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An Evaluation of the Effects of Hyper-Natural Components of Interaction Fidelity on Locomotion Performance in Virtual Reality

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Abstract

Virtual reality (VR) locomotion techniques that approximate real-world walking often have lower performance than fully natural real walking due to moderate interaction fidelity. Other techniques with moderate fidelity, however, are intentionally designed to enhance users' abilities beyond what is possible in the real world. We compared such hyper-natural techniques to their natural counterparts on a wide range of locomotion tasks for a variety of measures. The evaluation also considered two independent components of interaction fidelity: bio-mechanics and transfer function. The results show that hyper-natural transfer functions can improve locomotion speed and some aspects of user satisfaction, although this can come at the expense of accuracy for complicated path-following tasks. On the other hand, hyper-natural techniques designed to provide biomechanical assistance had lower performance and user acceptance than those based on natural walking movements. These results contribute to a deeper understanding of the effects of interaction fidelity and designer intent for VR interaction techniques.

Categories and Subject Descriptors (according to ACM CCS): I.3.6 [Methodology and Techniques]: Interaction Techniques; H.5.2 [User Interfaces]: Input Devices and Strategies

1. Introduction

When designing interaction techniques for virtual reality (VR) systems, a common approach is to begin with a real-world, natural interaction. For the task of travel, for example, a designer might start with the concept of walking from the real world. With this concept in mind, the designer then has several choices. First, the designer can strive for the highest level of naturalism, or *interaction fidelity*. Interaction fidelity is defined as the objective degree of exactness with which real-world interactions are reproduced by a system [Mcm11]. In the walking example, the most *natural* technique (i.e., the one with the highest level of interaction fidelity) would be to allow the user to walk naturally through the virtual world at a one-to-one scale.

However, this is typically not possible or practical, because the virtual world is larger than the real-world tracked space, or because real walking might become too fatiguing for the tasks involved in the application. Thus, designers may adopt a second approach and settle for a technique that is *semi-natural*, with moderate interaction fidelity. For example, walking may be approximated with walking-in-place [SUS95], a locomotion device [Hol02, Iwa99], or redirected walking [RKW01], each of which have a different level of interaction fidelity. Although higher fidelity, in general, is believed to improve effectiveness (e.g., because it increases the sense of presence, it provides better proprioceptive cues, or it results in greater spatial awareness [Hol02]), there is also evidence that semi-natural techniques can reduce task performance compared to completely non-natural interfaces [MBZB12, Mcm11, NSBK15].

Designers may therefore consider a third approach: enhancing users' real-world abilities with a *hyper-natural* interaction technique [BMR12]. For example, the Seven League Boots technique [IRA07] dynamically scales real walking movements so that the user can virtually walk great distances even in a small tracking workspace. Hyper-natural techniques use natural metaphors to extend users' interaction abilities [BMR12], so while they have moderate interaction fidelity like the semi-natural techniques described above, the "reduction" in fidelity is intentionally designed to enhance the interaction and improve effectiveness.

Evaluations of hyper-natural techniques have often shown that they outperform their natural counterparts [PBWI96, IRA07, BMR12]. However, these evaluations typically include only a few metrics, while they might be detrimental in other ways. For example, a technique like Seven League Boots may reduce spatial orientation in users due to the mismatch between visual and proprioceptive cues [Hol02]. A deep understanding of hyper-natural techniques requires a thorough evaluation of a variety of performance metrics.

Finally, designers can make the choice to reject the real-world metaphor altogether and design a non-natural interaction technique with low levels of interaction fidelity.

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This could take the form of a *non-natural* technique in which the designer simply determines an efficient mapping between the input and desired actions, such as the joystick or keyboard controls used in many video games. On the other hand, designers can create *super-natural* techniques that go far beyond reality to provide users with unrealistic superpowers. In both the non-natural and super-natural approaches, developers have tremendous freedom to design effective techniques without the constraints of the real world. We summarize these approaches to VR interaction technique design in Figure 1.

The overarching goal of our research is to understand, through empirical studies, the effects of interaction fidelity and these design approaches on the effectiveness of interaction techniques (specifically locomotion techniques) in VR. Our prior work [NSBK15, Mcm11] examined non-natural, semi-natural, and high interaction fidelity techniques, and found that semi-natural locomotion techniques have some inherent shortcomings because users expect them to work like the real world, as if they had high fidelity. We hypothesize, however, that hyper-natural techniques, although they are also at a moderate level of interaction fidelity, could have similar or even greater effectiveness as compared to natural techniques. The work presented in this paper examines this hypothesis.

