), or *inside-out*, completely relying on the headset's tracking capabilities (like with the Microsoft® Mixed Reality, the Oculus® Quest, the Vive™ Focus, etc.). Thus, these systems can usually provide a six degrees-of-freedom (DOFs) tracking of the user allowing for a natural movement within the available space allocated in the room where the VR experience is being enjoyed.

When it is necessary to overcome the physical, room-scale limit of the above space in order to explore a larger Virtual Environment (VE), we face the problem known as that of "incompatible spaces", for which the literature as well as the industry have developed already a wide number of solutions. The work reported in this paper qualifies as an extension of a previous study [1], in which a comparison between two of these solutions, namely, the Arm Swinging and the Cyberith Virtualizer omni-directional treadmill [2], was performed using a VR-based serious game scenario, named FréjusVR, depicting a fire scenario inside the Fréjus road tunnel. Keeping the Arm Swinging as reference (as it scored better than the other solution), the results of comparison with two further locomotion techniques is reported herewith, i.e., Walk-in-Place (obtained through some additional inexpensive sensors placed on the user' legs), and another treadmill recently appeared on the market, the KATWalk by KATVR.

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II. State of the Art

As said, a wide number of different techniques have been proposed, studied and developed to tackle the problem of locomotion in VR. A taxonomy for all these techniques was proposed by Templeman et al. in [3]; in particular, a first classification subdivides the techniques in two categories: "magical", which use paradigms not applicable in the reality, and "mundane", which try to exploit metaphors coming from the real world.

An example of the magical techniques is teleporting, as proposed by Bozgeyikli et al. in [4]; this is one of the most adopted paradigms, as well as the default locomotion method adopted by commercial HMDs in order to overcome the physical limit of room-scale movements. The mundane techniques can be subdivided again in "vehicle-centric", which rely on virtual vehicles like in the work by Fiore et al. [5], or "body-centric", which exploit physical gestures like walking, running or swimming, as in the work by Fels et al. [6]; the "body-centric" methods can be then split into three further sub-categories, corresponding to techniques based on "repositioning", "proxy gestures" or "redirect walking" [7].

Locomotion treadmills such the Virtualizer and the KatWalk fall under the first sub-category, which also includes other methods designed to cancel the effect of the physical execution of the walking gesture through either passive or active components [8], [9].

Fig. 1. Locomotion methods considered in the study: Arm Swinging, KATWalk treadmill by KATVR and Walk-in-Place.

Proxy gestures include a wide set of techniques in which the user can generate virtual motion through movements of his or her body. For instance, Arm Swinging lets the user generate a locomotion input by swinging the arms back and forth; it could be implemented with additional sensors like in [10], or exploit the hand controllers of the VR system, when available. Walk-in-Place, instead, takes advantage of two additional sensors placed on the legs of the user in order to generate movement through a walking gesture executed in place. Compared to the previous technique, Walk-in-Place leaves the user's hands free. Numerous gestures has been investigated, such as marching, wiping and tapping [11].

Finally, techniques based on redirect walking manipulates the scene in order to force the user to unconsciously remain in the available space through subsequent re-orientations.

Various authors already operated comparisons between some of the cited techniques, such as Wilson et al. in [12], or Bowman et al. in [13]. Notwithstanding, a consolidated methodology for carrying out this kind of evaluations has not been proposed or widely adopted yet. The goal of this work is to expand a previously performed evaluation which was limited to two techniques only, replicating the same steps already used at that time but on different locomotion methods, hence widening the representativeness and the applicability of the study under the considered conditions.

III. Case Study

The three techniques selected for the evaluation, i.e., the Arm Swinging, the KATWalk treadmill and the Walk-in-Place are depicted in Fig. 1.

The Arm Swinging (hereinafter AS) technique was chosen because it relies on a particularly natural gesture, it does not need any additional hardware, and it requires an amount of effort comparable with real walk [14]. When previously compared with the Virtualizer, results showed that AS was perceived as easier use, more precise and less tiring than the treadmill. No difference was observed w.r.t. interaction with objects and motion sickness, despite the hypothetically more natural walking gesture used with the treadmill and interferences of AS with hand-based interaction.

The KATWalk (hereinafter KAT) differs from the other omni-directional treadmill considered in the reference work from various perspectives. Regarding the user containment system, the KAT exploits an independent support structure that keeps the user slightly lifted from the floor; the foot platform then is concave, and must be used with shoes (or overshoes) bundled with the device and equipped with one sensor each (for detecting the walking gesture). A third sensor placed on the back of the hip harness has two functions: it gives the walking direction, and enables the locomotion input when the user tilts forward or backward, respectively generating forward or backward movement. Interaction at floor level turns out to be difficult, because of the maximum extension of the support structure which permits sitting but not crouching.

