Pneumatic Feedback for Wearable Lower Limb Exoskeletons Further Explored

Heidi Muijzer-Witteveen[1(✉)], Francisco Guerra[1], Victor Sluiter[1], and Herman van der Kooij[1,2]

[1] Department of Biomechanical Engineering, MIRA Institute of Biomedical Technology and Technical Medicine, University of Twente, Enschede, The Netherlands
h.j.b.witteveen@utwente.nl
[2] Department of Biomechatronics and Human-Machine Control, Institute of Mechanical, Maritime and Materials Engineering, Delft University of Technology, Delft, The Netherlands

Abstract. For optimal control of wearable lower limb exoskeletons the sensory information flow should also be (partly) restored, especially when the users are Spinal Cord Injury subjects. Several methods, like electrotactile or electromechanical vibrotactile stimulation, to provide artificial sensory feedback have been studied thoroughly and showed promising results. Pneumatic tactile stimulation might be an alternative to these methods, because the stimulation amplitudes can be larger and in cases of force feedback, the modality of stimulation and sensing can be matched. In this study we have developed a setup that can provide pneumatic feedback with four feedback levels via three stimulation modalities: (1) amplitude modulation, (2) position modulation and (3) frequency modulation. The differences in subject stimulus perception between these three stimulation modalities were evaluated through a magnitude estimation task performed with 10 healthy subjects. Percentages correctly identified feedback levels were significantly higher for frequency modulation than the other two stimulation modalities. Also through questionnaires the subjects indicated that feedback through frequency modulation was the most intuitive and the only method where addition of an extra feedback level was indicated as possible. The results of this study show that pneumatic feedback is feasible, can provide high percentages of feedback level discrimination that are at least comparable to vibrotactile stimulation and therefore encourages further research to optimize the pneumatic setup.

Keywords: Pneumatic feedback · Wearable exoskeleton · Stimulus modulation

1 Introduction

In recent years, a large number of developments has been presented in the field of wearable lower limb exoskeletons. Despite the progress made, the exoskeletons still cannot provide a natural walking pattern and patients depend on crutches for balance. It is hypothesized that the lack of providing sensory information from the exoskeleton to the user could be one of the reasons for this latter shortcoming of the current

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exoskeletons. Furthermore, for Spinal Cord Injury users, also sensory information coming from below the level of the lesion is missing.

Sensory information that is used for human balancing normally comes from three sources: (1) the visual system, (2) the vestibular system and (3) the proprioceptive and exteroceptive system of the lower limbs. The latter source is disturbed in the case of SCI, which increases the burden on the other two sources. The consequence of loss of the proprioceptive and exteroceptive information on balancing is not really clear, but it seems to have a significant effect especially when the surface below the feet changes [1].

Providing artificial sensory feedback can possibly help to (partially) restore the original sensory information flow. It is hypothesized that besides improving balancing, the user will also be more in control, because more information about the behavior of the exoskeleton is provided. Hence, this can eventually increase the embodiment of the exoskeleton and increase the acceptance of the exoskeleton by the user.

One of the most commonly used methods to provide artificial sensory feedback is through vibrotactile stimulation. This method has been used in several studies already for applications in upper limb prostheses [2–6], but also for patients with vestibular deficits to restore their balance [7–9]. Advantages of vibrotactile stimulation are its non-invasive and comfortable application.

However, the amplitude of stimulation and the resulting deflection of the skin is limited for most vibration motors that are commonly used for this application. For the most often used and commercially available C2 tactor (Engineering Acoustics, Inc., Casselberry, Florida, US), the deflection is less than 1 mm. These small stimulation amplitudes may result in less perceivable stimuli, especially when amplitude modulation is used to transfer changing sensory information to the user of the system.

Alternatively, higher stimulation amplitudes can probably be reached through pneumatic stimulation via small balloons that are placed on the skin, providing pressure stimuli to the user. When sensory information that is related to pressure, like ground contact, will be fed back via pressure stimuli, this might be more intuitive compared to vibrotactile feedback as it is modality-matched [10, 11].