In our prior work, evaluations of the effects of interaction fidelity have been coarse-grained, considering interaction fidelity as a single construct. We have argued previously that interaction fidelity consists of various independent components, described in the Framework for Interaction Fidelity Analysis (FIFA) [Mcm11]. Thus, a secondary goal of this research was to study the effects of individual components of fidelity in a more fine-grained manner.

We present an experiment designed to compare natural (high interaction fidelity) and hyper-natural (moderate interaction fidelity with enhancements) locomotion techniques in VR. We do not include super-natural techniques in our study, since the effectiveness of them is primarily due to the quality of the technique design. We studied two important components of interaction fidelity: biomechanical symmetry and transfer function symmetry by evaluating task performance and other measures of effectiveness across a variety of travel task conditions. The results of this study give us a greater understanding of the benefits of natural locomotion techniques and the effectiveness of various enhancements to those techniques.

2. Related Work

Hyper-natural techniques allow users to perform interactions that would be impossible in real world, although unlike super-natural techniques, hyper-natural techniques use natural metaphors or interactions to extend users' abilities. For example, the Go-Go technique [PBWI96] allows the user to reach far into the virtual environment (VE) by extending his physical hand. This technique enables users to select and manipulate virtual objects at a distance based on the real-world interaction of reaching and grabbing objects. Similarly, in Wii Sports tennis, users can perform forehands and backhands based on the real-world action of swinging a tennis racket, but without a direct mapping of the physical movements to the virtual movements. This technique

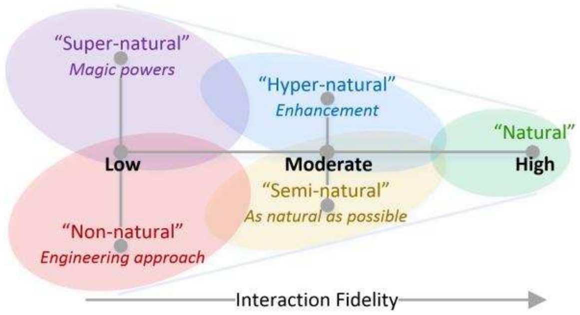

Figure 1: *VR interaction technique design approaches.*

enhances precision by mapping a wide variety of swing movements to "perfect" swings in the game.

Although magic travel techniques are numerous and diverse (e.g., camera in hand [NLB14] or flying techniques [NLB14]), only a few of them can be considered hyper-natural. Scaling up the user's movement with a constant factor allows faster movements through a larger environment [IRA07]. However, this may reduce precision and the user's distance estimation ability. Interrante et al. [IRA07] scaled up the movements of the user using a non-uniform scaling. To improve precision, this technique scales the movement only when the speed is higher than a certain threshold, like a mouse acceleration.

McMahan et al. [MBZB12] posited that the overall level of naturalness or interaction fidelity is determined by a combination of system characteristics, and that each component of interaction fidelity may fall at a different location in the fidelity continuum. This concept is embodied in the Framework for Interaction Fidelity Analysis (FIFA) [Mcm11]. This framework has been employed to determine the level of fidelity for locomotion interfaces [NSBK15]. As we noted above, however, studies to date have not evaluated the effects of independent components of interaction fidelity.

Like interaction fidelity, effectiveness is not a single construct. Researchers have been comparing different travel techniques based on different metrics. In an early battery of tasks and measures [LKG*95] developed to characterize the effectiveness of interaction techniques, task completion time and accuracy (number of collisions) were used as performance measures for locomotion tasks. Griffiths et al. [GSW06] also evaluated performance of navigation based on time and accuracy. They considered both errors from the ideal path and the number of collisions as accuracy measures. Other metrics such as amount of pressure on the foot or spatial awareness were used for locomotion devices based on walking [Iwa99]. Subjective measures such as presence, simulator sickness or ease of use have also been used to compare navigation techniques [SUS95, Hol02]. Other researchers used a combination of objective and subjective measures such as spatial ability and simulator sickness [CGBL98] in addition to object recall and object recognition [SFR*10]. Bowman et al. [BKH97] introduced a taxonomy of travel techniques along with a framework for evaluating the quality of different techniques for tasks including absolute motion, relative motion and spatial awareness. This framework was expanded into a testbed [BKH98] that allows evaluation of not only the effects of various travel techniques, but also the impact of different factors including environment, task and user characteristics. In our study, we

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wanted to test locomotion/travel techniques. We cover not only goal-directed movements (i.e., move to a target), but also movements where the other factors such as path and speed, are important. This set of tasks/metrics is useful beyond this experiment, and can be reused to test new techniques, interfaces or hypotheses.

