A New Approach to Walking in Place

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Abstract. Walking in Place (WIP) is an important locomotion technique used in virtual environments. This paper proposes a new approach to WIP, called Speed-Amplitude-Supported Walking-in-Place (SAS-WIP), which allows people, when walking along linear paths, to control their virtual speed based on footstep amplitude and speed metrics. We argue that our approach allows users to better control the virtual distance covered by the footsteps, achieve higher average speeds and experience less fatigue than when using state-of-the-art methods based on footstep frequency, called GUD-WIP.

An in-depth user evaluation with twenty participants compared our approach to GUD-WIP on common travel tasks over a range of short, medium and long distances. We measured task performance using four distinct criteria: effectiveness, precision, efficiency and speed. The results show that SAS-WIP is both more efficient and faster than GUD-WIP when walking long distances while being more effective and precise over short distances. When asked their opinion via a post-test questionnaire, participants preferred SAS-WIP to GUD-WIP and reported experiencing less fatigue, having more fun and having a greater level of control when using our approach.

Keywords: Walking in place, virtual locomotion, virtual speed control, performance, motor control.

1 Introduction

Virtual locomotion is the most common task performed by users in virtual environments (VEs). Although in many cases virtual locomotion is not the primary user objective [12], the motion supports numerous other tasks, such as manipulating objects, collecting information [1] and surveying virtual environments.

Navigation control can rely on either indirect interaction [17] using physical controls (buttons or joystick) or direct interaction based on gestures expressed by the motion of body parts. Physical locomotion [12] is a metaphor that groups different locomotion techniques, such as real walking and Walking in Place (WIP). WIP is a popular technique because it enables people to control virtual locomotion, thus mimicking real walking movements [6]. Unlike unrestricted real walking, the WIP technique allows users to operate in small areas of interaction. This technique also frees the subject's hands, making them available to perform other interaction tasks. One usage scenario is the architectural review task where reviewer moves through buildings or outside spaces using a WIP technique and points and writes notes using hands.

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Different WIP systems have been devised with different inputs, outputs, control laws of the virtual displacement and simulated movements [6]. Different technologies have been used to detect steps in place: magnetic trackers [2,4,5], force sensors placed on shoe insoles [5], optical camera trackers [8], Wiimote Nintendo^{TM} accelerometers [14] and Wii Balance Boards [13]. Several different body segment motions are tracked to generate virtual output, including the head [4], knees [5,10] and shins [2,8]. These evolutions in user input have enabled the improvement of footstep latency times (starting and stopping travel) [2,10] and have assured the continuity and smoothness of the movement between and within steps [2,8]. In addition, different types of virtual locomotion control laws are based on neural networks [2], knee pattern recognition [5], signal processing [2] and biomechanical state machines [8]. In reference to viewpoint movement, the Slater WIP system [4] updates a predefined virtual distance only when a footstep is detected. This type of displacement motion is discrete and confusing for users. Later systems [2,8] updated the viewpoint in each frame and attempted to simulate a sinusoidal forward velocity curve.

GUD-WIP [8] is a state-of-the-art WIP method that estimates walking speed based on the subject's height and mainly on the subject's step frequency. These metrics emanate from the gaiting biomechanics literature [15], which indicates that are positively correlated with footstep horizontal length [16].

However the physical movements of gaiting in place are slightly different. The feet movements are predominantly vertical and the time to perform footsteps can be different to the horizontal footsteps. To control speed using the step frequency users should manage the time variable. Due to different biomechanics features the minimum time to perform vertical footsteps can be lower than to the horizontal footsteps. So, in the WIP method user can achieve unexpected higher speed values which cause difficulties to control forward walking.

Other important metric derived from WIP biomechanics features is the footstep amplitude. This metric describes the footstep vertical length and is defined as the distance between the foot off (and foot strike) positions and the maximum foot height achieved. With this metric user manages the vertical distance covered by the foot to control virtual speed. We argue that user manages better this distance metric than the time metric to control virtual speed. So, our hypothesis states that is more affordable and perceptible to user control the virtual speed using the amplitude than the frequency metric in common walking tasks.

We developed an exploratory study to understand how subjects establish a relationship between step vertical length and three simulated virtual rates of speed (i.e., slow, moderate and fast). Based on the quantitative results, we propose a new approach to walking in place, called SAS-WIP (Speed-Amplitude-Supported Walking-in-Place), which models the forward linear virtual speed as a function of two kinematic metrics: footstep amplitude and speed. Our approach follows the main goals of the recent WIP systems and adds a simple and perceptible technique for transforming step amplitude as a primary factor to generate virtual speed.

Few studies have attempted to compare different WIP approaches and other interfaces [6]. Furthermore, many evaluations resort to subjective questionnaires, from which results are difficult to reproduce. To test our hypothesis we developed a comparative study of our SAS-WIP approach and GUD-WIP [8]. We measured the task performance of twenty participants in travel and stopping precision tasks through three different distances (i.e., short, medium and long). We assessed the user performance according different criteria: effectiveness, precision, speed and efficiency.

We argue that SAS-WIP outperforms GUD-WIP with the following features:

- Provides to users a better forecast of the virtual distance covered by a single step.
- Allows for higher average speeds to be achieved, especially when covering long distances.
- Requires less effort from users, resulting in less fatigue, especially when covering long distances.