There are some examples of the use of pneumatic feedback available for application in lower-limb prostheses [12], balance prostheses [13] and even for wearable exoskeletons [14], but their working principles are not well described, very small actuators are used and no comparison between different control options has been made so far.

In this study we have developed a pneumatic setup with balloon actuators that are comparable in size to the standard vibrotactile C2 tactors. Three different modulation techniques have been compared for differentiation of four different feedback levels. Stimulation was applied at the shoulder region to take into account the possible application for SCI patients, but tested on 10 healthy subjects.

2 Methods

2.1 Development of the Setup

Actuator balloons were made of a PDMS (polydimethylsiloxane) cylindrical housing covered by a 2 mm layer of spin coating silicone (Dragon Skin® high performance

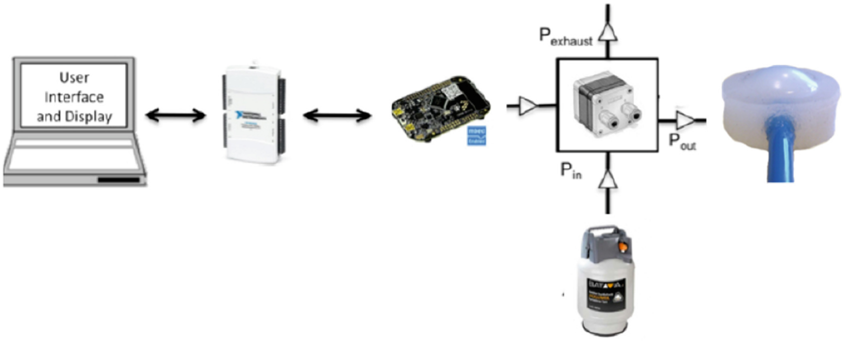

Fig. 1. Overview of the pneumatic setup (from right to left): the silicon balloon actuator that is filled with air coming from a portable tank with pressurized air and its pressure is regulated via a controlled valve. An mbed device is used to allow fast control of the pressure and is controlled via a NI-USB DAQ device, which in turn is controlled by a Labview interface running on a laptop.

silicone rubber). The outer diameter of the balloons is 35 mm and the thickness 18 mm (see Fig. 1), which makes them comparable in size to the C2 tactors (30 mm in diameter, but thickness of only 7 mm). Silicon was chosen because of its large flexibility (large deflections possible) and long-lasting characteristics (withstands many load-cycles).

The air supply was provided through a small air tank with an outlet pressure regulator. The outlet pressure was adjusted (between 1–1.4 bar) for each setup. A MATRIX 750 series air valve with 4 3–3 type valves was used to control the airflow to the actuators with a response time of 5 ms.

For the control of the pressure in the balloons (more precisely the pressure in the outlet tube) a pressure sensor (MPXV5050GP) was incorporated in the setup.

The regulation of the valves, opening and closing, was controlled via a NI DAQ device (NI USB-6218) in combination with Labview 2014 running on a laptop. An embedded platform (ARM mbed FRDM KL25Z) was used for the fast control of the device, which is needed for the stable control of the pressure. See Fig. 1 for a complete overview of the pneumatic setup.

2.2 Stimulation Modulation

Three modulation techniques for pneumatic stimulation, all capable of providing 4 feedback levels, were applied: (1) position modulation, (2) amplitude modulation and (3) frequency modulation. For the first feedback level, the zero level, there is no actuation at all and this is the same for all three modulation techniques. For position modulation three smaller (2.5 cm diameter) balloons were used. For each increase in feedback level, an extra balloon is inflated. So, for level 4 all three balloons are inflated. The level of inflation was kept the same for each balloon, for each feedback level and such that the stimulus was well perceivable, but not maximal. For amplitude modulation the pressure in the balloon is regulated. The maximum pressure that did not cause any membrane tearing during a long period of inflated state was empirically determined to be 0.55 bar and was set for the fourth feedback level. For the other two feedback levels the pressure was set to 0.27 and 0.41 bar. For frequency modulation the time between two periods of inflation was varied. The period of inflation was kept constant for each feedback level at 50 ms. The interval between inflation was 250 ms, 125 ms and 62.5 ms for feedback levels 2, 3 and 4 respectively, which corresponds to frequencies of 3.3 to 8.9 Hz.