3. Evaluating the Effects of Interaction Fidelity

In this section we describe the framework within which we evaluate the effects of interaction fidelity for VR locomotion tasks, the specific techniques evaluated in our study, and the testbed we designed for this and future evaluations.

3.1 Evaluation Framework

As described in the introduction, the level of interaction fidelity is an important characteristic of VR interaction techniques that can be used to understand differences in techniques and their effectiveness. Analyzing the level of interaction fidelity allows us to compare techniques to their real-world counterparts. FIFA [Mcm11] describes interaction fidelity in terms of multiple components, using the categories of biomechanical symmetry, control symmetry, and system appropriateness.

Biomechanical symmetry describes how similar the body movements used in the interaction technique are to the body movements used in real world for performing the same task. Biomechanical symmetry includes three sub-components: kinematics, which refers to body motions or trajectories; kinetics, which is concerned with the forces applied to produce body movements; and anthropometry, which considers the body parts being used. *Control symmetry* describes the realism of the mappings used by the interaction technique. In particular, transfer function symmetry considers how input data is interpreted and transformed into an output effect. Finally, *system appropriateness* describes how suitable the system is to perform a specific aspect of interaction.

However, it is also critical to understand the *designer's intent* for these techniques. As shown in Figure 1, semi-natural techniques strive for realism but fall short due to limitations of technology or space. On the other hand, hyper-natural techniques change the natural interaction intentionally to provide users with enhancements or compensate for natural human body limitations.

In the experiment described below, we manipulate the level of biomechanical symmetry and transfer function symmetry, and study hyper-natural technique components as compared to their natural counterparts. We chose to study biomechanics holistically, because its sub-components are tightly bound together for locomotion. Previous studies showed evidence of negative effects for low levels of biomechanical symmetry in semi-natural techniques [NSBK15, Mcm11]. We wondered whether it was possible to achieve hyper-natural biomechanics and whether the effects would be different. We evaluated transfer function symmetry because of its importance in technique design (e.g., redirected walking [RKW01] or seven league boots [IRA07] techniques manipulates the transfer function to achieve the designer's intent). System appropriateness mostly depends on the system specifications, so we used the best available system specifications and kept those levels constant in all of the experiment conditions.

	Natural biomechanics	**Hyper-natural biomechanics**
Natural transfer function	Real Walking	Jump Boots
Hyper-natural transfer function	Seven League Boots	Seven League Jump Boots

Table 1: *Interaction techniques used in our experiment*

3.2 Interaction Techniques

Our research questions for this study focus on the effects of hyper-natural techniques as compared to natural ones, and the specific effects of two components of interaction fidelity: biomechanical symmetry and transfer function symmetry. We identified natural and hyper-natural techniques for both of these components, leading to four conditions (Table 1).

Real walking in VR

We used the real walking technique as the technique that is closest to natural human walking. In this technique the user's head was tracked to show him the VE using a head mounted display (HMD). This technique used a one-to-one mapping of physical to virtual movements to be as natural as possible.

Hyper-Natural Transfer Function

Our hyper-natural transfer function technique was based on Seven League Boots [IRA07]. This technique scales users' movements and enables them to move faster and travel farther without increasing the amount of physical movement. This could be achieved using a uniform scaling factor; however, this would result not only in exaggerated head bobbing, but also a reduction in accuracy due to the speed-accuracy tradeoff. The method we designed was similar to the implementation in [IRA07]. The scaling was applied only in the direction of movement and parallel to the ground. We do not scale the movements orthogonal to the ground plane to avoid making users feel they are shorter or taller or their viewpoint bouncing up and down excessively.

Scaling is activated only when the user's velocity is larger than a certain threshold V_{th}. When moving slower than V_{th} there is a one-to-one mapping between physical and virtual movement to ensure control and accuracy over delicate movements. At each frame, we calculate the vector $\vec{D}$ that the user has moved in the last time window T_w. The amount $V_{user} = |\vec{D}|/T_w$ is the user's speed in the last time window. The scaling factor F_{7L} is a function of how much faster the user is moving over the activation threshold V_{th}. F_{7L} is multiplied by the user's movement in the last frame, $\overrightarrow{\delta d}$, to reduce acceleration latency and ensure an immediate termination as the user stops. We chose a sub-second T_w to allow users to activate the acceleration shortly after they start walking. Based on our experience, this can improve control over travel and mostly eliminate the need for predicting users' direction of travel by their gaze direction.

