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Assessment of Intuitiveness and Comfort of Wearable Haptic Feedback Strategies for Assisting Level and Stair Walking

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Abstract: Nowadays, lower-limb prostheses are reaching real-world usability especially on ground-level walking. However, some key tasks such as stair walking are still quite demanding. Providing haptic feedback about the foot placement on the steps might reduce the cognitive load of the task, compensating for increased dependency on vision and lessen the risk of falling. Experiments on intact subjects can be useful to define the feedback strategies prior to clinical trials, but effective methods to assess the efficacy of the strategies are few and usually rely on the emulation of the disability condition. The present study reports on the design and testing of a wearable haptic feedback system in a protocol involving intact subjects to assess candidate strategies to be adopted in clinical trials. The system integrated a sensorized insole wirelessly connected to a textile waist belt equipped with three vibrating motors. Three stimulation strategies for mapping the insole pressure data to vibrotactile feedback were implemented and compared in terms of intuitiveness and comfort perceived during level and stair walking. The strategies were ranked using a relative rating approach, which highlighted the differences between them and suggested guidelines for their improvement. The feedback evaluation procedure proposed could facilitate the selection and improvement of haptic feedback strategies prior to clinical testing.

Keywords: lower-limb amputees; vibrotactile belt; stimulation strategies; Elo rating; wearable robotics; assistive technologies; haptic feedback

1. Introduction

Walking and climbing stairs represent almost automatic tasks for intact subjects, requiring little or no cognitive effort. During locomotion, the mechanoreceptors on the foot and the proprioceptors in the muscles gather force and position information, which are delivered to the central nervous system through the afferent path [1]. Lower-limb amputation affects the sensorimotor system, causing significant functional and sensory impairments. In particular for lower-limb amputees, ascending and descending stairs are difficult and potentially dangerous activities. Foot placement on the steps is a dynamic task, requiring the individual to know the amount of toe overhang to adjust the movement of the rest of the body [2]. The absence of awareness and control over foot placement increases the risk and fear of falling and the visual dependency in amputees.

Recent years have witnessed striking advancements in the field of robotics, with the development of sensing and actuation technologies and control strategies aimed to facilitate the actions and interactions of robots and humans with the environment [3,4] and to promote human–robot cooperation [5,6]. In particular, the use of robotic systems such as augmented sensory feedback devices as part of rehabilitation programs of lower limb amputees has the potential to complement the action of clinical therapists and to continue the long-term therapy at home after hospitalization.

Several studies reported that the introduction of augmented sensory feedback systems in prostheses can improve the mobility function of amputees by providing information on the foot–ground contact or other gait parameters, and thus restoring part of the missing sensory input [7–18]. Among all the possible sensory feedback modalities, haptic feedback is widely employed to convey information, due to the possibility to tune the stimulation parameters (i.e., frequency, duration, amplitude) and to implement different stimulation strategies without adding extra loads to the visual and auditory channels [19].

When defining the stimulation strategy, it is crucial to identify the minimum amount of information needed for the achievement of a specific task, in order to limit the cognitive burden associated with the use of the feedback system [20]. The stimulation should be intuitive, i.e., the amputee should easily understand the information being transmitted (e.g., he/she should correlate the stimulation pattern to the foot/ground contact) and comfortable, i.e., the stimuli should not annoy the user. Most of the devices found in literature implement the so-called corrective feedback strategies, consisting of "simplified" activation patterns providing stimuli in the direction of error, denoting deviations of specific variables or performance parameters with respect to a given physiological range or a target [9,13,17,21]. When the strategy delivers direct feedback on the evolution of one or more measured variables [1,2,9,18,22–28], the so-called concurrent feedback, the complexity of the feedback pattern depends on the number of events and parameters encoded by the device. For example, the timing of the foot heel strike requires a single event-based activation, while providing information on the location of the center of pressure (CoP) and the intensity of the ground reaction force under the foot calls for a more complex activation pattern. Depending on the variables or the instructions mapped through the feedback pattern, stimulation strategies that are particularly informative in a specific locomotion task may be ineffective in other ones. For example, some feedback strategies designed for level walking [18,25,29] depend on specific sequences of gait-phase transitions, which are not preserved while climbing stairs or walking on uneven terrains.

The present study reports on a new wearable haptic feedback system providing concurrent augmented sensory information on the foot–ground interactions and designed to assist lower-limb amputees in different locomotion scenarios—i.e., ground-level walking, ascending/descending stairs—while enabling smooth locomotory transitions. Multiple stimulation strategies have been implemented in the feedback system, translating the spatiotemporal evolution of the CoP under the foot into vibrations delivered onto the user's waist, and in some cases providing also information on the ground reaction forces. Along with these stimulation patterns already presented in a preliminary study [23], a strategy that mimics the temporal characteristics of skin mechanoreceptors [30–34] was included. All these strategies have been conceived with the idea to guide the amputees in the execution of level and, especially, stair walking tasks, for which information on the prosthetic foot placement and the toe overhang on the steps may prevent the risk and incidence of falls, favor the embodiment of the prosthesis and reduce the visual workload. However, complex, poorly intuitive, and bothersome stimulation strategies may prevent the effectiveness and the usability of the feedback system.

When it is not possible to establish the most suitable strategy for sensory feedback *a priori*, multiple candidate stimulation patterns should be tested on amputees. Nonetheless, the introduction of two or more strategies significantly complicates the experiment and lengthens the time needed to complete the trials, with the risk to increase the physical and cognitive effort of the subjects. Furthermore, restrictive inclusion criteria and difficulties in enrolling amputees for the clinical studies requires pre-selecting a proper stimulation strategy to prevent wasted trials and time. Indeed, studies addressing the testing of augmented feedback systems on lower-limb amputees often involve a small pool of subjects, with a maximum of three patients recruited for the experiments [10,17,18,28], and a reduced number of trials with a single feedback strategy, due to the limited availability of the subjects for the experiments. In this context, it is useful to define an assessment protocol to benchmark the proposed strategies on intact subjects. In order to guarantee that the results obtained on intact subjects can be transferred to amputees, the protocol should be designed to simulate the disability [2,9,35,36] or should adopt a metric that is valid for both intact subjects and amputees.

