A Direct-drive, Wearable Armband Device to Experiment Combined Continuous and Vibrotactile Haptic Feedback for Guidance in Motor Tasks

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Abstract. Wearable haptic devices have been proposed to convey guidance and feedback information in a variety of applications, ranging from navigation to virtual interaction and prosthetics. A design approach for armband devices using an actuated fabric belt and gearmotors actuators has been proposed and widely experimented in the field. In this work we experiment whether the use of direct-drive actuation in place of servomotors proves effective in rendering lower intensity, but cleaner linear feedback. Interestingly, the method allows for modulation of vibrotactile feedback as well, with the same actuation design. Here we present the design of a wearable haptic device for the upper limb, implementing a 2 degrees of freedom direct drive transmission and a soft belt interface. Experiments evaluate the capability of the haptic feedback to guide participants in two different motor tasks, exploiting the two haptic modalities the device can render: clenching and lateral stretch. Moreover, the addition of modulated vibrotactile feedback to the conventional linear motor activation is explored as a viable modality to enhance the perception and effectiveness of the perceived stimuli.

Keywords: Wearable Haptics · Haptic feedback · Tactile · Touch · Armband

1 Introduction

The sense of touch can be used to convey proprioceptive and directional information to humans, allowing for more informed interaction with the environment through the use of interactive data. Wearable haptic devices are developed to extend the mobility and dexterity of the user when interacting in immersive virtual experiences [16], and also to convey guidance or situational awareness information in other application fields, such as rehabilitation [19], prosthetics [5] and navigation [11].

Among the many haptic modalities, skin stretch and clenching emerge as a widely explored alternative to vibrotactile feedback, offering intuitive intensity modulation and enhancing proprioceptive awareness, especially in relation to prosthetics applications [3]. In response, various wearable haptic devices have been developed to deliver such tactile stimulations to the arm.

Ion *et al.* [14] developed the skin drag display, a forearm-worn device providing skin-stretch feedback with a lower error rate compared to vibrotactile feedback. Chinello *et al.* [8] presented a wristband for haptic guidance, utilizing servomotors to generate skin stretch feedback for both human guidance and robotic telemanipulation. The device offers rotation and translation cues based on the combination of actuated motors and their direction of rotation. Moriyama *et al.* [17] introduced a wrist-worn haptic device for virtual reality interfaces, providing the sensation of grasping an object with fingertips using two five-bar mechanism devices. *HBracelet* [15], designed for telepresence in remote robot control, combines servomotors and a shearing belt for various haptic feedback. Aggravi *et al.* [2] combines a shearing-belt approach with vibrotactile feedback in a forearm-worn device. *MISSIVE* developed by Dunkelberger *et al.* [10] encodes phonemes for haptic communication using vibrotactors and servomotors. *Movelet* [9] conveys both momentary and positional feedback using self-movement along the forearm, with its hardware comprising four interlinked segments, each containing a wheel powered by a servomotor.

Casini *et al.* [7] introduces a lightweight wearable device, CUFF, designed to render the grasping force of a prosthetic hand through distributed mechanotactile stimulation of the user's arm skin with pressure and stretch cues. Buist *et al.* [6] have designed a haptic device aimed at delivering somatosensory stimulations. This device incorporates a tactile display for touch and vibration sensations, along with a set of bands for sliding, pressure, and strain sensations. Pezent *et al.* [18] present Tasbi, a multimodal haptic wristband offering radial squeeze forces and vibrotactile feedback at discrete locations. Utilizing force sensing capacitors for closed-loop control and linear resonant actuators (LRA) for vibration, Tasbi demonstrates effective user perception in psychophysical experiments, including vibrotactile identification accuracy and preferences for squeeze actuation magnitudes. It is important to note that there are several other wearable haptic devices with different types of actuators, such as pneumatic and shape memory alloy, which are not covered in this paper. A comprehensive review of these devices can be found in [1].

All wearable haptic devices developed for the transmission of these cues have consistently employed servo motors as the actuation means, typically characterized by a high gear ratio. While this high gear ratio ensures adequate torque output from the motors, it simultaneously introduces undesirable effects in haptic rendering such as vibrations, inertial effects, gear cogging, and acoustic noise produced from these geared motors. These adverse effects have the potential to interfere with a user's perception of the haptic cues provided by the respective devices.