2.3 Comparison of the Three Modulation Techniques

10 healthy subjects (students) participated in this study. They were all male subjects who could easily fit the neoprene adjustable chest vest. The balloon actuators were attached with Velcro strips to the interior of the vest and placed directly on the skin of the subjects. For the amplitude and frequency modulation, the exact placement of the actuator at the front side of the shoulder region was selected by searching for the most comfortable location for the subject. For the position modulation the distance between the actuators was at least 4 cm to ensure that the subjects could discriminate between the different stimuli (checked before the start of the experiment and adjusted if necessary).

Subjects were seated behind a desk in a quiet room and wore headphones to cancel out the noise of the valves. To further reduce any auditory clues coming from the valves, a box with isolating foam was placed over the valve setup.

Psychophysical Tests. A basic psychophysical test of magnitude estimation was used to investigate possible differences in stimulus perception between the three modulation techniques. Subjects were asked to indicate the perceived level of the stimulus. The feedback levels were fixed (4 levels including the zero level with no stimulation) and the subjects had to select one of these levels. This is contradictory to the standard method of magnitude estimation where a free scale is used, but in this way we could determine the percentages of correctly identified stimuli.

We did not follow a forced-choice protocol in which a pair of stimuli is presented directly after each other and the subjects have to indicate the stronger stimulus, because this is not representative for the daily situation in which the feedback will be used. However, a stimulus will always be related to the perception of the previous stimulus. Therefore, it was ensured during the tests that each possible transition in feedback levels was present and repeated 5 times. For 4 feedback levels this means that 61 stimuli were provided per modulation technique and thus 183 in total per subject.

Before starting the real tests, subjects were given some time to get familiar with the different feedback levels. They were sitting behind the measurement laptop and by selecting one of the feedback levels, stimulation was provided. The participants were allowed to receive a stimulus as long and often as necessary to get comfortable with the perception of the different levels.

During the tests, the subjects were seated behind the measurement laptop and by pressing “start” the first stimulus was applied. Subjects were instructed to select the perceived feedback level on the computer screen and press the ‘confirm’ button, after which the next stimulus was presented. This procedure was followed for all three modulation techniques. The order in which the modulation techniques were presented, was randomized between the subjects.

Questionnaire. After finishing the test for each modulation technique, a short questionnaire was presented to the subjects to gather information on their experience with the used modulation technique. The questionnaire consisted of two VAS scales to determine the perceived comfort and intuitiveness. The scale ranges from 'not comfortable at all' or 'not intuitive at all' to 'very comfortable' or 'very intuitive'. Furthermore it was asked whether the subjects thought it would be possible to add another feedback level. This last question could only be answered by yes or no.

Data Analysis. The percentage correctly perceived feedback levels, the accuracy, was determined by comparing the presented feedback level and the selected feedback level by the subjects. Furthermore, it was determined whether the subjects could, regardless of the perceived feedback level, identify the increase or decrease in feedback level (comparable to selecting whether a stimulus was stronger or not in the case of a forced choice procedure). The percentage correctly identified transitions in feedback levels was calculated for each subject for each modulation technique.

Means and standard deviations per modulation technique for both outcome parameters were calculated for the whole group of subjects. A repeated measures ANOVA was used to determine, with a significance level of $p = 0.05$, whether there is a difference between the modulation techniques for both outcome parameters and afterwards a Bonferroni corrected post-hoc test was performed to determine the actual differences between the modulation techniques.

The marked positions on the VAS scales were converted to values between 0 and 10, means and standard deviations were calculated for all three modulation techniques and also for those two parameters an ANOVA test was performed. For the other question the total number of yes and no responses was determined for each modulation technique.

