Auditory movement feedforward for a lower-limb exoskeleton device (AIDER) to increase transparency

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Abstract: A lower-limb exoskeleton (LLE) is a device intended to assist patients with spinal cord injury (SCI) with standing and walking in daily life. Due to the lack of proprioception in lower limbs, SCI patients wearing an LLE need the gait information feedforward from the human-exoskeleton system for walking safety. It is necessary, therefore, to explore how to improve the transparency of LLE systems to help the wearer get gait information from LLE. This study conducted several auditory prompt experiments to determine the most adaptive movement feedforward method to improve transparency for an exoskeleton called AIDER. The results indicated that auditory movement feedforward could remind wearers of the next motion state. Moreover, the subjects felt more secure with auditory movement feedforward than with no feedforward when wearing AIDER.

Keywords: lower-limb exoskeleton; spinal cord injury; transparency; movement feedforward; auditory prompt; AIDER.

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1 Introduction

In recent years, the number of spinal cord injury (SCI) patients has increased because of traffic accidents and disease (WHO, 2013; Cao et al., 2014). Lower-limb exoskeleton (LLE) systems significantly improve the walking ability (Farris et al., 2013) and quality of life (Xu et al., 2017) of patients with SCI. These wearable robots make use of developments in fields such as wearable sensing, control engineering, electronics, biomedicine, and mechanics (Kazerooni and Steger, 2005). As gait-training and walking-assistance devices, LLE systems play an important role in patients' daily lives and have become widely used (Raab et al., 2015). Several exoskeleton systems are already on the market for walking assistance among SCI patients and motor rehabilitation among stroke patients. ReWalk, for example, was designed for SCI patients to use throughout the day at home and in the community (TheStreet, 2020). It can be controlled through buttons on the crutches. EksoNR, meanwhile, was designed for patients with acquired brain injuries (Kubota et al., 2013). The therapist can control its motion state and parameters through a human-computer interface on the back. Indego is a modularised exoskeleton that can recognise motor intention according to the body posture of the wearer (Tefertiller et al., 2018). REX is a hands-free (no crutches), a self-supporting exoskeleton that enables a person with mobility impairment to stand up and walk (Smith and Terry, 2016). Its human-exoskeleton interaction is also based on physical methods; specifically, the wearer controls it by pressing buttons on the armrests. The Hybrid Assistive Limb exoskeleton enables the monitoring of muscle contractility through surface electromyography in the lower limbs (Contreras-Vidal and Grossman, 2013). The present LLE systems were controlled based on master-slave strategy (Lee et al., 2012; Huang et al., 2014), in which the wearer makes commands of walking patterns and the exoskeleton executes them (e.g., standing, sitting, and walking). The interaction between current LLE systems and the wearers is not yet natural and effortless.

It is known that humans' walking can adjust step amplitude and stance duration because walking is a voluntary rule-based movement (Kuo, 2002), which can be skill- and rule-based behaviour according to Rasmussen's human performance model (Rasmussen, 1983). An LLE fills the role of a paraplegia's legs to complete the skill- and rule-based behaviour such as adjusting gait according to terrain changes. Hence, an LLE and its wearer should coordinate with each other to complete walking in daily life. The wearer proceeds with knowledge-based behaviours (decision-making). Therefore, LLE and its wearer can be considered as a team to finish tasks (e.g., walking, standing, sitting). Shared expectations and mutual understanding are critical for teamwork (Hayes and Shah, 2017) and help enhance human-robot collaboration (Chadalavada et al., 2015). This has gradually drawn increasing attention (Gong and Zhang, 2018).

Article 4 of the EPSRC Principles of Robotics asserts that robots should be transparent (Boden et al., 2011). The principle of robots is that they enable the human to understand problems encountered by the robot and help to compensate for limitations of autonomy (Fong et al., 2003). Robot-human interaction needs to provide users information before, during, or after interactions (Lyons, 2013). Therefore, the transparency of robot systems should be enhanced to improve human-robot collaboration. Wortham et al. (2017) indicated that naive users of robots have difficulty in comprehending a robot's behaviour merely through observation. They have found significant improvement when using vocalisation transparency approaches. Nakata et al. (1998) conducted two experiments that produce familiarity with tactile reaction and express the robot's emotion by dances. The results prove that interpreting a robot's intention can improve human-robot collaboration efficiency. Moore et al. (2019) observed that auditory stimuli (e.g., motor sounds) can help the user recognise the characteristics of the robot's motion state.