Moreover, it has been demonstrated that the minimum required displacement on the skin for recognition is 2 mm [7]. It is hypothesized in this context that this recognition threshold can also be achieved by a haptic device incorporating direct-drive motors. It is also hypothesized that devices using direct-drive motors could effectively apply the squeeze cue to the user, providing a grasping sensation similar to devices with geared motors.

Building upon these hypotheses, this paper introduces a direct-drive wearable haptic device, featuring two degrees of freedom, proficient in applying both squeeze and skin stretch cues to the user's forearm. A set of experiments using this device was undertaken to empirically test our hypotheses related to the direct-drive approach. In addition, experiments investigated a feedback condition augmented by modulated vibrotactile feedback. This feedback modality could be intrinsically generated through the direct-drive transmission design. These experiments were designed to examine whether subjects could enhance their performance in a motor task, guided by different feedback modalities.

2 Wearable Haptic Device Design

The device comprises three primary modules, namely the structural frame (denoted as B, C, and E in Figure 1), the actuation unit (A, D), and the interaction interface (F). The actuation unit is powered by a Maxon DCX22S, providing a nominal torque output of 14.4 mNm. Notably, no gearhead is integrated, as the device is intended for a fully direct-drive application.

The spools are connected to the motor shaft, and the straps, serving as interaction interfaces, are attached to the spools to convey the intended feedback to the user's skin. For user-device attachment, the system can be affixed to the forearm using the interfaces in A and C, where Velcro bands are positioned for circumferential securing around the user's forearm. Additionally, cushions are positioned beneath A and C, serving to eliminate any potential discomfort between the device and the user's skin.

To minimize the perceived weight of the device, careful attention has been given to reducing its overall mass. Consequently, the design prioritizes a lightweight structure, and the device itself weighs a modest 196 g. This thorough design approach is intended to enhance user comfort and promote overall usability. An exploded view of the assembly and of the final design is shown in Figure 1.

3 Experimental Methods

A perception study was conducted to evaluate the effectiveness of feedback provided by the device as guidance in a motor task. The selected task exploited the two degrees of freedom the device could render, namely clenching and lateral stretch stimuli. It also took into account further applications in neurorehabilitation, involving grasping and pronosupination motor tasks. The clenching feedback was associated with modulation of hand opening and closing, in a similar manner to the experiments conducted for prosthetic applications in [4]. The

(a) (b)

Fig. 1: The exploded CAD model of the device (a) and the assembled view (b).

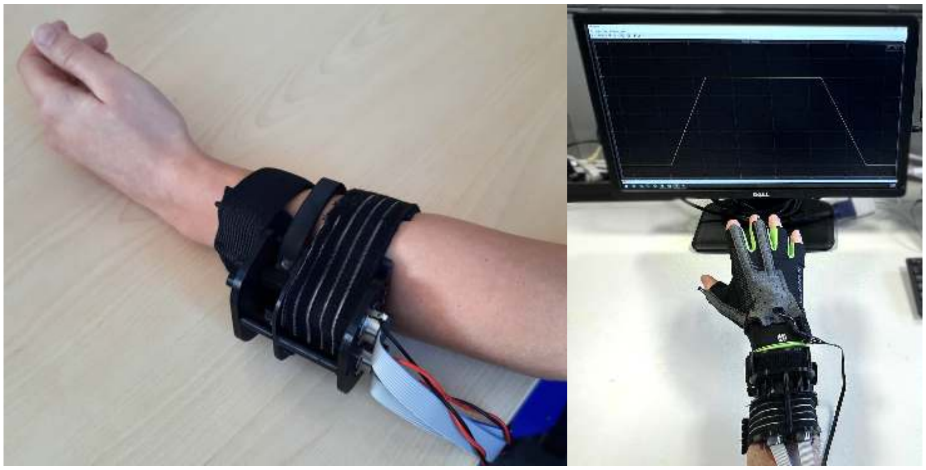
lateral stretch in the upper limb was instead related to the guidance of a prono-supination movement. Feedback signals were provided proportional to the hand pose error.

Seven participants (3 females and 4 males), all right-handed and with an average age of 27.28 ± 3.09, engaged in the experiments. Each participant provided written informed consent and had the option to discontinue participation at any point during the experiment. All experimental conditions occurred on the same day, with each session lasting approximately one hour per subject. Ethical approval for the experimental procedures was granted by the Ethical Committee of the Scuola Superiore Sant'Anna (approval number 412023).