The results show that the SAS-WIP interface exhibited greater effectiveness and precision than the GUD-WIP interface in stopping precision tasks for short distances. Additionally, SAS-WIP was both more efficient and faster than GUD-WIP for long distances.

The remainder of this paper is organized as follows. Related work is presented on the next section. Next, we describe the SAS-WIP approach, followed by the experiment description, the results and the discussion of the main outcomes. In the conclusion section, we introduce the guidelines and summarize our work.

2 Related Work

Virtual locomotion is a common task involved in controlling virtual environments. This motion can either be the primary task or a secondary goal that allows people to perform specific tasks, such as manipulating objects or collecting information [1]. Different interaction techniques have been developed to support locomotion in VEs, and these techniques are typically used in complex navigation, including changes in direction and speed [6].

The WIP technique, which is considered a physical locomotion interface [12], was designed to improve the sensation of walking while providing efficient navigation in VEs [4]. This technique allows users to use small areas of interaction in the real world, unlike real walking, while freeing their hands for other interaction tasks. To this end, the users' bodies are tracked and analyzed to simulate virtual locomotion in the VE. The movements of different body parts are detected to steer virtual displacement via distinct approaches.

Slater developed the first WIP system for controlling virtual locomotion in VEs [4]. This approach used a neural network to recognize patterns of head movement that correspond to walking-in-place actions. The starting and stopping step detection was not extremely precise, which confused users and caused them to overshoot their target stopping location. Moreover, the forward viewpoint movement is updated only one time for each step by one predefined length. User testing with this system revealed that WIP can increase presence compared to classical joystick-based interaction [7], which is similar to the conclusion reached by Razzaque et al. [9]. In that study, it was suggested that WIP might also increase cybersickness [7].

The Gaiter system [5] for military simulators is dependent on leg movement, and WIP is treated as a gesture that indicates that the user intends to take a virtual step. Gaiter uses the direction and the extent of knee movement to compute an implicit horizontal displacement of a body in the VE. However, to recognize a virtual step, the system must wait until the knee reaches the point of maximum extent, causing a half-step latency [2].

Another WIP system developed by Yan et al. [10] used the speed at which the knee lifts in stepping in place actions to determine the virtual locomotion speed. The authors related different variables of the real locomotion (forward velocity/leg lifting speed, leg lifting speed/step frequency) and the stepping in place (leg frequency/leg lifting speed). The authors report that this system is more responsive than Gaiter system without explicit proof.

The output speed of the LLCM-WIP [2] system is dependent on a continuous signal of the foot heel position. This approach accomplishes the following goals: low starting and stopping latency, smooth locomotion between steps, continuous control of locomotion speed within each step and the incorporation of real-world turning and short-distance maneuvering into virtual locomotion [8]. The output speed curve varies considerably when the position differentiation is 0 when maximum foot height is achieved and between steps.

The state of the art GUD-WIP model creates output speeds that better match those occurring during real walking and that better respond to variations in step frequency, including realistic starting and stopping control of virtual speed using the observed footstep frequency [8]. The virtual speed of this implementation shows considerably less within-step fluctuation than LLCM-WIP. The virtual speed is dependent on a walking equation from the biomechanics literature, which relates to step frequency and subject height and relies on in-place step events. The user-study analysis presented that real walking and GUD-WIP each provide a consistent step frequency to resulting speed.

Although Wendt et al. hypothesized that consistency improves the user experience, which leads to improved usability [8], we are not certain that users correctly interpret step frequency to forecast the virtual distance covered by a single step in precision targeting tasks (short distances). For certain types of applications, such as traveling long distances in VEs at high speed, step frequency usage could be inefficient and tiring. The stopping latency of the GUD WIP may also be unacceptable for certain applications, as mentioned by the authors.

The system of Wendt et al. was not evaluated by participants during VE travel tasks for comparison with other WIP systems or other navigation techniques to understand the task performance addressed and the user experience.

In this paper, we present a participant study to evaluate our SAS-WIP approach in comparison with GUD-WIP. The participants executed travel and target stopping tasks, and the performance is measured based on quantitative metrics. The user experience is articulated with a subjective questionnaire. In this manner, it is be possible to understand the usability provided by each system related to those criteria.

3 Our Approach

To test our hypothesis we developed an exploratory study to understand how subjects establish a relationship between step vertical length and three simulated virtual rates of speed (i.e., slow, moderate and fast). The quantitative results showed a correlation between the two variables; higher footsteps correspond to higher simulated speed. Another feature emerged during this analysis: foot speed. Subjects also related the simulated virtual speed to different levels of foot swing speed. This relationship also proved to be consistent.

Based on these results we develop the SAS-WIP model which primarily takes advantage of the foot height achieved during in-place steps and is complementary to the foot vertical speed. Our system addresses requirements similar to LLCM-WIP [2] and GUD-WIP [8] as smooth between-step locomotion speed, continuous within-step speed control, real-world turning and maneuvering, low starting latency, low stopping latency, in-place step events detection and biomechanics-inspired state machine.