A normal person can perform movements naturally and effortlessly because humans' movement relies on the combination of feedforward and feedback control (Franklin and Wolpert, 2011). Perceiving gait-phase information is critical when walking (Strange and Hoffer, 1999). However, patients with SCI have no proprioception in lower limbs, leading to the lack of feedforward and feedback control information. Therefore, gait information interpretation of an LLE is crucial when changing the motion state. However, an existing issue is that LLE's wearers cannot perceive how and when the exoskeleton will execute the next motion. As a result, they always confirm gait information through vision when walking with an exoskeleton, which is cumbersome when walking outdoors (Qiu et al., 2020). For a human-exoskeleton cooperation system, feedforward of motion intention is helpful to improve the exoskeleton's transparency and the wearer's motor response and is also beneficial to accomplish desired motions (Wächter et al., 2020). Motion interpretation can provide the wearer next gait information about the exoskeleton and remind the wearer of weight shifting, thus enhancing the transparency of the exoskeleton and avoiding the dangers caused by the sudden change of gait pattern. Nevertheless, little research concentrates on the transparency of LLE systems. Current LLE systems on the market do not provide an interpretation method for an exoskeleton's intention to wearers.

This study, therefore, proposed an auditory motion feedforward novel method for information prompt in an LLE system to enhance the transparency of the exoskeleton to the wearer. An efficient movement prompt can guarantee the accuracy and effectiveness of information interaction between a subject and the exoskeleton. However, few exoskeleton systems provide effective feedforward mechanisms for wearers. Patients with SCI cannot continually obtain the lower extremity movement status of the exoskeleton through vision when walking in complex environments. In this regard, an auditory feedforward system may enhance the transparency of an exoskeleton, thus improving information reception and collaboration efficiency. To identify an efficient auditory feedforward method and implement it in the exoskeleton, we conducted a preliminary study comparing two aural-prompt modes. As a result of comparing two modes, the better mode was selected as the auditory feedforward method and was set to provide next motor state information to the wearer. Moreover, the auditory movement prompt mode was compared with a no-prompt mode to investigate the efficiency of the auditory feedforward method.

2 Methods

2.1 Experimental design

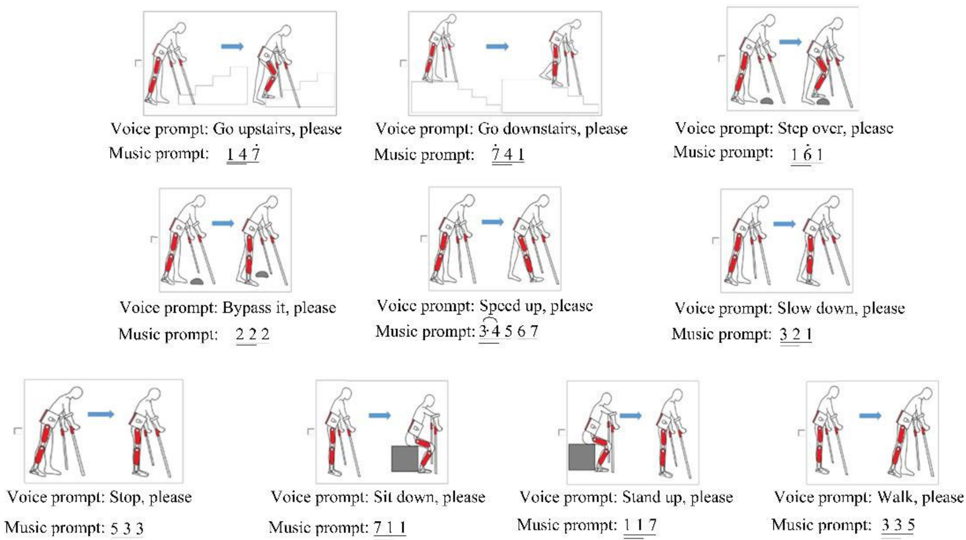
This study included three experimental sessions. Figure 1 shows the experimental design. Sessions 1 and 2 tested voice- and music-prompt auditory modes, respectively. The prompts and corresponding actions are shown in Figure 1. Numbers 1–7 correspond to 'do re mi fa so la ti'. We experimented with the study to identify the most adaptive music prompt for each scene; the prompts shown in Figure 1 were the most acceptable to the subjects. Sessions 1 and 2 were set as the ideal hypothesis, aiming to test accuracy and reaction time under the two auditory movement feedforward modes. Session 3 was conducted using the actual system, in which subjects wore an exoskeleton called AIDER (assistive device for paralysed patients) to complete tasks under the auditory movement feedforward mode and non-movement feedforward mode.

