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Vibrotactile Feedback to Control the Amount of Weight Shift during Walking – a First Step towards Better Control of an Exoskeleton for Spinal Cord Injury Subjects*

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Abstract— **People with Spinal Cord Injury do not only lack the ability to control their muscles, but also miss the sensory information from below the level of their lesion. Therefore, it may become difficult for them to perceive the state of the body during walking, which is however often used to control wearable exoskeletons. In the present study the possibilities of providing vibrotactile feedback about the Center of Mass (CoM) during walking were investigated. The results showed that healthy subjects could successfully interpret the provided vibrotactile cues and change their walking pattern accordingly. Vibrotactile stimulation was either provided in a concurrent (over the complete CoM movement) or terminal (only when the desired CoM displacement was reached) way. The latter led to a better accuracy and can be easily implemented in a wearable exoskeleton where a certain amount of CoM displacement is needed to initiate stepping.**

I. Introduction

A Spinal Cord Injury (SCI) always has a tremendous effect on the lives of the affected person. All bodily functions below the level of the lesion are usually diminished or even completely disrupted, not only on the motor level, but also the sensory level. For people with SCI who are usually condemned to the use of a wheelchair for mobility, a recent development that can let them walk again is a wearable exoskeleton. Standing and walking will not only have positive psychological effects for the users, but also physiological effects like reductions in bone loss, pressure sores and an improved cardiovascular system response [1].

Although the technological developments in the design of wearable exoskeletons are evolving fast and first results indicate improvements in gait with several patient groups, there are still many disadvantages like the weight, costs and the long and complex training required for independent use of the exoskeleton [2]. An important aspect in the training with exoskeletons is the weight shift of the users, which is required for every step. For some exoskeletons (e.g. the Mindwalker [3] and the Ekso [4]) the amount of weight shift is used to initiate stepping and for other exoskeletons with a timed walking pattern (e.g. the Rewalk [5]), the timing and amount of weight shift is crucial for crutch placement. However, in SCI subjects not only the motor pathways are damaged, but also the sensory input from below the level of the lesion is affected. Therefore, SCI subjects also lack important information regarding the state of their body [6].

It is hypothesized that by providing some of the missing sensory information about the state of the body, e.g. the Center of Mass (CoM) movement, back to the user of the exoskeleton, he will be able to better use his remaining body functions to change his CoM movement to either balance with the exoskeleton or initiate stepping.

A common method to provide sensory feedback is the use of vibrotactile stimulation. Vibrotactile stimulation can be applied in a non-obtrusive, but distinct way, is comfortable to the user and stimulators are small enough to be worn under clothing. Vibrotactile sensory feedback has been applied already in the field of balance prostheses [7-9]. In these cases the CoM movement of the subject is usually fed back through a belt with incorporated vibrotactile stimulators that is worn around the chest. The deviation from the neutral position is related to the amplitude of vibration of one of the stimulators in the direction of the deviation [7]. Using these balance prostheses, Goodworth et al. [8] found a reduction of the body sway in subjects with vestibular problems, especially for slow movements (<0.5 Hz.). In a study by Dozza et al., vibrotactile feedback about medio-lateral trunk movements was provided during tandem gait, resulting in a reduction in trunk tilt for subjects with vestibular loss [9].

Only a few studies have tried to incorporate sensory feedback in a wearable exoskeleton. An example is the work of Yin et al., where joint torques and joint angles are fed back to the user of the exoskeleton via a pressure cuff around the upper arm [10]. Although this study showed that subjects were able to produce the desired knee angles based on pressure feedback, the experiments were only conducted with two healthy subjects and one degree of freedom (only the knee angle of one leg). Hasegawa et al. [11] provided proprioceptive information about posture during gait via electrotactile stimulation at the fingers for enabling paraplegics to walk without visually checking the state of their legs. Results on healthy subjects showed that they could accurately interpret hip angles and leg inertia from the provided electrotactile stimulation, but no further work was presented with paraplegic subjects or the incorporation in an exoskeleton. Instead of using healthy subjects there are also a few studies involving paraplegics. For example Matjacic et al. [12] used auditory feedback to provide information about the inclination of a balancing device. Results with one paraplegic subject indicated that the auditory feedback

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increased the balancing capabilities with the device. In another study sensory feedback was applied during FES walking and evaluated with paraplegic subjects. In this study of de Castro et al. [13], electrotactile stimulation was applied on the upper limbs and/or shoulder to provide feedback about foot position. The subjects preferred the simplest method where only discrete feedback indicated the moment of foot clearance of each foot. The promising result was that the subjects did not have to look down to watch their feet or legs during walking.