The next sections describe the development process, the features and the model algorithm of the SAS-WIP technique.

3.1 Exploratory Study

In the early stages of our research, we conducted informal observations of people walking in place. We asked subjects to perform sequences of in-place steps with the intention to represent different virtual speed levels (i.e., slow, moderate and fast). We only requested that participants relate foot height during steps to each virtual rate of speed.

Most subjects exhibited common behavior patterns. When asked to simulate slow locomotion, subjects raised their feet to the lowest maximum height at slow foot speed. For moderate locomotion, the footsteps were raised higher and faster than for slow walking. Maximum height and foot speed were observed when we instructed participants to walk briskly. These observations allowed us to identify a subject-consistent pattern in the use of foot height to control virtual speed, which suggests that people perceive that this metric controls different levels of speed. Another metric in subject behavior was also revealed: vertical foot speed. To achieve faster virtual speed, the subjects raised the feet faster. Therefore, we considered it important to study this feature in greater detail.

We conducted a formal exploratory study to quantitatively confirm the results of those observations. We aimed to confirm that subjects consistently relate footstep amplitude and speed with the intended virtual speed. Five participants, four male and one female, aged 22 to 45, took part in the user study and were recruited from our local university campus. None of the participants had motor or physical impairments. The experiment was conducted in a laboratory equipped with an optical tracker system [11] based on infra-red cameras, providing 6DOF tracking data at 100 Hz. To record the foot height and speed, one reflective marker was mounted on each heel. The heel position data for each foot is received as a continuous signal and allows for the calculation of the foot speed by vertical position differentiation.

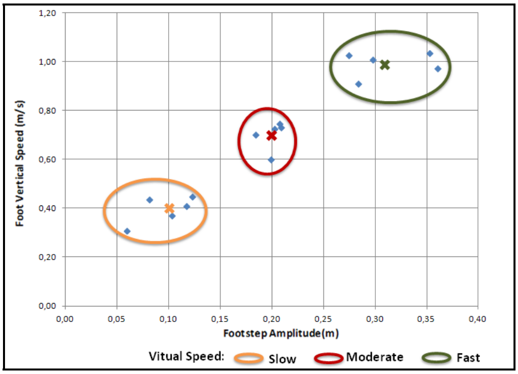

Fig. 1. The footstep amplitude and vertical clustered for the five participants

All participants were asked to walk in place inside a 3x3 meter square. At the beginning of the experiment, the participants were informed of the purpose of the experiment and were asked to perform three series of ten in-place steps for each level of simulated virtual locomotion speed: slow, moderate and fast. The position and timestamp data gathered allowed for the analysis of descriptive footstep amplitude and speed statistics and for the determination of the consistency between those metrics and the virtual speed levels perceived by the participants. As all the samples presented a normal distribution then we used an ANOVA to assess differences between the three speed levels on the two metrics within a significance of 0.05.

A one-way repeated-measures ANOVA revealed significant differences among the three speed levels (F2 =65.071, p<0.001) as a function of footstep amplitude sample. A Bonferroni post-hoc test revealed significant differences between all speed levels: slow and moderate (p=0.009), slow and fast (p=0.001), and moderate and fast (p=0.023).

These results suggest that participants expected that virtual speed changes consistently with the footstep amplitude. Fig. 1 shows that amplitude values are consistent with each simulated rate of speed.

We use mean speed to characterize foot motion during one step. This calculus is based on the vertical distance covered by the foot in the descendent and ascendant phases and the respective time periods as defined in Equation (1). The vertical distance value is the double of the amplitude value, *ta i*s the ascendant time and *td* is the descendant time. The amplitude is the distance between the foot-off (and foot strike) detected position and the maximum foot height position.

$$\text{Vel}= 2*\text{amplitude}/(ta+td) \qquad (1)$$

A one-way repeated-measures ANOVA revealed significant differences among the three speed levels (F_2 =154.981, p<0.001) as a function of footstep mean speed. A Bonferroni post-hoc test revealed differences between all cadences: slow and moderate (p=0.003), slow and fast (p<0.001), and moderate and fast (p=0.008).

These results show that participants naturally and consistently adapted their footstep speed to match each requested simulated speed. Fig. 1 confirms these results by demonstrating the variation of the vertical mean speed values of the five participants for each of the three simulated speed levels.

Table 1. Descriptive stats of kinematic variables

Virtual Speed	**Amplitude (m)**				**Mean Foot Speed (m/s)**			
	Min.	Mean	St. Dev.	Max	Min.	Mean	St. Dev.	Max
Slow	0.05	0.10	0.03	0.14	0.24	0.40	0.08	0.59
Moderate	0.08	0.20	0.03	0.30	0.38	0.70	0.09	0.84
Fast	0.22	0.31	0.06	0.46	0.68	0.99	0.09	1.13

Table 1 shows the descriptive statistics of the footstep amplitude and mean speed metrics in greater detail. One can see that the amplitude values related to slow, moderate and fast speeds are grouped at approximately 0.10 m, 0.20 m and 0.31 m, respectively. Regarding the mean foot speed, their values are grouped at approximately 0.40 m/s, 0.70 m/s and 0.99 m/s for the same speed levels, respectively.

