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Vibrotactile Motion Guidance for Stroke Rehabilitation: A Comparative Study

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ABSTRACT

Stroke is one of the most common causes of death globally and a reason for severe impairments. Many stroke survivors report a loss of muscle strength and, thus, need to regain motor control of their upper limbs with rehabilitation. In some cases, patients may compensate for muscle weakness with harmful compensatory movements using other muscles. We envision that VR-based training can provide multimodal feedback during sensorimotor training to avoid compensatory movements. However, feedback may be hampered by changes in patients' somatosensory system, resulting in both weakened and intensified tactile perceptions. We explored the differences in perception of vibration metaphors for motion guidance between healthy participants and stroke patients and assessed the efficiency of multimodal feedback for the correction of arm trajectory. Multimodal stimuli for trajectory correction benefited the patients but there were also differences in their tactile perception. These patient-specific findings call for the involvement of patients in the design process of haptic rehabilitation devices, following the recommendations of patient-centric healthcare.

CCS CONCEPTS

• **Human-centered computing → Haptic devices**.

KEYWORDS

vibrotactile feedback, motion guidance, stroke, rehabilitation

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1 INTRODUCTION

Stroke is an event where blood flow to the brain is inadequate due to a blocked or narrowed artery (ischemic stroke) or blood vessel leakage (haemorrhagic stroke) [15]. *The resulting damage to the brain involves significant economic and individual-level implications.* In the European Union, it is projected that the number of people living with a stroke will grow by 30% from 2000 to 2025 [19]. Globally in 2019, stroke was in fact the second most common cause of death. Reported by 80% of stroke survivors, acute hemiparesis (weakness of limbs) in the upper extremities is one of the most common deficits after stroke. Impairments in motor control can hinder daily-life motor activities such as grasping, picking, or reaching [8]. Furthermore, approximately half of ischemic stroke cases reveal impairments in the somatosensory system which is concerned with the perception of touch, pain, temperature, vibration and proprioception [5].

Due to the complication of muscle weakness, stroke survivors often move their limbs strategically to give extra freedom to other joints. This is defined as *compensatory movement* [4]. Compensatory movements, such as excessive trunk movements or shoulder lifting during reaching exercises, help patients to enhance their limbs' function instantly but may harm the full functional recovery of the affected limb [4, 6]. On the other hand, it has been proven that the function of upper limbs can be restored better when these compensatory movements are minimised [13]. Therefore, it is essential to detect and correct patients' compensatory movements during exercises, which is typically done manually by physiotherapists assisting the patients.

Due to the lack of personnel resources, there is a growing need for digital solutions including virtual reality (VR) based rehabilitation systems to enable patients to do exercises correctly and independently. A key requirement here is to be able to automatically detect compensatory movements and to provide effective and real-time guidance for correcting limb trajectories. The first can be satisfied by utilizing state-of-the-art motion tracking technologies. However, the latter still remains a challenging issue.

Learning of correct movements is most successful when multisensory information is provided, because the combination of various sensory modalities helps patients "to detect, discriminate, and recognize stimuli" [9, p. 1]. Taking VR-based rehabilitation as example, VR headsets and wearable interfaces like smart gloves and garments may allow the provision of multisensory stimuli in the form of visual, auditory, and haptic feedback. In order to design intuitive multimodal feedback that can assist patients to reduce compensatory movements in VR-based rehabilitation, we investigated *how stroke patients perceive vibrotactile feedback (VTF) for motion guidance*, taking into account the changes in patients' somatosensory system and the potential impact on their tactile perceptions.

We built a vibrotactile wristband prototype and evaluated attractive/repulsive signals as well as a saltatory vibration pattern to instruct arm movement. Assuming that multimodal feedback in the form of visual and tactile information is most beneficial, we also explored *the efficiency of multisensory signals compared with unimodal signals for the correction of arm trajectory.* With this study, we followed a more humanistic approach of Patient Centred Care (PCC), which centers patients' individual experiences and preferences, in contrast to an Evidence-Based Medical (EBM) model of healthcare.

2 BACKGROUND

The focus of this study was on vibrotactile information and how it is perceived by stroke patients who may suffer from somatosensory impairments. Since visual feedback has been the primary modality in VR-based rehabilitation systems, this chapter will cover previous works on both vibrotactile and visual motion guidance.

2.1 Vibrotactile Motion Guidance

Vibrotactile motion guidance systems can increase performance of simple motion tasks with the presence of VTF [17]. This was proven by studies which explored movements of violin playing [20], sports training, dancing [11, 12], martial arts [3, 14], or rehabilitation [1, 2, 11]. It has been suggested that in guidance tasks such as above, the key for successful vibrotactile feedback design is to choose an appropriate metaphor [17]. However, the perception of vibration signals or metaphors in stroke patients or older adults remains under-explored [16]. In this study, we investigated two different metaphors to guide the patient's arm.

2.1.1 Attractive vs. repulsive polarity. One metaphor that is particularly interesting for rehabilitation purposes refers to vibration signals that appear when errors occur in angle, position or acceleration of limb joints. In turn, tactile cues can be delivered to the location where a correction is needed. These cues can be communicated by gentle tactile nudges inspired by a therapist guiding limbs for correct movement with force. It is possible to construct the vibration pattern such that the recipient moves their limb towards (*attraction*) or away (*repulsion*) from the stimulus [10], as shown in Figure 1.

In the context of rehabilitation, repulsive cues that resemble a therapist's practice of pushing limbs for correction may be more appropriate [2]. While repulsive feedback may indeed show increased performance [10], there are also findings that fail to prove that movement execution would improve with one or the other feedback modality [18].