A suitable acceleration method should allow a seamless transition from real walking to Seven League Boots, and, once activated, should provide the user with enough acceleration to effectively and significantly increase movement speed. We prototyped and implemented different linear and polynomial functions for the scaling factor F_{7L}. A linear function does not provide a seamless activation. We used the polynomial function $F_{7L}=ax^2+bx+c$ with $x=V_{user}$ -

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V_{th}, a=1.2, b=0.7 and c=1. The constant values were selected to provide a seamless change of transfer function and appropriate acceleration for higher speeds.

Hyper-Natural Biomechanics

To study the effect of biomechanical symmetry in hyper-natural techniques we required a method to biomechanically assist users for walking. Robotic exoskeletons such as the Honda walking assist device [IAH*09], can physically help people walk by reducing the floor reaction force, leg muscle activity and total body energy consumption. Such devices were designed mainly to help elderly or physically challenged people walk and might not serve our purpose of helping healthy users walk faster and easier. On the other hand, spring-based athletic shoes have shown positive effects on cardiovascular and athletic activities [MZF03]. Among those we reviewed, Kangoo Jumps™ boots (Figure 2) appears to provide better balance because of the large contact surface with the ground and high friction surface.

It is claimed that these boots provide an effective method for improving aerobic capacity comparing to normal running shoes [MZF03]. Moreover, the reduction in the level of peak pressure and regional maximum force on the sole of the foot [SGDC05] can provide users with an easier means of jogging and running. Since these boots have shown advantages the real world we used them to develop our hyper-natural biomechanical technique. The user walks in the boots while wearing the HMD. We had the user wear knee and elbow pads since balance may be an issue.

Figure 2: *Setup for the experiment with Kangoo Jumps Boots (KJB).*

3.3 Locomotion Testbed

The large number and wide variety of novel VR applications makes it impractical to evaluate locomotion techniques directly for each application. A general testbed can provide a practical solution for mapping techniques to a set of performance requirements.

Various path-following, spatial awareness, search or cognitive load tasks have been introduced in previous testbeds [BKH97, BKH98, LKG*95] or sets of tasks [SFR*10, CGBL98, GSW06, SUS95]. We added newly designed locomotion tasks of speed control and maximum movement speed. Our testbed can be reused to provide consistent and comparable measurements between different techniques. The set of metrics we currently include in our testbed for locomotion interfaces includes:

- Accuracy (deviation from desired path)
- Speed control (control ability over movement speed and distance from a moving object)
- Movement speed (task completion time)
- Spatial awareness (users' knowledge of their surroundings and their orientation in the environment)
- User comfort (cybersickness [KLBL93])
- User experience (to capture presence, enjoyment, flow and users' experience with the techniques [IDP13])
- Fatigue (tiredness in general and specifically in feet and legs, based on users' ratings and heart rate)
- Ease of learning (novice users' ability to utilize the technique)
- Ease of use (user's opinion about the complexity of the technique [BKH98])

We use general locomotion tasks in this testbed to reveal different performance metrics. We measure accuracy of travel using path-following tasks which require users to move as accurately as they can on the indicated lines. Since we track the users' heads, to move on the line they need to keep the indicated line underneath them. We do not set a time limit for this task, which could persuade users to move fast and lose accuracy. Likewise, we do not want users to move very slowly since it could make the comparison unfair. Therefore, we instruct them to use their "normal" walking speed to make it more ecologically valid. Different techniques might provide specific maneuvering abilities (e.g., a gamepad can be accurate for moving on straight lines but not curved paths). Thus, we designed six different maneuvering tests including: straight line, paths with 45°, 90° and 135° turns and paths with 1m and 2m diameter curves (Figure 3), all with the same total length of 16m. The total area between the indicated path and the user's track signifies the deviation.

To capture speed control abilities with different speeds we include three courses with slow (relative to normal human walking speed), fast (human jogging speed) and random speed (varies randomly between the slow and the fast). Users follow a moving virtual robot in a hallway and attempt to maintain a certain distance (2m). As shown in Figure 3, an indicator on the upper left provides them with distance hints. Green indicates the ideal distance, while yellow, orange, and red indicate distances too far behind and light to dark blue tones indicate that the user is too close. We use discrete colors instead of a continuous color range to avoid confusion about the color of the ideal distance. We also decided against using a bar as a distance indicator so that users would focus on the robot and not just on controlling the indicator. We used the score function, $F_1+C_1+2(F_2+C_2)+4(F_3+C_3)+0.1H$ based on the amount of time user spent in each zone (F_1/C_1: warning far/close, F_2/C_2: far/close, F_3/C_3: too far/close) and the number of times the user hit the walls (H) which indicate lack of control over walking.

