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Evaluating Plausible Preference of Body-Centric Locomotion using Subjective Matching in Virtual Reality

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Abstract

Body-centric locomotion in Virtual Reality (VR) involves multiple factors, including the point of view, avatar representations, tracked body parts for locomotion control and transfer functions that map body movement to the displacement of the virtual viewpoint. Understanding the role of these factors in evoking a plausible walking experience using within- or between-subject experimental designs based on questionnaires and/or objective measurements can be time-consuming and challenging due to the interrelated effects of these factors. This study employed the subjective matching method to evaluate the sense of plausible walking experience during body-centric locomotion in VR. Five relevant factors that may affect locomotion experience were identified by analyzing existing studies, i.e., point of view, the avatar appearance, body parts for locomotion control, transfer functions and the coefficients of transfer functions. A virtual locomotion experiment with these five factors based on subjective matching was conducted. Results showed that participants regarded the point of view as the most critical factor for walking experience enhancement, followed by body parts, transfer functions, the coefficients of transfer functions and finally the avatar appearance. Additionally, participants' preferences for different body parts and the coefficients of transfer functions affected the choice of transfer functions. These results could serve as the guidelines for virtual locomotion experience design that involves combinations of multiple factors and can help achieve a plausible walking experience in VR.

Index Terms: Human-centered computing—Virtual Reality—User study and evaluation methods

1 Introduction

As a crucial component of Virtual Reality (VR), virtual locomotion can be implemented through either gait-enabled or gait-free methods [1]. Gait-enabled techniques usually involve physical walking movements to simulate real walking in VR. These techniques include natural walking, redirected walking, walking-in-place and repositioning techniques based on mechanical devices [9, 10]. On the other hand, gait-free techniques do not require physical walking through legs and can be further categorized into locomotion techniques based on eye gaze tracking, hand tracking, handheld controllers [6, 43, 48, 53], and body-centric locomotion techniques [19, 20].

Body-centric locomotion is achieved through the mapping of tracked body movements, such as head, arm, and knee movements, to the speed and/or the direction of virtual locomotion through a transfer function. For example, head movements can be used to control the speed and the direction of the virtual viewpoint using linear or non-linear mapping in VR. The advantages of body-centric locomotion are: 1) body movements for virtual locomotion closely resemble walking movements in the real world; 2) locomotion can be easily implemented with a VR headset or controllers and performed in a small physical space while supporting concurrent interactions; 3) different transfer functions enable variable movement speed and direction in VR. However, studies on body-centric locomotion in VR mainly focused on how to achieve better performance in terms of higher accuracy and locomotion speed (e.g., [19, 20]) while the aspects of user experience (e.g., plausibility [13] or believability [18]) were ignored. By plausible walking experience, we mean that users could engage in an illusion of virtual walking through coherent and dynamic feedback during body-centric locomotion, even though users were not performing real walking. This closely follows the concept of plausibility illusion [47]. Eliciting a plausible sense of walking experience allows the users to better engage in virtual locomotion, thereby improving their overall walking experience in VR using current consumer headsets, without equipping users with full-body tracking devices.

Although body-centric locomotion methods provide many advantages as discussed, there are three major challenges associated with the design of plausible walking experiences during body-centric locomotion in VR. First, existing body-centric locomotion methods focused on the locomotion performance instead of the experience. To provide a plausible walking experience, it is necessary to consider a combination of different factors (e.g., body parts, transfer functions and the coefficients of transfer functions) when designing locomotion experiences. The goal is also different from the existing studies that aimed to achieve faster and/or more accurate performance [19, 20]. Second, besides the factors listed in the first challenge, other factors such as the point of view and the avatar appearance could also affect the body-centric locomotion experience. However, understanding the effects of these factors on locomotion experience using between- or within-subject design can be challenging due to the interrelated effects between them. Third, the risk of discomfort may easily occur for body-centric locomotion if the virtual movement does not match the user's physical movements under the combinations of the above-mentioned factors.

To address the above challenges, we designed an experiment with five factors relevant to the plausible preference of body-centric locomotion: the point of view, the avatar appearance, body parts, transfer functions and the coefficients of transfer functions. Participants evaluated configurations of different levels of these five factors using the subjective matching method. Based on the experimental data, we analyzed which factors to prioritize in order to enhance experience in locomotion tasks, and which configurations lead to plausible preference when performing the body-centric locomotion task in VR. Lastly, we suggest design implications based on the findings of this experiment, discuss the limitations and point out the directions for future work.

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2 Related Work

2.1 Factors of Body-centric Locomotion Experience

Point of View: Previous studies have found that users' perception of their virtual avatars from a first-person or a third-person perspective can influence factors, such as embodiment, presence and spatial awareness. These factors can ultimately impact users' sense of walking illusion. Existing studies showed that the first-person perspective helps to create a sense of embodiment or improve walking experience during virtual locomotion tasks [16, 24, 31, 33]. Studies have also revealed that the third-person perspective is effective in enhancing spatial awareness [33] or reducing motion sickness [44]. Previous work also investigated the enhancement of the sensation of walking by introducing foot vibration feedback to locomotion of first- and third-person perspectives [41]. Overall, although both first- and third-person perspectives have the advantages of supporting VR experience, their effects on body-centric locomotion experience are still largely unknown.

Avatar Appearance: The use of a virtual avatar is regarded as an important factor for evoking the sense of presence and plausibility in VR [16, 30, 33]. For example, Medeiros et al. [33] suggested that users' sense of presence and spatial awareness were highly influenced by their virtual representations and their virtual avatars could make the experience more engaging.

The physical features of virtual avatars also influenced the sense of embodiment and plausibility. These physical features typically include the avatar representation (abstract, cartoon and realistic) and the appearance (gender, skin tone, height and weight) [40, 41]. The most important aspect to induce the sense of plausibility for virtual scenarios is the coherence [45], which also guided us to design personalized realistic avatars in our experiment.

The use of avatars in the locomotion task is still under-explored, particularly in terms of the interrelation between avatar appearance and locomotion techniques. Existing studies [14] showed that the presence or absence of a virtual avatar did not alter their performance in navigation tasks. However, they did not consider the relationship between the avatar and the body-centric locomotion method. In this study, we consider this avatar-related factor in body-centric locomotion experience evaluation.