Participants were seated in front of a monitor while wearing the developed haptic device and a data-glove (Figure 2). The data-glove incorporated resistive bending sensors (SpectraSymbol 110 mm bending sensors, 10 $kOhm$ resistance at rest) and an inertial measurement unit (IMU) module (Bosch BNO085) for estimating finger pose and hand rotation. During the experimental procedure, the averaged finger opening pose and the pronsupination angle were taken into consideration. The experiment was divided into two sessions and motor tasks.

3.1 Grasping Task

The first session involved modulation of the grasping pose. Subjects were asked to match a normalized reference signal, shown on the monitor, ranging from the completely open hand pose to the fully closed pose. A sequence of fifteen repetitions was proposed for each feedback condition. In each repetition, the reference signal started from the fully open pose and reached a discretized random value of four different hand closing levels. The reference signal held that level for 3 s before returning to the open pose. Feedback conditions were provided as follows:



(a) (b)

Fig. 2: The device prototype used in the experiment (a) and the experimental setup including a data-glove for tracking of the hand pose (b)

- **V** (*Visual feedback*) No haptic feedback was provided; the measured hand closing level was shown as a signal superimposed to the reference.
- **C** (*Continuous feedback*) Continuous, linear modulation of the clenching feedback was provided according to the measured grasping pose error. In case subjects had to increase hand closing with respect to the target, clenching feedback was perceived, while in case they had to reduce the hand closing, the actuated band was released and no additional feedback was perceived. The reference signal only was shown on the monitor. The force applied by the device to the actuated belt was 0.17 $N/\%$ of the measured hand closing error (expressed as force divided by the percentage of the full hand open-close range).
- **CT** (*Continuous and Vibrotactile feedback*) Building upon condition **C**, modulated vibrotactile feedback was rendered symmetrically by both actuators in case of negative error (measured hand closing over the reference signal). The vibration was applied by generating a sinusoidal reference signal at a frequency of 20 Hz, with the intensity modulated by the error.
- **NF** (*No feedback*) The reference signal only was shown on the monitor, and no feedback was provided to subjects.

3.2 Rolling Task

The second session involved pronosupination of the hand. A reference signal was visually provided on the monitor with the same modalities and pacing of the Grasping Task. In the Rolling task, the target levels ranged between $-30/deg$

and 30/*deg* prono-supination angle in six discrete levels with respect to the rest hand position. Feedback conditions were as follows:

- **V** (*Visual feedback*) No haptic feedback was provided; the measured prono-supination angle was shown as a signal superimposed to the reference signal.
- **C** (*Continuous feedback*) Continuous, linear modulation of the lateral stretch feedback was provided according to the measured angular error: lateral stretch was generated in the direction subjects had to roll the forearm in order to reduce the error. The reference signal only was shown on the monitor. The force applied by the device to the subject's forearm was 0.17 $N/Degree$ of the measured error.
- **CT** (*Continuous and Vibrotactile feedback*) In addition to condition **C**, modulated vibrotactile feedback was rendered asymmetrically, by the pulling motor only, with intensity proportional to the measured angular error. The method of vibration rendering was identical to that used in the grasping task.
- **NF** (*No feedback*) The reference signal only was shown on the monitor, and no feedback was provided to subjects.

Participants were given a 10-minute adaptation period for both grasping and rolling conditions, as well as for familiarizing themselves with the various feedback modalities before each session. Following each condition, subjects responded to a questionnaire and took a 3-4 minute break. The presented questionnaire consisted of the *NASA Task Load Index* [13,12] questionnaire (Table 1), which collects mental demand (MD), physical demand (PD), temporal demand (TD), performance (PR), effort (EF), and frustration (FR), through the questions. The questionnaire also includes four additional questions that focus more on the haptic feedback perception (Table 2) assessing intuitiveness (IN), clarity (CL), reliability (RE), and guidance (GU) of the provided feedback. Responses were collected using a 5-point Likert scale, where a rating of 5 indicated strong agreement and 1 signified strong disagreement. The feedback perception and nasa questions are as follows:

Table 1: NASA Task Load Index Questions

Code	Question
MD	How mentally demanding was the task?
PD	How physically demanding was the task?
TD	How hurried or rushed was the pace of the task?
PR	How successful were you in accomplishing what you were asked to do?
EF	How hard did you have to work to accomplish your level of performance?
FR	How insecure, discouraged, irritated, stressed, and annoyed were you?

