

Exoskeleton Training through Haptic Sensation Transfer in Immersive Virtual Environment

Yang Ye¹, Yangming Shi, Ph.D.², Youngjae Lee³, Garret Burks, Ph.D.⁴, Divya Srinivasan, Ph.D.⁵, Jing Du*, Ph.D., M. ASCE⁶

¹ Ph.D. student, Informatics, Cobots and Intelligent Construction (ICIC) Laboratory, Department of Civil and Environmental Engineering, University of Florida; e-mail: ye.yang@ufl.edu

² Assistant Professor, Department of Civil, Construction and Environmental Engineering, University of Alabama. Email: shiyangming@ua.edu

³ Ph.D. student, Industrial & Systems Engineering Department, Virginia Tech; e-mail: yjl2394@vt.edu

⁴ Research Scientist, Industrial & Systems Engineering Department, Virginia Tech; e-mail: garretb7@vt.edu

⁵ Associate Professor, Industrial & Systems Engineering Department, Virginia Tech; e-mail: sdivyal@vt.edu

⁶ Associate Professor, Informatics, Cobots and Intelligent Construction (ICIC) Laboratory, Department of Civil and Environmental Engineering, University of Florida; e-mail: eric.du@essie.ufl.edu. Corresponding Author.

ABSTRACT

Exoskeleton as a human augmentation technology has shown a great potential for transforming the future civil engineering operations. However, the inappropriate use of exoskeleton could cause injuries and damages if the user is not well trained. An effective procedural and operational training will make users more aware of the capabilities, restrictions and risks associated with exoskeleton in civil engineering operations. At present, the low availability and high cost of exoskeleton systems make hands-on training less feasible. In addition, different designs of exoskeleton correspond with different activation procedures, muscular engagement and motion boundaries, posing further challenges to exoskeleton training. We propose an “sensation transfer” approach that migrates the physical experience of wearing a real exoskeleton system to first-time users via a passive haptic system in an immersive virtual environment. The body motion and muscular engagement data of 15 experienced exoskeleton users were recorded and replayed in a virtual reality environment. Then a set of haptic devices on key parts of the body (shoulders, elbows, hands, and waist) generate different patterns of haptic cues depending on the trainees’ accuracy of mimicking the actions. The sensation transfer method will enhance the haptic learning experience and therefore accelerate the training.

INTRODUCTION

Construction is a labor-intensive industry that involves heavy labor. Construction practitioners are more frequently exposed to work-related musculoskeletal disorders (WMSD) (Cho Yong et al.). The rate of WMSDs in construction was about 9% higher than all industries combined in 2017 (Bureau of Labor Statistics, 2019). As an emerging technology that can augment workers’ physical capability and reduce the occurrence of WMSD in the construction industry, an exoskeleton is considered as a prospective transformative technology for civil engineering operations (Kim et al. 2019; Yu et al. 2018). Current evidence, however, suggests that the effectiveness of exoskeletons

as an intervention largely depends on diverse industrial tasks and user characteristics (Kim et al., 2019). New exoskeleton technologies are also rapidly emerging: hence, there is a critical need for a training framework that can enable workers to experience different exoskeletons while developing the necessary motor skills to operate an exoskeleton safely and effectively. For instance, a powered exoskeleton has a variety of supportive torque profiles to choose from, restrictions on safe ranges of motion, enhances human physical capacity, and often makes the user unaware of their contribution to the motion vs. its outcome. It is hence necessary to establish an effective motor training method to improve users' awareness of the capacities and restrictions of such an exoskeleton.