Body Parts: Body-centric locomotion refers to controlling virtual characters' movement in a virtual environment through body motions, such as head-tilting [19, 20, 22, 29, 49, 50], arm-swinging [9, 19, 20, 32, 37, 52], knee-bending [19, 20, 23, 36, 39]. A noteworthy work by Gao et al. [19, 20] examined the impact of the movements of various body parts, including the head, arms, torso, and knees, on the effectiveness and accuracy of locomotion in VR. Their findings suggest that torso-based locomotion should be avoided for standing posture as it is difficult to control locomotion speed with this configuration and it may lead to tiredness. By studying the role of different body parts in virtual locomotion, we aim to identify the body part that contributes to creating the most plausible sense of walking experience, which could provide insights into enhancing the virtual walking experience.

Transfer Functions: Transfer functions are essential components in body-centric locomotion and are used to map tracked user body movements to the movement speed of the virtual viewpoint and virtual avatars [19, 20]. In prior research, different types of transfer functions have been investigated, including linear functions [7, 19, 20, 42, 43, 54, 55], power functions [9–11, 19, 20, 32, 32, 37, 52], and piecewise functions [5, 18, 19, 23, 38, 39, 49, 51, 54]. The application of these transfer functions offers a diversified approach to virtual locomotion. For example, Gao et al. [19, 20] evaluated the locomotion performance of different combinations of tracked body parts and transfer functions and identified the combination that achieved better locomotion performance.

The present study aims to address the challenge of identifying the "optimal" combination of body parts, transfer functions and the coefficients of transfer functions to enhance the plausible experience during body-centric locomotion.

Coefficients of Transfer Functions: The selection of the coefficient of a transfer function influences the locomotion speed and the displacement of a user's viewpoint, thereby impacting the virtual locomotion experience for the user. Previous studies have investigated the selection of the coefficients for transfer functions. The coefficient was set to 3.0 for the linear function [55], 1.4 for the power function [11], 3.5 for the piecewise function with a constant and a linear sub-function [49, 54], and 1 for the piecewise function with a constant and a power sub-function [23, 39]. However, in other studies [42, 43], the coefficient for the linear function was set to 1.4, and in [32], the coefficient for the Power function was set to 1. This indicates that different combinations of transfer functions with different coefficients of transfer functions have been employed in exploring locomotion experience design of various purposes.

Existing studies on the use of a transfer function with a tracked body part typically specified a fixed coefficient but did not explore the impact of different coefficients within the same transfer function. In this study, we aim to investigate the effects of different coefficients of transfer functions in combination with transfer functions on the plausible walking experience across different body parts.

2.2 Evaluation of Behavioral Responses

Slater et al. [47] proposed a subjective matching method to evaluate two orthogonal illusions that constitute a sense of presence: Place Illusion (PI) and Plausibility Illusion (Psi) [3, 13, 27, 45]. This method has also been applied to evaluate various subjective responses [16, 18, 34]. In addition, studies have combined this method with techniques, such as reinforcement learning and electroencephalogram (EEG), to achieve enhanced evaluation results [2, 28].

To date, this method has not been utilized to evaluate walking experience in body-centric locomotion techniques. We selected this evaluation method in our study for three main reasons. First, the sense of walking experience is a subjective response of users. Second, other measurement methods such as post-questionnaires and physiological/behavioral measurements have limitations. For instance, evaluations based on questionnaires rely on participants' recall of the experimental process, while physiological and behavioral measurements require specific environments and devices [46]. Third, for a study involving multiple factors and factor levels, comparing all possible combinations in a post-experiment evaluation would be difficult for participants. Particularly, it is challenging for participants to provide clear and accurate evaluations for each combination. Therefore, by applying the subjective matching method to investigate the sense of walking experience in body-centric locomotion techniques, the experiment and data collection are more manageable. The analysis of experimental data can reveal factor combinations that align with user subjective preferences, without the need for participants to fill out numerous questionnaire items to compare the combinations of different factor levels. Additionally, the method allows for the assessment of the relative contributions of the involved factors to the overall plausibility during virtual locomotion.

3 Assessing Plausible Preference

3.1 The Subjective Matching Method

In this study, we consider different walking experiences as the perception of different colors. Consequently, we asked participants to adjust the levels of each factor subjectively to match the given walking experience. The factors involved in this study include the point of view, the avatar appearance, body parts, transfer functions and the coefficients of transfer functions. Each factor has different factor levels. The combination of factors at different levels is referred to as a "configuration". Different configurations may result in varied walking experiences. Furthermore, the perceived walking experi-

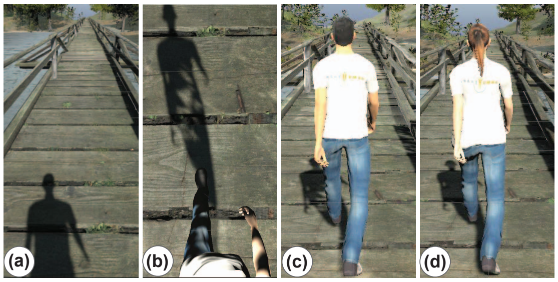

Figure 1: (a) Male avatar's eye-level first-person PoV. (b) Female avatar's downward-looking first-person PoV. (c) Male avatar's third-person PoV. (d) Female avatar's third-person PoV.

ence in a specific configuration may be equivalent to the experience in another configuration.

We followed the existing studies to design this subjective matching experiment. First, we assume that setting all factors to their highest levels lead to the "optimal" configuration, in which participants are more likely to experience the best walking sensation. At the beginning of the experiment, participants were instructed to perceive and memorize the predefined "optimal" configuration. Subsequently, they were presented with an initial configuration and asked to adjust the level of each factor to match the walking experience in the "optimal" configuration. Through the results of the subjective matching experiment, we can obtain the following information: 1) the factors that participants are more likely to upgrade and the priority of those upgrades, and 2) the configurations that ultimately correspond to the walking experience matching the "optimal" configuration.

3.2 Bayesian Analysis of Matched Configurations

Bayes' theorem is a mathematical principle for calculating conditional probabilities that describes how to update the probability estimates for an event when certain information is known. For example, for event A and event B, P(A|B) can be used to represent the probability of event A occurring if event B occurs. This can be obtained by calculating the ratio of the joint probability of event A and event B, P(A, B), to the marginal probability of event B, P(B), i.e., P(A|B) = P(A, B)/P(B).

Typically, the probability of event A occurring under conditions where event B has already occurred is different from the probability of event B occurring under conditions where event A has already occurred. Bayes' theorem provides us with a way to analyze and understand data from a different perspective. In this study, the event "*match*" is defined as the current configuration being a matched configuration, and the event "PoV, AP, BP, TF, C" is defined as a participant choosing a factor in a certain configuration. We calculated and analyzed the following conditional probabilities: P(PoV, AP, BP, TF, C|match), which represents the percentage of a matched configuration out of the total matched configurations, and P(match|PoV, AP, BP, TF, C), which represents the probability that a participant selects a configuration as a matched configuration. In addition, we marginalize the conditional probabilities for each level of each factor. For example, the probability that the level of factor BP is selected as 1 in the case that the current configuration is the matched configuration is denoted as P(BP=1|match).

