Multi-cue haptic guidance through wearables for enhancing human ergonomics

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***Abstract*— Wearable haptic systems can be easily integrated with the human body and represent an effective solution for a natural and unobtrusive stimulus delivery. These characteristics can open interesting perspectives for different applications, such as haptic guidance for human ergonomics enhancement, e.g. during human-robot collaborative tasks in industrial scenarios, where the usage of the visual communication channel can be problematic. In this work, we propose a wearable multi-cue system that can be worn at the arm level on both the two upper limbs, which conveys both squeezing stimuli (provided by an armband haptic device) and vibration, to provide corrective feedback for posture balancing along the user's frontal and sagittal plane, respectively. We evaluated the effectiveness of our system in delivering directional information to control the user's center of pressure position on a balancing board. We compared the here proposed haptic guidance with visual guidance cues. Results show no statistically significant differences in terms of success rate and time for task completion for the two conditions. Furthermore, participants underwent through a Subjective Quantitative Evaluation and a NASA-TLX test, evaluating the wearable haptic system as intuitive and effective.**

I. Introduction

In recent years, we have been observing an increasing deployment of Wearable Haptics (WH) systems in a wide range of scenarios of human-human and human-machine interaction [1]. These systems can be integrated with the operator's body and easily carried around, providing a natural and unobtrusive way for the delivery of different types of stimuli, which has found fertile applications in various applications.

A specific type of stimulation for which WH systems have shown great potential is related to directional feedback, e.g. for guidance purposes, usually relying on vibration [2] or skin-stretch [3]. These solutions have been usually used to increase the mobility of blind people [2], [4], or targeting training/rehabilitation purposes [5].

For what concerns the latter point, a specific attention has been devoted to investigate the usage of WH devices to provide directional feedback for kinematic guidance for ergonomics enhancement. Most of the solutions rely on the usage of uni-modal tactile cues, mostly vibration [6], [7] - which was also investigated to produce experiences of cutaneous saltation along paths that do not match the actuator configuration [8] - eventually complemented with auditory cues [9] and/or targeting a specific body segment, usually the upper limb [10]. The importance of ergonomics enhancement has recently gained further attention with the deployment of wearable interfaces and robotic technologies for Human-Robot Collaboration (HRC) in industrial settings, and the concurrent need for reducing work-related musculoskeletal disorders in human workers [11]. In such environments, wearable haptic modality has emerged as a privileged solution to provide corrective postural feedback to the human operator [12], or to increase the reciprocal awareness of the human-robotic dyad [13], compared to audio devices - which are often unsuitable in noisy industrial scenarios - or visual displays, which still represent a widely used approach in working use-cases [14] - whose usage, however, could generate safety issues for the workers, who are requested to move their visual attention from the task to the display [15].

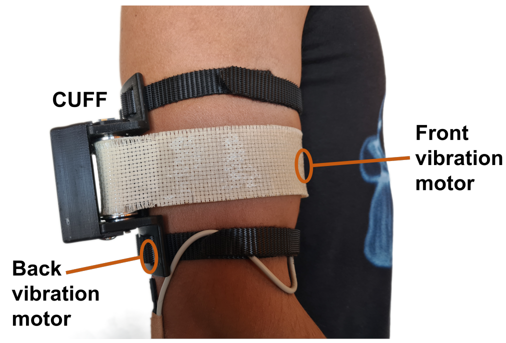

Fig. 1. Integrated multi-cue haptic guidance system with a view of the CUFF and of the vibrotactile motors positions.

However, also in this case, the majority of solutions are not designed to deliver guidance feedback regarding the correct direction of motion [12] and/or provide only vibrational stimuli [16], as in [17], where the authors presented a modular wireless sensor network suit for body postural measurements with distributed vibrotactile ON/OFF feedback (without any modulation of the duration of the OFF periods) to convey warning information and limb guidance.