2.2 Subjects

Ten healthy subjects (seven males and three females aged 22.9 ± 2.0 years, height 168.8 ± 8.5 cm, weight 59.7 ± 9.5 kg) were recruited from the University of Electronic

Science and Technology of China. All the subjects reported that they did not suffer from any physiological or psychological disease. All provided signed informed consent before the experiments. This study was approved by the Civilian Ethics Committee of the School of Life and Science and Technology, University of Electronic Science and Technology of China.

Figure 1 Voice and music prompt for each action (see online version for colours)



2.3 Equipment and materials

Research has shown that humans can perceive information with an accuracy of up to 99% at a rate of 4.3 Chinese characters per second and with a maximum preference level (Chan and Lee, 2005). Therefore, the speaking speed of the commands in the voice movement feedforward mode was set at three or two characters in Chinese per second. A female voice package from Iflytec Co. Ltd. was used to perform the voice prompts. Music prompts with up to four syllables were set at one second while those with more than four syllables were set to 1.5 seconds. In sessions 1 and 2, subjects played and listened to prompts from self- developed Python-based software on a computer (Dell G3 3590, 15.6 in. screen) and headset (Beats EP). The prompts were played randomly. A questionnaire concerning auditory movement feedforward was created to record subjective feelings about voice- and music-prompt modes. Response items included ‘can judge directly’, ‘do not need to remember deliberately’, ‘widespread application’ and ‘have good effects’. Response items on the questionnaire for auditory and non-movement feedforward modes were ‘can perceive the next movement’, ‘didn’t interfere with normal walking’, ‘can respond promptly the first prompt time’, ‘can respond promptly in the second prompt time’, ‘feel more secure than no movement feedforward’ and ‘auditory movement feedforward is necessary’. Subjects scored each item on a five-point Likert scale (Albaum, 1997), ranging from 1 = ‘completely different’ to 5 = ‘almost the same’. Figure 3 shows the user interface. After subjects selected their answers, the software recorded them in the database (XLS format).

Figure 2 AIDER exoskeleton system (see online version for colours)

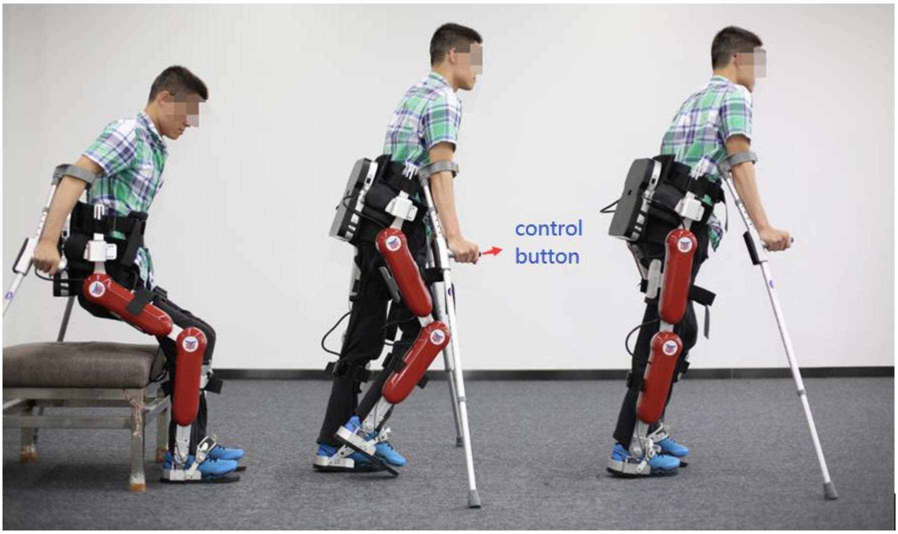
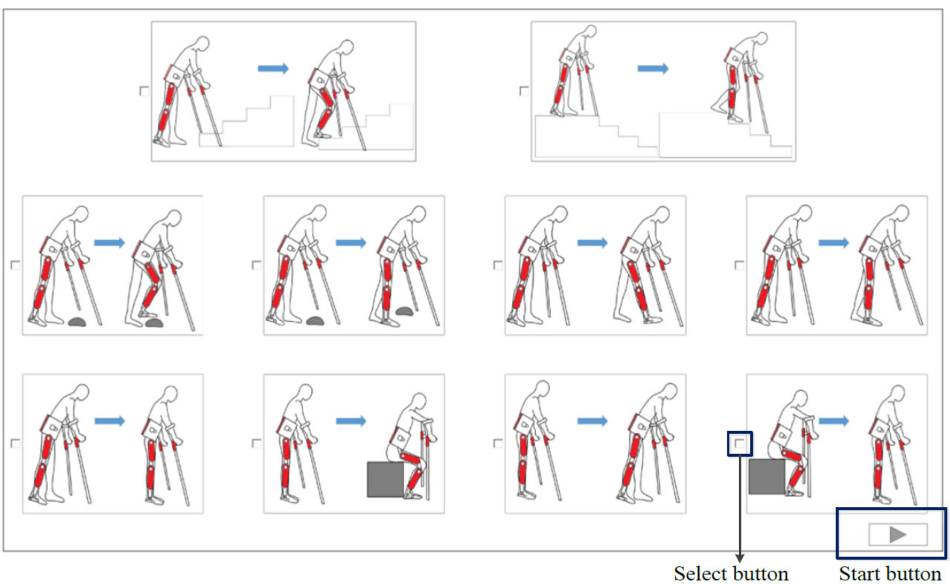


