First Steps Towards Accelerating the Learning of Using Exoskeletons with Immersive Virtual Reality

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***Abstract*—Learning to use a lower-limb wearable exoskeleton for people with spinal cord injury is time-consuming and requires effort from the user and extensive therapists' time. In this study, we aim at exploiting visual feedback through immersive virtual reality using a head-mounted display to accelerate motor learning for the purpose of using a wearable exoskeleton with minimal supervision.**

Keywords—SCI, exoskeleton, motor learning, VR, feedback

I. Introduction

Wearable exoskeletons have developed quickly in recent years to assist people with spinal cord injury (SCI) to recover independent stand and walk. To control a robotic exoskeleton, the user needs to learn how to trigger steps, e.g., by shifting the weight between legs [1], [2]. This learning process is generally lengthy, as people with SCI not only lose the control over their muscles, but also might suffer from somatosensory loss [3].

Motor learning literature suggests that augmented feedback is beneficial in the early stages of motor learning [4]. However, only a few studies have investigated the effectiveness of augmented feedback in learning to control exoskeletons, mainly focusing on vibrotactile and electrostimulation feedback [5], [6]. Yet, this type of feedback requires an intact somatosensory system to be perceived. In recent years, virtual reality (VR) has been demonstrated to be a powerful tool to provide concurrent visual feedback to enhance learning [4]. Further, current off-the-shelf head-mounted displays (HMD) that incorporate stereoscopic displays and head/body-tracking capabilities allow a highly realistic movement visualization using avatars, which enhances motor performance [7] and might accelerate learning.

Here we present our advances on developing an immersive VR to investigate whether visual feedback through immersive VR could reduce the time needed to learn to use an exoskeleton.

II. Methods

A. Measurement set-up

The set-up consists of a commercial HMD (HTC Vive, HTC, Taiwan & Valve, USA), and two HTC Vive trackers (Fig. 1 A). One tracker is attached to the participant's pelvis (at iliac crest level) and a second one on a 4-wheeled walker to record their movements. An IMU (Delsys Inc., Boston, MA) is attached to the tracker on the pelvis to measure its acceleration. The walker, which the user must hold at all times, only allows movements in the sagittal plane. As we aim to run a first experiment with healthy participants who do not suffer from proprioception loss, we included a balance board to induce that participants rely on the walker to maintain balance, thus, increasing trunk inclination and arms fatigue, as it happens in people with SCI in real settings.

B. Virtual walking task

In the virtual environment (VE), an avatar with a walker mimics the movements of the participant recorded through the HMD and trackers using the Final IK library for Unity (Fig.1 B). The avatar is scaled to match the participant's proportions.

The virtual walking task consists in triggering virtual steps performed by the avatar. This is accomplished by executing three consecutive movements: (1) participants move the walker forward, (2) they align (weight shift) the pelvis and the leading foot position (observed in the VE), and (3) trigger the step by accelerating the hip forward (hip thrust). The avatar leg then moves forward (while the real leg remains on place) simulating that a wearable exoskeleton is responsible for the movement. The pelvis acceleration, measured with the IMU, determines the step length following a linear relationship.

These three movements resemble those that people with SCI usually need to follow to safely trigger wearable exoskeletons, e.g., weight shifting is commonly used as control input to trigger steps [1], [2]. After each step, participants must move the walker back to start another step with the other leg. Note that the movement of the legs occurs only in the VE, therefore

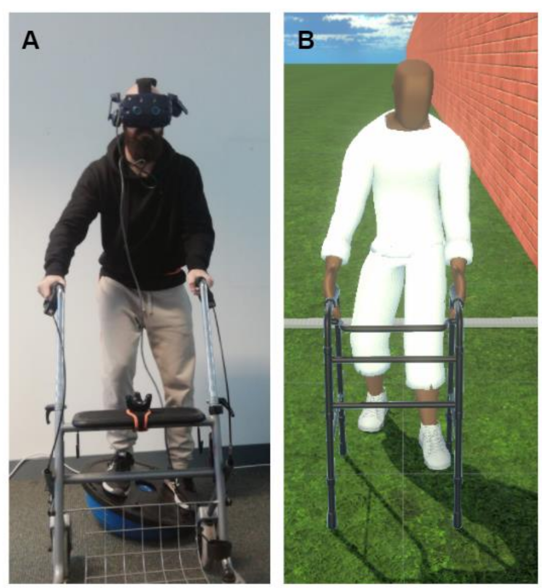

Fig. 1. (**A**) Set-up in the real environment. (**B**) Avatar in the virtual environment.