4 Experiment

The goal of this experiment is to investigate and understand the correlation of different factors in evoking the plausible preference during body-centric locomotion in VR.

4.1 Experimental Factors

To achieve a comprehensive coverage of factors related to virtual locomotion experience, five factors were selected based on previous studies and incorporated in the study as independent variables. These factors are the point of view (PoV) [16, 24, 31, 33, 41, 44] the avatar appearance (AP), [16, 40, 41], body parts (BP) [19, 20], transfer functions (TF) [19, 20] and the coefficient (C) of transfer functions [19, 20]. We further explain each factor in detail.

4.1.1 Point of View (PoV)

We selected two levels for PoV based on participants' viewing perspective of the virtual avatar, motivated by existing studies [4, 12, 15, 17, 21, 31, 33, 44]. Previous studies have shown that the first-person perspective is more suited to navigation tasks [16, 33]. Therefore, it was regarded as the highest level of this factor.

Third-person perspective (PoV = 0): Participants see their virtual body as if they are behind the avatar (similar to how they see others' bodies from behind in real life). The camera was positioned 2 m behind the avatar's eyes, and participants were able to rotate their head to look around the virtual environment. (Figure 1 c&d) [16, 17, 31].

First-person perspective (PoV = 1): Participants see their virtual body as if they are above the avatar's head (similar to how they see their own body in real life) (Figure 1 a&b) [33, 41].

4.1.2 Appearance of Avatar (AP)

There are two main considerations for selecting the three types of avatar appearances (abstract avatar, stickman and personalized realistic avatar) (Figure 2). First, three appearances (abstract avatar, stickman, and personalized realistic avatar) were selected from six predefined appearances based on the results from a previous study [16] as these are reasonable representations of a user at different abstract levels. Second, we generated realistic avatars for participants based on their physical appearance (gender, skin tone, weight and height) for use in the experiment as realistic avatars may give a better sense of embodiment [40]. The combination of these factors correspond to different levels of realism and fidelity of the virtual embodiment (Figure 2d).

Abstract avatar (AP = 0): Only the limbs of the body are represented visually by white spheres (Figure 2a).

Stickman (AP = 1): The limbs and body joints are represented visually by white spheres and cylinders (Figure 2b).

Personalized realistic avatar (AP = 2): The avatar's gender, skin tone, weight, and height are based on the participants' physical appearance (shown in Figure 2c).

4.1.3 Body Part (BP) for Locomotion Control

Followed with existing studies [11, 19, 20, 23, 39, 42, 43, 49, 54, 55], we selected head, arms and knees as the body parts for locomotion control, and employed the same mapping mechanism as in [19, 20, 23, 39, 55] in this study, (illustrated in Figure 3). In addition, existing studies [19, 20, 39] collected participants' subjective evaluations of body parts in linear locomotion through a post-experiment questionnaire. The results showed that the combination of the head and the linear function performed the best, followed by the combination of the arm and the linear function. This provides a reference for the prioritization of body parts in this experiment (i.e., the order as knees, arms, and head).

In the experiment, participants generated certain angles θ when performing "Bend Knees", "Swing Arms", and "Tilt Head" movements, as depicted in Figure 3(a). To normalize the angle θ, we utilized the maximum angle Θ for normalization, resulting in $r = \theta / \Theta$ (where Θ is the maximum value of θ, $r \in [0, 1]$, and $\theta \in [0^\circ, 20^\circ]$). Subsequently, the normalized value r is mapped to the virtual viewpoint's velocity through a transfer function, generating displacement of virtual movement.

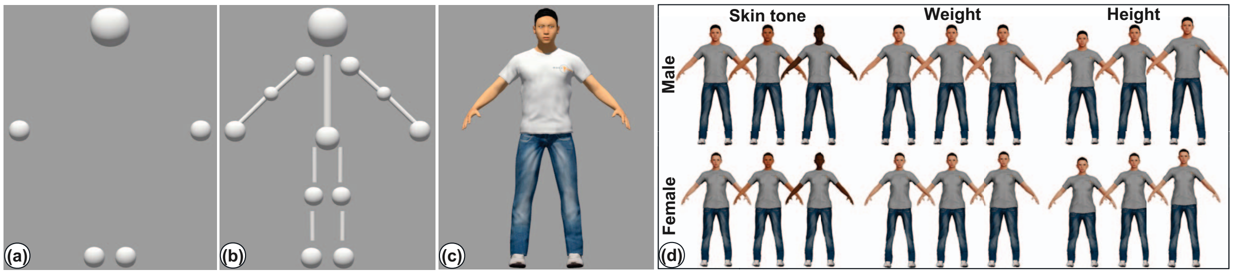

Figure 2: (a) Abstract avatar. (b) Stickman. (c) Realistic avatar. (d) Physical features of personalized realistic avatars, the participants can select three features based on the skin tone, weight and height to generate the corresponding realistic avatar.

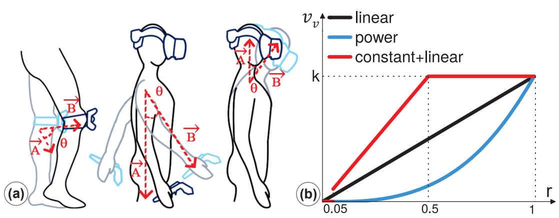

Figure 3: (a) Body parts (left to right: knee bending, arm swinging and head tilting) [20] and (b) transfer functions for locomotion control.

Knee (BP = 0): The knee flexion angle is calculated by using the tracking data from trackers attached to participants' knees. During normal standing, the trackers form $\vec{A}$, and when the knees bend, the trackers form $\vec{B}$. The angle θ is computed as the angle between $\vec{AB}$.

Arm (BP = 1): The shoulder flexion angle along the sagittal plane is calculated by using the tracking data from controllers held by participants. The controllers form $\vec{A}$ and $\vec{B}$ when standing and swinging the arms respectively. The average angle θ between $\vec{AB}$ during a unit of time is calculated.

Head (BP = 2): The head tilt angle is calculated through the VR headset worn by participants. During normal standing, the VR headset forms $\vec{A}$, and when tilting the head, the device forms $\vec{B}$. The angle θ is computed as the angle between $\vec{AB}$.