In the maximum movement speed task we ask users to move as fast as they can in a simple hallway that goes around the tracked area for two laps, for a total length of approximately 45 meters. This task evaluates users' ability to move quickly, although it still requires them to maintain some control over their path. Users are instructed not to collide with the walls. Collisions add a penalty to the score, although the software keeps the view inside the corridor. We note that this task might not be applicable for evaluating techniques with constant speed or a fixed maximum speed, but for techniques based on real walking it allows evaluation of the user's ability to walk quickly.

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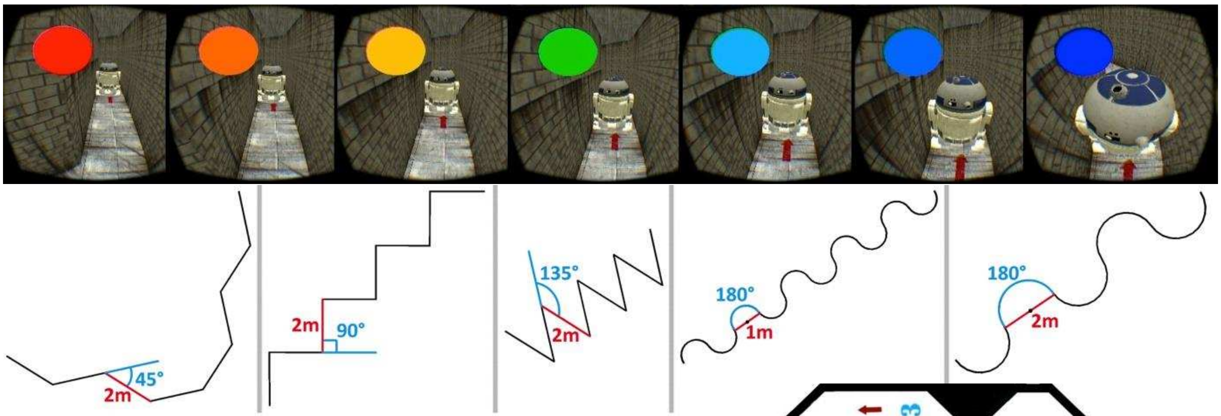

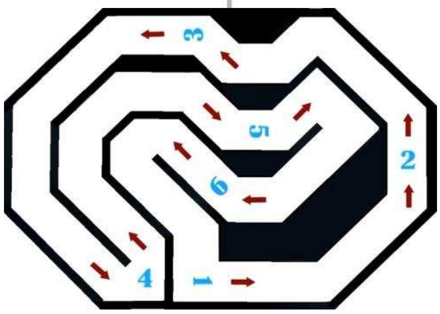

Figure 3: ***Above***: *Speed control task and the distance indicator.* ***Middle***: *Courses of path-following task to evaluate maneuverability. All courses are 16m long.* ***Below***: *Spatial awareness task environment.*

To evaluate spatial orientation, we designed a task similar to Bowman et al. [BKH97] and Chance et al. [CGBL98]. We designed a complicated hallway with six numbers on the ground. At each numbered location, users must stop and turn their head to face towards the previous numbered location, which is no longer visible (Figure 3). We capture the head orientation at each location and calculate the error relative to the actual direction toward the previous number. We use the accumulated errors for all six points as a measure of the user's spatial orientation.

As part of this testbed, to quantify presence, enjoyment, flow and the general user experience as well as ease of use and ease of learning, we include the Game Experience Questionnaire [IDP13] and an interface questionnaire we designed. To evaluate fatigue, we include questions about tiredness in general and in specific body parts, and also measure users' heart rate. The standard Simulator Sickness Questionnaire [KLBL93] quantifies user comfort. In a background questionnaire, we ask about the user's age, gender, visual acuity, ability to fuse stereo images, experience with computers, games, 3D games and VR, physical fitness, technical background and proficiency.

4. Experiment

Using this framework we designed and ran a controlled experiment comparing natural and hyper-natural components of biomechanical and transfer function symmetry in VR locomotion techniques.