Based on these results, we propose to compute the linear virtual speed in our SAS-WIP metaphor using the observed kinematics variables and their value ranges. The next section describes the primary decisions concerning SAS-WIP.

3.2 SAS-WIP Model Parameters

Our approach uses a biomechanics state machine with three states: ascending, descending and foot support. The main events detected are foot-off, foot max height and foot strike. Fig. 2 shows the foot states and the conditions that trigger each event. The start event (foot off) occurs when the foot vertical position (Pvert) exceeds 0.035 m (P1) and the vertical velocity (Vvert) exceeds 1.0 m/s (V1). The transition from ascending to descending state occurs when the maximum height is achieved (i.e., Vvert is less than 0.05 ms (V2)). The foot strike occurs when Pvert is lower than 0.035 m.

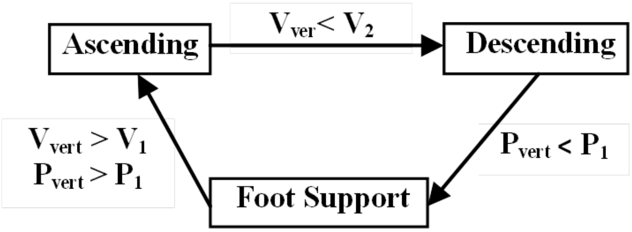

Fig. 2. The state transition diagram for an in-place step for a single foot

In the WIP starting phase, the virtual speed of the first step is updated at three moments, when the following events occur: foot off, max height and foot strike. Therefore, when the foot off of the first step is detected, the system assigns a value of 0.24 m/s to the initial virtual speed, which is the minimum value corresponding to the slow simulated speed achieved in the exploratory speed (see Table 1).

In rhythmic phase, the speed is updated at two moments for each step cycle during the following events: max height and foot strike. The first event occurs at the end of the ascending phase, and the second event occurs at the end of the descending phase. Only for these two moments, the speed is updated based on Equation (2), allowing for the maintenance of steady speed within and between steps.

Equation (2) to compute the virtual speed is supported by the kinematics results of the exploratory study. We separate the calculus into two conditions: (i) subjects that intend to achieve a slow speed or (ii) subjects that want faster speeds (moderate or fast).

To achieve slow virtual speed, the footstep amplitude should be lower than 0.13 m. This value corresponds to the sum of the foot mean amplitude (0.10 m) and the standard deviation (0.03 m) of the slow simulated speed (see Table 1). We observed that users control slow speeds better using only their footstep mean speed.

To achieve faster virtual speed, the main factor is footstep amplitude, which should be higher than the slow speed threshold (0.13 m). In this case, the amplitude is divided by that threshold to obtain a linear scale factor of the virtual speed. This decision was made according to our concept that users expect that virtual speed changes consistently with the step amplitude. To calculate the virtual speed, the amplitude scale is multiplied by the foot speed. This metric assures consistency in the updating of the virtual speed and allows users to allocate or not allocate more walking effort or energy.

$$\mathbf{Speed} = \begin{cases} \text{footSpeed}, & \text{if } Amplitude \leq 0.13 \\ \text{footSpeed} * \dfrac{\text{Amplitude}}{0.13}, & \text{if } Amplitude > 0.13 \end{cases} \tag{2}$$

Accurate stopping is important to users to better predict how to reach the desired locations. Two types of problems exist: false positives (the system stops without user intention) or stops long after the user orders a stop. In the stopping movement phase, we attempted to avoid these problems in the SAS-WIP system. The motion stops when one timeout occurs at the double support (when the feet are supported on the ground) state as described by Equation (3). This value is computed as a function of the mean foot speed of the last descending phase before the double support. This formula was computed from data gathered from the exploratory study. We investigated how long the double support was sustained after different footstep speed levels (from slowest to fastest) occurred.

$$\text{Time} = (-0.2 * \text{foot\_speed} + 0.41) * 1000 \tag{3}$$

We identified a trend in the foot speed variation from the slowest to the fastest motions before the user stop actions. When the foot speed is higher, the timeout is shorter. We opted to stop the virtual movement immediately after the timeout is achieved. GUD-WIP slows and smoothly stops the virtual speed. Our method decreases the stopping latency relatively to GUD-WIP, preventing unintentional motion stoppage.

3.3 Speed Features

Fig. 3 (right image) shows the virtual speed curve generated by the SAS-WIP algorithm from two independent series of in-place footsteps (blue and red lines). The first three steps are slows, the following three steps are moderate and the three final steps are fast. The “Virtual Speed” axis discriminates the output speed generated by SAS-WIP, and the “Position” axis represents the foot height achieved by each foot (left and right).