4.1.4 Transfer Function (TF)

We selected three types of transfer functions from existing studies [11, 19, 20, 42, 43, 49, 54, 55] (Figure 3). The findings from [19, 20] indicated that Linear function (L), Power function (P), and Piecewise function with Constant and Linear function (CL) received higher scores in UEQ-S, UEQ-S Pragmatic and UEQ-S Hedonic. Specifically, L function obtained the highest score, followed by P and CL functions. Therefore, we ranked the levels of transfer functions based on this result.

P function (TF = 0): The power function takes a cubic form, mapping the normalized value r generated by body parts to the user's viewpoint speed in VR (v_v) using the coefficient k.

$$v_v = k \cdot r^3 \tag{1}$$

CL function (TF = 1): The CL function sets two thresholds: R_{min}=0.05, to prevent unnecessary movement due to slight angle changes in body parts; R_{max}=0.5, narrowing down the range of angles generated by body parts, following prior research [49]. Another normalized value, v_r ($v_r \in$[0, 1]), is derived from the normalized value r through processing with R_{max}. The CL function uses the coefficient k to map v_r to the speed of the user's viewpoint in VR (v_v).

$$v_r = \frac{min(r, R_{max})}{R_{max}} \tag{2}$$

$$v_v = \begin{cases} 0 & if \quad v_r < R_{min} \\ k \cdot v_r & otherwise \end{cases} \tag{3}$$

L function (TF = 2): The linear function uses the coefficient k to map the normalized value r generated by body parts to the user's viewpoint speed in VR (v_v).

$$v_v = k \cdot r \tag{4}$$

4.1.5 Coefficient of a Transfer Function (C)

As shown by previous studies [7, 9–11, 19, 20, 23, 32, 37–39, 42, 43, 49, 51, 52, 54, 54, 55], the coefficient of a transfer function determines the maximum speed of body-centric locomotion after normalization of body motion, so we added this factor for this experiment. The normal and fast walking speeds of humans were included as factor levels based on previous studies [11, 19, 20, 42, 43]. Moreover, the findings from user subjective evaluations of transfer functions [20] suggested that the user ratings for UEQ-S, UEQ-S Pragmatic, and UEQ-S Hedonic for the L function were higher compared to those for the P function (with a coefficient of 3.0 for the L function and 1.4 for the P function). Consequently, we employed the results of these user subjective evaluations as the basis for ranking the coefficients of transfer functions.

k = 1.4 (C = 0): the normal walking speed of humans in the real world is approximately 1.4 m/s, so k = 1.4 is used as the coefficient of both Linear and Power functions [11, 19, 20, 42, 43].

k = 3.0 (C = 1): the fast walking speed of humans in the real world is approximately 3.0 m/s [55], so k = 3.0 is used as the coefficient of the Linear function. This condition showed the best performance in body-centric locomotion tasks [19, 20].

4.2 Apparatus and Material

We used an HTC VIVE Pro headset (with a refresh rate of 90 Hz and a resolution of 1440 × 1600 pixels per eye), two handheld controllers and two HTC trackers for the experiment. Two trackers are attached to the participants' left and right knees for collecting body motion data. The headset was connected to a computer with an Intel core i7 8700 CPU (3.2GHz), 16GB RAM and a Geforce GTX-1060 graphics card. The experimental program was developed with Unity 2021 in C#.

The virtual scene implemented using Unity includes elements such as trees with varying heights, small hills, lakes, and flowers. Participants mainly engaged in a virtual locomotion path on a 50-meter-long wooden bridge, spanning across the lake (Figure 4). The virtual avatars were created using Maya 3D and MakeHuman, with different avatar settings for participants based on gender (male and female), skin tone (fair, medium and dark), weight (skinny, fit and

Figure 4: The virtual scene includes a virtual wooden bridge situated on a lake surrounded by forests.

fat) and height (short, medium and tall) to match their physical appearance [40, 41]. These options were combined to form the personalized realistic appearance of the virtual avatar. The walking animations for the avatars were sourced from Mixamo's standard walking animation, and the animation controller (i.e., the angles of a tracked body part, a transfer function and the coefficient of the transfer function) was used to adjust the playback speed of a walking animation to ensure that the walking animation was consistent with the avatar's movement speed [24–26, 31, 35, 40, 41]. For example, if the participant chose to use their head and the L function with a coefficient of 1.4 for the virtual locomotion task, when the participant controlled the relative angle of the head to the largest degree (normalized to 1 from [19, 20, 39, 55]), the walking animation speed of the virtual avatar would correspondingly be 1.4 m/s.

4.3 Participants

We recruited 18 participants (9 females, 11 had experience using VR devices) from the local campus, aged from 22 to 26 (M: 23.67, SD: 1.15). Twelve participants had experience using VR devices, and six participants had experience with body-centric locomotion in VR. All participants had normal or corrected-to-normal vision. Each participant was paid 8 dollars for their participation.

4.4 Experimental Procedure

During the preparation stage of an experiment, a brief introduction of the experiment was first given to the participant to ensure that they understood the experiment tasks. Subsequently, the participant was asked to sign an informed consent form and complete a demographic survey questionnaire.

After wearing the VR headset, the participant was then required to get familiar with the different factors and factor levels to ensure that they had a full understanding of the experimental factors. The participant could quit the experiment at any time during the experiment if they felt uncomfortable. Prior to the commencement of the formal experiment, researchers reiterated the experiment's objectives, procedures, and relevant information to ensure that the participant had a thorough understanding that after each walking task, they were required to gradually increase the level of a specific factor until they felt that when using the current configuration for walking tasks, it felt "as if they were walking naturally and engaged within the environment." This sensation is the result of the combination of the factor levels of the current configuration.

The formal experiment was conducted after the preparation steps described above. During the formal experiment, the participant was first asked to perform a body-centric locomotion task under the highest configuration (i.e., <1,2,2,2,1>) to experience the locomotion experience. Subsequently, the participant was required to start a locomotion task from one of the six initial configurations (i.e., <0,0,0,0,0>, <1,0,0,0,0>, <0,1,0,0,0>, <0,0,1,0,0>, <0,0,0,1,0>, <0,0,0,0,1>). In each trial, the participant could choose to increase one level only from one of the five factors after each transition (except for factors that have reached the highest level). The upgraded configuration could be evaluated for "improved walking experience" compared to the previous configuration, and the evaluation was scored by the participant on a 5-point scale from -2 to 2, where -2 represents "disagree" and 2 represents "agree" (Figure 5a). This process continued until the participant regarded that the walking experience of the current configuration was greater than or equal to the highest configuration, or it was already the highest configuration. The participant could choose to finish the current trial if the matched configuration was reached (Figure 5b). Each participant needed to complete a total of six trials, which started from each of the six initial configurations, and the order of these configurations was random.