Figure 3 The user interface of the self-developed software (see online version for colours)

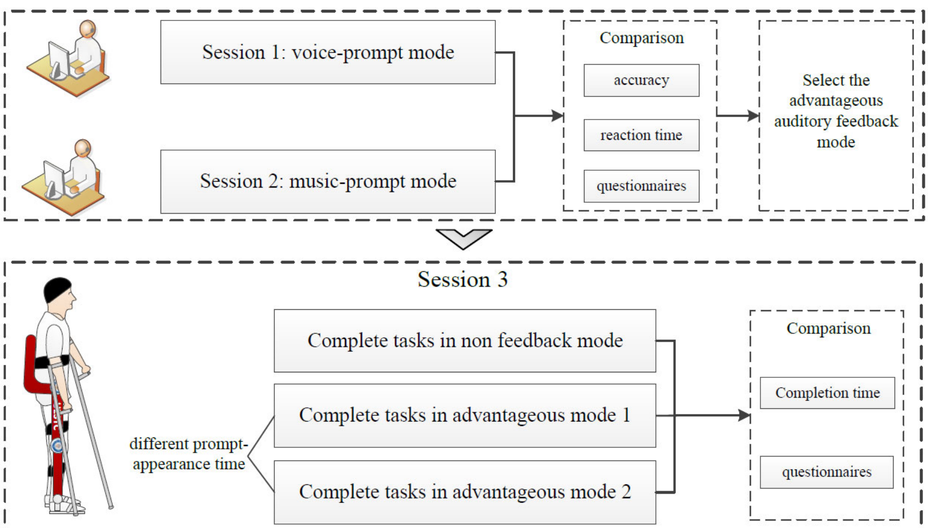


The AIDER system (Figure 2) is a wearable exoskeleton for walking assistance developed in 2015 by the Center for Robotics, University of Electronic Science and Technology of China. The wearer uses buttons on the crutches and body posture to control the exoskeleton. The right button can control walk/stop, and the left controls walking speed. If the wearer pushes the two buttons for more than two seconds, the exoskeleton will sit down or stand up. The wearer needs to push the right button after one step. If the wearer wants to change the walking speed, he or she can click the left button once to slow down or twice to speed up. An inertial measurement unit is used for sensing the wearer's posture. If the wearer stands before a stair and leans forward with the upper part of the body, the exoskeleton will go upstairs. When there are obstacles, leaning forward will indicate stepping over them, and leaning to the right (left) will indicate bypassing them from the right (left). Subjects wore AIDER to complete the tasks in session 3.

2.4 Procedure

Figure 4 depicts the three sessions conducted in this study. Before sessions 1 and 2, the subjects received training on the self-developed software. Based on comparisons of accuracy, reaction time, and the questionnaires, an advantageous auditory mode was selected. In session 3, the selected mode was tested under different prompt-appearance times and compared with the non-movement feedforward mode. Subjects were required to complete the walking tasks wearing AIDER, and their completion times were recorded. After the three sessions, the subjects filled out questionnaires.