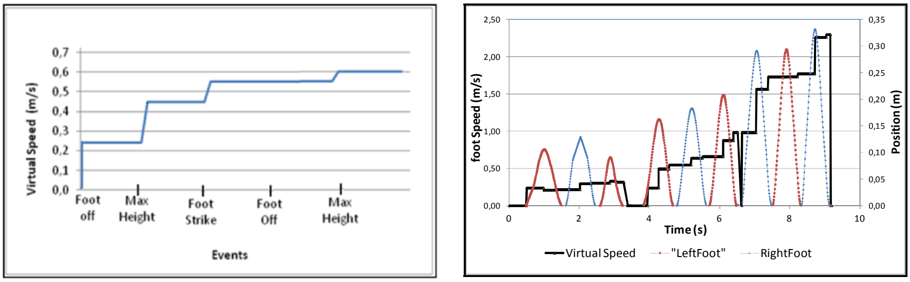

Fig. 3. Virtual speed is updated at the starting and rhythmic phases (left image); virtual speed curve generated by SAS-WIP (right image)

In Fig. 3 (left image), it is possible to identify several features, such as the assignment of the initial speed (0.24 m/s) at foot off of the first step as well as the speed updates at the max height and foot strike events. Regarding the rhythmic phase of the slow steps, the curve shows that the output speed is steady because the foot speeds are similar. Regarding the moderate steps, the effect of amplitude is evident. The virtual speed curve grows consistently with footstep amplitude. The speed control is continuous and responsive to amplitude changes between- and within-step.

The stopping latency is exhibited in the last step of each sequence. There is an evident delay between the end of the last step and the virtual stopping. However, this timeout is detected immediately and is assigned a null speed in the virtual movement.

4 Experiment

To assess the performance afforded by SAS-WIP, we developed a participant study to compare our approach with GUD-WIP.

4.1 Tasks

The participants were asked to execute two different tasks: (i) travel through nine paths of different distances and (ii) stop in front of nine prescribed target locations. The sequence and the distances of the nine paths traveled are as follows: P1 (6.0 m), P2 (1.0 m), P3 (12.0 m), P4 (0.5 m), P5 (24.0 m), P6 (1.5 m), P7 (3.0 m), P8 (48.0 m) and P9 (2.0 m). These different paths covered different distances: short (0.5 m, 1.0 m, 1.5 m, 2.0 m and 3.0 m), medium (6.0 m and 12.0 m) and long (24.0 m and 48.0 m). The short distances are suited to test the precision and the effectiveness provided by the interfaces in the stopping task, and the medium and long distances can check the efficiency and the speed offered to participants by the locomotion interfaces.

In the stopping task, the participants attempt to stop as close as possible in front of a target without overshooting it. This task occurred at the end of the travel task. Each of the nine paths is bound by rectangular targets (length: 1 m, width: 0.1 m) positioned on the sidewalk floor (length: 100 m), as exhibited in Fig. 4. The participants control the viewpoint in this experiment by using the first person model and perceive the proximity to the target by measuring the distance between that object position and the bottom line of the viewport. Therefore, the participants should stop the viewpoint motion when the rectangle is as near as possible to the bottom line of the screen.

The task performance offered to participants by the interfaces is determined by the following criteria: effectiveness, precision, mean speed and efficiency.

4.2 Participants

Twenty participants, 15 male and five female, ranging in age from 20 to 33 years (mean=24.5 years) took part in the user study and were recruited from our local university campus. The majority of the participants had played videogames that use virtual navigation, and no one had motor or physical impairments. No participant had previously tested physical locomotion interfaces like the WIP systems.

4.3 Procedure

At the beginning of the experiment, the participants were told the purpose of the study, and the script was explained. A pre-test questionnaire was administered to gather demographic and navigation skills data for each participant.

Before testing each interface, participants practiced for at least 10 minutes in an environment similar to the formal tests, performing travel and stopping tasks. When ready, the participants began each interface trial, traveling all the nine paths and making stops before each target. When a system error occurred or a participant sensed a particular difficulty, the trial was repeated. Regarding the travel task, the participants were asked to complete each assigned path as fast as they could. At the end of each interface, the trial subjects completed a post-test questionnaire to respond to questions about their experience. Each participant experimented with both interfaces in an order determined using a Latin Square approach to avoid bias associated with the sequence of the trials.

After all the participant trials were complete, a post-experiment questionnaire was administered in order to allow the participants to compare and rank the interfaces based on their subjective preferences.

4.4 Apparatus

This experiment was developed in the same laboratory where the exploratory study occurred. The output of the virtual environment was displayed on a large-scale screen (4x2.25 square meters) as shown in Fig. 4 (bottom picture). The participants are positioned approximately 2.0 m from the screen, within a 3x3 meter square area. The foot motion capture was supported by an optical tracker system [11], which determines the heel position for each foot.

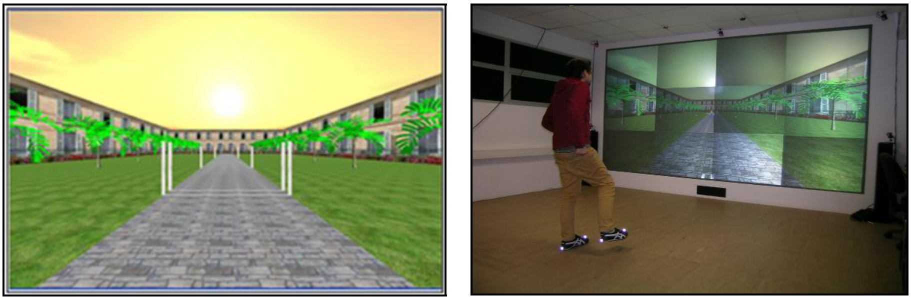

Fig. 4. The 3D virtual environment and the experiment apparatus (from left to right)

4.5 Ensure Equity with GUD-WIP

To ensure a fair comparison between our approach and GUD-WIP, we implemented several adjustments to this system. Because the GUD-WIP stopping latency is slow, we adapted the SAS-WIP stopping mechanism, which described by Equation (3). Therefore, the effectiveness and precision of the two interfaces were only affected by the interface features provided to the participants.