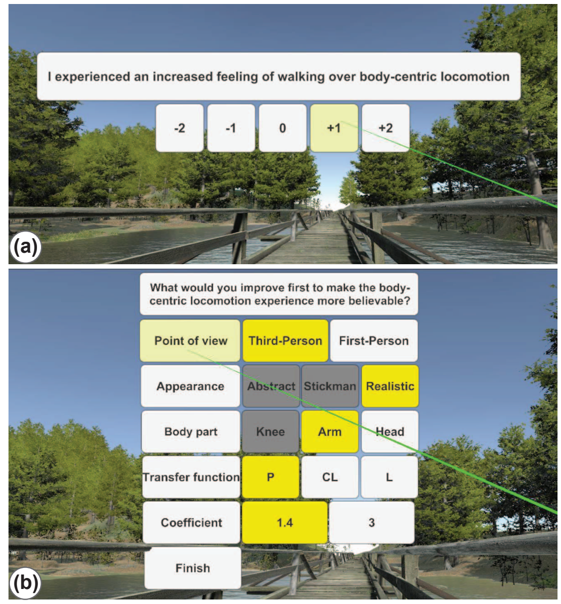

Figure 5: (a) In each transition, participants were required to use a rating scale ranging from -2 to 2 to assess the extent of "increased walking experience" after testing. (b) The highlighted blocks represent the current configuration, while the gray blocks indicate previously selected factor levels. Participants were asked to use a ray to select one factor for a unilateral upgrade after each transition or use the ray to select the "Finish" button if they considered the current configuration to be the matched configuration to conclude the current trial.

After completing the experiment, the participant was required to complete a factor ranking questionnaire for each factor and the levels involved in the experiment on the walking experience. At last, an interview with the participant was conducted to understand their detailed thoughts on the ranking considerations for their choices. The whole experiment lasted about 45 min.

4.5 Metrics

We included three sets of dependent variables. The first was the matched configuration that the participants chose. With the matched configurations, we investigated the factors that were judged to be unnecessary or went unnoticed by participants, i.e., the factors of body-centric locomotion that were unlikely to be active in the matched configuration. The second variable was the transition data, which depicted the chronological changes made by a participant from configuration i to another configuration j across two adjacent transitions. The sequence of transitions that participants took to reach it; with these transitions, we investigated the order that participants judged

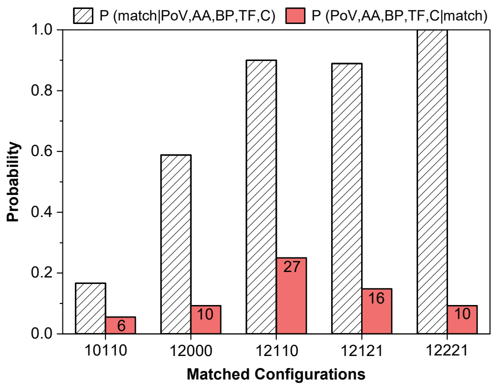

Figure 6: The probability P(match|PoV, AP, BP, TF, C) of matched configuration and their percentage P(PoV, AP, BP, TF, C|match) out of the total matched configuration. The numbers on the red bars represent the frequency of the matches for each configuration. (Only configurations with a percentage higher than 0.05 of the total matched configuration are shown for better readability).

Table 1: Probabilities of factor levels for individual factors within matched configurations.

PoV		AP		BP		TF		C	
0	0.028	0	0.157	0	0.315	0	0.167	0	0.556
1	0.972	1	0.037	1	0.537	1	0.463	1	0.444
	×	2	0.806	2	0.148	2	0.370		×

to be optimal in improving the plausible experience of body-centric locomotion. Third, we also included a post-questionnaire, which asked participants to fill in the ranking of the investigated body-centric locomotion factors. The questionnaire was delivered outside of VR. Participants also completed a semi-structured interview.

5 Results and Analysis

A total of 108 trials (18 participants $\times$ 6 trials) were conducted, with each trial comprising a maximum of 8 transitions. Across all participants, a total of 569 transitions were observed in this study. On average, each participant made 5.27 transitions per trial. We next analyzed the matched configurations, transitions, the sense of increased walking experience and the post-experiment questionnaire. We used the Shapiro-Wilk method to test whether the experimental data followed the assumption of a normal distribution, and used non-parametric hypothesis testing methods for the violation of the normal distribution.

5.1 Matched Configurations

We used Bayes' theorem to calculate the probability P(match | PoV, AP, BP, TF, C) that participants perceived a matched experience under a specific configuration during the experiment (the matched configuration) and the proportion of the matched configuration in the total matched configurations P(PoV, AP, BP, TF, C| match). The probabilities of the matched configurations that are higher than 0.05 are shown in Figure 6.

Most participants selected the matched configuration $\langle 1,2,1,1,0 \rangle$ (Figure 6), followed by $\langle 1,2,1,2,1 \rangle$. Interestingly, the assumed optimal configuration $\langle 1,2,2,2,1 \rangle$ was not accepted by a majority of participants, indicating that the above configurations can generate the similar experience as the best design scheme for plausible walking experience during body-centric locomotion in VR.

In addition, we used P(PoV, AP, BP, TF, C | match) to calculate the marginal probabilities of each factor at each level in the matched configurations. For example, P(BP = 1| match) = 0.537 means that the probability of the body part being at level 1 in all the matched configurations is 53.7% (Table 1). The point of view is set to level 1, which has the highest marginal probability; the avatar appearance is set to level 2, which is the second to the viewpoint level; the body part and transfer function are most commonly set to level 1; and the coefficient of a transfer function is the factor with the highest probability of being set to the basic level (C = 0).

5.2 Transitions

Figure 7 illustrates the most likely path through the Markov chain and the total of 108 possible configurations. The total number of possible transitions was not 108 $\times$ 108, as only single-step improvements were allowed by following previous studies [13,27]. Using the transitions made by all participants (569 in total), a sparse Markov transition matrix was constructed. The probability of each transition was calculated using Markov chain theory. Figure 8 presents the estimated probability distributions over the factors at each transition, with only probabilities greater than 0.05 shown.