Figure 4 Experimental procedures (see online version for colours)



In session 1, the subject randomly received any one of ten voice prompts, determined the corresponding scene or state, and selected and confirmed the corresponding picture on the user interface. A single experiment consisted of 40 trials. Information was recorded in each trial (e.g., subject selections and reaction times) for approximately 10 minutes. Subjects completed the trials within five days. After completing session 1, the subject can undertake session 2. In session 2, the subjects received random musical prompts. Then, they selected the corresponding picture on the experimental interface. A single experiment consisted of 40 trials, each of which recorded information such as subject selections and reaction times for approximately minutes. Subjects completed three repetitions of one session within five days and completed questionnaires after completing the tasks. After session 2, the subjects scored the voice- and music-prompt auditory movement feedforward modes on the five-point Likert scales. In session 3, the advantageous auditory movement feedforward mode and non-movement feedforward mode were compared. Subjects were required to wear the AIDER system to complete tasks in the auditory movement feedforward mode and non-movement feedforward mode. As mentioned above, we tested two different prompt-appearance times for auditory movement feedforward. In the first mode, the prompts appeared at the swing phase of the previous step [Figure 5(a)]. In the second mode, the prompts appeared at the stance phase of the previous step [Figure 5(b)]. Figure 6 demonstrates the tasks and the non-movement feedforward without the prompts. Subjects were required to complete the tasks wearing the AIDER, and task completion time was recorded. Subjects scored auditory movement feedforward and non-movement feedforward using five-point Likert scales.

Figure 5 Gait phases of AIDER system, (a) the swing phase (b) the stance phase (see online version for colours)

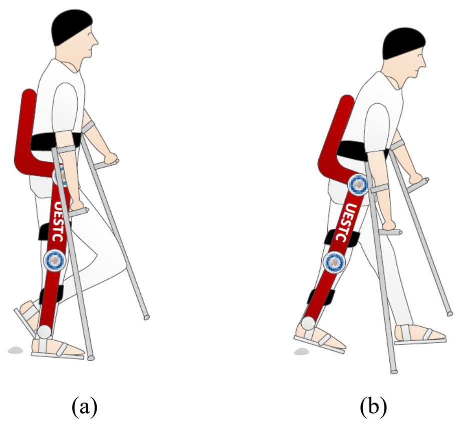
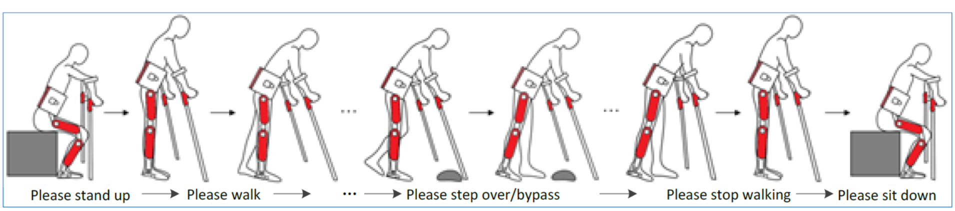


Figure 6 Process for session 3 (see online version for colours)



2.5 Data collection and analysis

Before the experiment, the basic response time of each subject was collected as the baseline for the subsequent experimental data. The experiment was videotaped to record its duration and subjects' responses upon receiving movement feedforward. After the experiment was completed, subjective perceptions of the voice and musical movement feedforward modes were collected using the self-developed questionnaire. Information on subjects' selections and reaction times was recorded during the experiment. The parameters included the accuracy and reaction time after receiving the prompts, as well as the scores from the questionnaires. IBM SPSS Statistics 22 was used for statistical analysis. Completion times were recorded for the three methods. A paired *t*-test was used to analyse statistical differences in accuracy, reaction time, and task completion time. A non-parametric Wilcoxon test was used to analyse statistical differences in subjective feelings. The significance level was set to 5%.

3 Results

3.1 Comparison of two auditory movement feedforward modes

In the comparison of voice and musical prompts as auditory movement feedforward modes, subjects selected the corresponding motion states according to the prompts they received. The accuracy rate of those options was recorded, as shown in Figures 7 and 8. The accuracy rate for voice movement feedforward was 100%, indicating that all the subjects could receive information about the next motion solely by voice (Figure 7). The average accuracy rate under the music-prompt mode was 97.4%, with a median of 97.5%, indicating that most subjects were able to confirm the next movement of the exoskeleton through a musical prompt. The results showed significant differences between the two movement feedforward modes (p = 0.012). Figure 8 shows the accuracy of the eight motion states under the music-prompt mode. The accuracy of the second stair scene, third cross-barrier scene, and fifth acceleration scene was 100%, indicating that subjects had a clear perception of the corresponding musical prompts for these scenes. However, the accuracy of other scenes did not reach 100%. The results indicated that the voice-prompt auditory movement feedforward mode was more accurate than the music-prompt auditory movement feedforward mode.