One problem that may arise with the usage of vibrotactile feedback is the adaptation/saturation of the receptive channels, which imply an impairment of the tactile sensitivity after the application of the stimulus. Adaptation paradigms to investigate the characteristics of high-frequency vibration, usually in the range of Pacinian PC fibers, revealed that a few seconds of vibration stimulus reduced participants' tactile sensitivity even after the stimulus had ceased [18]. This can more likely occur when the kinematic feedback is

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provided through vibrations along multiple body axes or in a distributed manner, implying a continued over-usage of this type of stimulation.

To overcome these limitations and avoid the usage of other sensory channels than touch, in this work we present a multi-cue wearable haptic device that combines arm squeeze and only two vibration locations on the two user's arm to provide postural guidance along the user's frontal and the sagittal plane (x-axis and y-axis of the standing board used in the experiments, respectively), for the control of the Center of Pressure (CoP). The position of the CoP is indeed of paramount importance for a good balance and posture maintainance [19]. Multi-cue WH systems have been also proposed in literature [20], but their usage for multiple body axis postural guidance has not fully explored yet. In [21] the authors presented a wearable haptic device, which can provide skin stretch, pressure, and multiple-distributed vibrotactile stimuli. The system was validated in two teleoperation tasks in virtual reality (shared-control of a robotic telemanipulator; teleoperation of Unmanned Aerial Vehicles). However, these applications targeted the forearm of the user, and postural guidance along multiple body axes was not considered.

In this paper, we propose the usage of two Clenching Upper-limb Force Feedback wearable device (CUFF - [22]), which use a fabric-band actuated through two DC motors to provide normal and tangential force stimuli on the user's skin at the arm level, each integrated with two vibration motors (one, the *front*, sewn on the belt and acting on the ventral part of the arm; one, the *back*, fixed to the frame of the CUFF and acting on the dorsal part of the arm), as shown in Fig. 1.

Contrary to what we did in [4], where the CUFF device was used to provide steering commands for obstacle avoidance to blind users relying on tangential skin stretch, in this work we use only the normal force stimulation. In other words, the CUFF squeezes the user's arm with a force that is proportional to the error between the current position of the CoP along the user's frontal plane and the desired one. Two CUFF devices were used to provide corrective feedback: if the user moves from the desired position to the right, the CUFF device placed on the left arm is activated, and the other way around. Analogously, when the user is far from the desired CoP position along the sagittal plane, the two motors placed on the opposite site with respect to the direction of the error start vibrating, following an ON/OFF pattern with decreasing OFF periods proportional to the amount of error.

The main motivation that pushed us to use this solution are: (1) the need for not overusing the vibrational stimuli (also in terms of number of distributed actuators); (2) the need for substituting the tangential force stimuli for delivering right/left commands as in [4] - we observed that when the CUFF motors returned to the reference position could cause a misleading perception in users; (3) the possibility to differentiate the directional commands along the two axes, also at the mechanoreceptor level, to avoid the possible misperception that haptic multi-cue delivery can produce [15].

The proposed device may allow a more flexible and low-cost implementation with respect to exoskeletons [23]. Moreover, the device here described has not the goal of correcting the posture physically moving the user but guiding the user to perform the movements by himself, allowing also a possible long term learning effect.

We compared the here proposed haptic guidance with visual guidance cues. Results show no statistically significant differences in terms of success rate and time for task completion for the two conditions. Furthermore, participants underwent through a Subjective Quantitative Evaluation and a NASA-TLX test, evaluating the wearable haptic system as intuitive and effective. These results are promising and suggest that our system can represent a viable solution for ergonomics enhancement and posture correction.

II. A MULTI-CUE WEARABLE HAPTIC GUIDANCE SYSTEM

As introduced in the previous section, in this work, we propose a novel multi-cue WH system for providing guidance feedback for postural correction. The system consists of two sub-systems: (1) a CUFF device; (2) two vibrotactile motors, the *front* and the *back* one, see Fig. 1. Regarding (1), the CUFF is composed of two DC motors that are attached to a fabric band covered with a bio-compatible silicone layer: the two motors can be controlled to move in the same direction, generating a sliding of the fabric (in this manner a tangential force is delivered to the skin), or in opposite directions (squeezing or releasing the fabric over the limb). The latter is the stimulation mode used in our work. The two DC motors are controlled with a double loop, one in current and one in position, to maintain precise and stable positions and allow a stable grip of the fabric band on the users' skin. The wearable haptic device in its original structure weights ≈ 230 g, and its dimensions are $12.4 \times 7.0 \times 5.8$ cm. For further details, see [4]. It was already successfully applied in telerobotics and for training/assistive applications [3], [4], [22]. The CUFF is controlled using an on-board custom control board capable of managing the two motors movements and the communication with the computer through bus RS485.