The results showed that a clear majority of participants preferred to immediately upgrade their point of view from the starting configuration ($\langle 0,0,0,0,0 \rangle$), resulting in a first-person perspective ($\langle 1,0,0,0,0 \rangle$). However, the next sequence of transitions was dependent on the initial configurations. First, if the initial configuration was started from the body part ($\langle 0,0,1,0,0 \rangle$), most participants preferred to upgrade the transfer function to level 1, transitioning from the P function to CL function ($\langle 0,0,1,1,0 \rangle$). Subsequently, the participants tended to upgrade the point of view to level 1, reaching configuration $\langle 1,0,1,1,0 \rangle$. After that, the participants preferred to upgrade the virtual appearance twice to reach the matched configuration ($\langle 1,2,1,1,0 \rangle$), which was also the most matched configuration (Figure 6). Second, if the initial configuration was from level 1 of the coefficient of a transfer function ($\langle 0,0,0,0,1 \rangle$), the participants tended to first upgrade the point of view, reaching configuration $\langle 1,0,0,0,1 \rangle$, and then upgraded the body part ($\langle 1,0,1,0,1 \rangle$). After that, the participants preferred to upgrade the transfer function twice ($\langle 1,0,1,2,1 \rangle$). Then the participants tended to upgrade the virtual appearance twice to reach the matched configuration ($\langle 1,2,1,2,1 \rangle$), which was the second most matched configuration.

5.3 The Sense of Increased Walking Experience

The study assessed the change in the sense of increased walking experience during body-centric locomotion in VR for a specific factor and level. Participants were asked to respond to the statement "I experienced an increased sense of walking over the components of body-centric locomotion" on a 5-point scale ranging from -2 to 2, where -2 means "Disagree" and 2 means "Agree". The average score among participants is presented in Figure 9. We adopted the Wilcoxon signed-rank test, as collected samples were small and violated the normal distribution. The responses showed statistically significant agreement with the statement ($p < 0.05$) for all body-centric locomotion feature improvements except for AP = 1, BP = 1, and C = 1 ($p = 0.084$), indicating that the participants did not agree with the improvement of the avatar appearance from abstract to stickman, the body part from knee to arm, and the coefficient of transfer function ranging from 1.4 to 3.0. Additionally, the highest level of agreement was obtained for point of view (PoV = 1).

5.4 Questionnaires

After finishing the subjective matching experiment, participants were asked to perform a preference ranking of all factors that enhances the walking experience, with the feature of factors that has the greatest improvement ranked first. The results of the sorting analysis for all participants are shown in Figure 10. In line with existing

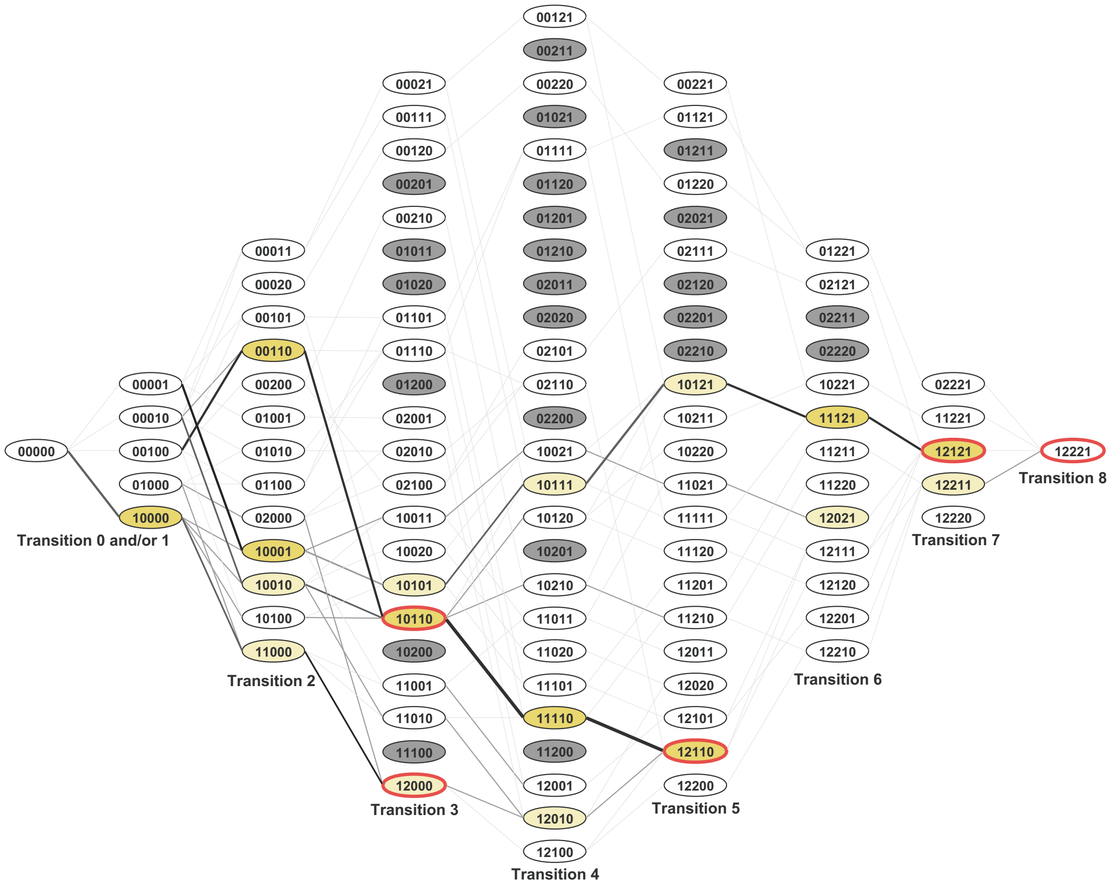

Figure 7: All configurations <PoV, AP, BP, TF, C> involved in the experiment and their transition relationships. Configurations selected by participants can only transition from left to right nodes. The thickness and darkness of the lines between nodes represent the frequency of transitions between the two nodes. Thicker and darker lines indicate a higher occurrence of transitions from the left node to the right node. Gray nodes represent configurations that have not been selected in any of the trials. Highlighted nodes with yellow represent configurations with the highest probability of being selected during each transition, then followed by the light yellow nodes for the second and third highest probability. The configurations highlighted with red borders are those matched configurations with a percentage greater than 0.05.

studies [16], we adopted the Friedman test to compare the differences among multiple related samples. The responses showed statistically significant differences in the distribution of the importance rankings of each factor ($\chi^2 = 33.2$, $p < 0.001$, $df = 4$). The median of InterQuartile Range (IQR) of point of view, appearance, body part, transfer function and coefficient of transfer function was 1 (1 to 3), 5 (5 to 5), 2 (2 to 3), 3 (2 to 3), and 4 (3 to 4), respectively. Participants reported that point of view was considered the most important factor in enhancing locomotion experience, followed by body part, then transfer function and coefficient of transfer function. The change of avatar appearance was considered the least important to body-centric locomotion experience. In addition, the comments about the interview are included in the discussion section.