3 Results

In the figures below (Fig. 2) the percentages correctly identified feedback levels and the percentages correctly identified feedback level transitions are shown. ANOVA analysis showed that there is a significant difference between the three feedback modalities for both outcome parameters (the mean accuracy and the mean transition accuracy), with p-values of < 0.001 and 0.002 respectively. Bonferroni corrected post-hoc analysis revealed that frequency modulation resulted in higher accuracies compared to the other two modalities (p-values between < 0.001 and 0.008 for all comparisons and both outcome parameters). No significant differences were found between amplitude and position modulation for both outcome parameters.

The perceived comfort and intuitiveness of the three modulation techniques are presented in the next figure (Fig. 3). For both outcome parameters a significant effect of the modulation technique was found ($p < 0.001$). For the perceived comfort, the amplitude modulation was rated as the most comfortable ($p = 0.001$ compared to

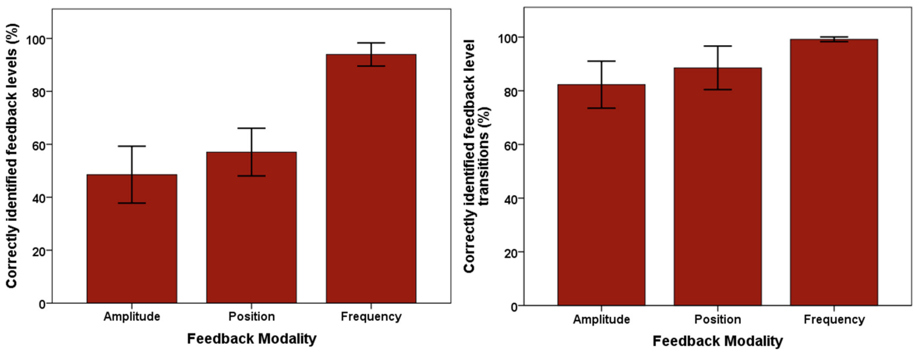

Fig. 2. Percentages correctly identified feedback levels (left chart) and percentages correctly identified feedback level transitions (right chart) for all three feedback modalities. Mean values and standard deviations are given.

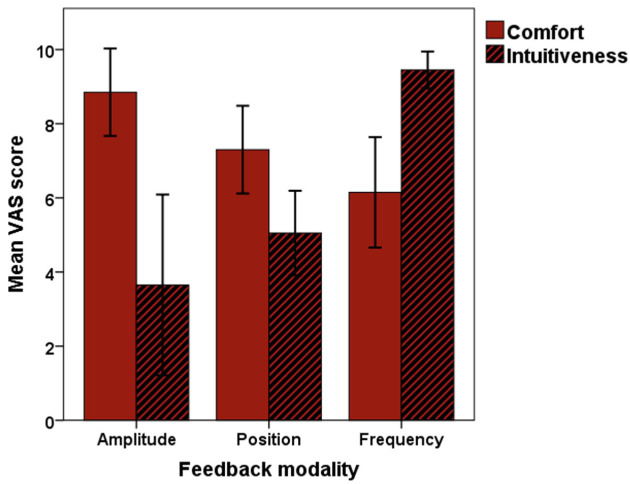

Fig. 3. Mean and standard deviations of the VAS scores for the perceived comfort and intuitiveness of the three modulation techniques.

position as well as to frequency modulation), while no differences in perceived comfort were found between position and frequency modulation. The perceived intuitiveness was rated highest for the frequency modulation ($p < 0.001$ compared to amplitude as well as to position modulation) and no differences between amplitude and position modulation were found.

For both amplitude and position modulation all ten subjects indicated that they believed it is not possible to add another (fourth) feedback level, while for frequency modulation 9 out of the 10 subjects though it would be possible to add an extra level.

4 Discussion

The goal of this study was to develop and test a pneumatic setup that can be used to provide artificial sensory feedback to users of a wearable lower limb exoskeleton.