Here, we introduce a novel assessment protocol designed to pre-select the stimulation strategy to be used in clinical trials, through experiments involving intact subjects. The different strategies implemented in the haptic feedback system were ranked in terms of intuitiveness and comfort perceived by the subjects, during level and stair walking using a relative rating approach. Specifically, the subjects were asked to compare couples of consecutive strategies (i.e., the last strategy is better, same, or worse than the previous one) and the final ranking of the strategies was obtained by applying the Elo rating algorithm [37,38]. The Elo rating is a statistical system based on a logistic distribution, which was originally developed to assess the skill levels of chess players [38]. Before starting a match, each player is assigned an initial score. Then, if a player wins or loses the match, his/her score is updated based on the formula reported in [38] and detailed hereafter. Following the same approach, in the present paper, each feedback strategy was treated as a player and each comparison between couple of strategies (in terms of intuitiveness and comfort) was regarded as a match. The relative comparisons were introduced to highlight the differences among the strategies, avoiding the possible biases towards intermediate scores given by a rating performed on an absolute scale.

The energy cost of ascending stairs is considerably higher than descending stairs and walking overground [39–43] and requires a greater demand of attentional resources, even in unimpaired subjects [44]. The different physical and cognitive effort associated with the specific motor task performed might affect the perceived intuitiveness and comfort of the haptic feedback, biasing the rating of the stimulation strategies assessed by the subjects. Thus, the effect of the specific task of ascending or descending stairs on the ratings reported by the subjects was also examined.

The paper is organized as follows. Section 2 presents (i) an overview of the wearable haptic feedback system architecture, (ii) the feedback strategies implemented, (iii) the experimental protocol for their comparison, and (iv) the Elo rating system used for data analysis. Then, the results of the comparisons of the feedback strategies are shown (Section 3) and discussed (Section 4). Lastly, general conclusions and future applications of the device and the assessment protocol described in the study are reported (Section 5).

2. Materials and Methods

2.1. Wearable Haptic Feedback System

The haptic feedback system designed for this study and shown in Figure 1a is a redesigned version of the device presented in [45]. The system is a stand-alone, wireless device comprising a sensing module and a wearable haptic interface, integrating a set of vibrotactile (VT) units and a haptic control unit for data processing and motor control.

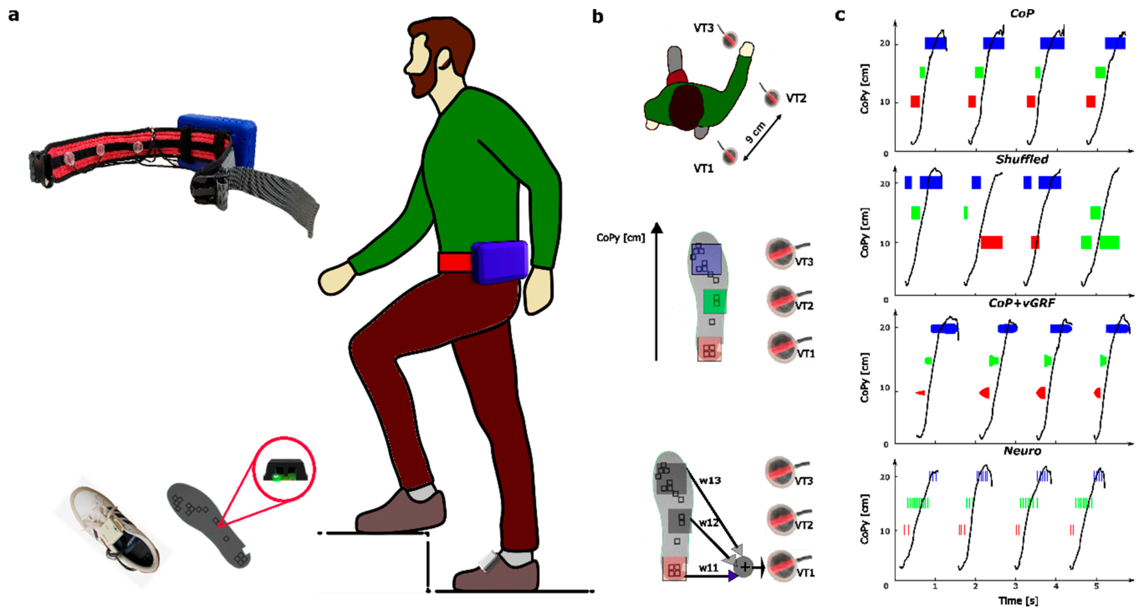

Figure 1. Experimental set-up: (**a**) overview of the haptic feedback system: the sensorized insole (bottom left) and the belt integrating three vibrotactile (VT) units and the 3D-printed box (top left); the sketch on the right shows qualitatively the wearability of the two components; (**b**) spatial distribution of the VT units around the user's waist (top), and schematics of the activation patterns based on the center of pressure (CoP), with segmentation of the insole in three regions activating corresponding VT units along the axis of increasing CoPy (middle) and neuronal network mapping, with activation of sensors at the heel and inhibition of other regions at the heel-strike, as the input to the neuron model that activated VT1; (**c**) CoP progression with time (x-axis) for four steps of ground-level walking showing the activation of the three VT units (y-axis) for each stimulation strategy.

