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**Abstract.** Haptic feedback is envisioned to be a powerful tool in (digital) orthosis fitment procedures. In context of a larger research project on digital molding and developing a glove for orthopedic experts, we explored the use of vibrotactile feedback on the wrist for wrist angle adjustments. Five different patterns are presented on both the inside and outside of the wrist as well as crossing signals. Participants were asked to indicate whether the pattern was communicating that the wrist angle had to be increased or decreased by moving the hand up or down. The results show that the vibrotactile stimuli are being interpreted consistently by the participants, provided the patterns are presented on one side of the arm. Although the interpretations were consistent within participants, there were individual differences in the reported directions of the signals, which makes it important to take into account personal preferences and calibration when implementing haptic feedback.

**Keywords:** Haptic feedback · Orthopedic fitment · Vibrotactile

## 1 Introduction

In the development of orthoses, typically, a physical mock-up is made to base the design of the aid on. To make this mock-up, plaster is used in order to create a mold around the patient's affected body part. Although the method has proven to be successful, there are some downsides to this method. First, it produces an excess of waste, and second, there is a rather small amount of objective data on the fitment process of orthoses which limits further research and development. In order to solve this, SmartScan is being developed [1]. SmartScan is a glove, which is meant to provide the practitioner digital support to develop orthopedic aids. This glove will allow the user to move their hands over a target body part to generate a digital 3D model of it, including the locally applied pressure patterns. To further improve the functionalities of SmartScan the possibilities of adding haptic feedback to help the practitioner in the fitment procedure are being explored.

One of the use cases envisioned for haptic feedback is the fitment of an ankle-foot orthosis. An ankle-foot orthosis is typically used for correcting drop-foot [2]; a condition in which the patient is unable to effectively control their foot. This results in an uncontrolled drop of the foot during loading, and the foot might also be dragged during the swing. In this case, it can prove effective to constrain the foot in a certain direction, where obtaining the right angle is vital [3]. Therefore, it would be useful to give haptic feedback on this angle to practitioners during the fitment procedure, which they perform with their hands (see Fig. 1A). This feedback information needs to be easy to understand


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by the practitioners to be effective. In this study, feedback about directionality of desired movement direction of the wrist (and thereby changing the wrist angle) is given by a wristband with vibrotactile motors. The four vibrotactile motors can be activated at different times creating different spatial and temporal patterns, which allows to study the consistency of the perceptual interpretation of vibrotactile feedback patterns about directionality on the angle of the wrist.

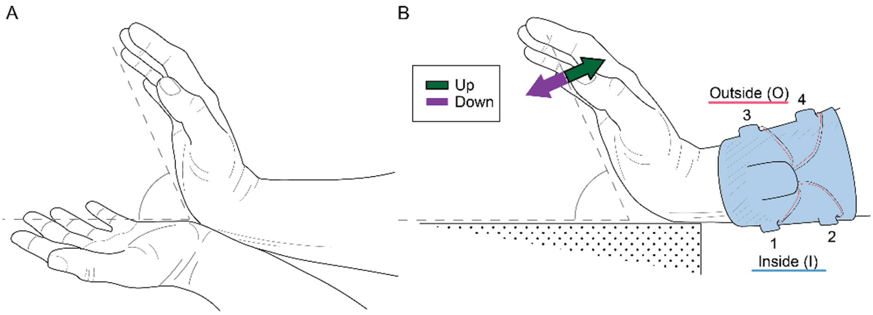


**Fig. 1.** **A.** Angle between the two hands used by practitioners during fitment of an ankle-foot orthosis. **B.** Schematic representation of the experimental set-up. Vibrotactile patterns were presented on the inside (actuator 1 and 2) and outside (actuator 3 and 4) of the arm. Participants were asked to indicate whether the presented pattern was communicating to move the hand up or down by moving their hand in the perceived direction and verbally answering 'up' or 'down'.

## 2 Vibrotactile Feedback on the Wrist Through a Wristband

Vibrotactile stimuli can be used for haptic feedback (e.g. [4, 5]) as well as for haptic communication e.g. [6, 7] or social touch (e.g. see [8] for a review). Typical findings in these studies are that spatiotemporal patterns created by vibrotactile motors can be used for communication, but the results are not always veridical (e.g. [9]). In this study, we use vibrotactile patterns as an indicator for the desired wrist angle adjustments. The actuators (Arduino vibration motor modules) are placed in a sweatband on the wrist. Two actuators are placed on both the dorsal (outside) and the ventral (inside) side of the arm, with one being on the proximal side (actuators 1 and 3 in Fig. 1B) of the wrist joint and one being on the distal side (actuators 2 and 4 in Fig. 1B) of the wrist joint. Two patterns were designed as a warning signal with either simultaneous or alternating actuation on/off actuation of the two motors on one side of the arm. The three other patterns were designed to create an illusion of movement (e.g. [10, 11]) by having a short overlap in the actuation of the subsequent motors. Actuation consisted of two motors vibrating subsequently on one side of the arm or switching between both sides. The five spatiotemporal vibration patterns that were designed for this experiment can be found in Fig. 2 (upper and middle row) and Table 1.