We performed a preliminary characterization to understand the squeezing force workspace exerted by the CUFF. More specifically, we encapsulated a 3-axis force sensor, the ATI Gamma (resolution 0.01 N), into a 3D printed ABS structure with radius 85 mm (which is coherent with the related anthropometric range [24]) and we measured both the force applied to the structure and the current absorbed by the CUFF motors. We identified a range between 3 N (pretensioning) and 20 N (corresponding to 0 and 1000 mA respectively, which was the upper limit imposed via firmware to the CUFF device). These values identified the lower and upper limits for a correct usage of the device. Future work will target a more in depth and detailed characterization of the CUFF system.

Regarding (2), we used flat resonant motors (diameter 10mm, height 3mm, weight 2g). The actuators dimensions and geometry enabled a fast integration with the CUFF device, without affecting the overall system wearability. The vibration motors were controlled through an ELEGOO NANO V3.0 Controller Board (by ELEGOO, China) with custom firmware control on board.

The choice of using the arm location for the feedback is driven by the potentiality of the device, that in future

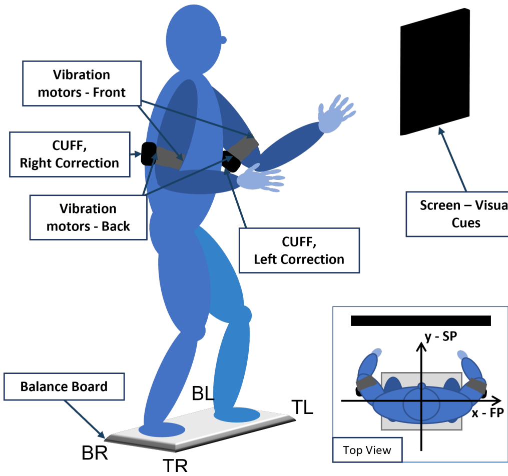

Fig. 2. Schematic visualization of the experimental setup. In the scheme it is possible to observe the position of the participant with respect to the board and the screen, as well as the position of the haptic systems. BR (Bottom-Right), BL (Bottom-Left), TR (Top-Right) and TL (Top-Left) indicate the four force sensors on the board. In the top view square, the two axes of movement and relative body reference planes are shown: SP stands for Sagittal Plane and FP for Frontal Plane.

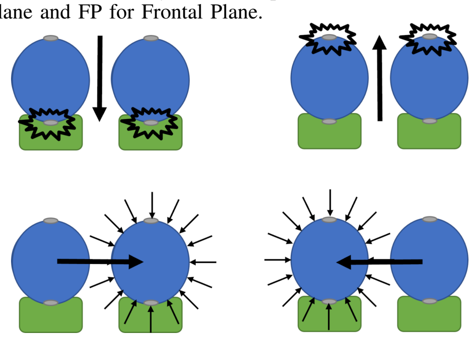

Fig. 3. Schematic visualization of multi-cue haptic guidance implementation. In blue the section of the arm, in green the frame of the CUFF, placed on the dorsal part of the arm, in grey the positions for the vibration motors. The large black arrows represent the direction of the guidance feedback; the signs around the vibration motors indicate the motors that are activated; the small arrows around the arm indicate the squeezing stimuli provided through the CUFF.

implementation can be used to provide also control and correction of the upper body rotation.

III. Experimental Setup

The experimental setup consisted of three main components: the multi-cue haptic guidance system; the sensorized standing/balancing board; the visual display (see Fig. 2).