Figure 7 Accuracy of two auditory movement feedforward modes (see online version for colours)

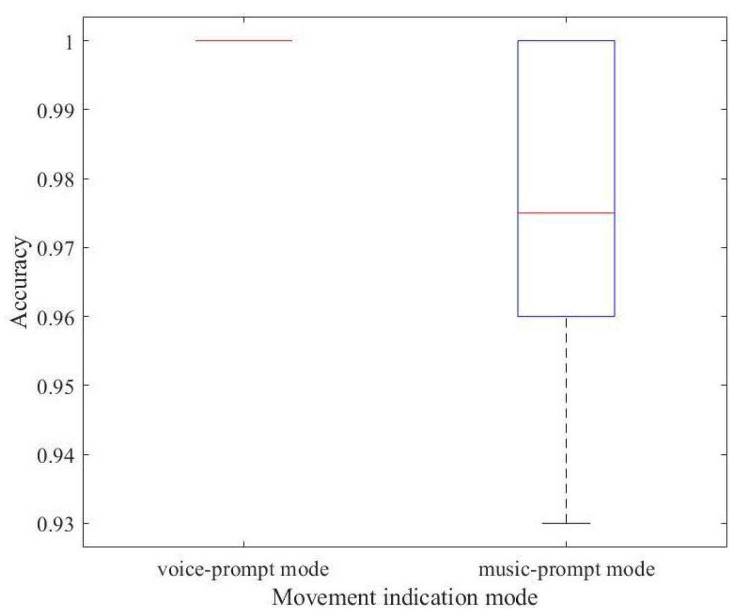


Figure 8 Accuracy of each scene in the music-prompt mode (see online version for colours)

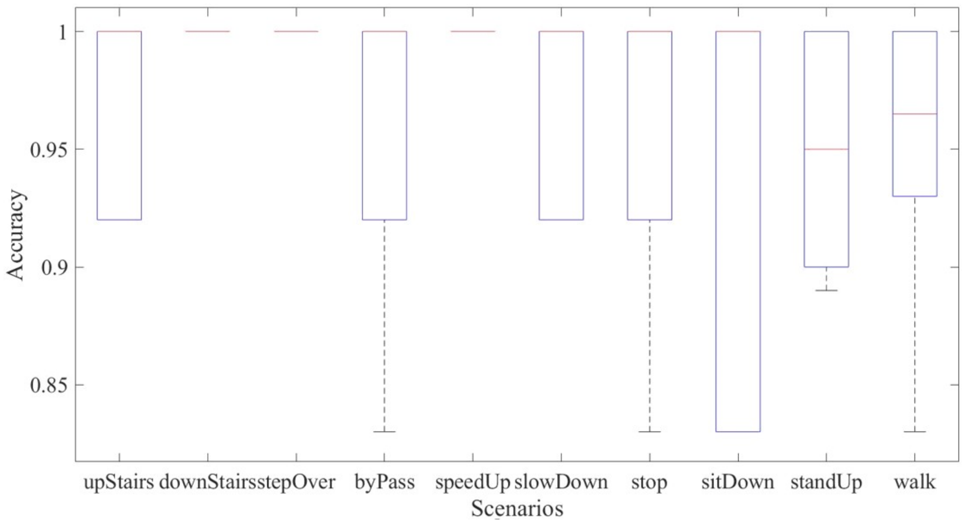


Figure 9 Reaction times under the two auditory movement feedforward modes (see online version for colours)

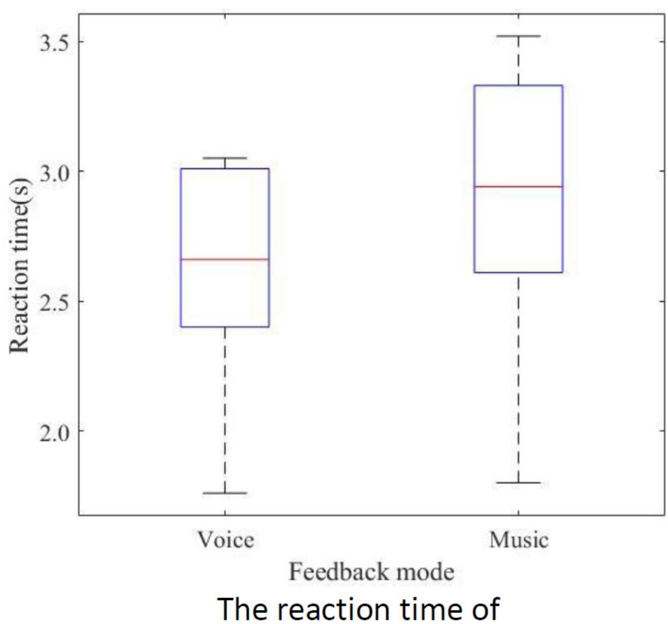


Figure 9 shows that the reaction time to voice prompts was lower than to music. Significant differences were found between the two methods ($p = 0.000 < 0.05$). Subjects completed questionnaires for the two auditory movement feedforward modes. Figure 10 shows the subjects' questionnaire scores for the auditory movement feedforward modes on five-point Likert scales. The results revealed a significant difference between the voice- and music-prompt auditory movement feedforward modes ($z = -4.672$, $p = 0.000$

< 0.05). Subjects evaluated voice movement feedforward as much better than music movement feedforward.