Table 2: Feedback Perception Questions

Code	Question
IN	How intuitive was the provided feedback?
CL	How clear was the provided feedback?
RE	I relied on the provided feedback to perform the movement.
GU	The provided feedback allowed me to guide the movement precisely.

3.3 Data analysis

To detect whether differences among conditions were significant, a statistical analysis was conducted on the results dataset. Initially, a normality test was performed using the Shapiro-Wilk test. Given the non-normality of the dataset, non-parametric tests were employed. The Kruskal-Wallis test was utilized to evaluate differences among groups (i.e., experimental conditions), followed by the paired Wilcoxon signed-rank test to assess differences between the two conditions. To mitigate type-I errors during multiple comparisons, Holm-Bonferroni correction was applied to the p-values.

4 Results and Discussion

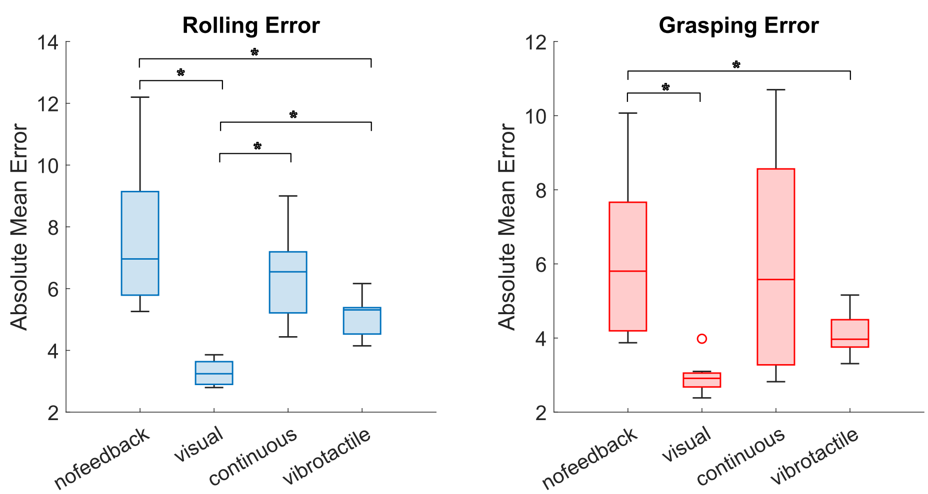


Fig. 3: User absolute error in tracking profiles for both grasping and rolling tasks across four conditions. The plot depicts the tracking error of subjects as they engage in the tasks under varying conditions.

In the experiments, the NF and the V condition were performed for comparison with the investigated haptic feedback condition: while the NF condition

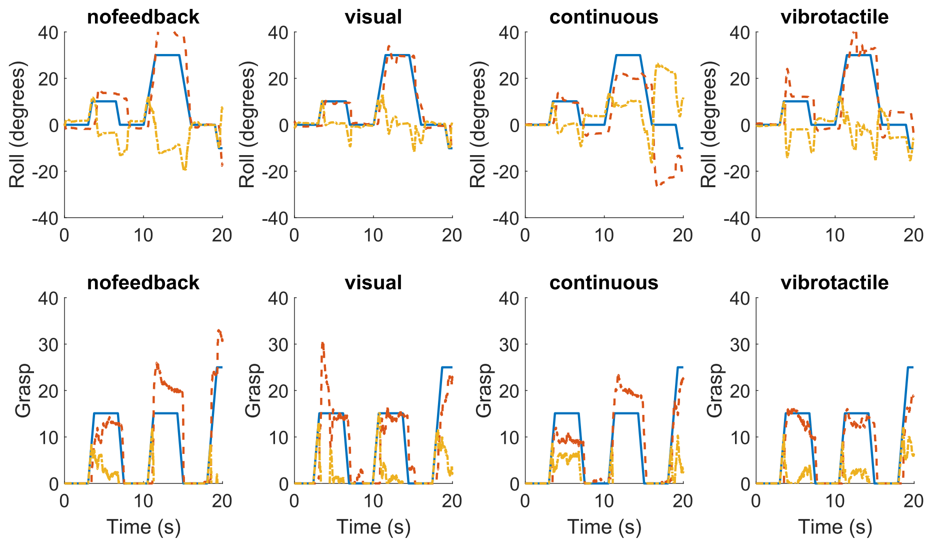


Fig. 4: The desired profile, measured profile, and error profile of a representative subject for both grasping and rolling tasks across four conditions. The blue, red, and yellow profiles correspond to the desired, measured, and error profiles, respectively.