This paper proposes an innovative exoskeleton training approach, called haptic sensation transfer, which migrates and transfers the motor experience of a person wearing a real exoskeleton system to another person (without wearing an exoskeleton) via a haptic-tactile system in an immersive virtual environment. With a whole-body haptic device, motion tracking devices, and a VR headset, the simulated virtual environment is created to simulate the motor experience of wearing an exoskeleton and provide visual and haptic guidance according to the real-time motor performance of the user. We conducted a human-subject experiment (n=15) to assess the effectiveness of this training approach. We pre-recorded 6 trials of the direct ground lift motion (EMT-training, 2021) from an experienced exoskeleton user who was wearing a back exoskeleton and then modeled the motions in Virtual Reality (VR). The subjects were then asked to follow the motions in VR as accurately as possible under different view perspectives and haptic-tactile patterns. To reduce learning effects, random deviations were added in the motions and the correspondence between motion and task conditions was shuffled. To minimize individual differences, a within-subject design was used to assess the effectiveness of our training approach. The remainder of this paper introduces the point of departure, the experiment, and the findings.

RELATED WORK

Exoskeleton Motor Training

Robotic exoskeletons were widely discussed as tools that can potentially change multiple industries like medical (Kagirov et al. 2021), military (Hong et al. 2019), industrial applications, and construction industries (Kim et al. 2019; Zhu et al. 2021). Although exoskeleton usage is generally considered safe, exoskeleton training is necessary to familiarize new users with not only the operation methods but also the triggering motions and safety ranges of the motion (van Herpen et al. 2019). For instance, Wang et al. (2015) utilized the center of mass (CoM) as the indicator to trigger the powered exoskeleton for walking assistance. Young et al. (2017) tested a pneumatically powered hip exoskeleton and found the torque output and user's rectified physical load were different if the user's motions were different. Apart from failing to trigger the exoskeleton, an inappropriate motion could also cause body injuries, such as bone fracture accidents caused by a misalignment between exoskeleton joints and users' lower extremities joints (van Herpen et al. 2019). Thus, the pre-use training for the exoskeleton is critical (He et al. 2017).

Hands-on training with multiple sessions has been adopted for typical exoskeleton training (Banala et al. 2009; He et al. 2017; Park et al. 2021). However, exoskeleton products are typically expensive (Sanngoen et al. 2017), and physical training with an actual powered exoskeleton could sometimes be unsafe, time-consuming, and resource-intensive. Together with the variability of exoskeleton designs for different use cases (Yang et al. 2008; Kim et al. 2021), availability and accessibility are barriers that impede a wide application of hands-on exoskeleton motor training

(Kim et al. 2019). There still lacks an accessible method that can facilitate exoskeleton motor training, possibly in a simulated way, when real exoskeleton systems are not available.

VR and Haptics for Motor Learning

VR can provide multiple modalities of sensory feedback to support training effectively (Lee et al. 2021). In motor training tasks, VR produces feedback in the forms of movement visualization, performance feedback, and contextual guidelines (Schüler et al. 2015; Shi et al. 2021). Among all, visual feedback is the most commonly adopted method for motor learning in VR. Doniger et al. (2018) conducted a controlled experiment to study the influence of VR visualizations for the lower extremities motor rehabilitation of Alzheimer's disease patients and suggested that augmented visual information in VR was beneficial for motor training. Lee et al. (2021) suggested that VR vision was significantly effective for motor learning after testing VR for upper extremities rehabilitation of stroke patients. In addition, haptic-tactile is widely used for motor training (van Breda et al. 2017; Williams and Carnahan 2014). In motor rehabilitation training, haptic-tactile hints and visual guides are often combined to realize the comparable learning effectiveness as the traditional rehabilitation sessions (e.g., Liu et al. (2006). VR systems are flexible in terms of integrating haptic-tactile hints for motor learning via additional haptic devices, for instance, haptic generators as a supplement for visual information (Schüler et al. 2015). As a scalable and effective solution, VR plus haptic generators are potentially an effective method for the exoskeleton motor training.