Figure 10 User-experience questionnaire scores for the two auditory movement feedforward modes (see online version for colours)

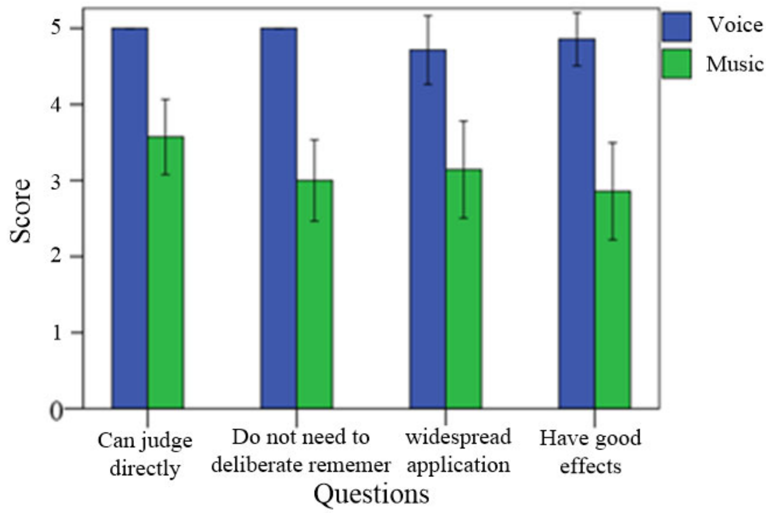
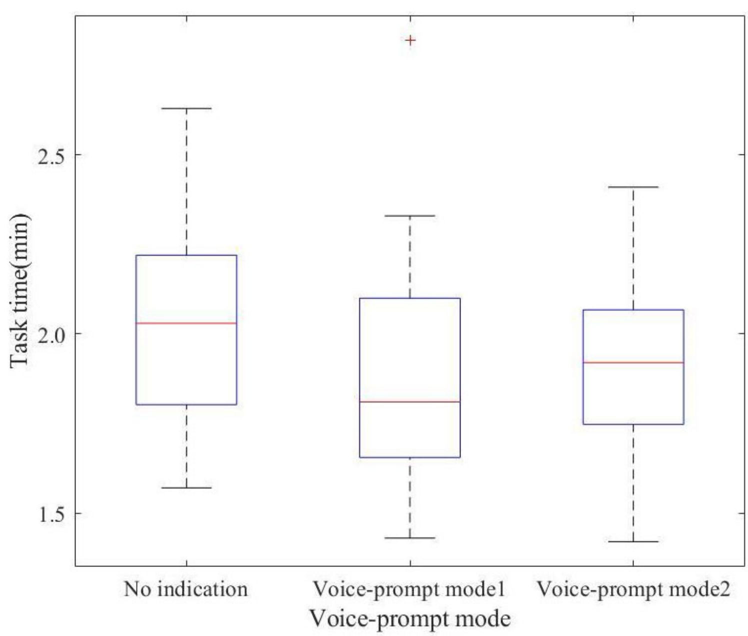


Figure 11 Effects of no movement feedforward and two kinds of voice-prompt movement feedforwards at different times in a walking task (see online version for colours)