The sensing module consists of a pressure-sensitive insole lodged in one shoe (size 43 EU) integrating an array of optoelectronic sensors for the measurement of the plantar pressure distribution [46]. The shoe is equipped with onboard electronics for data acquisition and wireless transmission to the haptic control unit.

The wearable haptic interface is a textile belt equipped with three VT units (Pico Vibe 304-116, Precision Microdrives). The VT units are equally spaced at 9 cm apart on one side of the waist to provide ipsilateral feedback (Figure 1b, top). The VT units have been encapsulated in a polymeric matrix of PDMS (Sylgard® 184 Silicone Elastomer, Dow Corning) to guarantee comfortable contact with the skin.

The belt further integrates a haptic control unit, which is enclosed in a 3D-printed box, physically attached to the belt. The board wirelessly acquires pressure data from the insole at 100 Hz and calculates the coordinates of the CoP and the vertical ground reaction force (vGRF) from the raw sensor signals (Figure 2). The commands for the activation of the VT units are generated according to multiple stimulation strategies implemented in the control unit and described in Section 2.2.

2.2. *Stimulation Strategies*

Four stimulation strategies providing information about the step dynamics through stimulation of the user's waist were implemented and compared. Figure 1c shows the activation patterns of the VT units during level walking for each stimulation strategy.

The CoP mapping strategy (*CoP*) was designed to convey information about the CoP progression under the foot. Specifically, the insole was virtually segmented in three regions (heel [0 cm, 5 cm], sole [5 cm, 18 cm], toe [18 cm, 25 cm]), and each region was associated to a specific VT unit (Figure 1b, middle). Every time the CoP entered one region, the corresponding VT unit was activated with 100%

pulse width modulation (PWM) duty cycle (maximum activation). Figure 1c (top) shows the sequential activation of the VT units at the set intensity and following the CoP progression as described above, during four level-walking strides. The CoP shuffled (*Shuffled*) strategy was introduced as a control for the assessment of the efficacy of the feedback patterns. In this case, the mapping between the CoP segments and the VT units was shuffled every time the CoP moved to a different region (Figure 1c, second plot from top).

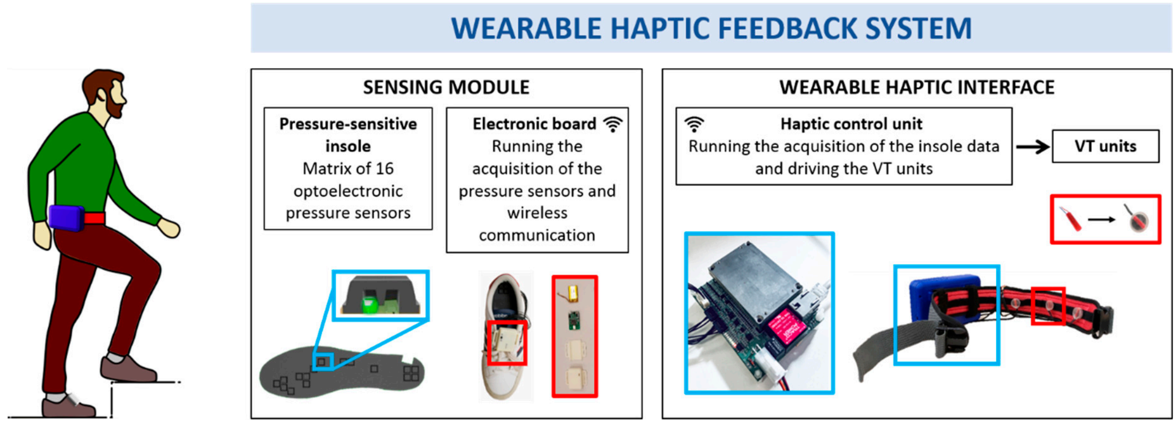

Figure 2. Schematic representation of the electronic systems integrated in the sensing module and wearable haptic interface.

The CoP mapping + vGRF (*CoP + vGRF*) strategy adopted the same VT activation pattern as for the CoP but included an intensity modulation. Such a vibration amplitude modulation was obtained by setting the duty cycle of a PWM (carrier at 1 kHz) to be a linear function of the vGRF, with 0% activation at 1 N activation threshold and 100% duty cycle with forces above 60 N. The stimulation pattern is displayed in Figure 1c (third plot from top), with VT units activation plots denoting amplitude modulation. This strategy was designed to enrich the sensory information, by providing synchronous information about the foot position and the forces under the foot.

Along with the CoP-based activation patterns, a feedback strategy based on a neuronal network mapping (*Neuro*) was defined and tested. Specifically, sensors data, x^n, generated sequences of neuronal spikes after being mapped into inputs to three Izhikevich artificial neurons tuned to regular spiking dynamics [47,48]. The three neurons were defined as heel-strike, flat-foot, and toe-off neurons, and associated with VT1, VT2, and VT3 respectively (Figure 1b, bottom). Each neuron received an input current, I^n_{VTi}, computed as in Equation (1)

$$I^n_{VTi} = g_{VTi}\max\left(w^T_{VT_i}x^n, 0\right), \tag{1}$$

where g_{VTi} is the gain and w^T_{VTi} corresponds to the afferent receptive field weights, which can be positive (excitatory) or negative (inhibitory) in order to identify the region of the insole where the CoP lies and, in turn, activate the corresponding VT unit. In the experiment, the signs of the weights were chosen to associate the active region of the foot to the respective VT unit, i.e., [$w_{13} = -1$, $w_{12} = -0.1$, $w_{11} = 1$] for the heel-strike neuron, [−0.3, 1, −0.1] for the flat-foot neuron, and [1, −0.8, −1] for the toe-off neuron. Gains of 10, 60, and 25, were used for heel-strike, flat-foot, and toe-off neuron, respectively. The artificial neurons were updated at a frequency of 16 kHz in a Zynq-7020 FPGA embedded in a system on a module (sbRIO-9651, National Instruments, Austin, TX, USA) [48,49]. Every neuronal spike produced a 15 ms constant activation of the corresponding VT unit. Based on this activation mechanism, the *Neuro* strategy provided both the spatial mapping of the foot–ground contact and the contact pressure, achieved through the modulation of the vibration intensity given by changes in the firing rate (Figure 1c, bottom).