Although the discussed studies showed encouraging results, the application of sensory feedback in a wearable exoskeleton for paraplegics is still in its early phase and more work is needed to determine which sensory information should be fed back to the user and which feedback methods work the best. In the current study we have made a first step towards the implementation of vibrotactile CoM feedback during walking in an exoskeleton, by evaluating if healthy subjects could change their CoM movements based on cues provided through vibrotactile stimulation. Two different methods of feedback timing, concurrent (CF) and terminal (TF), have been compared to determine whether it would be better to provide rich continuous information or selective discrete information when providing CoM feedback.

II. METHODS

A. Subjects

8 healthy subjects (24.7 ± 2.1 years, 4 male) participated in this study. The experiment was performed with healthy subjects to test the set-up and the protocol before proposing them to SCI subjects.

B. Measurement setup

During the experiments the subjects walked in the exoskeleton LOPES (LOwer extremity Powered ExoSkeleton, [14]) to have real-time recording of all kinematics data and an estimation of the CoM movements. Furthermore, the LOPES can simulate most of the control methods and walking patterns of wearable exoskeletons that are available, and therefore will be used to evaluate the exoskeleton control in combination with the vibrotactile feedback in a later stadium.

Vibrotactile feedback was provided through C2 tactors (Engineering Acoustics Inc., Casselberry, USA) that are placed in an elastic belt and worn around the chest. The stimulation frequency and amplitude were kept constant (230 Hz and 4V respectively) during the whole experiment. Position modulation with 4 C2 tactors was selected over amplitude or frequency modulation with one C2 tactor, to provide feedback levels that are easily distinguishable. To also provide a feedback signal when the upper level of CoM movement was reached, error feedback was provided through a pair of coin motors (Precision Microdrives, London, UK) that was placed in an elastic band around the lower arm of the subjects. This error feedback signal can be implemented in an exoskeleton to have an upper level of CoM that should not be exceeded to prevent the users from losing stability and falling. Both vibrotactile actuators were controlled through EtherCAT.

Feedback about the CoM was only provided during CoM movements to the right. The start of this movement was determined by the moment that the pelvis started moving to the right, which was defined as the moment that the derivative of the pelvis position changed direction. The end of the movement was determined by the detection of left toe off (derived from the kinematics data and walking pattern). Only the CoM movement to the right was taken into account to start with a simple setup, but everything can be simply extended to movements to both sides and in the forward direction.

C. Protocol

To get familiar with walking in the LOPES, subjects started with a short trial of a few minutes of normal walking (zero impedance mode of the LOPES) and the subjects were instructed how they could change their CoM movements during walking. Afterwards, they performed a baseline walking trial of 40 steps, followed by 40 steps with a maximally exaggerated CoM movement to the left and right. The averaged exaggerated and baseline CoM movements of this trial were used to determine the desired levels of CoM movement for the experiments. The intermediate CoM level

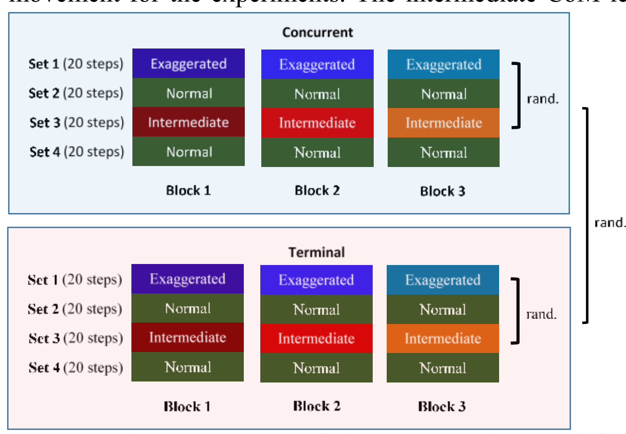

Figure 1. Schematic overview of the experimental protocol for the concurrent and terminal feedback timing methods.

was approximately 55% (constant for each subject, but variable between 50-60% due to an error in the calculation) of the range between the exaggerated and baseline CoM. The range between exaggerated or intermediate CoM and the baseline CoM displacement was divided in four equal levels.