To compare the speed provided by each interface, it is necessary to assure that their value ranges are similar. Theoretically, the two WIP interfaces allow similar speed levels for the slowest and fastest cases, as exhibited in Table 2.

Table 2. Comparison of 3 representative speed levels generated by SAS-WIP and GUD-WIP

GUD-WIP		SAS-WIP		
Freq. (hz)	**Virtual Speed(m/s)**	**Ampl.(m)**	**Foot Speed (m/s)**	**Virtual Speed (m/s)**
2.50	2.54	0.31	0.99	2.36
1.75	1.24	0.20	0.70	1.07
1.00	0.41	0.10	0.40	0.40

Table 2 compares three representative speed levels for each interface, corresponding to slow, medium and fast values. In this comparison, the GUD-WIP virtual speed is computed with a constant height of 1.72m. The variable values of SAS-WIP are obtained from the mean values of Table 1 for the three speed levels. The GUD-WIP frequency values are based on reference values from the literature [15] that are representative of the range speed. The comparative virtual speed values suggest that the two interfaces can provide similar speed levels. Therefore, the speed achieved by the participants should depend on the affordance provided by each interface.

4.6 Design and Data Analysis

We used a within-subjects design where each participant tested all the three interfaces. The nine paths were grouped in three different distance classes: short, medium and long, as explained previously. Therefore, the analyzed data consisted of 20 participants x 3 distance classes x 3 interfaces, which equals 180 paths/targets.

The quantitative results are dependent on the following task metrics: target overshoots frequency, final distance to target, mean speed and number of steps. The data samples of the overshoot frequency and the final distance to target did not present a normal distribution, so we used the non-parametric Wilcoxon test to determine the pairwise differences among the interfaces.

Regarding the "mean speed" and "number of steps" metrics, a two-way repeated-measures ANOVA (interfaces x paths) was applied. In this case, the Greenhouse-Geisser's sphericity corrections were applied whenever Mauchly's test of sphericity showed a significant effect. In both metrics, the paired t-test was used to determine the pairwise differences among the two interfaces.

The subjective questionnaire results were analyzed using the Friedman non-parametric test on the different six criteria (i.e., Fun, Ease of use, Fatigue, Precision, Naturalness and Global Appreciation) and the Wilcoxon post-hoc test.

The level of significance used for all of the hypothesis tests was $\alpha=0.05$.

5 Results and Discussion

The quantitative data gathered from the trials were statically analyzed to understand the comparative performance provided by the two interfaces. In this section, we explain the effects of the interfaces on the metrics, which are the overshoot frequency, final distance to target, mean speed and the number of steps.

Table 3. Mean and interval confidence values of the metrics: A-Frequency Overshoots, B- Distance to Target (m), C-Mean Speed (m/s) and D-Number of Steps

	SAS-WIP						GUD-WIP					
	Short		Med.		Long		Short		Med.		Long	
	μ	CI	μ	CI	μ	CI	μ	CI	μ	CI	μ	CI
A	0.58	0.25	0.48	0.21	0.48	0.25	0.80	0.35	0.65	0.28	0.60	0.26
B	0.05	0.02	0.08	0.03	0.12	0.12	0.14	0.14	0.14	0.14	0.14	0.14
C	0.50	0.06	1.21	0.23	2.64	0.39	0.50	0.07	0.88	0.11	1.93	0.23
D	4.63	0.62	11.6	1.87	19.3	1.87	3.73	0.49	14.2	1.53	37.0	4.75

In this section, results obtained from the subjective questionnaire post-test are also described.

5.1 Effectiveness

The target overshoot data were recorded during the stopping tasks. One overshoot represented an error by the participant. The performance effectiveness criterion is related to the overshoot frequency. Fewer overshoots indicates greater effectiveness.

Table 3 shows the mean overshoot frequency for the two interfaces grouped by distance classes. The SAS-WIP interface allows, on average, a lower overshoot frequency than GUD-WIP for the three distance classes.

Relative to short distances, the test showed significant differences between SAS-WIP and GUD-WIP (p=0.004). For medium and long distances, significant differences between SAS-WIP and GUD-WIP (p=0.080, p=0.856, respectively) were not found. We contend that short distances are suited to assess the effectiveness provided by the interfaces because users have less time and space to forecast the virtual distance covered by each footstep, in contrast with longer distances. We argue that smaller distances allow for better understanding of which interface provides the best effectiveness control. These arguments and the results suggest that SAS-WIP provides more effectiveness to users than GUD-WIP. In contrast, for medium and long distances, SAS-WIP and GUD-WIP assured similar effectiveness in those tasks. In these cases, the distances do not affect the interface results because participants had greater time and space to predict and adjust the distances covered to stop at the desired point.