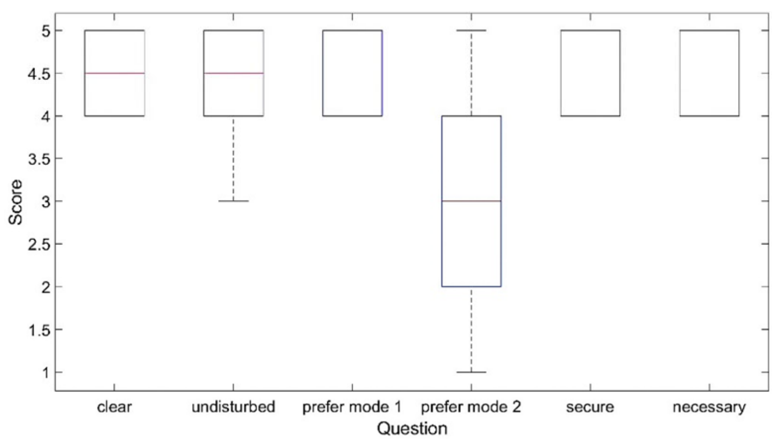


3.2 Comparison of auditory movement feedforward system and no movement feedforward system

Figure 11 shows the results for the recorded completion times. Completion time for the walking task with voice-prompt movement feedforward was less than that with no movement feedforward. A significant difference was observed between the no movement feedforward mode and the two voice-prompt modes (no movement feedforward mode and first voice-prompt mode: t = 3.307, p = 0.0.004; no movement feedforward and second voice-prompt mode: t = 2.56, p = 0.0.019). However, there was no significant difference between the two voice-prompt modes (t = –0.392, p = 0.699).

The questionnaire results (Figure 12) showed that most subjects could clearly perceive the next gait information of the exoskeleton through voice movement feedforward, and they believed that voice movement feedforward made it safer to wear the exoskeleton. In the first voice movement feedforward mode, subjects indicated that movement feedforward could prompt their next step promptly. In the second voice movement feedforward mode, however, most subjects were incapable of a timely response. Significant differences were observed in subjective feelings toward the two voice-prompt modes (z = –2.060, p = 0.039).

Figure 12 Questionnaire results for voice movement feedforward (see online version for colours)



4 Discussion

This study undertook exoskeleton auditory movement feedforward experiments based on voice and music prompts. There were significant differences between the two methods. Short, specific action phrases were used in the voice-prompt mode and different musical tones in the music-prompt mode. Another auditory-prompt mode that was not proposed in this study is numerical. We hypothesised that numerical prompts would have a similar ‘decoding’ process with musical prompts. The subject would first ‘decode’ the prompts to corresponding movements and then match the corresponding gait phase. Hence, voice prompts are more intuitive than musical or numerical prompts. Furthermore, sufficient training should be conducted before using an exoskeleton with a number- or music-prompt mode, which is not suitable for native users.

Several studies had concentrated on information feedback of exoskeletons instead of feedforward. Meanwhile, these studies were most suitable for patients with stroke. In addition, comparisons of auditory, tactile, and visual feedback were conducted in previous studies. Thielman (2010) compared tactile and auditory feedback in the rehabilitation of trunk control in individuals with stroke. The results indicated that auditory feedback is a feasible alternative for use in trunk stabilisation. Zanotto et al. (2012), meanwhile, devised the ALEX II exoskeleton. Subjects assigned a combination of kinetic guidance and rhythmic cue modality showed improved gait symmetry after training while those assigned kinetic and visual guidance modality did not. Zahariev and Mackenzie (2008) proposed that providing auditory information while grasping virtual objects can improve movement speed, and auditory information can improve spatial accuracy when tactile information is unavailable. In conclusion, auditory information is more appropriate in feeding a robot's motion state back to human users than tactile or visual information. Combined with our current research on movement information feedforward from an LLE system, the auditory- prompt method is more suitable for our study.

This study has some limitations. One is that the subjects in this study were all healthy. The AIDER system was designed for paraplegics with an injury plane between T5–T12. One of the exclusion criteria is cognitive impairment. Further, reaction time, accuracy, and subjective feelings might not have much difference between healthy subjects and eligible patients with SCI (Chiaravalloti et al., 2020). The purpose of this study was to identify the best method for a real auditory movement feedforward system. Hence, the differences between the methods have more importance than their numerical values. In addition, the age of the subjects was 22.9 ± 2.0. Their reaction times and subjective perceptions showed few differences. However, various age groups may have discrepant reaction times and subjective perceptions. Meanwhile, this study was conducted in lab environments with flat ground and little noise. Not all the topographic changes were verified in this study. Future research should consider paraplegic subjects with different age groups and conduct experiments outdoors.

5 Conclusions

This paper presented a pilot study of the movement feedforward method to enhance the transparency of exoskeleton AIDER. As a result of comparing accuracy, reaction time, task completion time, and questionnaires, the voice-prompt mode has advantages than music- prompt mode. Thus, voice prompts should be used as the movement feedforward for the next gait information of an exoskeleton. To apply movement feedforward using an actual LLE, we carried out a dynamic verification experiment using an exoskeleton system based on voice prompts. Movement feedforward enables users to clearly perceive the next gait information of the exoskeleton and makes the exoskeleton more secure. When voice prompts during the last swing phase, the user is better able to perceive the movement feedforward promptly compared to the last stance phase. Therefore, in an actual system, the next gait information of the exoskeleton can be fed forward by voice at the previous swing phase.

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