4.1 Goals and Hypotheses

Hyper-natural techniques, like semi-natural techniques, change the way users naturally interact. Broadly, our goal is to understand how hyper-natural techniques influence the performance. This leads us to our first research question:

1. *What is the effect of hyper-naturalism on performance of locomotion techniques?*

Although hyper-natural techniques are known to have positive effects on some performance metrics for certain tasks [PBWI96, IRA07], this may not be true in all situations. Moreover, different components of fidelity can have different effects on performance. This inspires our second research question:

2. *How does the level of fidelity of a locomotion technique's biomechanics and transfer function affect performance?*

Since the intent of hyper-natural techniques is to enhance the user's abilities, they may improve effectiveness for some performance metrics. However, since they change the way users naturally interact, they may be worse than natural (high interaction fidelity) techniques in other ways. For example, we expect the scaling in Seven League Boots to have a detrimental effect on accuracy in difficult path-following tasks.

Based on prior results with semi-natural techniques [NSBK15], we expect hyper-natural biomechanics to have some detrimental effects on performance. We also hypothesize that users will be able to adapt more easily to hyper-natural transfer functions, since this has been shown for various manipulation techniques [Mcm11] and even occurs in real-world locomotion (e.g., moving sidewalks). Thus, we expect that hyper-natural transfer functions will have more benefits than disadvantages.

4.2 Apparatus

The study took place in the Cube at UNIVERSITY. The Cube is a four-story facility with a 50x40-foot floor area. A Qualisys optical tracking system with 24 cameras tracks passive reflective markers in a 36x28-foot area. The tracking data was streamed via Wi-Fi from the Qualisys server PC, directly connected to the tracking system, to a rendering laptop. We tried to minimize the latency as much as possible. In all four conditions the VE was displayed to the user with an Oculus Rift Development Kit 2 (DK2) HMD with a FOV of 100°, resolution of 1920x1080 for both eyes and stereoscopic rendering. We used a rigid body of four reflective markers attached to the HMD to track the user. Users carried the laptop used for rendering in a backpack. We used a wireless keyboard to control the study. We used

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Unity3D to interface with the hardware, render the VE, log the data and manage the flow of the experiment.

4.3 Participants

We recruited 24 participants, 17 males and 7 females, on a voluntary basis for this study. Participants were undergraduate and graduate students, ranged in age from 18 to 31, and one had prior experience with the Kangoo Jumps.

4.4 Experimental Design

The primary independent variables in the experiment were transfer function symmetry (varied within subjects) and biomechanical symmetry (varied between subjects). As described above, the Seven League Boots (7L) technique was used as a hyper-natural transfer function (lower level of transfer function symmetry), while the natural technique (high level of transfer function symmetry) was a one-to-one transfer function we called real walking (RW). Hyper-natural biomechanics (lower level of biomechanical symmetry) was achieved via the Jump Boots (JB) technique, while the natural biomechanics conditions (high level of biomechanical symmetry) used the user's own shoes. This resulted in four conditions (Table 1). We called the condition with both hyper-natural biomechanics and transfer function the Seven Jump Boots (7JB) technique.

We divided the 24 participants into two groups of 12 based on whether or not they were using the Jump Boots. We counterbalanced the ordering of the 7L and RW techniques so that half the participants used 7L first and the other half used RW first. A secondary independent variable was course type for the path-following and speed control tasks.

4.5 Procedure

The study was approved by the university's Institutional Review Board. As participants arrived, they were asked to read the informed consent form and sign it if they agreed. Next, they completed a background questionnaire asking for their age, gender, eyesight and any prior experience with different types of video games, stereoscopic displays or the jump boots. They were provided with an outline about the facilities to be used, our experiment background and the locomotion techniques, followed by a training course in which they got used to the technique they were going to use.

For each locomotion technique, participants were asked to perform four sets of tasks. The first task was the set of path following tasks. In the maximum speed task participants walked through the hallway before they start the task, to make get familiar with the path. In the speed control task, deviation was not calculated until after the participant had walked about ten feet, so that she had time to adjust her speed with the moving robot. The last task was the spatial orientation task. After completing all tasks, participants were asked to fill out an interface questionnaire followed by the GEQ [IDP13] and SSQ [KLBL93]. The interface questionnaire used a seven-point scale to measure users' opinions regarding naturalness, similarity to walking in the real world, being fun, ease of learning and fatigue.

5. Results

We present the statistically significant results of the study in this section. All dependent variables were numeric continuous variables, except for the questionnaire data which were numeric ordinal values. To understand the two-and three-factor interactions and main effects of our three independent variables (transfer function symmetry level, biomechanical symmetry level, course type), we used a three-way analysis of variance (ANOVA) on the values of the performance metrics for each task, and an Ordinal Logistic Regression analysis based on a Chi-square statistic on the questionnaire data. Student's t-tests with appropriate corrections were used for post-hoc pairwise comparisons between combinations of the performance metrics.