METHODOLOGY

We designed a whole-body haptic system for user sensation transfer. The system consists of (i) a motion tracking system (i.e., Xsens IMUs system) (Xsens, 2021) that tracks and documents the whole-body motion of an exoskeleton expert at the frequency of 64 Hz; (ii) a body motion modeling system that reproduces the tracked exoskeleton expert's body motion as an avatar in VR; and (iii) a haptic system that generates haptic feedback of different magnitudes and frequencies at the following body locations of an exoskeleton trainee: hands, elbows, trunk, and knees (Fig. 1). When the exoskeleton trainee repeats the motions in an accurate way, i.e., following the desired motion trajectories and velocities in the 3D body motion space, the haptic devices provide the strongest haptic-tactile feedback, creating an illusion of physical contacts, or the feeling of wearing an exoskeleton. When the exoskeleton trainee veers off the track of more than 20 cm, the haptic sensation disappears completely, generating a feeling of having taken off the exoskeleton. And when motion is followed but not accurately, the sensations experienced are in between the extremes described above. Depending on the training phase, VR also provides augmented visual cues, i.e., color-coded trajectories in the 3D space, facilitating an even more immersive experience.



Figure 1: Device set up of subject (trainee)

In order to test the effectiveness of the proposed haptic sensation transfer method, as well as the marginal contributions of haptics-only and haptics+augmented visual cues, we conducted a human-subject experiment (n=15) following the frameworks shown in Figure 2. We recorded the exoskeleton motions of an expert and reproduced them in VR, which provided sample motion data for new users to follow. Haptic cues were initiated according to key body components of the recorded exoskeleton motion. This framework enables VR motor training with egocentric or non-egocentric visual information, and with or without haptic cues.

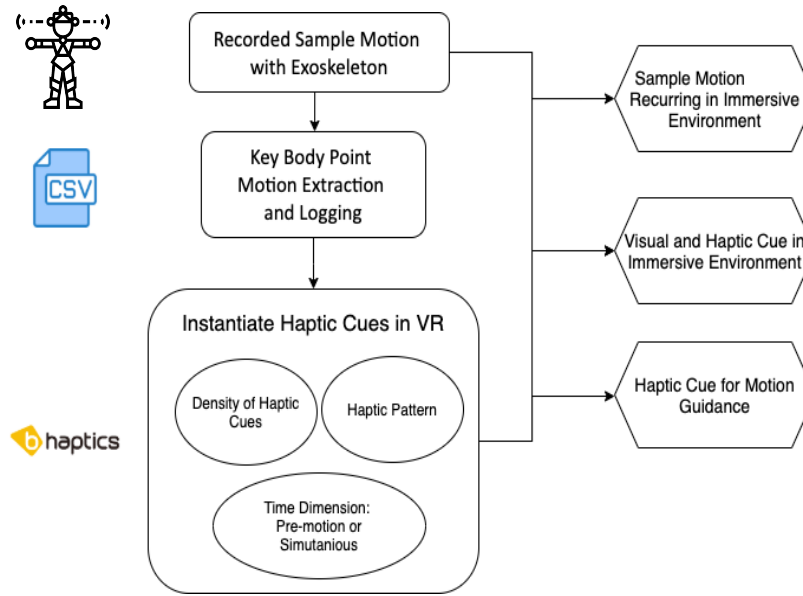


Figure 2: Study Framework

In construction operations, bending and lifting are common motions that result in WMSD. Direct ground lift (DGL) involves bending and lifting. So we pre-recorded 6 trials of direct ground lift motion from an experienced exoskeleton user who was wearing a back exoskeleton as shown in Figure 3 (a). Randomness was added to each motion such that the on-set time and motion magnitude were different between the 6 trials to reduce the learning effect. The expert's key body components were extracted and logged. Then the expert's motions were reproduced in VR and used as sample motions (Figure 3(b)). The first step of an experiment was subject screening. To reduce the familiarization burden, the subjects were then pre-trained to understand the VR system, haptic devices, and general steps of DGL motion. VR devices included HTC headsets, HTC controllers at two hands, and VIVE trackers at elbows, pelvis, and feet. This VR set-up enabled full-body tracking in VR which duplicated the users' whole-body motion from real life to VR environment thus we could track and evaluate user's motion. The haptic sensation was provided by bHaptics devices (bHaptics, 2021). The haptic devices were placed at hands, elbows, trunks, and knees. Vibration at a certain position was triggered when the corresponding body component of a subject was moving correctly. Figure 1 and 3(c) shows the device set-up for subjects.