2.3. Experimental Protocol

Six intact subjects (three females and three males, age 24 ± 2, weight 62 ± 10 kg, height 170 ± 6 cm, foot size 41 ± 2 EU) were recruited as volunteers for the experiments. The experiments were conducted in accordance to the ethical guidelines of Scuola Superiore Sant'Anna.

The subjects wore the haptic belt and the shoes with the sensorized insole lodged in the right one (Figure 1a). VT feedback amplitude was predefined and might be modulated according to the feedback strategies (Figure 1c). Before starting the trial, the subjects walked for 2–3 min to familiarize with the vibration intensities. The volunteers were not informed about the stimulation strategies and they were instructed to focus on the feedback, trying to understand the vibration pattern. They were asked to maintain a uniform pace and walk on a specific path that included 11 steps on a stair and 2 short overground walks. A single trial consisted of ascending the path or descending the same track while receiving one of the pseudo-randomized feedback patterns described in Section 2.2.

In order to simplify the measurement of the time taken in each trial, subjects were instructed to start each trial with the sensorized foot (right foot), and to stop upon reaching the end of the path. This ensured that the duration of the task was unbiased, computing it as the difference between the last time the sensorized foot touched the ground and the time it was raised for the first time. Figure 3 shows an example of the sequence of stimulation strategies delivered to Subject 1 during the experiment.

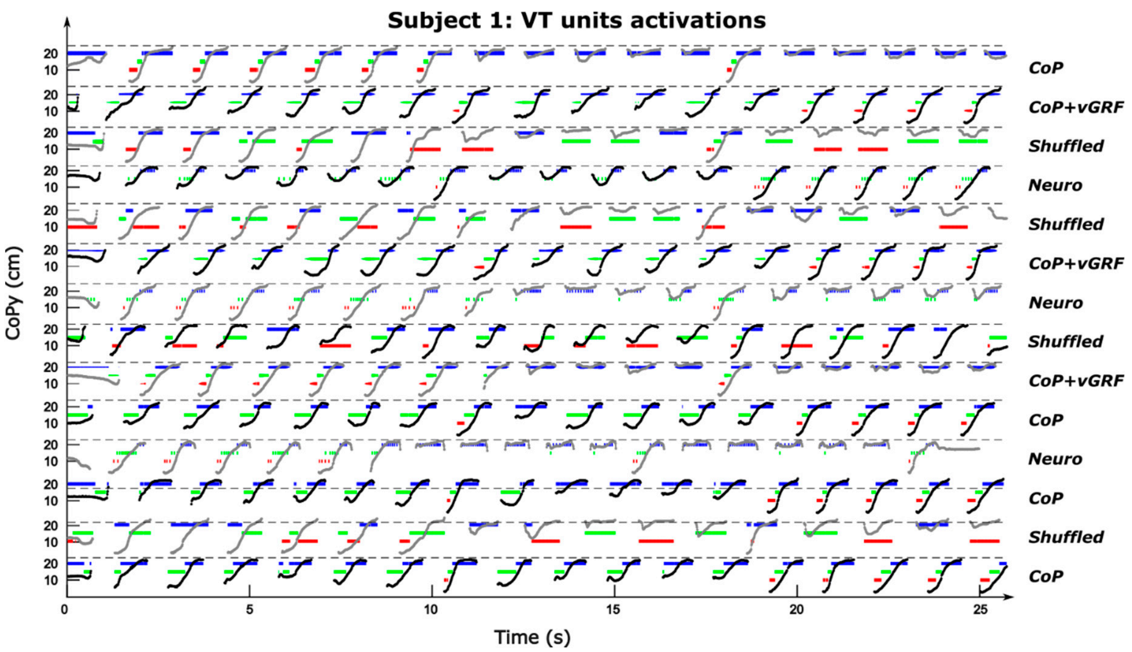

Figure 3. Example of sequence of stimulation strategies (*CoP*, *Shuffled*, *CoP+vGRF*, and *Neuro*) delivered to Subject 1. VT1 is depicted in red; VT2 in green and VT3 in blue. Stairs ascending steps are represented in black and descending in grey.

At the end of two consecutive trials, the subjects were asked to compare the last strategy with respect to the previous one in terms of both intuitiveness and comfort, as *better*, *same*, or *worse*. The order of the stimulation strategies provided in each trial was pseudo-randomized for each subject such that all the possible pairs of consecutive strategies were repeated three times. Pairs (1, 2) and (2, 1) were considered as different, to account for possible bias in the order of presentation.