Two different methods of feedback timing were evaluated: (1) concurrent feedback about the CoM movement and (2) terminal feedback only when the desired CoM position was reached (see Fig. 2). For the concurrent feedback timing method, each of the four levels of CoM displacement corresponded to the activation of one of the four C2 tactors (placed from left to right on the chest, 7 cm apart). So, during walking the CoM displacement to the right was presented through the consecutive activation of the four C2 tactors on the chest. For the terminal feedback only the fourth C2 tactor (the most right/lateral) was activated when the desired CoM displacement was reached. For both feedback methods a pair of coin motors at the forearm was activated as an error signal when the CoM displacement exceeded the upper limit, which was defined as the desired CoM displacement +15%.

The feedback timing methods were evaluated separately and the order of the presented feedback timing was randomized over the subjects. For each feedback method, subjects performed 3 blocks of walking at a constant walking speed of 0.3 m/s. and each block consisted of 4 sets of 20 steps. During two of these walking sets the subjects were requested, through vibrotactile feedback, to either perform intermediate or exaggerated CoM movements and each feedback set was followed by a set of 20 steps of normal walking without vibrotactile feedback (see Fig.1). In the case of concurrent feedback it was clear when the vibrotactile walking set started, because the vibrotactile stimulation started already at step initiation. However, for the terminal feedback sets, the experimenter had to indicate when the vibrotactile feedback set started, because the vibrotactile stimulation was only activated at intermediate or exaggerated CoM displacements, which usually don't occur during normal walking.

D. Data analysis

The following outcome variables were calculated for each set of 20 steps, for each measurement block and both feedback timing methods: (1) settling steps, (2) accuracy and (3) deviation. The first outcome parameter, the number of settling steps, was defined as the number of steps it took the subject to enter the desired range of CoM movements (between the fourth feedback level and the error limit) and stay inside it for at least three consecutive steps. From that