A. Multi-cue Haptic Guidance Implementation

The haptic multi-cue guidance system introduced in Sec. II was placed on each upper arm, in correspondence with the biceps.

Two different cues were used to guide the movement along two perpendicular directions, i.e. the squeezing cue on the arm delivered through the CUFF was used to guide the movement along the x-axis of the standing board, meanwhile the vibration delivered through the resonant motors was used to provide corrective postural feedback along the y-axis of the standing board as in Fig. 3. When the CUFF squeezes the right arm, the user is informed to move the weight toward the right side of the balancing board. The same concept but in a specular way applies to the left arm. A vibration of the two motors placed on the front side is used to guide the user to move the weight toward the front side of the board. The same concept but in a specular way applies to the two vibration motors placed on the back side.

The two cues are modulated in order to be proportional to the error between the current CoP position and the desired reference position in the x-y plane.

Regarding the guidance along the x-axis, when the subject is placed in the goal position and the error is null, the force exerted on both the arm is 3 N, which is the pretensioning force. If the user moves from the goal position, the CUFF on the opposite side starts squeezing with a force intensity proportional to the error - see Sec. III-B and Eq. 5. A maximum squeezing force of 20 N is exerted when the error modulus is equal to or larger than 1. Considering this control protocol, only one CUFF at a time was controlled to squeeze the arm, while the other one was in the pretensioning state.

Regarding the guidance along the y-axis, when the subject is placed in the goal position and the error is null, no vibration is provided through the resonant actuators. If the user moves from the goal position, the two motors on the opposite side start vibrating following an ON/OFF pattern with decreasing OFF periods proportional to the error. The activation of the vibration is always synchronized in both the arms. The squeezing and the vibration can be provided simultaneously as in [21]. When the actuator is active (correction is needed) the ON period is always 100ms, while the OFF period goes from 500ms to 0ms (continuous vibration) if error modulus is equal to or larger than 1.

The values for the ON/OFF periods and the proportional coefficients were chosen relying on previous related works [21] as well as to minimize the effects of adaptation [18] and users' unpleasantness. This also applies to the proportional coefficient used to control the squeezing force of the CUFF. The tuning of these coefficients was performed heuristically, after some preliminary pilot experiments.

The haptic system is connected through two cables to the computer, one for the two CUFF devices and one for the four resonant motors.

B. Balancing Board and Error Computation

The board was used to reconstruct the CoP position. The used platform is a Nintendo Wii Balance Board (by Nintendo, Japan). The board dimensions are 510 mm (l) along the frontal plane and 310 mm (h) along the sagittal plane. The proposed platform is capable of computing the CoP position starting from the measurement of the weight in the four corners through four force sensors (m_{TR}, m_{BR}, m_{TL} and m_{BL} - see Fig. 2). Defining $m_R = m_{TR} + m_{BR}$, $m_L = m_{TL} + m_{BL}$, $m_T = m_{TR} + m_{TL}$, $m_B = m_{BR} + m_{BL}$, and $m_{tot} = m_T + m_B = m_R + m_L$, the computation of the position is performed per coordinate (x and y axes of the board) as

$$PP_x = \frac{m_R - m_L}{m_{tot}} \tag{1}$$

$$PP_y = \frac{m_T - m_B}{m_{tot}} \tag{2}$$

where PP_x and PP_y are the coordinates of the center of pressure and range from -1 (weight completely on the left/back) to 1 (weight completely on the right/front).

Given this, defining $OP = [OP_x, OP_y]$ as the objective point, the error is given by

$$E_x = \frac{OP_x - PP_x}{l/2} \tag{3}$$

$$E_y = \frac{OP_y - PP_y}{h/2} \tag{4}$$

where E_x and E_y are the error along the x and y direction respectively. We can define the error as $E = [E_x, E_y]$ Consequently the input for the CUFF is

$$F = \begin{cases} 3 + 17|E_x| & \text{if } |E_x| < 1 \\ 20 & \text{if } |E_x| \geqslant 1 \end{cases} \tag{5}$$