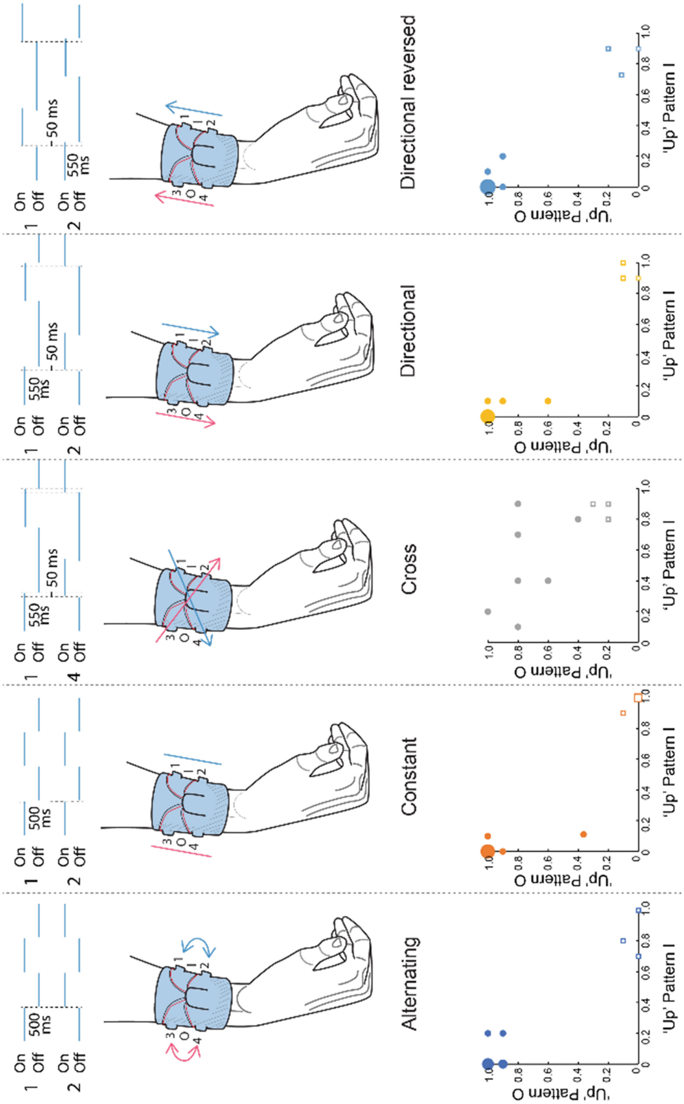


**Fig. 2.** The top row and middle row show the different vibrotactile patterns used in the experiment. At the wrists (middle row) the patterns are indicated with arrows, while on the top row the timing (two cycles) of the stimuli is schematically shown for the patterns on the inside of the arm (I, congruent with blue arrows in the middle row). Note that there was no overlap between the first and the second stimulus in the signals for the Alternating and Constant patterns, and 50 ms overlap for those in the Cross, Directional and Directional reversed patterns (which also lead to stimuli being 50 ms longer). The latter three signal types also had a 500 ms break in between the repetitions of the directional stimuli. The graphs at the bottom show the interpretation of each signal for all participants. Larger markers indicate more participants having the exact same results. Note that the data is clustered around the top left and bottom right corners (except for the Cross pattern), indicating consistent interpretations within the participants. The seven participants that interpreted the Alternating signal on the outside of the arm as 'Up' are indicated with filled circles in the graphs of all patterns, and the three participants that interpreted the Alternating signal on the inside of the arm as 'Up' are presented as open squares in the graphs of all patterns.

**Table 1.** Overview of the spatiotemporal vibrotactile patterns used in the experiment as well as the type of signal and the motors involved in the pattern.

| Pattern | Abbreviation | Type | Motors pattern inside (I) | Motors pattern outside (O) |
|---|---|---|---|---|
| Alternating | Alt | Warning | 1 & 2 | 3 & 4 |
| Constant | Cons | Warning | 1 & 2 | 3 & 4 |
| Cross | Cross | Directional | 1 & 4 | 2 & 3 |
| Directional | Dir | Directional | 1 & 2 | 3 & 4 |
| Directional reversed | Dir-Rev | Directional | 1 & 2 | 3 & 4 |

# 3 Experimental Design

## 3.1 Participants

Ten right-handed participants (seven female, 18–28 years, mean age 24.6 ± 6.5 years) volunteered to take part in the experiment, including two of the authors (FB, IK). None of the participants had known haptics deficits and except for the authors all participants were naive about the details of the experiment. All participants gave their written informed consent prior to the experiment. The study was approved by the Ethics Review Board of the TU/e.