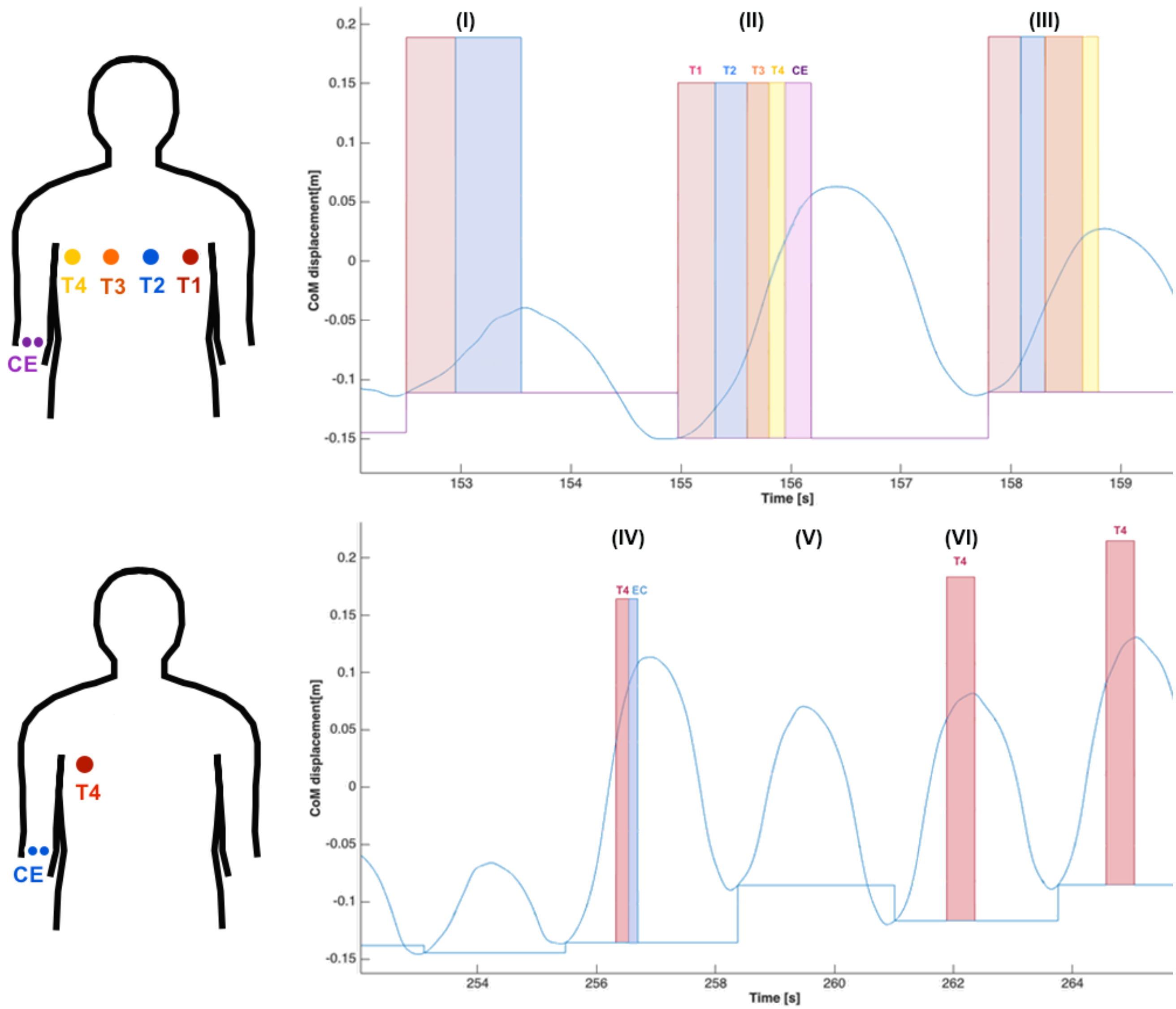

Figure 2. Placement and activation of the C2 tactors (T1-T4) and the coin motors (CE) for both methods of feedback timing. The activation of the C2 tactors and coin motors during several steps with varying CoM displacements is presented by the filled bars in the right graphs for both methods of feedback timing. Top panel: concurrent feedback through four C2 tactors moving from T1 to T4 during weight shift from left to right: (I) subject did not reach the desired CoM displacement, only 2 tactors were activated, (II) the CoM displacement was too large and the error signal was provided through the pair of coin motors, (III) the CoM displacement was perfect and all four C2 tactors were activated. Lower panel: terminal feedback through 1 C2 tactor when the desired CoM displacement is reached: (IV) the CoM displacement was too large resulting in activation of the error signal by the pair of coin motors on the arm, (V) the CoM displacement was not large enough and no vibrations were felt by the subject, (VI) the CoM displacement was perfect as indicated by the activation of the C2 tactor.