5.1 Accuracy

We found a significant interaction effect of transfer function symmetry level and course type ($F_{5,282}$=7.06; p<0.0001) on deviation from indicated line. For easy tasks (straight line, 45° turns, 90° turns), transfer function symmetry did not affect accuracy, but for more difficult tasks (135° turns, 1m and 2m diameter curves), high transfer function symmetry (i.e., natural) conditions were significantly better (Figure 4A). We also found a significant effect of biomechanical symmetry level on deviation ($F_{1,286}$=19.58; p<0.0001). Users had significantly less deviation with a high level of biomechanical symmetry (mean = 1.59 meters) than with hyper-natural biomechanics (mean = 1.94 meters).

5.2 Speed Control

We found a significant interaction between the levels of biomechanical symmetry and transfer function symmetry

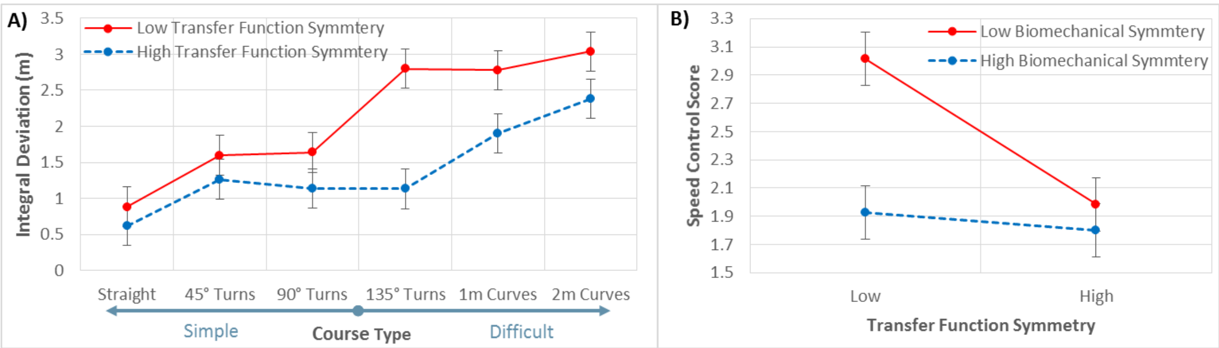

Figure 4: ***A:*** *Interaction between course type and level of transfer function symmetry for the task of path following.* ***B:*** *interaction between level of transfer function and biomechanical symmetry for the speed control task. Lower score is better.*

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($F_{3,140}$=5.77; p=0.0177) on speed control ability. The locomotion technique with low levels of both biomechanical and transfer function symmetry (7JB) was significantly worse than the other three conditions (Figure 4B). As mentioned in section 3, scores were a combination of completion time and number of collisions to walls, and lower scores were better. We also found a significant effect of course type ($F_{2,141}$=22.35; p<0.0001). Speed control score for the random speed course was significantly worse than the scores for the slow and fast speed courses.

5.3 Maximum Movement Speed

We observed a significant effect of transfer function symmetry level on maximum movement speed ($F_{1,43}$=7.70; p=0.0081). Users with low transfer function symmetry (Seven League technique) could move significantly faster. We did not observe a significant effect of biomechanical symmetry on maximum speed.

5.4 Spatial understanding

We did not observe any significant effect of transfer function symmetry ($F_{1,47}$=0.72; p<0.40) or biomechanical symmetry ($F_{1,47}$=0.42; p<0.52) or any significant interaction ($F_{1,47}$=0.18; p<0.67) between them on spatial orientation. The mean values for errors for the different techniques were: RW=16.08°, JB=17.76°, 7L=19.26° and 7JB=19.81°.

5.5 Questionnaire Results

Using low levels of both biomechanical symmetry and transfer function symmetry (the 7JB technique), users felt significantly more annoyed compared to JB (χ^2=2.18; p=0.0342), 7L (χ^2=2.06; p=0.0453) or RW (χ^2=2.53; p=0.0152). Similarly, the techniques with low levels of both components (7JB) was significantly more tiresome (χ^2=2.10; p=0.0413) than just 7L. Chi-square analysis indicated that users felt 7L (χ^2=4.428; p=0.0354) was significantly more similar to real-world walking compared to JB or 7JB. Subjective ratings for simulator sickness showed significantly more sweating (χ^2=2.71; p=0.0096) using the low level of biomechanical symmetry compared to other techniques. We did not observe any significant differences in other comfort measures. Users felt that the RW and JB techniques were more comfortable, natural, precise, and easy to learn compared to the 7L and 7JB techniques respectively. On the other hand, users had more fun with the 7L technique compared to RW.