One of the reasons to investigate pneumatic feedback, while vibrotactile feedback has shown already good results for several applications, was that pneumatic feedback could be more intuitive due to the modality-matching that can be achieved when providing feedback about pressure. Furthermore, the amplitude of stimulation can be larger than with vibrotactile feedback, which would provide more distinctive stimuli. These two aspects have not been addressed explicitly in this study, but will be studied in more detail in future work. In this study a first step towards a pneumatic setup that can compete with the existing feedback methods has been made.

The psychophysical comparison that was made between the three feedback modulation techniques clearly revealed that frequency modulation outperformed amplitude and position modulation in this study. Especially when looking at the percentages correctly identified feedback levels, the performance with frequency modulation was high with an average of almost 94 %.

To be able to compare the results of our study with some other work on pneumatic feedback, the percentages correctly identified level transitions were also calculated. The protocol is not completely the same as used for the forced-choice procedure, but in both cases it can be determined how well subjects can discriminate between an increase or decrease in feedback level. In a study of Fan et al. [12] level transitions between three feedback levels (0, 40 and 100 % of inflation) could be discriminated successfully in a forced choice protocol in 94 % of the cases. In our study, transitions between four feedback levels (pressure amplitudes) were perceived correctly on average in 83 % of the cases. These lower values might be due to the higher number of feedback levels or the more efficient setup used by Fan et al. In our setup the maximal pressure level was empirically determined by trying to avoid tearing of the silicon membrane, which might be optimized in the future.

In the same study by Fan et al. [12] and also in a study by McKinney et al. [15], balloon actuators placed around the leg were used and subjects were asked to identify which balloon was inflated. Subjects succeeded in 95 and 99 % of the cases, respectively, for 4 balloons. This position modulation technique is different from the one used in our study, where balloons were inflated in a cumulative way instead of one by one. Cumulative position modulation was also investigated in the same study of McKinney where they found a performance of 62 %, which is comparable to the 57 % we found in our study. It might be worth looking into position modulation with sequential stimulation for future applications, although the number of actuators is larger compared to amplitude or frequency modulation, which will be more cumbersome for the users.

Frequency or pulse width modulation has, as far as we know, not been described for other studies with pneumatic feedback before. An advantage of using frequency modulation over amplitude modulation would be that the effect of adaptation due to prolonged continuous stimulation will be less or delayed, as was already shown for electrocutaneous stimulation [16]. The main disadvantage of the use of frequency modulation is the inevitable delay that is caused by the time between the two stimuli.

In case of the lowest feedback level, the time between two stimuli was 250 ms, which is the minimum time required by the subject to be able to determine the feedback level. These response times might be a bit larger than the minimum delay between sensing and actuation that can be detected by a subject [17], but is comparable to the reaction times of subjects provided with vibrotactile stimulation [18]. Reduction of the time between stimuli would be one of the first things to improve in a future setup.

From this study it is clear that frequency modulation is superior over amplitude and position modulation for pneumatic feedback. Such a direct comparison between different modulation techniques has not been reported for pneumatic feedback before. For vibrotactile stimulation some more comparisons have been made between different modulation techniques, especially for applications in upper-limb prosthetics. In a study of Stepp and Matsuoka [5] a comparison was made between amplitude and pulse-width modulation and they found a clear preference for amplitude modulation and concluded that this is likely due to the fact that amplitude modulation was more intuitively related to the application they tested, namely feedback about grasping force. Other studies did not show major differences between modulation techniques for vibrotactile stimulation, even when the feedback was modality-matched by relating position modulation to feedback about hand aperture and amplitude modulation to grasping force feedback [6].

In a study of Patterson and Katz [11], a comparison between vibrotactile and pressure (cuff) feedback was made, which showed that pressure feedback scored better, which they related to a more modality-matched application. Based on this latter study and the results of our study, we think that it is worthwhile to further investigate and optimize the pneumatic feedback setup to make it suitable for the application of artificial sensory feedback for users of a wearable lower-limb exoskeleton.

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