5.2 Precision

During the stopping tasks, the participants were instructed to stop as near as possible to the target without overshooting the target. From the trials, the distance between the stop position and the target position was recorded for all targets that were not exceeded. The exceeded cases are analyzed on frequency overshoot metric. This metric was named “final distance to the target” and determines the precision level that an interface provides to participants. A smaller final distance to the target indicates greater precision.

Table 3 shows the mean final distance to the target provided by the interfaces grouped by the three distance classes. On average, the SAS-WIP interface provided the lowest final distance to the target. Regarding short and medium distances, the test showed significant differences between GUD-WIP and SAS-WIP (p=0.002, p=0.015) in contrast to the long distances, where differences between the two interfaces were not revealed (p=0.466).

Similarly to effectiveness, we consider that smaller distances allow for better understanding of which interface provides the finest action control and consequently the best precision. From these arguments and from the short distance results, we can conclude that SAS-WIP provides more precision to users than GUD-WIP in stopping tasks. This last conclusion was complemented by the medium distance results. The long distance precision results were consistent with the long distance effectiveness results.

5.3 Mean Speed

The time and the distance traveled across the different paths were recorded to calculate the mean speed for each path. Greater mean speed indicates faster participant travel. This metric provides how fast the user can walk using each interface.

Table 3 shows the averages of the mean speed provided by the interfaces for the three distance classes. For medium and long distances, on average, SAS-WIP is faster than GUD-WIP, although for short distances, the two WIP interfaces are similar.

The two-way repeated-measures ANOVA revealed the significant effect of the interface ($F_{1.0,16.0}$ =8.067, p=0.012) and of the distance ($F_{2.0,32.0}$=216.722, p<0.001) on the mean speed. Interactions between interfaces and distance classes were found ($F_{2.0,32}$ =7.600, p=0.002).

For short distances, the paired t-test did not reveal differences between the two interfaces regarding the mean speed (t_{17} =-0.148, p=0.884). Concerning medium and long distances, the paired t-test revealed significant differences between the interfaces on the mean speed (t_{17} =3.104, p=0.006; t_{16} =2.805, p=0.013, respectively).

For medium and long distances, the SAS-WIP approach induces participants to travel faster than GUD-WIP, but for short distances, the two WIP interfaces are similar. The speed in performing paths is more important and critical to longer distances. In this manner, the results show that SAS-WIP provides to participants a higher average speed than GUD-WIP. This conclusion suggests that participants more consistently map the virtual speed values to the footstep amplitude than to the footstep frequency.

The tests allow for the identification of several errors committed by participants when they want to achieve faster speeds with GUD-WIP. When the step frequency is high (e.g., 20 Hz) because the footstep period is very short (e.g., 50 ms), the speed achieved is “supersonic” (e.g., 169.91 m/s). This problem occurs when participants increase the step cadence, shortening times between footsteps to travel faster (sometimes the viewpoint moves out of the VE scenario).

5.4 Efficiency

No references were found in the gaiting literature about what is the footstep factor which causes more energy expenditure: frequency or amplitude. So, we chose the number of steps as the metric that indicates the level of effort allocated to this task because is the common element for the two interfaces. So in our concept, this metric provides a measure of efficiency provided by the WIP interfaces. Fewer steps to travel the paths indicate greater efficiency provided by the interface. During the travel task across the different distances, the number of footsteps performed was recorded.

Table 3 shows the mean number of footsteps provided by the interfaces grouped by distance classes. For the medium and long distances, on average, the GUD-WIP interface induced a greater number of steps than did SAS-WIP. For short distances, GUD-WIP provided a lower number of steps than did SAS-WIP.

The two-way repeated-measures ANOVA revealed the significant effect of the interface ($F_{1.0,14.0}$=38.522, p<0.001) and the distance ($F_{2.0,28.0}$ =160.112, p<0.001) on the number of footsteps performed. Interactions between interfaces and distance classes were identified ($F_{1.103}$, $_{15.446}$ =32.855, p<0.001).

For the two WIP interfaces, regardless of the distances, the effect of the interface was significant ($F_{1.0}$ =38.522, p<0.001). The post-hoc test revealed significant differences between SAS-WIP and GUD-WIP (p<0.001). In contrast, accounting for the three distance classes, the distance had a significant effect ($F_{1.502}$ =160.112, p<0.001) on the number of steps, as we expected. The post-hoc test revealed significant differences between SAS-WIP and GUD-WIP (p<0.001). For short distances, the paired t-test revealed significant differences between the two interfaces (t_{14} =3.450, p=0.004) regarding the number of steps. Concerning medium distances, the paired t-test revealed a significant difference between the two interfaces (t_{14} =-2.419, p=0.030) regarding the number of steps. For long distances, the paired t-test revealed a significant difference between the interfaces (t_{14} =-6.095, p<0.001).

For short distances, GUD-WIP is more efficient than the SAS-WIP approach. When the user intends to move slower with GUD-WIP, the footsteps should be slower so the user performs fewer footsteps during the displacement. In contrast, with SAS-WIP, the user should raise the foot to a short height to move slower, so the footsteps are faster, allowing a greater number of steps.