The Walk-in-Place method (hereinafter WIP) was chosen because its gestures are more natural than the AS ones, it leaves the user's hands free and does not require additional expensive or cumbersome hardware apart from two small sensors on the legs. The implementation of this technique which is adopted in the current work was created by expanding the AS implementation presented in [1], by using two HTC® Vive™ Tracker devices properly placed on the user's legs by means of ad hoc 3D printed supports.

Keeping the same logic of the VR application exploited in the previous comparison, a two-meter tall cylinder with a radius of 0.65 meters, visually signaled through a cyan circle at ground level, was left at user disposal so that he or she can freely move the head and perform actions in place (e.g., crouching, grabbing items on the floor, etc.). Should the user try to overcome this limitation, at 90% of the maximum reachable distance a continuous warning vibration is activated on the two controllers to signal the nearby limit. If the user passes the maximum allowed distance, the head is locked in the VE, forcing him or her to get back to the center of the virtual cylinder to re-gain freedom of movement. In an initial design, the screen also faded to black when the view was blocked, pushing the user even more to get back to the allowed area, but this feature was ultimately dropped to avoid confusion with the visual effect associated with the smoke used in the particular scenario considered in the study.

As in the reference application, a direct mapping is used between the locomotion input and the movement in VR. In particular, with the two new methods considered in the current work, every movement tracked by the leg sensors is used, through a transfer function, as input for the locomotion, whereas the direction of the movement is calculated as the average rotation of the leg trackers. There are other common solutions for handling direction, such as exploiting the user's gaze or adding a third sensor on the user's back; however, the solution adopted allowed us to decouple the movement direction from both the head and the chest, resulting in a good trade-off between precision and freedom of movement.

The gesture selected for WIP implementation is the marching one, for two main reasons. First, it is an easily recognizable gesture, which can be executed in various ways (slow, fast, wide stride, little stride); given the use of a direct mapping

Fig. 2. FréjusVR scenario: road tunnel fire and available interactions.

strategy, different effects can be obtained. Second, it made it possible to add a mitigation for unwanted movements. In fact, the marching gesture is characterized by vertical leg movements, whereas the action of turning around is primarily composed by horizontal plane movements. Hence, user input was filtered in order to consider the sole contribution of the vertical movements, so that the user was allowed to change direction avoiding false positives at the cost of keeping the feet approximately at floor level while rotating.

As said, the scenario selected for the experiments was the FréjusVR application used in the reference work, which was developed using the Unity game engine. The original goal of the application was to communicate to generic users the emergency procedures to be followed in case of a fire event in the Fréjus road tunnel, as well as to study their behavior during a simulated emergency. This scenario was chosen as it is particularly suited for testing locomotion techniques because of the length of the tunnel environment; the scenario also offers a number of hand interactions (Fig. 2) which the user could/should perform while moving along the tunnel; in particular, the actions considered as objective results were the ones prescribed through the official security brochure of the Fréjus tunnel (which was also made available during the simulation), and were the following:

- stop the car at 100 meters (minimum) from the vehicle on fire;
- turn off the engine;
- turn on the hazard lights;
- press the alarm button (not cited on the brochure, but available in the real tunnel);
- ask for help by mean of a SOS telephone;
- reach the emergency shelter.

The brochure also informs on the presence of extinguishers which are free to use but not recommended; they are available in the simulation too, but their usage is not considered mandatory, also because they would not be effective with the heavy vehicle fire depicted in the scenario. The same hardware setup for VR, i.e., a HTC® Vive™ system (in wired configuration) with hand controllers, was used too.

IV. Experimental Methodology

Thirty volunteers were asked to participate in the experiments, fifteen for the KAT and fifteen for the WIP. Data of fifteen AS users were taken from the previous comparison[1].

[1]Footage of the experiments: http://tiny.cc/d2vcaz

For the sake of comparability of achieved results, the preparation to the experiment remained the same of the reference work. Users were introduced to the experience through a presentation which explained the context of the scenario, the hardware devices and the locomotion technique they were going to work with. Then, they were immersed in a testing scene in which they had the possibility to try the locomotion and the hand interaction modalities until they felt comfortable with both of them. Finally, they were invited to start the simulation, which had to be completed with no external help.

Comparison was based on subjective observations, which were collected by means of the questionnaire used in the reference work, based on the VRUSE [15] tool (for evaluating usability aspects), and the Simulation Sickness Questionnaire (SSQ) [16] tool (for analyzing possible motion sickness).