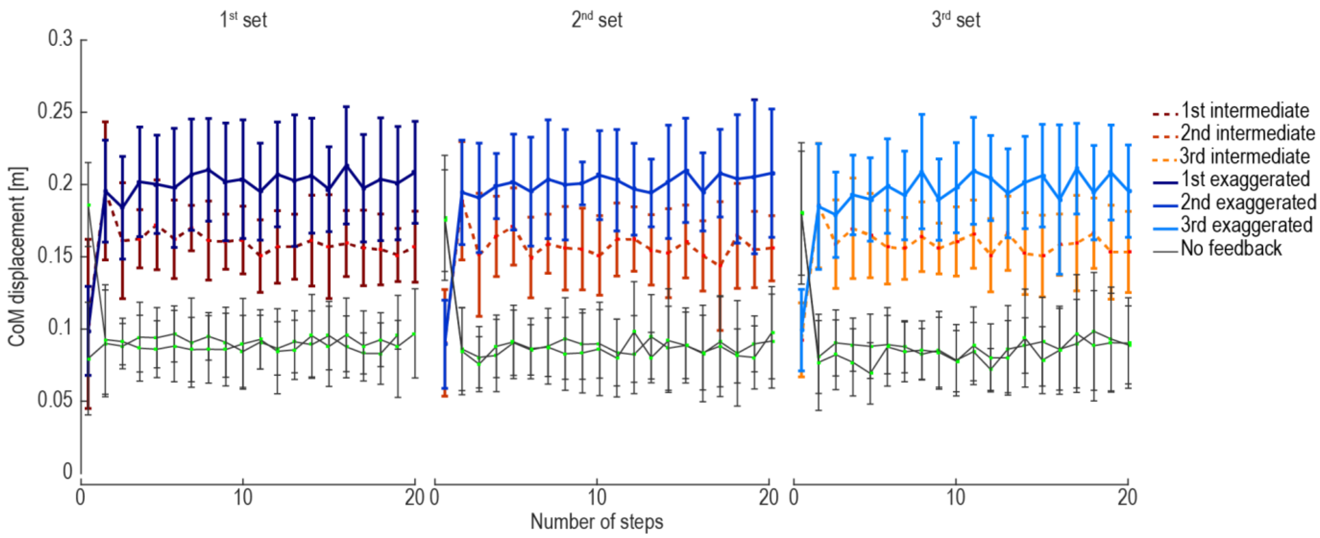

Figure 3. CoM displacements per step (mean values and standard deviations over all 8 subjects) for the concurrent feedback timing method. Each set consisted of 20 steps. 3 blocks consisting of a set with exaggerated CoM displacements (blue) and a set with intermediate CoM displacements (red) and two sets with no vibrotactile cues (green) in between are shown.

step the following steps were seen as the stable phase and the second and third outcome variable were both calculated over these steps. The accuracy is the percentage of steps that the CoM was kept within the desired range. Besides the percentages of correct CoM displacements, also the percentages of steps that were above and below the limits were calculated. The third outcome variable, the deviation, is calculated as the absolute difference between the desired CoM displacements and the actual CoM displacements, averaged over all steps in the stable phase.

To investigate whether the vibrotactile cues about the CoM movement could be used to reach a certain walking pattern, the CoM displacements in the normal, the intermediate and exaggerated conditions were compared. A repeated measures ANOVA, with the TASK (4 levels: 2x normal, 1x exaggerated and 1x intermediate CoM displacements) as factor, was performed for each walking block.

The intuitiveness of the feedback was evaluated by the number of settling steps and the accuracy over the different measurement blocks. To evaluate the differences between both feedback timing methods (concurrent and terminal) all three outcome variables were compared. A three way repeated measures ANOVA, with the BLOCK (3 levels: 3 repetitions of the walking sets), the FEEDBACK TIMING (2 levels: concurrent and terminal) and the TASK (2 levels: exaggerated and intermediate) as factors, was performed. A p-value of 0.05 was taken for significance. Post hoc tests (General Linear Model with one of the factors as the dependent variable) with Bonferroni corrections were performed when a significant main effect was found to further evaluate the differences.

III. Results

Subjects were well able to modify their amount of weight shift using the vibrotactile stimulation, shown by the distinguishable CoM displacement levels in Fig. 3. The results of the repeated measures ANOVA showed that there was a main effect of the TASK on the CoM displacements of the subjects ($p<0.001$) and post-hoc analysis revealed that the CoM displacements were significantly larger for the intermediate and exaggerated tasks ($p<0.001$ in all cases) compared to the normal walking tasks and also the exaggerated CoM displacements were significantly larger than the intermediate CoM displacements ($p<0.001$) for all three walking blocks. The feedback can be considered intuitive for the subjects as they only needed a few steps to reach the desired levels and this was even already the case for their first exposure (walking block 1). During the first step the CoM displacement was within the range of the previous task, the second step was already close to the desired CoM displacement and from the third step a clear separation between the different tasks is visible.

No significant main effect was found for the FEEDBACK TIMING and TASK, but there was a significant FEEDBACK TIMING x TASK effect. Post hoc testing indicated that for the exaggerated conditions the accuracy of the subjects was higher for the terminal feedback condition compared to the concurrent feedback condition (TF: 88.6±1.9, CF: 77.8±2.3). This better performance with terminal feedback was also found for the deviation, which was lower in the exaggerated conditions (TF: 0.009±0.002 CF: 0.014±0.003) (see Fig. 5).