where F is expressed in N and it is the CUFF input that is sent to the right CUFF if $E_x > 0$, to the left CUFF otherwise. The other CUFF is kept to 3 N. The input for the vibration is instead

$$T_{OFF} = \begin{cases} 500 - 500|E_y| & \text{if } |E_y| < 1 \\ 0 & \text{if } |E_y| \geqslant 1 \end{cases} \tag{6}$$

$$T_{ON} = \begin{cases} 0 & \text{if } |E_y| = 0 \\ 100 & \text{if } |E_y| > 0 \end{cases} \tag{7}$$

where T_{OFF} and T_{ON} are expressed in ms and they are the duration of the OFF and ON periods respectively of the pattern generated by the front resonant motors if $E_y > 0$, the back ones otherwise. The other couple of resonant motors is kept deactivated ($T_{ON} = 0$ ms)

C. Visual Display

The visual display always shows a top view of the board and can be used to provide multiple information, see Fig. 4 for a detailed view. The visual information is provided through a 27″ monitor placed at the participant's eyes height.

To maintain a parallel representation with the haptic cues, also the visual guidance cue (Fig. 4(d)) has been designed to provide both the amount of error and the movement direction. In this case, the amount of error is coded with the color of a circle placed in the center of the board. The color varies from green when the participant is on the goal position, to red when $\|E\| \geqslant 1$. The direction of correction is instead represented by a small black circle anchored to the color-changing circle diameter.

D. Synchronization

The whole system used for the experiment is managed by a Python master program, which collects the measurements from the board and sends the outputs to manage the visual system and haptic system. It also collects the experimental times and the fulfilment of the goal of the experimental task.

The Balancing Board is connected via Bluetooth to the PC managing the whole experiment. The choice of using this wireless connection for the board, despite possible delays due to the connection, has been done considering that the final goal of our work is to build a completely wireless system for posture correction in an industrial environment. The CoP position is computed through the Python master program.

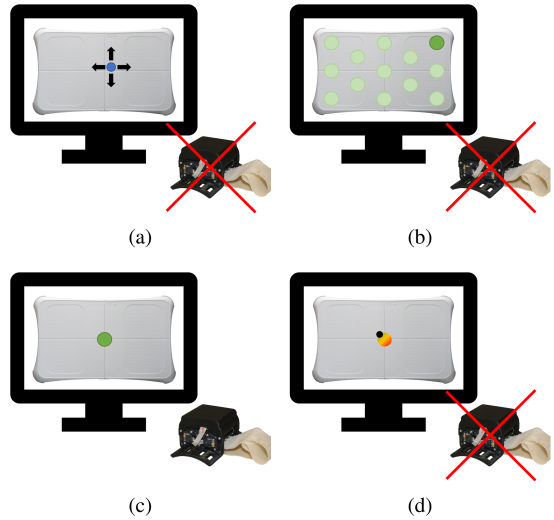

Fig. 4. A schematic view of the four experimental conditions, with visual cues and haptic condition: Training (a), NGc (b), Hc (c) and Vc (d). The CUFF image with a red cross means that no haptic feedback is used in that condition. In (a) the blue circle is the actual position of the CoP, it moves in real time with the movements of the participant. In (b) the green circles are the goal positions, the visualization of all the possible positions in the figure is only for descriptive reasons, only one circle is presented per trial. In (c) the green circle represents the "active trial" cue, it is showed only during the experimental time. In (d) the shaded from green to red dot represent the amplitude of the error cue for the Visual Guidance; the small black circle is the direction of the corrective direction with respect to the center of the target.

On the same computer, a second custom made C++ program computes the position errors that are used to generate the inputs for the haptic system and the data to send to the visual feedback system manager.

The visual display is managed through a third custom Python program running on the same computer.

The control system managing the experiment execution runs at 200Hz, updating every 5 ms the position of CoP, the signal sent to the haptic system, and the screen state. The lag between force data request and the haptic actuation commands is 102 ± 21 μs (mean$\pm$SD over 5000 samples), with worst case 260 μs.