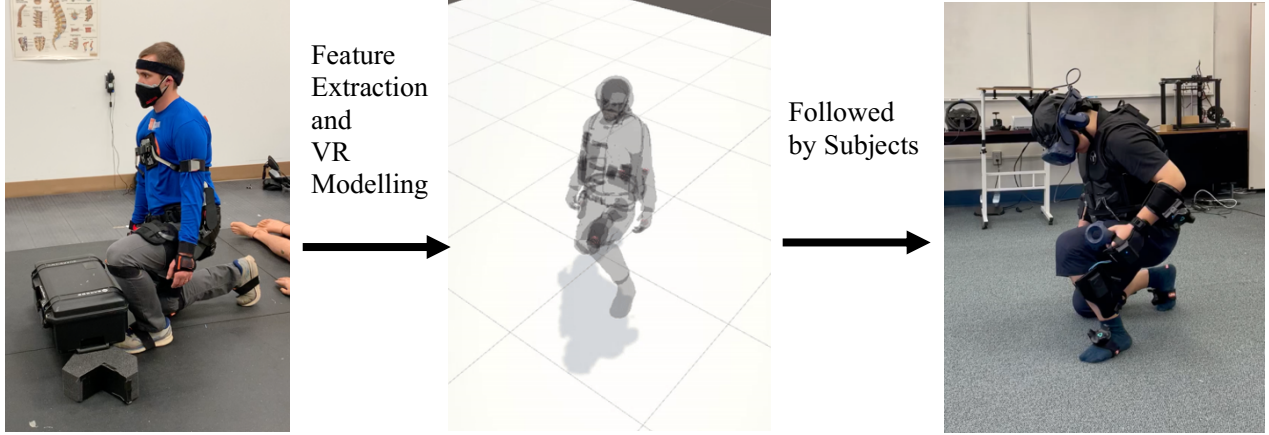


Figure 3: (a): DGL by experienced exoskeleton user with a back exoskeleton
(b): Re-constructed VR tutor according to the DGL motion by the experienced user
(c): Training scenario where a system user (subject) is following the DGL motion in VR

The subject's body positions were tracked and reconstructed as a virtual avatar in VR. The subjects were instructed to follow the sample motions in VR as accurately as possible under different visualization and haptic conditions for 6 trials. We prepared four conditions: 3rd person view without haptic (3V), 3rd person view with haptics (3VH), 1st person view without haptic (1V), and 1st person view with haptic (1VH). For conditions with 3rd person view, a sample motion was displayed in front of the subject to mock a traditional demonstration-follow method. In 1st person view conditions, subjects performed the motion by following a semi-transparent trainer avatar around their body. Vibration at key body components was triggered if the subject was moving correctly under haptic conditions. To minimize individual differences, we applied a within-subjects design. The orders of conditions and corresponding sample motion were shuffled across subjects. The experiment protocol is shown in Figure 4.