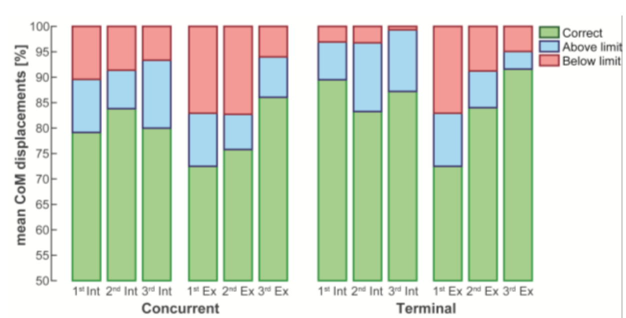

Figure 4. The percentages of CoM displacements that were correct (green), above (blue) or below (red) the desired range, for all three walking blocks of both tasks (int = intermediate and ex = exaggerated CoM displacements) and both feedback timing methods (concurrent and terminal).

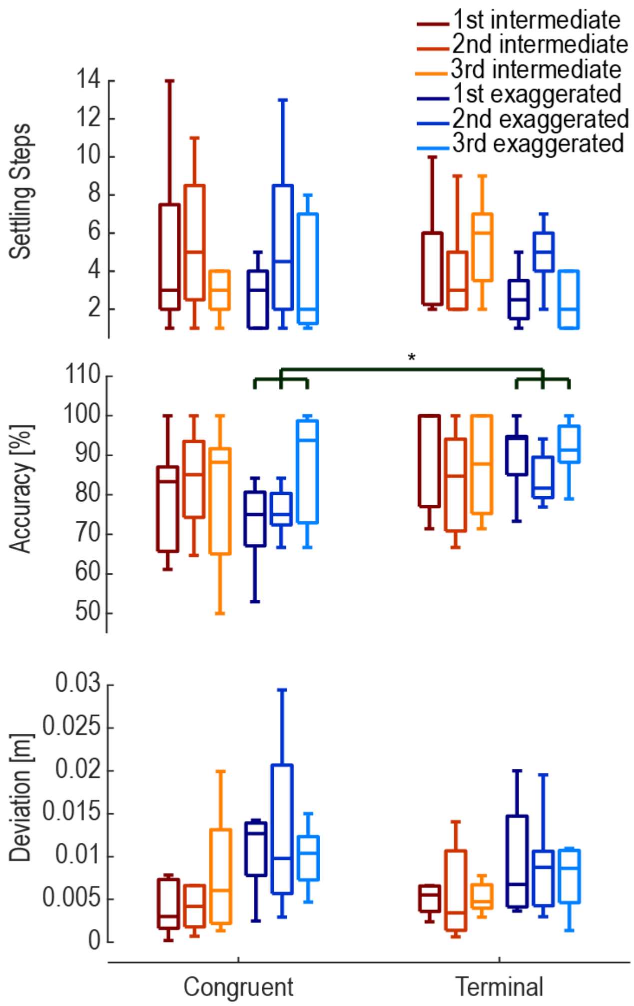

Figure 5. Boxpots, showing the total range, the median and 25 and 75 percentiles of the 3 different outcome parameters: number of settling steps, accuracy and deviation. Data is split for both feedback timing methods (concurrent and terminal). The different colors represent the different tasks (red=intermediate CoM displacements and blue=exaggerated CoM displacements) for each measurement block. Statistical differences are indicated by asterisks.

For the intermediate conditions no differences in performance were found.

Statistical analysis also highlighted that the performance of the subjects did not change over the three different BLOCKS for any of the variables (see Fig. 5). So, the number of settling steps, the accuracy and the deviation from the desired CoM displacement did not change over the three repetitions of the walking sets.

A further inspection of the accuracy data was performed by splitting the incorrect CoM displacements in displacements that were above or below the desired range (see Fig. 4). The percentages of CoM displacements that were below the desired range were higher for the concurrent feedback method compared to the terminal feedback ($p=0.023$). Furthermore, a significant difference between the three walking blocks was found ($p=0.004$), with lower percentages for the third block compared to the second block ($p=0.007$). In contrast, for the percentages of CoM displacements that were above the desired range, only an effect of the TASK was found, with higher percentages for the intermediate displacements ($p=0.007$).

IV. DISCUSSION

The main aim of this study was to investigate whether vibrotactile cues can be used to change the walking pattern of healthy subjects. From the CoM displacements of the subjects it can be concluded that the walking patterns could indeed be changed and that the subjects were able to interpret the vibrations and distinguish between the three CoM displacements (normal, intermediate and exaggerated) that were asked.