relied only on proprioception of the hand pose, the V condition allowed for precise matching of the hand pose with the reference. Concerning the grasping task, the Kruskal Wallis test revealed significant differences among groups ($p = .011$) so paired Wilcoxon signed rank tests have been performed showing a statistically significant difference between NF and V conditions ($p = .014$) and between NF and CT conditions ($p = .035$). Concerning the rolling task, also, in this case, the Kruskal Wallis test revealed significant differences among groups ($p < .001$) so paired Wilcoxon signed rank tests have been performed revealing a statistically significant difference between NF and V conditions ($p = .004$), between NF and CT conditions ($p = .033$), between V and C conditions ($p = .004$), and finally between V and CT conditions ($p = .003$).

As expected, the visual feedback (V) demonstrated a significant difference in both tasks, as can be inferred from Figure 3. The continuous haptic feedback (C) did not exhibit any significant difference compared to the NF condition. On the other hand, the CT feedback showed a significant difference from the NF condition in both rolling and grasping tasks. This behavior can be qualitatively evaluated in Figure 4, reporting repetitions of a sample subject in the time domain.

Regarding the grasping task, the C condition showed a very high variability between subjects and an average performance close to the NF condition. This can be explained by both a not clear perception of the provided stimuli, and also by the role of the error modulated feedback approach chosen in the experi-