IV. Experimental Protocol

Eleven naïve volunteers (8 males and 3 females, age 27.00 ± 2.37) took part in the experimental tests. All participants gave informed consent to perform the experiments. No subjects reported physical limitations that would affect their ability to perform the task. The experimental procedures were approved by the Committee on Bioethics of the University of Pisa - Review No. 30/2020.

Thirteen locations were chosen as position goals for the experiment (see Fig. 4(b)); their selection was performed through a preliminary study with 5 subjects considering the average deviation for 10 s around 40 different equally distributed positions on the board, while the current CoP position was visualized. The chosen locations were selected in order to be spaced more than the average oscillation and were equally distributed on the board. The participant was considered to be in the goal position if his/her position was in a surrounding of the exact point with a radius equal to 5% of the size of the board, which is less than the average deviation that we previously introduced.

Before starting the experiment the subject was instructed on the different tasks to perform. During the experiment the subject was asked to stand on the balancing board in front of the screen, wearing the haptic system on the two upper arms as showed in Fig. 2.

The experiment was composed of four blocks, a training block and three experimental conditions, with a mandatory 5 minutes pause in between, showed in Fig. 4 in a schematic view. The first block was always the Training (Fig. 4(a)). This block was a 120 s fixed time trial in which the participant was able to see on the screen the actual position of the CoP and was asked to take confidence with the setup. This session had the goal of showing to the participant how to move in the whole board workspace. No training was provided on the use of the haptic device nor the visual feedback system. The three experimental condition blocks were composed of 65 trials each (5 trials for each goal position). Each trial stopped when one of the following conditions was met: a limit time of 30 s was reached, or the participant spent 5 continuous seconds on the goal point (considering the confidence range previously defined). If the latter condition was met and the total trial duration was below 30 s, the trial was considered successful.

The three experimental conditions were i) No Guidance condition (NGc), in which only the goal point was showed and no guidance was provided (Fig. 4(b)), ii) Haptic condition (Hc) (Fig. 4(c)), iii) Visual condition (Vc) (Fig. 4(d)). The three experimental conditions were presented in the same experimental session using a Latin square reduction, to balance the order between subjects and avoid alterations of the results due to a possible learning of the task. In each session, the different positions were provided with a pseudo-random order.

At the end of the experiment, the participant was asked to fill a 7-Points Likert-Scale questionnaire (1: strongly disagree; 7: strongly agree) for the whole experiment and a NASA-TLX questionnaire [25] for each condition. It allows to get a subjective self-evaluation of 6 parameters, i.e. Mental Demand (N1: How mentally demanding was the task?), Physical Demand (N2: How physically demanding was the task?), Temporal Demand (N3: How hurried or rushed was the pace of the task?), Performance (N4: How successful were you in accomplishing what you were asked to do?), Effort (N5: How hard did you have to work to accomplish your level of performance?), and Frustration (N6: How insecure, discouraged, irritated, stressed, and annoyed were you?). All scores range from 0.0 to 10.0.

V. Results and Discussion

Considering all trials of all subjects, divided in the three conditions, the success rate was 31% for NGc, 88% for Hc and 96% for Vc, with trial duration (mean±STD) of 24.78 ± 8.65, 13.87 ± 8.12 and 10.57 ± 5.99 respectively.

We performed a Wilcoxon signed-rank test with false discovery rate (FDR) adjustment through the Benjamini-Yekuteli correction. We found that there are no significant differences in terms of success rate at 0.01 significance level

TABLE I

7-Points Likert-Scale.