6. Discussion

As we expected, we found mixed results for our hyper-natural locomotion techniques. The 7L technique had performance similar to or better than RW in several situations, while the other two hyper-natural techniques, JB and 7JB, were sometimes harmful or undesirable for users (Table 2). This demonstrates that the effects of various hyper-natural interaction fidelity components are not uniform. Supporting our second hypothesis, a hyper-natural transfer function demonstrated mostly positive effects. The 7L technique improved maximum movement speed and was more fun for users. However, techniques with the hyper-natural transfer function (7L and 7JB) were significantly less accurate than techniques with a natural transfer function for more complicated path-following courses. Overall, then, we infer that well-designed hyper-natural transfer functions can be understood and adapted to by the user, resulting in improved speed performance (as in [IRA07]), but that they may still be more difficult to control when complicated, precise movements are required.

	7L	JB	7JB
Accuracy	Decreased	Decreased	Decreased
Speed control	n.s.	n.s.	Decreased
Movement speed	Improved	n.s.	Improved
Spatial awareness	n.s.	n.s.	n.s.
User comfort	n.s.	Sweating	Sweating
User experience	More Fun	n.s.	Annoying
Fatigue	n.s.	n.s.	Tiresome
Ease of learning	n.s.	n.s.	n.s.
Ease of use	n.s.	n.s.	n.s.

Table 2: *A summary of our findings. Green shows improvement over RW technique, red shows a disadvantage, and orange shows partial disadvantage.*

Our findings were not the same for biomechanical symmetry. As we have hypothesized, hyper-natural biomechanics did not improve locomotion performance in VR, despite published benefits for real-world locomotion [MZF03]. The conditions using Jumps Boots not only decreased accuracy but also disturbed user comfort. Moreover, we observed that users' movements with the boots did not appear similar to real-world walking. Although one might expect the JB technique to increase the maximum movement speed, we did not find a significant advantage in our study. We observed that JB and 7JB users in our study did not walk confidently, and that they tended to walk more slowly than they would in the real world. Changing biomechanical forces and movements with the boots, while at the same time removing real-world visual cues (including the user's view of his own body) seems to be too difficult for users to cope with all at once. However, we note that our participants were not trained extensively with the boots, and effective training has shown some positive effects on improving VR locomotion performance [NSD*15].

Combining hyper-natural components of fidelity was mostly harmful to performance. The 7JB technique decreased speed control ability and caused users to feel more annoyed and tired. Modifying multiple components of fidelity, even in ways that are intended to enhance performance, can affect users' ability to understand their interaction and adapt to the differences.

We did not observe any effects of the hyper-natural techniques on users' spatial orientation. Our subjects had different strategies in the spatial understanding task. Based on our observation and the literature [BKH97], the strategy users took for performing this task might have had a greater effect on their results than the techniques themselves.

7. Conclusions and Future Work

This work contributes a deeper understanding of the effects of interaction fidelity, specifically for the hyper-natural design approach, and separates the effects of two critical interaction fidelity components. Revisiting our research

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questions in section 4.1, we found that not all the effects of hyper-natural locomotion techniques are positive. Such techniques can improve some performance metrics while they might be harmful to some others. Additionally, we learned that methods that improve real-world interactions might not be beneficial in VEs. Our results also showed that well-designed hyper-natural transfer functions can improve movement speed and user experience, while they might decrease accuracy. Designers should consider the possibility of losing accuracy and use hyper-natural transfer functions for suitable applications. In applications where tracking space is large, but not large enough (e.g., simulating outdoor augmented reality systems), techniques like 7L may be good alternatives when natural walking is the desired mode.

On the other hand, the biomechanical component of interaction fidelity appears to be more sensitive to changes and might not be a good candidate for hyper-natural technique design. Designers should use caution when manipulating this component in their designs. Finally, we saw that modifying multiple fidelity components decreases the naturalness of the technique and can affect the users' ability to adapt to and learn the interaction.

This work has contributed not only empirical results related to hyper-natural locomotion techniques, but also a theoretical framework for understanding interaction fidelity and designer intent in VR interaction techniques, and a testbed for evaluating locomotion technique performance holistically. Although we learned about the effects of manipulating the biomechanical and transfer function components of interaction fidelity, other components such as latency still needs to be studied. We also plan to compare these results to those obtained by semi-natural locomotion techniques, such as locomotion devices (e.g., Virtuix Omni) using the same testbed and metrics. Finally, we will study the potential of design approaches not based on real-world actions (non-natural and super-natural) to produce effective locomotion techniques.

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