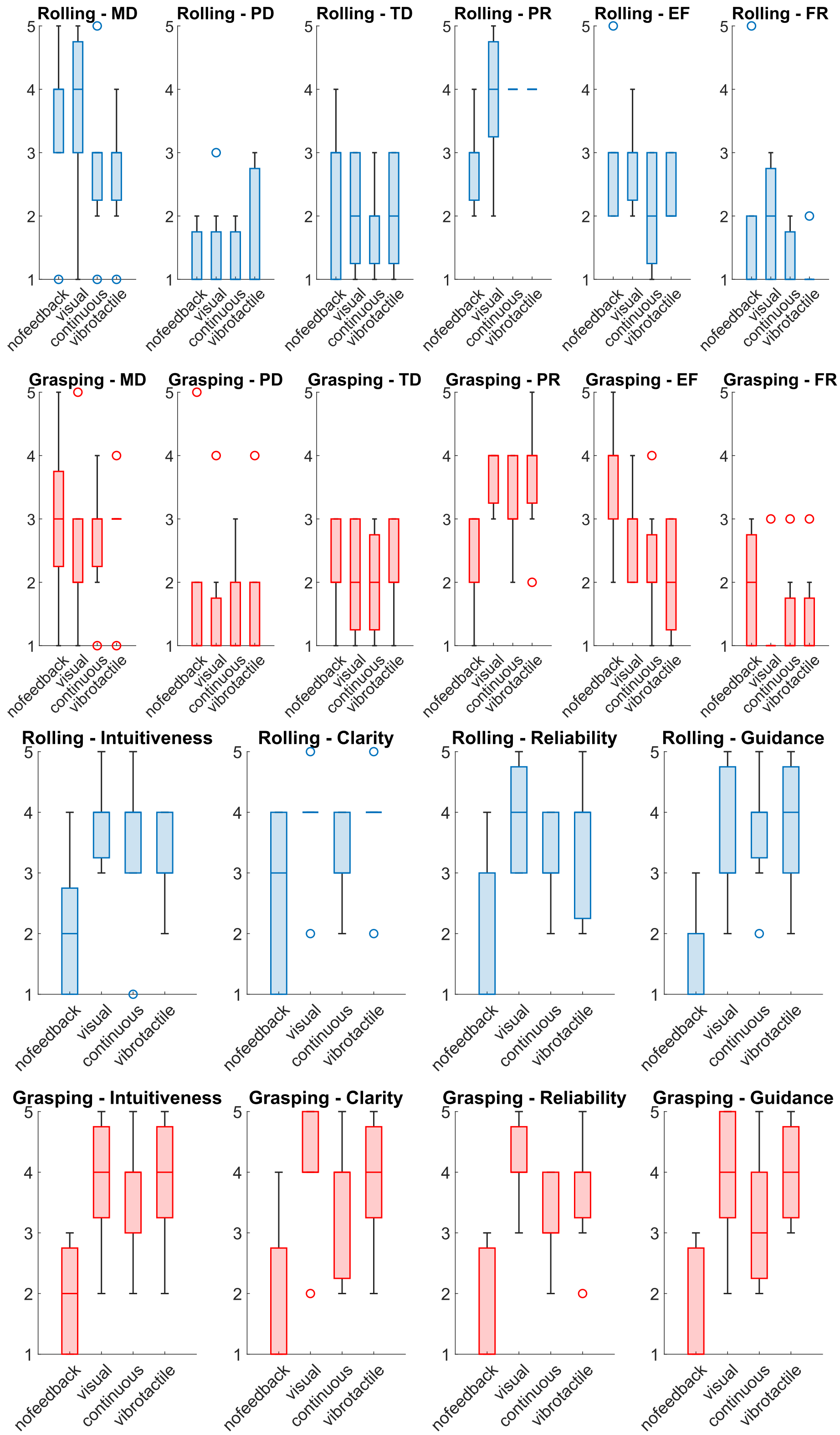


Fig. 5: Results of the questionnaire answers in the different feedback conditions.

ment. On one hand, modulating feedback proportional to the error is effective for precise matching of the target reference, on the other hand, it requires a bidirectional feedback that was not possible to render through the continuous feedback only for the grasping task paradigm. Here, negative error (hand more closed than reference) resulted in loosening the actuated belt, which is perceived as similar to the zero error stimulus. The addition of vibrotactile feedback covered the negative error modulation, resulting in improved performance and reduced variability between subjects, with a significant difference with respect to the NF condition.

In the rolling task, the C condition displayed higher between-subject variation, similar to the grasping task. The lack of significant improvement may be related to the amplitude and type of stimuli presented to the subjects. By actuating the motors associated with the rolling error direction and deactivating the other to follow the active motor passively, continuous haptic feedback has been delivered in an open-loop manner, modulating the exerted force. An alternative control method is to provide continuous feedback in terms of displacement, by means of a closed-loop position control on the motors. This might improve the sensitivity of the modulation and could enhance the overall perception of subjects regarding rolling with continuous haptic feedback.

Regarding the questionnaire results which are depicted in Figure 5, the answers of both the NASA group and the feedback perception group did not show evident differences among the different feedback conditions. The NF condition reported lower scores throughout the feedback perception group, yet this is expected since no actual feedback was provided. Interestingly, the mental load question reported higher values for the V condition, probably due to the higher resolution the feedback could provide, hence recruiting a higher mental load to precisely match the measured and reference signals. Another interesting point is that both the C and CT feedback reported similar scores in the feedback perception group, although they achieved different performances in the quantitative error results.

5 Conclusion

In this work, we investigated further developments of armband wearable haptic devices based on the clench/stretch effect of an actuated fabric band. In particular, we explored a direct-drive design solution that allows linear, low-noise actuation of the band, and the intrinsic possibility of rendering vibrotactile feedback through the same actuated band. On the other hand, the signal amplitude is scaled with respect to conventional solutions implementing gearmotors.

The envisaged application is guidance in motor tasks typically used in conventional rehabilitation, such as grasping and hand pronosupination. Therefore we developed a direct drive wearable device and experimented capabilities of the feedback in two experimental scenarios involving hand closing and pronosupination control, with feedback modulation strategy proportional to the hand pose error.

Results showed that, although continuous feedback alone was not sufficient to provide effective haptic guidance (no significant differences from NF condition), the addition of vibrotactile feedback was able to improve performance with a significant difference.

In conclusion, the linear, yet low amplitude feedback provided by the direct drive solution was not sufficient alone as reliable guidance for the intended task. On the other hand, the addition of vibrotactile feedback, made possible by the proposed design approach, could provide haptic guidance in the proposed motor tasks. Further works will deal with different amplitude modulations of the combined feedback, relevant for dimensioning mass of the actuators; and with the application of the device to the envisaged grasping and pronosupination virtual rehabilitation exercises.

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Disclosure of Interests. The authors have no competing interests.

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