6 Discussion

6.1 Factor Analysis

First-person perspective (PoV = 1) is the most important factor for body-centric locomotion experience, compared to the other four factors. Participants generally felt that body-centric locomotion with the first-person perspective provided a more immersive experience than that with the third-person perspective (see results in section 5), as it felt more like they were walking themselves rather than observing someone else leading the way. This was consistent with previous work [33], which showed that the first-person perspective was still better suited to navigation tasks than the third-person perspective, regardless of the avatar appearance. In addition, compared to third-person perspective, the full-body avatar with the first-person perspective enhanced the sensations of walking, leg action, and telepresence [31]. This is similar to findings in previous studies [31, 33]. However, our experiment adopted the pre-defined avatar animation as with previous studies [24, 26, 35, 41, 42] while they employed full-body tracking techniques for natural walking.

Realistic avatar appearance (AP = 2) had the second highest probability among matched configurations, but the upgrade of the avatar appearance was the least important to participants for plausible preference during body-centric locomotion in VR. First, in line with existing studies [14, 33], the avatar appearance had little influence on locomotion performance, due to the fact that participants mainly focused on the locomotion task itself rather than their virtual representation in VR.

Second, the avatar appearance is the least preferred factor from the collected transitions among the participants, because of the high priority for upgrading other factors. In particular, when participants tended to upgrade the viewpoint to the first-person perspective, the representation of the avatar's appearance in the field of view was reduced from a full body to a projected shadow. In such cases, the

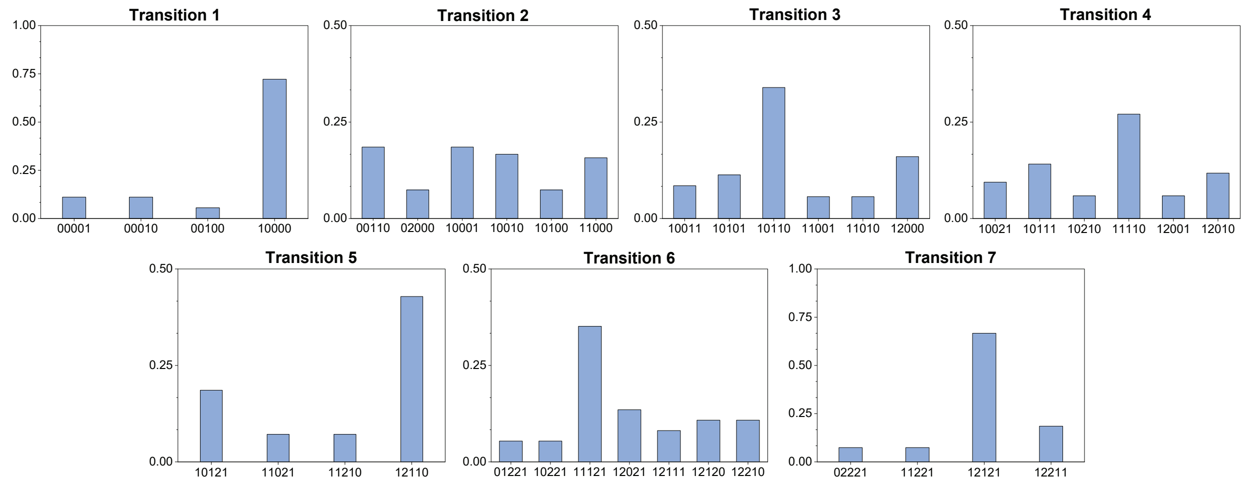

Figure 8: Probability distribution of each configuration <PoV, AP, BP, TF, C> after each transition (probabilities greater than 0.05 are shown).

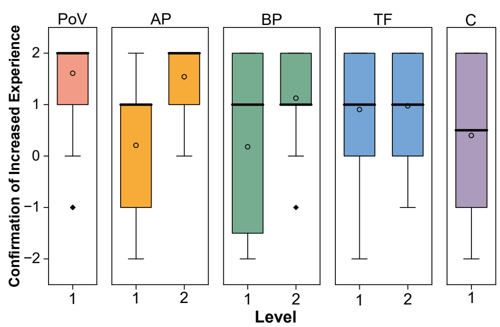

Figure 9: After upgrading a specific factor and completing the task, participants evaluate the "walking experience improvement" of the upgraded factor on a scale from -2 to +2, where -2 indicates a negative improvement and +2 indicates a positive improvement.

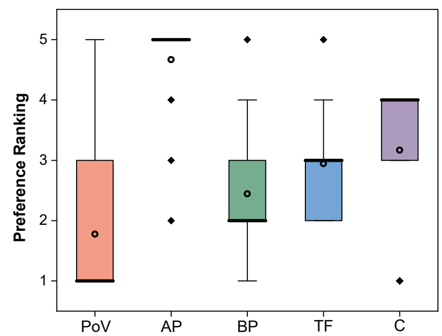

Figure 10: Participants' preference ranking of the factors after the experiment.

participants would not notice the changes in the avatar appearance, so they did not upgrade the avatar appearance as a high priority. Third, the post-experiment interviews showed that most participants upgraded the avatar appearance to the highest level at the end, as it seamlessly integrated the synchronized movement of projected shadows of full avatar appearance through the first-person perspective viewpoint, creating a sense of plausible walking experience. In addition, some participants expressed a preference for the abstract body over the stick man in the first-person perspective. As the projected shadow of the stick man on the ground differed significantly from that of a normal or realistic avatar, the sense of credibility in VR was disrupted.

Body parts, transfer functions and the coefficients of transfer functions had inter-relation to evoke the plausible walking experience. We discuss this result from the matched configurations across the participants for the following aspects. Regarding the matched configuration <1,2,1,1,0>, using arm swinging to control virtual movement exhibited the highest similarity to arm swinging during natural walking. Using the CL function with a coefficient of 1.4 allowed participants to map arm swinging control to a speed equivalent to natural walking, maintaining a natural amplitude and frequency. Unlike <1,2,1,1,0>, configuration <1,2,1,2,1> employed the L function with a coefficient of 3.0, enabling participants to linearly control a broader range of speeds through arm swinging.