Some objective measures pertaining the users' behavior were also collected, such as the time to finish the experience and the indication about whether the user performed or not a particular operation / reached or not a given goal (e.g., alarm button pressed, fire extinguisher used, shelter reached, etc.)

V. Results

Statistical significance of results was evaluated through a One-Way ANOVA possibly followed by a Tukey's test to identify groups for which the differences were significant. All the questions coming from the VRUSE had to be answered on a five-point Likert scale (0 Totally disagree, 1 Disagree, 0 Undecided, 2 Agree, 4 Totally agree). Questions from the SSQ regarding severity of sickness symptoms had to be rated on four levels (0 None, 1 Slight, 2 Moderate, 3 Severe).

Each section from the VRUSE had a closing summary question asking users to provide an overall evaluation on the aspects tackled by the section, whose scores are reported in Fig. 3. Focusing first on these questions, significant differences emerged for the section about locomotion, where the KAT resulted as significantly less effective than both AS and WIP (average scores AS 3.09, KAT 2.27, WIP 2.92, $p = 0.0002$), flexibility, where the WIP resulted as significantly better than the KAT (AS 3.25, KAT 3.05, WIP 3.3, $p = 0.0240$), and error correction/handling, where the KAT was perceived as significantly worse than AS (AS 3.00, KAT 1.53, WIP 2.26, $p = 0.006$).

Entering into detail, AS resulted as significantly better in terms of easiness of use compared to KAT (AS 3.40, KAT 2.20, WIP 2.93, $p = 0.0010$). The KAT was perceived as significantly inferior w.r.t. both AS and WIP in terms of system

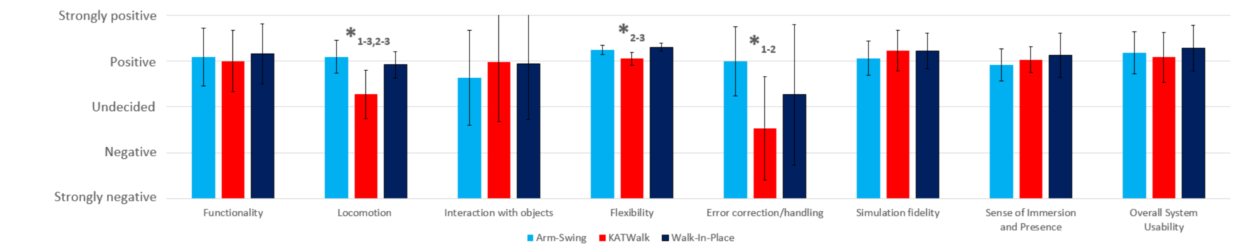

Fig. 3. Overall scores for the usability factors (questions adapted from the VRUSE questionnaire). Statistical significance is indicated with a star (*) symbol, standard deviation expressed through error bars.

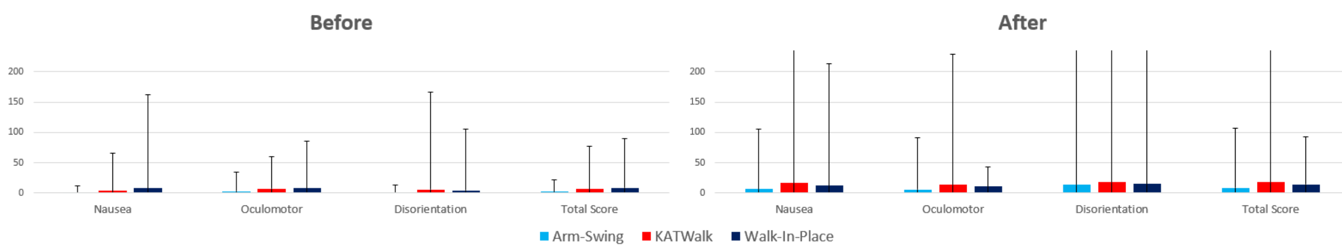

Fig. 4. SSQ scores calculated before and after the simulation, standard deviation expressed through error bars.