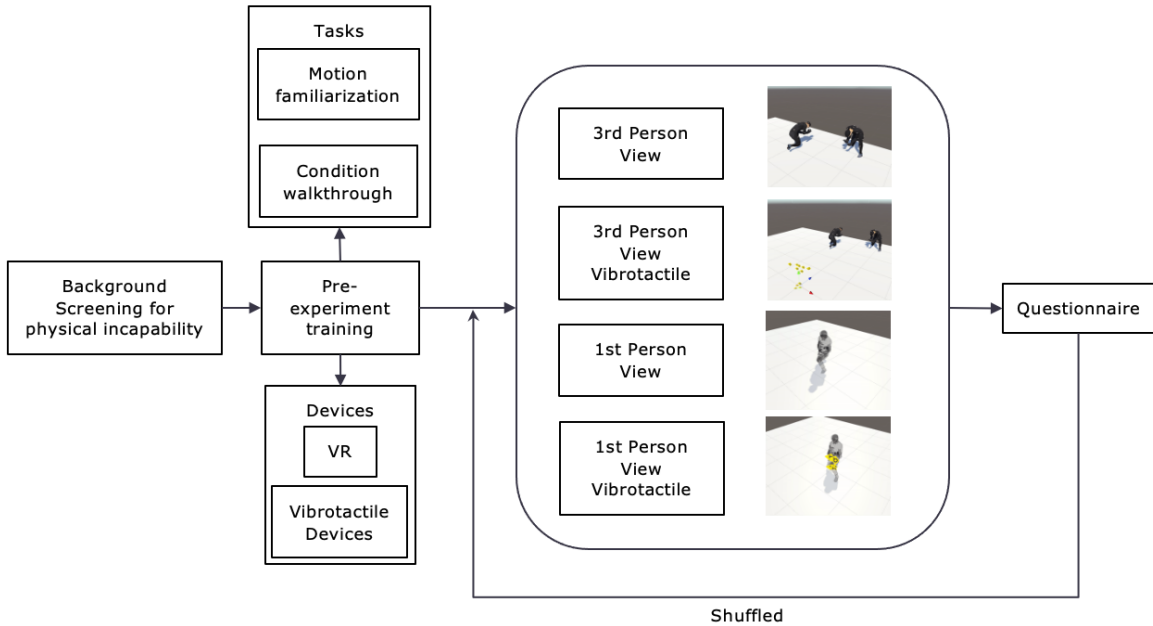


Figure 4: Experiment protocol

We quantified the subject's performance by comparing the cumulative spatial offset between sample motions and the subject's motions during the experiment. Figure 5 visualizes a trajectory comparison between the expert's sample motion (red line) and the subject's motion (green line). We sampled 7 body components for performance evaluation: left and right wrists, left and right elbows, left and right knees, and pelvis. The reconstructed expert's motion from Xsens was smoothed in VR and played back as a continuous motion. VR captured smoothed expert's sample motion and the spatial position of all tracked body components with a frequency of 90 frames per second. The motion lasted for 20-25 seconds.

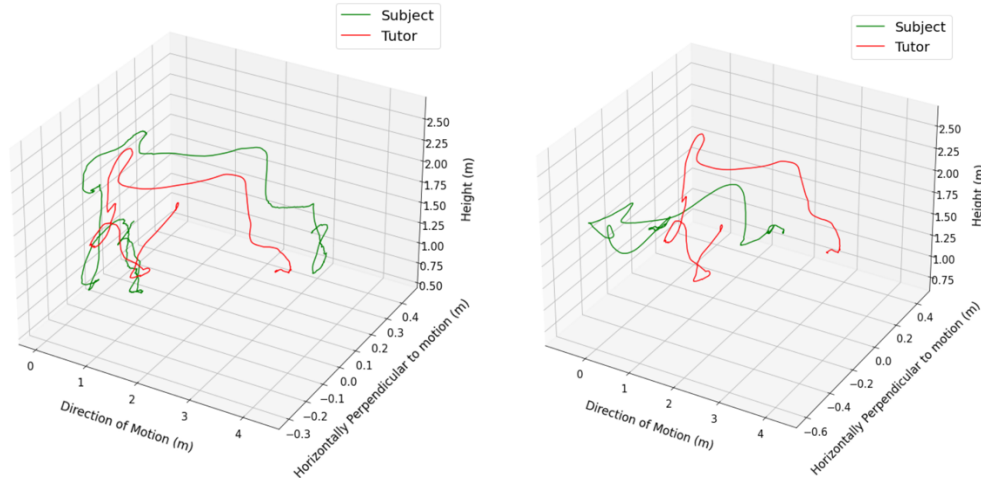


Figure 5: An example of trajectory comparison. Red lines represent the sample motion to follow; Green lines represent the subject's motion; From left to right, the figures represent the right wrist and hip from a randomly selected subject and trial