2.4. Elo-Based Data Analysis

Data analysis focused on assessing a ranking of the stimulation strategies based on the subjects' rating of intuitiveness and comfort of each strategy. The subjects were asked to perform relative comparisons between pairs of consecutive stimulation strategies. The final rating of each strategy was derived using the Elo rating algorithm, which was originally developed to rank chess players from the outcomes of their games [38]. The Elo rating is a system whereby the performance of each player is not measured absolutely but depends on the rating of his/her adversary and the result scored in the match against him/her. The difference in ratings of two players (here stimulation strategies) predicts the likely outcome of their comparison. Specifically, given ratings R_A and R_B of the strategies A and B, the probability of winning the comparison (expected score) is E_A for A, and E_B for B, as in Equation (2)

$$E_A = \frac{1}{1 + 10^{\frac{R_B - R_A}{400}}}; \qquad E_B = \frac{1}{1 + 10^{\frac{R_A - R_B}{400}}}. \tag{2}$$

At the end of each trial (comparison), the ratings are iteratively updated considering the reported outcome 'y' of each comparison (y = 1 if A wins, y = 0 if B wins, y = 0.5 if it is a draw) and the expected score associated to each strategy (E_A and E_B) such that more accurate estimates of the predicted outcome will be made in successive comparisons, as in Equation (3)

$$R'_B = R_B + K((1 - y) - E_B); R'_A = R_A + K(y - E_A). \tag{3}$$

The constant K can be set arbitrarily and corresponds to the maximum Elo points a feedback strategy can gain or lose in one comparison [37]. In the present work, K value was set to 30. All the strategies started with an initial rating value of 0. The initial value only defines a common offset that does not affect the final score.

Additionally, the time taken by the subjects to ascend and descend the pre-specified path was analyzed to estimate the possible interference between haptic feedback and movement.

Collected data will be made available on request.

3. Results

The different feedback strategies were compared in terms of intuitiveness and comfort during level and stair walking. The scores produced with the Elo rating algorithm and extracted from the comparisons made by the subjects on consecutive trials were analyzed. Figure 4 shows the subject-wise results, while Table 1 and Figure 5 report the statistics over the whole population.

The intuitiveness scores were found to be significantly different among stimulation strategies (χ^2 (3) = 13.61, p = 0.0035, Kruskal–Wallis H test). A further post-hoc comparison using a Wilcoxon rank sum test indicated that the mean score of *Shuffled* was significantly lower than *CoP* (p = 0.0152) and *CoP + vGRF* (p = 0.0411). Also the *Neuro* strategy resulted to be significantly less intuitive than both *CoP* (p = 0.0022) and *CoP + vGRF* (p = 0.0043). Thus, two levels of intuitiveness were found, with CoP-based strategies showing a similar high intuitiveness, while *Neuro* resulted to be as intuitive as the non-informative stimulations provided by *Shuffled*.

Likewise, significant differences were found between the comfort scores of the different stimulation strategies (χ^2 (3) = 14.35, p = 0.0025). A post-hoc Wilcoxon rank sum test found that both *Neuro* strategy and *CoP + vGRF* were significantly more comfortable than *Shuffled* (p = 0.0043 and p = 0.0022 respectively). *CoP* resulted to be significantly less comfortable than both *CoP + vGRF* (p = 0.026) and *Neuro* (p = 0.0152). Amplitude modulated stimulations were then found to be more comfortable independently from the temporal pattern of the stimulation.

To verify whether subjects' rankings were biased by the varying physical and cognitive efforts associated to ascending vs. descending stairs, Elo scores were computed aggregating trials going up or down (Figure 6). Though the Elo scores showed slightly higher intuitiveness and comfort for the descending trials compared to the ascending trials, the difference was not statistically significant (χ^2 (1) = 1.64, p = 0.2 for intuitiveness and χ^2 (1) = 0.1, p = 0.75 for comfort, Kruskal-Wallis H test).