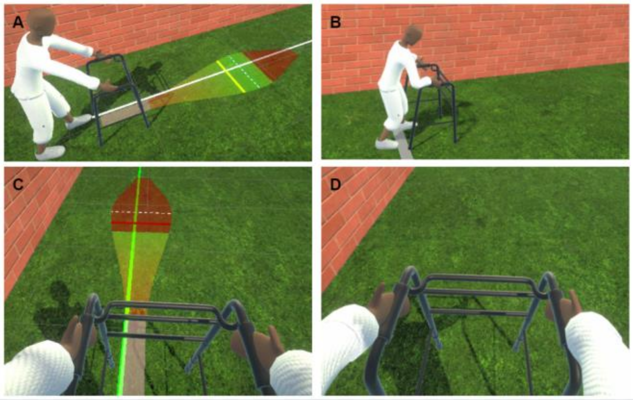

Fig. 2. The four conditions of the experiment. (**A**) Third-person perspective (3PP) with visual cues. (**B**) 3PP without visual cues. (**C**) First-person perspective (1PP) with visual cues. (**D**) 1PP without visual cues.

participants have to check their legs position - if needed - by looking at the avatar in the VE; as people with SCI would do.

C. Augmented visual feedback

We aim to design easy-to-understand highly informative augmented visual feedback. This was obtained by continuously "projecting" a fusiform object on the virtual floor in front of the avatar (Fig. 2 A&C). The lateral position of this object shows the position of the pelvis. When the object touches the longitudinal line displayed in front of the leading foot, the line turns green (Fig. 2 C), i.e., movement 2 (weight shift) is accomplished and the step trigger is allowed. The length of the object informs about the trunk inclination: when there is no inclination the length of the bar is maximum and vice versa. This information aims to reduce truck inclination, as this results in people with SCI to rely on the walker, and thus, increase fatigue.

The position of the walker relative to the back leg (i.e., the space to do the incoming step without collision with the walker) is also displayed in the fusiform object. This feedback split the object into a lighter and a darker area and provides information about the maximum step length that participants can reach without colliding with the walker (Fig. 2 A&C).

The fusiform object, initially translucent, turns opaque based on the acceleration peak reached during the hip thrust (i.e., movement 3). The opaque object shows different colors where green is on the wider part of the object, also shown by a white dashed line (Fig. 2 A&C). That zone shows the "optimal" step length of the participant based on their height [8]. The "optimal" zone guides participants to reach the most effort-length-ratio efficient hip thrust movement (i.e., not too fast, not too slow). By providing all the visual information through the same object, and thus, driving the user attention to only one region of the VE, we aim at reducing the cognitive load during training.

D. Experiment Protocol

To evaluate the effectiveness of our system to enhance motor learning of the virtual walking task, we designed an experiment protocol to answer the following questions: (1) Does the augmented visual feedback (Fig. 2 A&C) enhance learning vs. training without visual feedback (Fig. 2 B&D); (2) Does visualizing the VE from a first person perspective (1 PP, Fig. 2 C&D) enhance learning vs. visualizing the avatar from the 3 PP (Fig. 2 A&B)?; and (3) Is there an interaction effect between the visual feedback and the 1 PP vs 3 PP?

Forty healthy participants will be randomly assigned to one of four training modalities, each modality corresponding to combinations of two factors: augmented visual feedback (ON or OFF) and visualization perspective (1 PP or 3 PP). During baseline and final tests, all participants are requested to virtually "walk" the maximum distance possible for 2 minutes (2MWT) in 1PP and without augmented visual feedback while maximizing their score. The score depends on the distance walked, step length, and trunk inclination to encourage a proper walking performance. During training, participants will perform the walking task with the training modality they are assigned to.

The main outcome measures include the score, distance covered, trunk inclination, and step length. After baseline, training, and final test, participants are asked to answer questionnaires to evaluate the system usability, perceived workload, motivation, embodiment, and cybersickness. We hypothesize that groups that train with augmented visual feedback will outperform groups without visual feedback. We also expect better performance in the 1 PP than in the 3 PP, due to higher sense of embodiment in the 1PP condition [9].

III. Conclusion and Outlook

We designed a VE that aims to serve as a platform to learn to control lower-limb exoskeletons with minimal supervision based only on low-cost commercial technology. We augmented the VE with visual feedback to potentially further accelerate learning. Data collection is currently ongoing and study completion is expected by April 2022. We aim at presenting a preliminary analysis of the results at the RehabWeek 2022. Future work will study how this VE transfers to patients in the clinical setting.

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