DATA ANALYSIS

Figure 6 shows the distribution of the motion discrepancy of the whole body (all 7 body components) from 15 participants. Each data point represented the average discrepancies in meters across 7 tracked positions (full body) for all frames in one trial. The average spatial discrepancies varied from 10-35 cm due to the complexity of whole body motion control. Visual interpretation indicated that minor polarization existed in each condition and the datasets were not normally distributed. Statistical normality test (D'Agostino's K-squared test) was performed and the statistical result echoed visual interpretation ($p = 0.1$). For a dataset that is not following Gaussian distribution, a non-parametric analysis (i.e., Mann-Whitney U (MWU) test) was performed to test the null hypothesis that each pair of data was sampled from the same distribution. Each subject's data were normalized by its within-subject standard deviation of motion discrepancies before the pairwise MWU test. Table 1 summarizes the MWU test result.

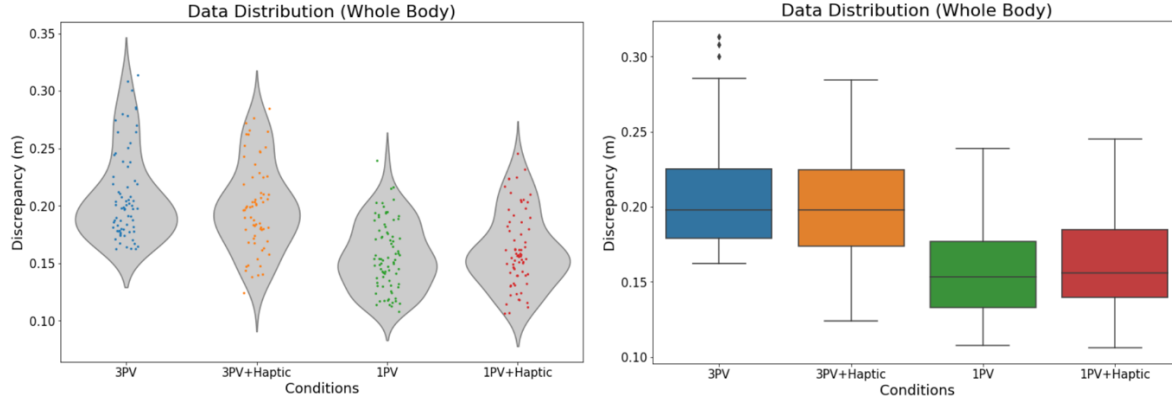


Figure 6: Whole-body performance data distribution

MWU result indicated that in terms of training performance, the 1st person view motor training was statistically different from the 3rd person view motor training ($p = 0.001$), showing lower average discrepancies for the 1st person view motor training than the 3rd person view motor training with the 95% confidence intervals. Although the motor training in all conditions was delivered in VR, the 3rd person view was simulating a real-life experience where the instructors were demonstrating the motions in front of the users. Such a result implies that the egocentric visualization in VR is beneficial for motor learning, which echoes some existing literature (Lindgren 2012; Schöler et al. 2015). But the addition of haptic cues did not show significant impact ($p = 0.137$ in 3rd Person View; $p = 0.177$ in 1st Person View).

Haptics as an augmented sensation may lead to cognitive overload in this relatively complex (full body) task (Hamilton et al. 2009). The dominant hand has more accurate motor positional control and sensation (Heuer 2007). Figure 7 shows the performance data on the dominant hand only. Similar procedures were applied to the dominant hand as in full body. The data was not normally distributed. MWU results are summarized in Table 1.