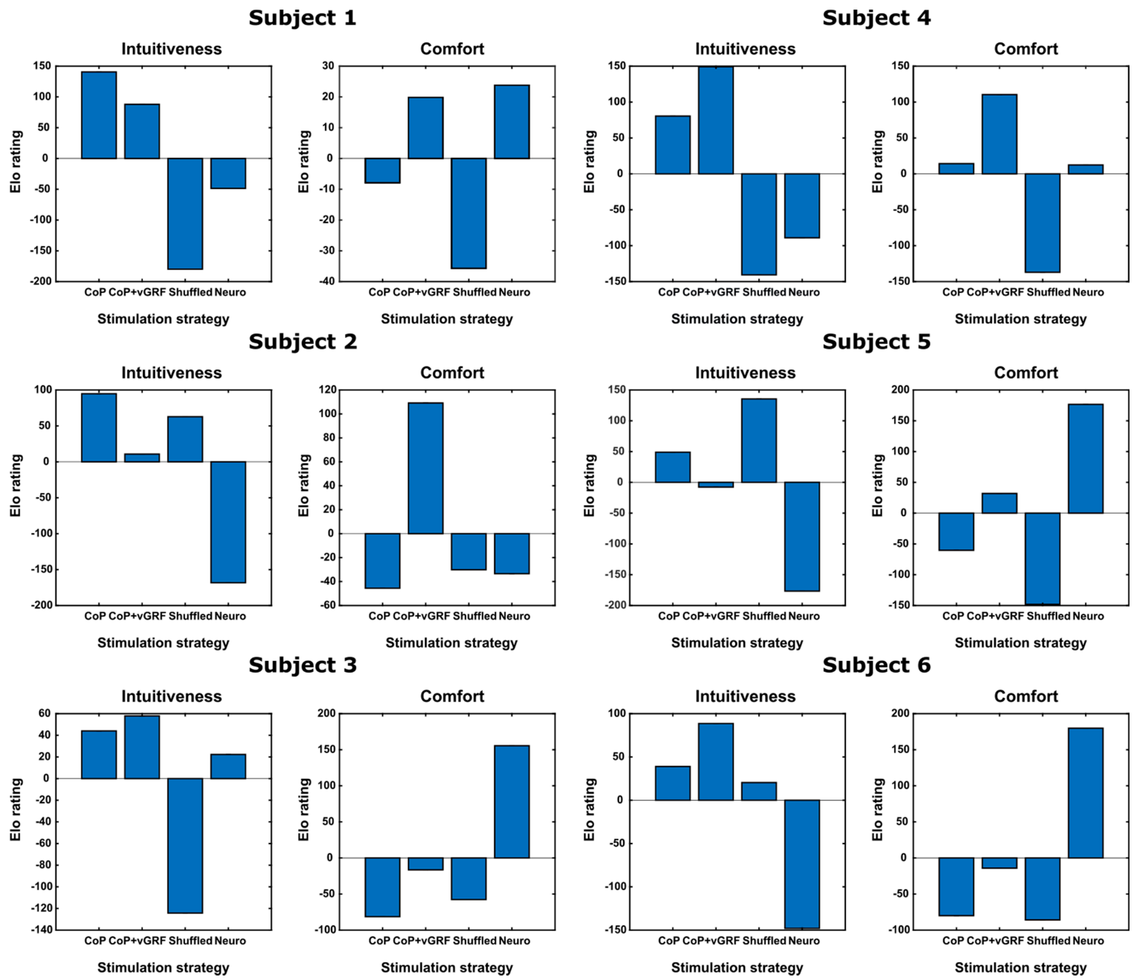

Figure 4. Results on Elo rating of intuitiveness and comfort of stimulation strategies, for each subject.

Table 1. Median (M) and interquartile range (IQR [Q1, Q3]) of the Elo scores for intuitiveness and comfort of each feedback strategy.

Feedback	Intuitiveness M [Q1, Q3]	Comfort M [Q1, Q3]
CoP	68.23 [38.98, 140.52]	−56.24 [−81.39, 14.23]
CoP + vGRF	72.9 [10.76, 149.16]	56.08 [−16.49, 110.4]
Shuffled	−51.91 [−173.8, 62.79]	−71.74 [−137.01, −30.14]
Neuro	−111.82 [−168.34, 22.27]	52.48 [−33.43, 179.86]

Successively, the different stimulation strategies were compared with respect to the possible decrease in the walking speed due to the cognitive load associated to the concurrent provision of the feedback. This feature was evaluated by measuring the median time the subjects took to walk through the path while receiving the feedback (Section 2.3). The analysis was performed for climbing, descending, and the combination of the two tasks. A fixed effects analysis was performed to look for statistically significant differences in the two paths (going up vs. going down) and then between individual stimulation strategies within each of them. The results are shown in Figure 7.

A Wilcoxon rank sum test indicated that the median time taken by the subjects when going up (M = 22.74 s, IQR = [21.52, 24.03] s) was statistically significantly higher than when going down (M = 20.96 s, IQR = [19.85, 23.52] s), with Z = 4.67, $p < 0.001$. However, no significant difference was found in the median times between the stimulation strategies ($p > 0.05$, Kruskal–Wallis H test), neither when going up (χ^2 (3) = 1.48, $p = 0.69$), nor when going down (χ^2 (3) = 7.28, $p = 0.06$), nor combining the two (χ^2 (3) = 3.49, $p = 0.32$).

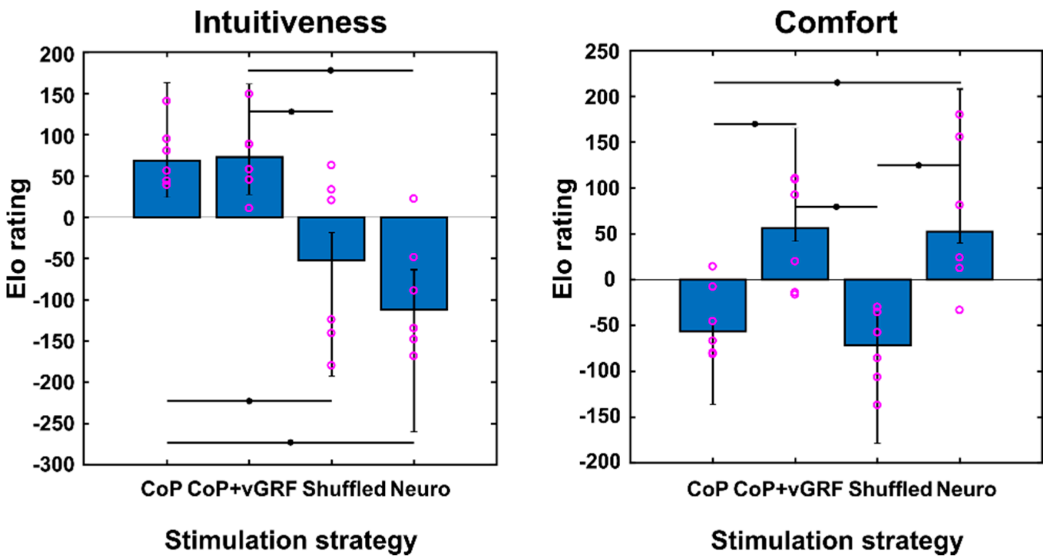

Figure 5. Median values of Elo scores. Pink circles correspond to data points. Bars indicate the upper and lower quartiles. Asterisks denote statistically significant differences.