## 3.2 Procedure

Participants received verbal instructions about the task. They were asked to sit in front of a table with their wrist on the table while wearing the sweatband with the actuators (Fig. 1B). Five different patterns were presented, once starting from the inside (I) and once starting from the outside (O). An overview of the patterns can be seen in Fig. 2. In each trial, a single pattern was presented and participants were asked to move their hand and answer ‘up’ or ‘down’ based on how they interpreted the presented signal. The pattern was repeated until the choice was made. All 10 stimuli (five patterns on two sides) were presented to the participant in a random sequence. After completing a sequence, a new random sequence was presented, for a total of 10 sequences, resulting in 100 trials per participant. The experiment took about 15 min to complete.

## 3.3 Analysis

For each participant, pattern and side the percentage of responses in which ‘up’ was chosen was calculated and compared for the inside (I) and outside (O) versions of the patterns. The consistency of the interpretation of the pattern was defined as the absolute difference between the fractions chosen ‘up’ in the inside and outside versions of the patterns. The consistency was analyzed with a one-way repeated measures ANOVA. Bonferroni corrections were used for post-hoc comparisons.

## 4 Results

The results showed large individual differences in the interpretations of the signals, as can be seen in Fig. 2, bottom row. For each participant a value between 0 and 1 for the inside (I) and (O) outside pattern is presented, which represents the fraction of 'up' responses for each pattern. For example, for the Alternating pattern, seven of the participants interpreted the pattern on the outside of the wrist as a cue to move towards the vibrated side (i.e. a value close to 1 for O and close to 0 for I), while the other three participants interpreted the signal as a cue to move away from that side (i.e. a value close to 0 for O and close to 1 for I). To assess the within-participant consistency of pattern interpretations, the three participants who had a value close to 1 for O for the Alternating pattern were indicated with a square marker in all subfigures. The same grouping of circles and squares arises in all subfigures except Cross, which suggests that there are two different (between participants), but consistent (within participants) interpretations for the same patterns.

The consistency values of all participants can be seen in Fig. 3. All participants gave consistent answers for all patterns that were on the same side of the arm (Alt, Cons, Dir, Dir-Rev), but not for the Cross pattern which gave vibrations on both sides of the arm (Fig. 3). The one-way repeated measures ANOVA showed a significant effect of pattern on the consistency ($F_{4,36} = 14.95$, $p < 0.001$, $\eta_p^2 = 0.624$). Post-hoc comparisons showed a significant difference between pattern Cross and all other patterns (all p's < 0.02) and no other significant differences.

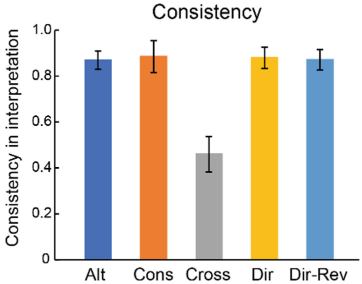


**Fig. 3.** Results. All patterns on one side of the arm show high consistency, while the Cross pattern is significantly less consistently interpreted. There is no difference between the other four patterns, indicating that the pattern itself might not be relevant.

## 5 Discussion and Conclusion

In this study we explored whether different vibrotactile patterns on the wrist could be used to give the user feedback about the desired change in wrist angle. The results show that the information can be consistently and efficiently sent by all patterns that have the vibrotactile actuation on one side of the arm. Only for the pattern in which the actuation switched sides, the consistency and therefore efficiency of the communication was low. This suggests that the side of the actuation seems to be more relevant than the actual pattern. Since no difference was found between directional patterns and warning patterns, it might be concluded that a single actuator on both sides of the arm could be enough for effective communication of the wrist angle.

An interesting finding is that there were individual differences in the interpretation of the actuations on the different sides of the arm. Seven participants interpreted the actuated side as the direction they had to move towards, while three participants interpreted the signal oppositely; they moved away from the actuated side. This means that for future application of such haptic feedback systems in practice, individual calibration will be needed, both on interpretation (similar to the preferred scrolling direction on a mousepad). Another aspect that should be individually calibrated is the intensity of the signal. Some participants indicated that the vibration was too intense, while others felt it was at the right intensity.

A next step for this project is to make the feedback signal dynamic and responsive to the real-time angle of the wrist to test whether the found solution would be suitable for online angle adjustment while developing an orthopedic aid.

To conclude, a simple vibration on one side of the wrist is an effective way to give information about the required direction of change of the angle of the wrist, but only if the interpretation of the signal can be individually calibrated.

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