	Question	Mean	STD
Q1	I had the feeling of performing better while receiving feedback by the cutaneous device.	5.9	0.7
Q2	I had the feeling of performing worst while receiving only the visual feedback.	1.7	1.3
Q3	Tactile feedback was intuitive.	5.6	1.9
Q4	I felt hampered by the cutaneous device.	2.3	1.5
Q5	I felt more tired while using tactile feedback.	1.5	0.5
Q6	Visual feedback was intuitive.	5.7	2.0
Q7	I felt tired in the end of the experiment.	4.5	0.9
Q8	I had the perception of performing faster while using the cutaneous device.	5.5	1.5

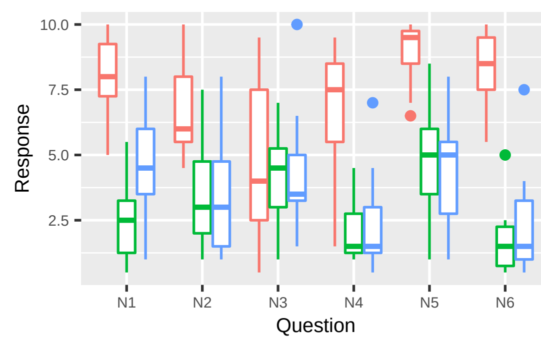

Fig. 5. NASA-TLX scores. Results considering a 21-points scale between 0 and 10, split per question and condition: in red NGc, green Vc, and blue Hc. All participants together.

between Hc and Vc (p-value 0.021). Significant differences were instead found between Hc and NGc and between Vc and NGc (p-value 0.0025 in both cases). Also taking into consideration the execution times, we found that with a p-value of 0.029 there are no significant differences at 0.01 significance level between Hc and Vc, but there are significant differences in the other comparisons (p-value 0.0029 both between Hc and NGc and between Vc and NGc).

Taking into consideration the subjective evaluation, through the 7-Point Likert-Scale Questionnaire reported in Table I it is possible to observe how the participants perceived to perform better while receiving feedback from the haptic device with respect to the other conditions (Q1) even if also the Visual feedback was considered effective (Q2). Comparing Q3 and Q6 it is possible to observe how the intuitiveness of the two feedback modalities is almost identical close, but at the same time the participants had the perception of performing faster and without fatigue with the haptic feedback (Q8 and Q5 respectively).

Considering the results of the scores provided to the NASA-TLX questionnaire, reported in Figure 5, we applied a Friedman test adjusted through the Benjamini-Yekuteli correction, to compare the three different conditions. We found a statistically significant difference between Hc and NGc and between Vc and NGc for all the parameters ($p < 0.05$), with the exception of N3 ($p = 0.36$), i.e. Temporal demand. Moreover there is no statistical difference between Vc and Hc, with the exception of N1, in which Vc performed better. Of note the haptic modality outperforms no guidance condition. These results related to Mental demand, which however are still in the low half of the range score for the Hc, can be explained in terms of a more structural attitude toward visual cues. However, a proper assessment of these aspects should be performed in real industrial scenarios.

VI. Conclusions and Future Works

In this work we tested a multi-cue wearable haptic system for the delivery of multi-axis guidance feedback for posture correction, more precisely for CoP position control. We integrated a pre-existing wearable haptic device, the CUFF, with two vibrotactile motors, in order to allow a multi-cue signal. We tested the performance of the system with respect to the visual guidance condition, which still represents a widely used modality in working settings, in an experimental session, where the ground truth condition was represented by the same experimental task without any guidance cue.

The experiment showed no statistical difference between the use of Haptic cues and the use of Visual cues in terms of success rate and time to task execution. The results of a Subjective Quantitative Evaluation and a NASA-TLX test confirmed that the wearable haptic system was perceived as intuitive and effective.

The obtained results are encouraging, suggesting that our system can represent a viable solution for ergonomics enhancement and posture correction in industrial settings, where the visual guidance could impact the level of safety of the worker in task execution. Of note future tests in real scenarios are required and already envisioned for effectively comparing the two modalities and with traditional vibrational cues. Another consideration is related to the device architecture: in this work we used only the squeezing force delivered through the CUFF. In the future, a combination of tangential and normal force cues will be investigated, also considering the effects of a combination between vibration and tangential stimulus. Future work will be also devoted to perform a more exhaustive characterization of the system and identify the relationship between the stimulus and the motor actuation as done in [21] as well as the JND of the device. Furthermore, we will also test the system in conjunction with continuous error measurement (CoP trajectory measured over time) during the task execution as in [26], and in integration with wireless and completely wearable devices for kinematic measurements as in [17].

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