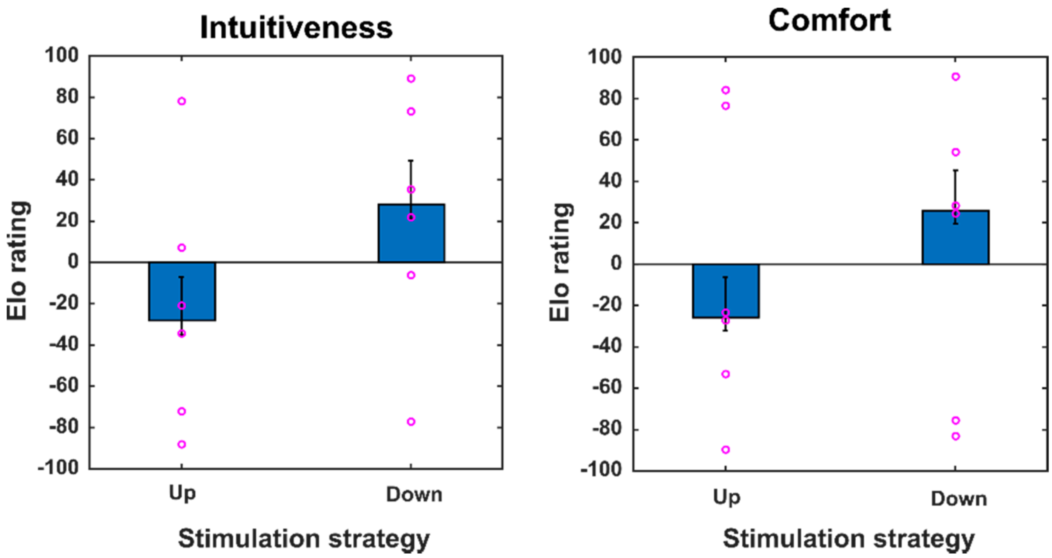

Figure 6. Median values of Elo scores computed clustering trials of going up and down. Pink circles denote data points. No significant difference was found between going up and down, for both intuitiveness and comfort. Bars denote the upper and lower quartiles.

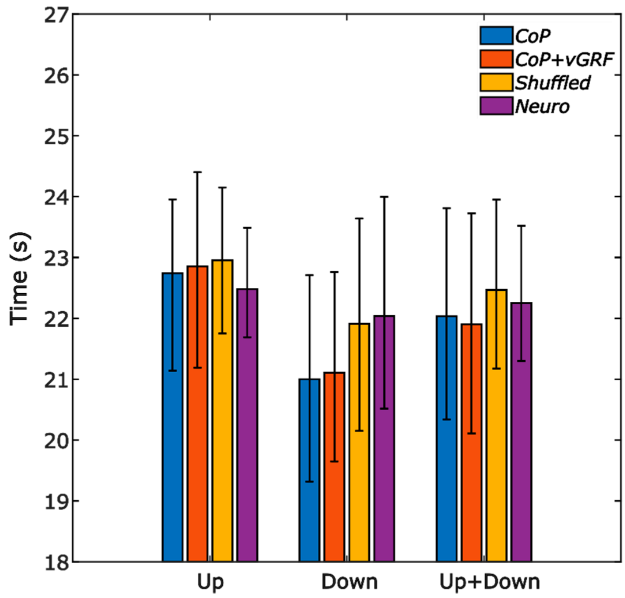

Figure 7. Comparison of the median time required by the subjects to walk along the indicated path, when going up, going down and combining all the trials together, under stimulation using the four stimulation strategies *CoP*, *CoP + vGRF*, *Shuffled* and *Neuro*. No significant differences were found between the stimulation strategies. Data were aggregated across all subjects' trials, with bars indicating the upper and lower quartiles.

4. Discussion

This work introduces a fully portable wearable haptic feedback system designed to convey augmented sensory information to lower limb amputees during level and stair walking tasks, and a novel assessment protocol to benchmark multiple feedback strategies, prior to clinical trials.

Different feedback strategies have been implemented to relocate the sensory information from the foot on the users' waist. The strategies were compared in terms of intuitiveness and comfort using a relative rating system, namely the Elo rating approach, in order to pre-select the most suitable stimulation strategy to be used in clinical trials. A key issue in the design of the assessment protocol was to guarantee that the results collected on intact subjects could be extended also to amputees. Only a few studies in literature reported on experimental trials involving intact subjects to compare different feedback strategies. For example, in the assessment protocol proposed by Plauché et al. [9], the applicability of the results on amputees was guaranteed by simulating the disability. Specifically, the subjects were asked to wear a bypass adapter to walk on an above-knee prosthesis, simulating novice prosthetic users. A different approach was adopted by Afzal et al. [35] who asked the participants to walk asymmetrically targeting a specific symmetry ratio to assess a suitable strategy to improve the gait symmetry of post-stroke patients. Both the studies proposed assessment protocols involving intact subjects mimicking the disability. In the present study, the comparison of the stimulation strategies was based on a set of parameters that are independent from the disability, such as the intuitiveness of the stimulation pattern and the comfort of the vibration. Intuitiveness and comfort have been considered as valuable metrics for the pre-selection of a suitable stimulation strategy for future clinical trials with amputees. Indeed, a counterintuitive and bothersome stimulation might increase the cognitive effort and limit the long-term use of the feedback device, resulting in a slow learning curve and poor gait performance. An advantage of the assessment protocol is that it can be used with intact subjects, potentially shortening the development time and associated costs of clinical trials. The final assessment of the effectiveness of the feedback in enhancing gait performance of amputees can however be achieved only through clinical trials.

The use of the Elo rating approach highlighted the differences between the stimulation strategies implemented in terms of intuitiveness and comfort. An initial pilot run using absolute scores (1–10) and involving two subjects (subsequently excluded from the main experiment) showed a strong bias towards intermediate values and small effect sizes (Figure 8). This evidence suggested that, with respect to absolute ratings, the relating comparisons provide a clearer and more reliable differentiation between the feedback strategies.