In the present study we varied the vibrational cues based on the required CoM displacement to instruct the subjects to reach one of the two specified CoM displacements. The ultimate goal will be to use the CoM feedback to give the SCI users of an exoskeleton more information about the state of their body in the exoskeleton. Due to the lack of all sensory information from below the level of their lesion, people with SCI can have difficulties in the perception of their CoM movement, which is however used in several exoskeletons to control the initiation of steps of the exoskeleton. In these cases a certain CoM displacement (in the sideways and forward direction) is required to initiate a step. SCI subjects who do have sufficient trunk control left will perform this CoM shift by movements of their trunk. For this situation the presented method can be implemented by setting the CoM threshold for step initiation as the required CoM displacement. In the current setup the vibrations are presented on the trunk of the subjects, but in case of a reduced sensation at this location, the stimulation locations can be easily switched to other body locations. A reduced sensory perception due to the injury can possibly influence the interpretation of the vibrotactile cues, which should be investigated for each exoskeleton user.

From experience with SCI test pilots that have been testing the Mindwalker exoskeleton [2] it is already known that it was hard for them to find the right CoM displacement to trigger the step initiation of the exoskeleton. It is therefore hypothesized that providing the CoM feedback will improve the step initiation procedure and therefore the overall control of the exoskeleton. The next step will be the implementation of the described method of providing CoM feedback in an exoskeleton and evaluate whether the users indeed are able to better control the step initiation of the exoskeleton, which could be shown by an increase in walking speed and more fluent walking (less interrupted steps).

The subjects were not only able to reach the required CoM displacements, but they could already reach it in about 3 steps, which shows that the vibrational cues can be interpret very easily. As the number of settling steps is already low for the first measurement block, there is not much room for improvement, which also follows from the comparison between the three measurement blocks. However, the accuracy of the steps in the stable phase is not perfect (<100%) and could possibly be improved, but again no improvement over the measurement blocks was found. So, by extended use of the system it is not expected that the performance with the system will significantly increase, but it might be possible that the system can be used more subconsciously, which can be investigated for example by using double tasks.

The comparison between both feedback timing methods showed that the performance of the subjects was better for the terminal feedback compared to the concurrent feedback, which was expressed in a higher accuracy and a smaller deviation from the required CoM displacement. It was expected that with concurrent feedback the subjects would be able to use the feedback already from the first step or at least faster than with terminal feedback, which could however not be concluded from the data. As the goal for the subjects was to reach a certain end point of CoM displacement, the intermediate levels were not really needed and apparently even made it worse for the subjects to determine the right CoM displacement. In applications where exoskeleton users should reach a specific level, the terminal feedback timing method will then likely be a better option than the concurrent feedback. Although the comparison between concurrent and terminal CoM feedback has not been made before, there is some work on feedback for upper and lower limb prostheses, where time-discrete feedback resulted in better performances compared to time-continuous feedback as well [15, 16]. Time-continuous feedback can be rather cumbersome for the users and adaptation effects can easily occur, while time-discrete feedback is more related to the natural time-discrete somatosensory information that is being processed by the human brain.

Besides the differences between feedback timing methods we also investigated the differences between both movement tasks: intermediate and exaggerated CoM displacements. Two levels of displacement were chosen beforehand to show that the subjects could distinguish different cues, but no large differences were expected. However, the number of settling steps for the exaggerated tasks was lower compared to the intermediate tasks, while the deviation was larger for the exaggerated displacement tasks. It seems that it was easier for the subjects to reach an extreme position, which was also confirmed by the lower percentage of CoM displacements that exceeded the upper limit, probably because they know what their most extreme displacement would be, but is was also harder to reach a constant extreme position, as this would require more effort during walking.

In conclusion: the presented method to provide CoM feedback during walking has shown to be intuitive and accurate to steer the walking pattern of healthy subjects. Furthermore, it shows the potential of being implemented in an exoskeleton to give the users information they need for step initiation based on CoM displacement, especially if the terminal feedback timing method will be used. In the present study the focus was on the step initiation of an exoskeleton, but the CoM information can also be useful during balancing with an exoskeleton while standing or walking. It is hypothesized that providing sensory information back to the SCI subjects not only improves step initiation or balancing, but also creates more awareness of what the exoskeleton is doing and therefore will probably enhance the acceptance of the exoskeleton.

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