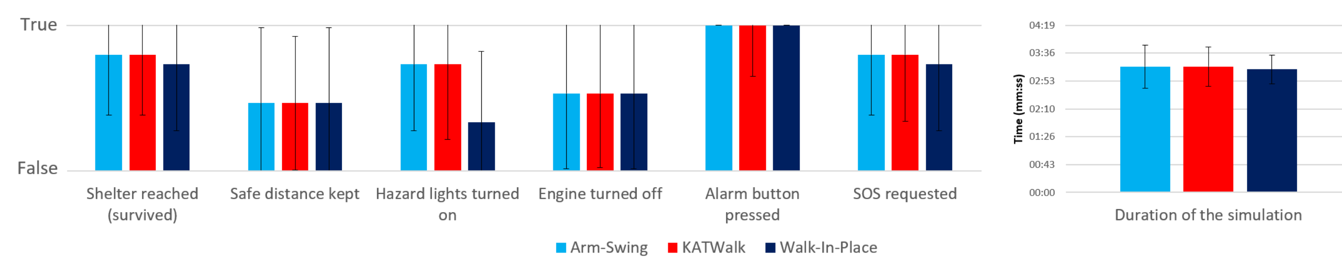

Fig. 5. Objective results related to user behavior and duration of the simulation, standard deviation expressed through error bars.

response to the locomotion input (3.40 AS, 2.66 KAT, 3.26 WIP, $p = 0.0020$) and over-sensitivity (1.26 AS, 2.40 KAT, 1.13 WIP, $p = 0.0040$). With the KAT, users also had the impression to continuously make mistakes when controlling locomotion, significantly more than with AS (AS 1.00, KAT 2.46, WIP 1.73, $p = 0.0060$). Users in both the AS and WIP groups stated that they had a higher level of control on where they wanted to go than users in the KAT group (AS 3.26, KAT 1.66, WIP 2.88, $p = 0.0002$). This outcome also follows from the comments provided by the users, who found the KAT as very tiring to use; the sliding gesture was not perceived as particularly natural, and numerous cases of unwanted movements in the process of turning around were reported, together with a too high sensitivity for small-scale movements.

Concerning section interaction with objects, although summary scores did not show significant differences, some individual questions provided interesting insights. KAT users perceived the controllers as the ideal means for interacting with the VE in a significantly higher way than AS users (AS 2.80, KAT 3.60, WIP 3.26, $p = 0.0300$). AS users found the visual feedback provided by the controllers when interacting with objects as significantly more inadequate than KAT and WIP users (AS 1.40, KAT 0.40, WIP 0.33, $p = 0.0100$). This result can be easily attributed to the necessity of holding two controller buttons and to swing back and forth the arms to generate movement, which could inevitably render the experience more detrimental when it comes to interact with objects while moving. A question related to simulation fidelity indicated that WIP users felt significantly more disoriented in the VE compared to KAT users (AS 1.00, KAT 0.40, WIP 1.33, $p = 0.0060$), probably because of some issues that characterize the WIP technique, namely, the tendency of users to drift away from the walk-in-place position and the consequent need to reposition, which could result in a disorientation also due to the involuntary movement generated by the process.

Data about motion sickness (Fig. 4) did not show any significant difference when comparing the three locomotion methods. The same consideration applies to objective data (Fig. 5).

Comparing the obtained results with the prior work, the situation remains similar; VRUSE sections such functionality, interaction with objects, simulation fidelity, sense of immersion and presence did not indicate any significant differences, whereas in locomotion, flexibility and error correction/handling the two treadmill-based techniques showed their weaknesses in comparison with the gesture-based ones. It is interesting to note that some significant differences found between AS and the Virtualizer treadmill, such as in overall system usability section as well as in some individual questions and objective results (always in favour of AS) were not observed again in the current evaluation, leading to surmise that the KAT treadmill could offer slightly better performance than the first, or that it could be characterized by an higher intuitiveness. More details about the results of the previous analysis can be found in [1].

VI. Conclusions and future work

The work reported in this paper allowed us to observe that the evaluated locomotion techniques are very close in terms of performance. In fact, even though the KAT appeared as significantly worse than the other two methods considering the sole locomotion, for the other dimensions analyzed in the study results were completely different, with the KAT prevailing, e.g., on AS in a number of questions concerning interaction with objects, so that, in the end, it was not possible to draw up a clear ranking between the three solutions.

Moreover, although the use of the same experience exploited in the reference work allowed us to widen the comparison, some of the limitations found in that experimental evaluation, like the short duration of the simulation (which does not permit a full investigation of motion sickness) and the non-compulsoriness of the interaction with objects (which could hide some of the constraints associated with AS when compared with the other techniques) impact also the present study. Finally, the scenario taken into consideration does not effectively stress all the functionalities provided by the considered locomotion techniques, nor evaluates every kind of possible movement. Hence, the future goal will be to develop a dedicated scenario subdivided in multiple sub-tasks, with the aim to better assess the pros and cons of the considered methods. Other techniques should also be included in the comparison, in order to draw a complete picture of performance offered by locomotion methods available to consumers.

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