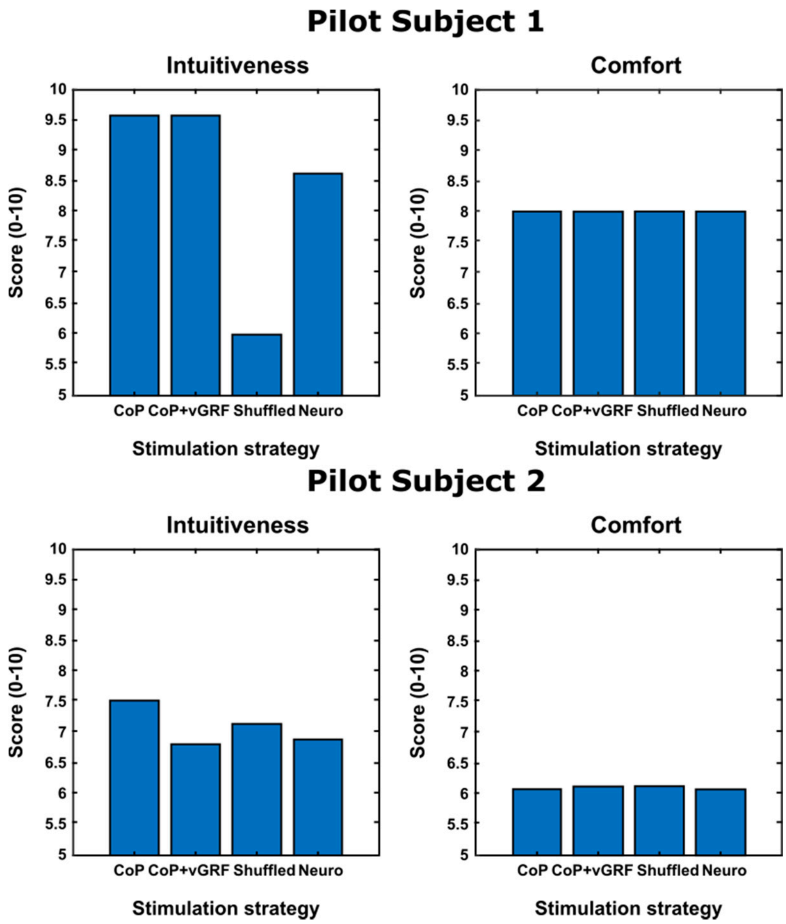

Figure 8. Results of the pilot experiments. Scores of intuitiveness and comfort of the stimulation strategies on absolute scale (0–10) computed for two subjects.

In the specific case of the three strategies proposed in the present study, *CoP* and *CoP + vGRF* were the most intuitive. As for comfort, *CoP + vGRF* and *Neuro* were found to be the best performing strategies (Figure 5).

Several studies involving young intact subjects, such as the ones recruited for the present work, reported that the subjects experienced an increased energy expenditure when ascending the stairs with respect to descending phases [39–43]. Furthermore, as stair walking is more cognitively demanding than level walking [44], also the specific task of ascending or descending the stairs may require different attentional resources. Differences in physical and cognitive effort related to specific motor tasks may affect the perceived intuitiveness and comfort of the stimulation strategies, thus biasing the results of the comparison. In order to verify such possible bias, Elo scores were computed separately for going up and down the stairs (Figure 6), demonstrating no significant influence of the specific motor task on the perceived comfort and intuitiveness of each stimulation strategy.

The outcome of the experiment can be used on one hand to pre-select the strategy to be adopted in clinical trials and, on the other hand, it can provide interesting insights on the users' perception that might guide the improvement of the stimulation strategy. For example, the lower comfort attributed to *CoP* suggested that the stimulation intensity was too high. Indeed, in *CoP* the VT units were activated at the maximum amplitude, as opposed to the other two strategies that provided either modulated activation (*CoP + vGRF*) or intermittent stimulation (*Neuro*), thus producing a softer vibration. The *Neuro* strategy was introduced because of promising studies performed on the upper limb [50,51], however for the specific application of stair walking the *CoP* strategy performed better than the other ones in terms of intuitiveness. This is presumably due to the richer information content delivered by the *Neuro* strategy, which was not fully appreciated in the specific gait task. Indeed, a more information-rich (and comfortable) feedback strategy such as *Neuro* may be more suitable for integrating the own sensorimotor scheme with information on the characteristics of terrains, and this is currently being investigated.

In order to compare the perception of the subjects against objective data, the time to complete a trial was analyzed. In the experimental protocol, the participants were asked to focus on the stimulation strategy, trying to understand the correlation between the vibration pattern and their gait. With this considered, it can be assumed that an intuitive strategy would require a lower cognitive effort to understand the stimulation signal, resulting in faster walking and thus in shorter time to complete the trial. However, no significant differences were found in the median times between the stimulation strategies and therefore the idea of using time as an objective metric for the intuitiveness must be rejected.

5. Conclusions

In conclusion, the assessment protocol presented in this study proved to be a viable way to compare stimulation strategies.

The augmented feedback strategies evaluated were capable of achieving smooth transitions among different locomotion scenarios such as ground-level walking, and ascending and descending stairs, thus showing potential for a future deployment in gait rehabilitation programs for lower limb amputees, but also in daily life use. Future studies will address the translatability of the haptic feedback system to a broader range of applications, targeting other sensory impaired subjects such as blind walkers, peripheral neuropathy, Parkinson's and post-stroke patients, or in telepresence and virtual reality applications.

In a final remark, the adoption of a protocol grounded on a relative rating system emphasized the differences among the strategies, preventing biases towards intermediate values typically observed with absolute rating methods, and it also has the potential to generalize to other quality indicators besides intuitiveness and comfort.

Future activities will involve the validation of these results with lower limb amputees to test the effectiveness of the wearable haptic feedback system and the CoP-based strategies in improving users' gait performance (e.g., temporal symmetry, speed, cognitive workload), during ground and stair walking tasks. The neuromorphic strategy will be tested on different terrains to verify the possibility of conveying terrain features, with the final goal of improving amputees' contextual awareness.

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Conflicts of Interest: N.V. and S.C. have commercial interests in the spin-off company IUVO Srl which is the exclusive licensee of the foot pressure sensors technology.

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