Configuration <1,2,2,2,1> differed from <1,2,1,2,1> in that the former configuration incorporated head tilting to control virtual movement. Participants perceived that head control can achieve prolonged movement tasks compared to arm swinging. Additionally, it allowed to free up hands to simulate the arm swinging during real walking. Using the L function with a coefficient of 3.0 not only allowed participants to linearly control a broader range of speeds by changing the tilt angle of the head but also reduced the need to tilt the head excessively to achieve speeds equivalent to real walking.

The configuration <1,2,0,0,0> is tied for third place in all matched configuration and is the only one that includes the knee and a P function with a coefficient of 1.4. Through participant interviews, we learned that some participants found controlling movement with the knee to be very comfortable during prolonged virtual movement tasks. They pointed out that bending the knee can easily generate large angles, and with the P function's coefficient of 1.4, it can achieve walking speeds comparable to real walking. Therefore, participants did not express particularly positive attitudes toward changes in transfer functions and coefficients. Additionally, some participants regarded that knee control did not require the involvement of both hands and the head, allowing them to freely swing their arms and observe the virtual environment around them.

6.2 Comparison with Performance-Based Evaluation

As the purpose of evaluation of body-centric locomotion varies depending on research focus (i.e., performance or experience), the combination of body parts and transfer functions may generate different effects in terms of locomotion speed and accuracy [19, 20, 54, 55]. For example, head tilting could enable fast and accurate locomotion performance [20], as it is tightly coupled with a user's viewpoint in VR. However, in our work, head tilting would affect their experience of viewing the virtual environment when performing locomotion, which is different from the results in [20].

Knee bending is suited to virtual locomotion with the standing posture. Some participants can easily control their knee to perform virtual locomotion without much effort while standing [19,20]. However, a few participants reported that knee bending is similar to real walking in this experiment. Most of the participants selected the arm, which is like swinging the arms while walking in the real world. So arm swinging is good for body-centric locomotion in terms of both performance and experience, as it is an easy-to-perform movement and similar to behaviors in the real world.

Compared to the existing studies [19, 20], we added three new factors (i.e., PoV, AP and C) in our locomotion experience study. These five factors and their factor levels were selected from the existing studies, as discussed in the experimental design. However, the assumed "optimal" configuration $<1,2,2,2,1>$ was not accepted by a majority of participants, indicating that the combination of these five factors had different effects on locomotion experience. Even with the same combination of these factors, their effects would differ depending on the requirement of locomotion experience (e.g., navigating fast, accurately or comfortably).

6.3 Gender Difference Analysis

From the perspective of transitions, Fisher's exact test was used to analyze the differences in the transition process between male and female participants. The results showed that there was no statistically significant correlation between gender ($p = 0.634$).

From the perspective of the final matched configurations, both male and female participants had the highest probability of matched configurations $<1,2,1,1,0>$ and $<1,2,1,2,1>$. However, in terms of PoV selection in matched configurations, only female participants considered the third-person perspective as a matched configuration, with a probability of 3/54 = 5.6%. Female participants who chose the third-person perspective reported that watching their controlled virtual avatar walking from the third-person perspective felt like watching themselves walking from an aerial view. In contrast, male participants never selected the third-person perspective as a matched configuration, they mentioned that the first-person perspective allowed them to feel more in control of the virtual avatar.

In terms of the appearance of the virtual avatar, male participants were more inclined than female participants to set the factor to an abstract avatar, choosing this factor level with probabilities of 12/54 = 22.2% and 5/54 = 9.3%, respectively. Some male participants felt that when walking in the first-person perspective, they paid less attention to their own avatar's appearance, so even if the avatar's appearance was set to the lowest level, they could still engage the plausible walking experience. This is similar to that of Fribourg et al. [16], which showed that male participants tended to select low-level appearance features compared to female participants in their boxing and walking tasks. However, the experimental task and factors of our study were different from [16].

6.4 Design Implications

Some VR applications generally need to provide a certain walking experience, such as VR games and education in virtual environments, designers can adopt related configurations to meet the needs of users who are restricted in terms of their physical space, VR devices, and accessibility of users. These configurations can be used to give users a plausible walking experience in a virtual environment. For instance, users may need to navigate through various obstacles in VR games, such as walking on a single-plank bridge. With the accepted matched configurations, designers can ensure that users experience a plausible walking experience in the VR game without wearing full-body tracking devices.

Moreover, special configurations can be provided in VR applications for disabled users who need to restore their walking ability by allowing them to practice walking in a virtual environment. This is very helpful for rehabilitation and exercise, as it provides a safe and effective way to help users gradually recover or enhance their walking ability. Designers can customize virtual avatars and walking experiences based on the specific needs and ability levels of users, to provide walking exercises with maximum effects.

6.5 Limitations and Future Work

In line with previous studies [8, 20, 42], the experimental task involved performing locomotion from a starting position to a destination using certain body parts with selected transfer functions. In this study, direction control was not considered the main focus, as we aimed to investigate the relative contributions of relevant factors to evoke a plausible preference for body-centric locomotion in VR.

As with existing studies [24, 26, 35, 41, 42], recorded avatar animations were used in this study. The animation of an avatar was only tracked and matched with the locomotion speed controlled by participants. This study did not use the full-body tracked avatar. However, we note that there are recent algorithms capable of generating synchronized full-body animation using the tracking data from hand controllers and a VR headset. So it would be interesting to do further study using a full-body tracked avatar in our future work.

As the goal of this experiment was to evoke a plausible preference for locomotion, participants tended to compare the configurations to real-world situations throughout the experiment. Some participants believed that a combination of factors that corresponded to real walking was needed. For example, the walking speed could be adjusted more naturally so that it resembles walking speed adjustment in the real world. We plan to investigate the above issues and their effects on the plausible preferences for body-centric locomotion in future.

7 Conclusion

This paper investigated the body-centric locomotion experience using a subjective matching experiment in VR. Specifically, it aimed to explore the contributions of five factors (the point of view, the avatar appearance, body parts, transfer functions and the coefficients of transfer functions) to plausible preference in the body-centric locomotion application. The results showed that the point of view is the most important factor for evoking plausible preference, followed by body parts, transfer functions, the coefficients of transfer functions and the avatar appearance. The results also revealed that the upgrade priority of body parts and transfer functions was dependent on the selection of coefficient (e.g., matched configuration $<1,2,1,1,0>$ and $<1,2,1,2,1>$). Finally, while realistic appearance had the second-highest probability from the accepted configurations (Table 5.1), the upgrade transition of appearance was the least important to participants due to the first-person perspective during locomotion. Overall, the present research provided important research data and empirical evidence regarding the impact of different factors on virtual locomotion experiences from the users' perspective. The results may serve as the guidelines for designing new virtual locomotion experiences.

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