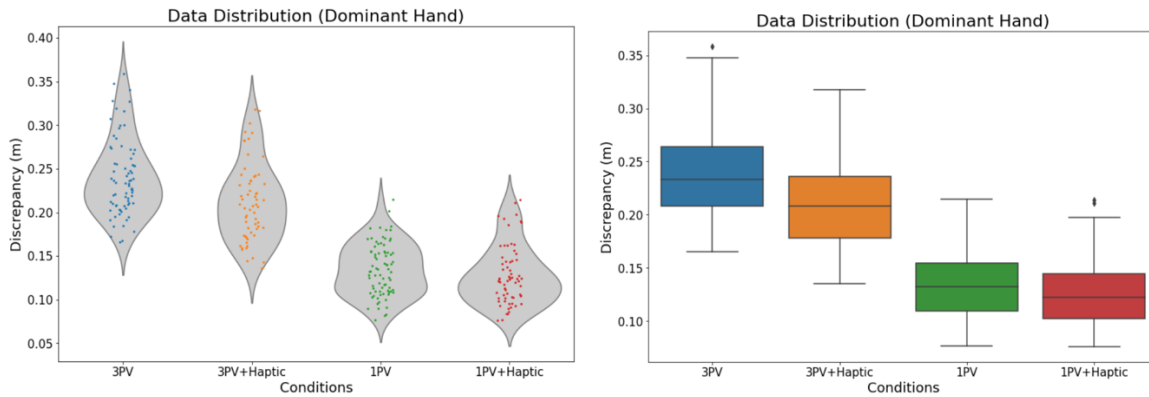


Figure 7: Dominant Hand performance data Distribution

For the dominant hand condition, the null hypothesis was rejected at 95% confidence intervals, in all the pairwise comparisons. The addition of haptic sensation in the dominant hand significantly impacted the motor performance in VR ($p = 0.001$ in 3rd Person View; $p = 0.044$ in 1st Person View). The mean discrepancies of 3PV with or without haptic were 0.240 m and 0.212 m respectively, while the mean discrepancies for 1PV with or without haptic were 0.134 m and

0.127 m. This implies that haptic sensation may positively impact the motor learning process for body components with higher motor control capability (i.e., dominant hand).

Table 1: Pairwise Mann–Whitney U test result

Condition -- Condition	Body Range	Statistics	P-value	Null-hypothesis rejected
3 -- 3H	Whole-body	2116	0.137	False
3 -- 1	Whole-body	781	0.001*	True
3 -- 1H	Whole-body	862	0.001*	True
3H -- 1	Whole-body	1015	0.001*	True
3H -- 1H	Whole-body	1075	0.001*	True
1 -- 1H	Whole-body	2553	0.177	False
3 -- 3H	Dominant Hand	1491	0.001*	True
3 -- 1	Dominant Hand	71	0.001*	True
3 -- 1H	Dominant Hand	94	0.001*	True
3H -- 1	Dominant Hand	313	0.001*	True
3H -- 1H	Dominant Hand	276	0.001*	True
1 -- 1H	Dominant Hand	2246	0.044*	True

Remarks: 3 refers to 3rd Person View; 3H refers to 3rd Person View with Haptic
1 refers to 1st Person View; 1H refers to 1st Person View with Haptic
Asterisk (*) remarks statistical significance

CONCLUSIONS

In this study, we designed a haptic sensation transfer method for migrating the subjective feeling of an exoskeleton expert using the exoskeleton to any new user who has no access to the exoskeleton system. A whole-body haptic system was used to generate haptic feedback of different patterns depending on how the trainees follow the motion trajectories of the expert user, captured and recorded by motion tracking techniques. To test the effectiveness of the proposed method, we conducted a human-subject experiment (n=15). The subjects were asked to follow the motion of an expert exoskeleton user with the 3rd person view or 1st person view, with or without haptic cues. The performance was evaluated by the summed average of spatial discrepancies between the subjects' motions and the expert's sample motion. The experiment result indicated that 1st person view motor training that visualized motion information from an egocentric perspective was significantly better than 3rd person view. By looking at the body component with higher motor control capability (the dominant hand), hapto-tactile feedback significantly improved the performance of the desired exoskeleton motions with both the 3rd person view and 1st person view. This finding suggested that haptics in VR may be an important sensation for further consideration. For future research, it is worth exploring whether a less frequent and less cognitively demanding haptic sensation protocol can improve transforming the motor experience further.

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