However, for medium and long distances, where the efficiency is a more important performance criterion, SAS-WIP requires fewer footsteps than GUD-WIP. The results suggest that SAS-WIP requires less effort from participants and causes less fatigue than GUD-WIP, especially when covering long distances, as we expected.

5.5 User Subjective Perception

After the participants finished the experiment, they completed a questionnaire in which they had to rank the interfaces (SAS-WIP and GUD-WIP) by their preference in the context of six subjective criteria: (a) Fun, (b) Easiness of Use, (c) Fatigue, (d) Precision of Control, (e) Naturalness and (f) Global Appreciation.

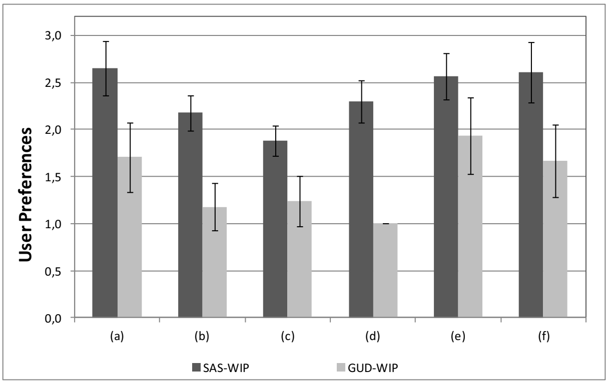

Fig. 5. The results of the subjective questionnaire for each criterion (a) – Fun, (b) – Ease of Use, (c) – Fatigue, (d) – Precision, (e) – Naturalness and (f) – Global Appreciation

To rank the interfaces for each criterion, the participants provided scores from 1 (worst preference) to 3 (best preference). Fig. 5 shows the preference results for each subjective criterion. In the fatigue case, grade 3 indicates that the interface provides the least fatigue.

We found significant differences between the SAS-WIP and GUD-WIP for the following criterion: Fun (p=0.012), Ease of Use (p<0.001), Fatigue (p=0.002), Precision (p<0.001) and Global Appreciation (p=0.02). Only for Naturalness, we didn't found significant difference between the two WIP interfaces.

The questionnaire results showed that SAS-WIP was ranked as the most appreciated interface (global appreciation) and most fun. Many participants commented during the experiment that they were greatly satisfied with the controllability provided by SAS-WIP and that they found it fun to move in the VE induced by its physical foot movements. SAS-WIP is perceived as less tiring than GUD-WIP.

The last result is consistent with the efficiency and the mean speed results achieved in this paper, which suggest that SAS-WIP induces less effort in participants and less fatigue than GUD-WIP. Several participants explicitly commented that SAS-WIP is less tiring than GUD-WIP, particularly for long distances.

6 Conclusions and Future Work

This paper introduced SAS-WIP (Speed-Amplitude-Supported Walking-in-Place), which is a new approach to WIP that allows for the control of linear virtual locomotion based on footstep amplitude and speed. We identified the features and kinematic variables that best describe the specific foot motions of the SAS-WIP approach via an exploratory study with five participants.

This paper provides a comparative study between two WIP alternatives concepts dependent on different metrics. The study explores common locomotion tasks, such as travel between targets and stopping before objects, and allows for the measurement of the performance provided and the user experience offered.

Table 4. Comparing the performance criteria provided by the interfaces ("~": Not Different, ">": Better than, "<": Worse than)

	Short	Medium	Long
Effectiveness	SAS > GUD	SAS ~ GUD	SAS ~ GUD
Precision	SAS > GUD	SAS > GUD	SAS ~ GUD
Speed	~ GUD-WIP	SAS > GUD	SAS > GUD
Efficiency	SAS < GUD	SAS > GUD	SAS > GUD

We argued that users can better forecast the virtual distance covered by a single step dependent on the footstep amplitude and speed than on the footstep frequency. The effectiveness and precision performance results obtained in our experiment for the stooping task suggest the confirmation of this statement (see Table 4). Even for medium and long distances, the speed control of one step is more perceptible for subjects (see Table 4).

Although theoretically, the speed equation dependent on the footstep frequency allows for greater speed, the results suggest that the approach dependent primarily on the footstep amplitude achieved a greater mean speed, particularly for medium and long distances.

Supported by the performance results and participant opinions, the effort allocated by users to cover medium and long distances using SAS-WIP seems to be smaller than that provided by those using GUD-WIP. This result suggests that SAS-WIP is more efficient, assuring less fatigue and possibly less energy expenditure.

The SAS-WIP system seems to be a promising WIP method, assuring controllable and comfortable interaction and good user perception, and should be the object of improvements and evaluations with other tasks and environments. However, our WIP approach has one open question related to the effect of the subject height in the virtual speed computed. One participant expressed this concern because of her small stature. We plan to develop a detailed study to understand this effect and how this personalized metric can be implemented in the motion control law.

A challenging task to measure the controllability provided by SAS-WIP is the pursuit of moving objects. We plan to develop a study for measuring the level of proximity to objects provided by our approach in different locomotion contexts.

In the future, we plan to evaluate the effect of the proprioception afforded by our approach on the perception of spatial dimensions in estimating distances in virtual environments. Additionally, we intend to add locomotion direction control (steering) dependent entirely on foot motions to SAS-WIP.

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