2.1.2 Saltatory Vibration Pattern. Another metaphor relates to instructions that follow the so-called *saltatory vibration patterns.* Sensory saltation is a perceptual phenomenon in which repetitive, linear vibrotactile pulses at close but distinct points on the skin are

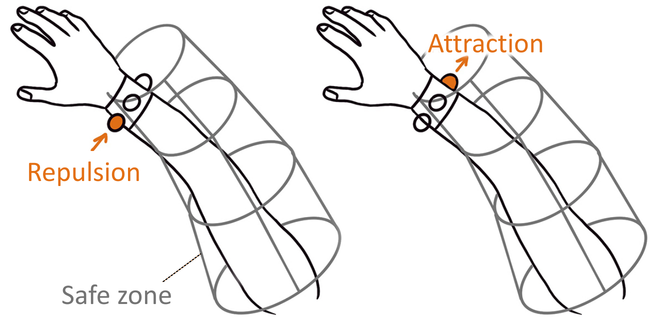

Figure 1: Once the patient deviates from the range of desired arm posture (i.e., "safe zone"), in which they are allowed to move, a repulsive/pushing or attractive/pulling vibration signal can be provided via wristband to guide the limb back into the safe zone. The vibration motor size in this figure is exaggerated to enhance readability.

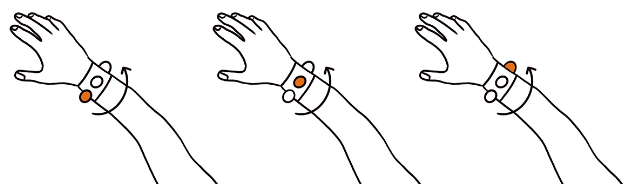

Figure 2: Saltatory vibration pattern: Short vibration pulses occurring after each other in a circular path around the wrist can instruct a wrist rotation.

interpreted to appear "as if a tiny rabbit were hopping" successively on a certain area of skin [7, p. 178]. This sensation creates a feeling of direction on the skin that could lead to moving one's limb into that felt direction. Sensory saltation has been used [11] to instruct participants to rotate their wrist by successively stimulating different vibration motors around the wrist to create a feeling of rotation (see Figure 2).

2.2 Visual Motion Guidance

Temporally, visual feedback for motion guidance can be displayed either *concurrently* or *terminally* [17]. *Concurrent* feedback provides information about movement performance simultaneously with the movement's execution, which enables immediate correction. *Terminal* feedback, in turn, is presented at the end of the execution. In stroke rehabilitation, concurrent information is more suitable since it immediately corrects the patient to avoid detrimental, compensatory movements [21].

Furthermore, feedback can be visualized either in an *abstract* or *natural* way [17]. *Abstract* information can be "lines, curves, gauges, bars, or points" [17, p. 27] which aid the learner visually to perform the movements. Also target trajectories and arrows can be used to visualise motions. Colours can indicate correct or incorrect movements. Abstract visual information may be efficient but can become boring for the learner at some point and hamper a long-term learning process. In addition, they may not be able to display complex movements in a 3-dimensional space [17]. *Natural* visualisations, in contrast, "incorporate superposition or side-by-side 3-D perspectives of a reference and the corresponding user's part" [17, p. 53]. This can be implemented with Augmented Reality or VR where parts of or the full body gets superimposed with virtual, simulated objects or bodies demonstrating the correct movement. The effectiveness of superimposition is affected by the number of superimposed objects. Learners may get confused when too many objects are displayed. In this study, we used abstract information in the form of red bars for visualising the borders of the safe zone.

3 EXPERIMENTAL STUDY

3.1 Participants

We recruited twelve healthy subjects (including six females) via our social networks. Six patient participants (including three females) were screened and recruited via the university hospital. The average age of non-patients was 36 years, while that of patients was 56. We sought for adults patients who were in their sub-acute post stroke clinical stage where most of the stroke-incurred bodily changes happen. In addition, the participant had to have motor skill impairments due to a stroke event. They had to be able to remain seated on a chair without help from an assisting person. The participants had to be able to speak Finnish, Swedish or English (thereby ruling out participants with severe stroke-caused aphasia), and be able to reflect on the haptic feedback experience (thereby excluding severe cognitive impairments such as confusion and memory losses). A haptic sensitivity assessment prior to the study revealed different levels of sensitivity among the six patients.

This study was ethically reviewed and approved by the ethics committee of the partnering University Hospital (for participants with stroke) as well as by the research ethics committee (for healthy participants) from the researchers' home university and was conducted according to the guidelines provided by the local government. Participant consent was obtained prior to the start of this study.

3.2 Setup

We sewed a custom wristband to provide vibrotactile feedback to the participants' wrists. It was designed to fit different sized wrists, was made from elastic Lycra fabric, could be attached to the wrist with a Velcro strap, and contained many small pockets that made it possible to adjust the motor locations for different-sized wrists. We equipped the wristband with four 10mm Eccentric Rotating Mass (ERM) vibration actuators placed equally around the wrist (top, left, bottom and right side). In order to control the vibration motors, we programmed an Arduino microcontroller. A Leap Motion device (https://www.ultraleap.com/) tracked the hand position (see Figure 3). The programmed application was able to communicate with the Arduino and the vibration actuators as soon as the participant deviated from the safe zone. To ease the patients' cognitive load of the task execution, we selected visual feedback as an additional feedback modality. We used the software Processing (https://processing.org/) to display red bars which represent the borders of a "safe zone": the restricted area in which the patient would be allowed to move so as to avoid performing erroneous movements. For an actual future rehabilitation application, the therapist would define this area. While Figure 1 depicts a 3-dimensional safe zone envisioned in a VR-based application, for this study, we used a 2-dimensional space that could be tracked by the Leap Motion.

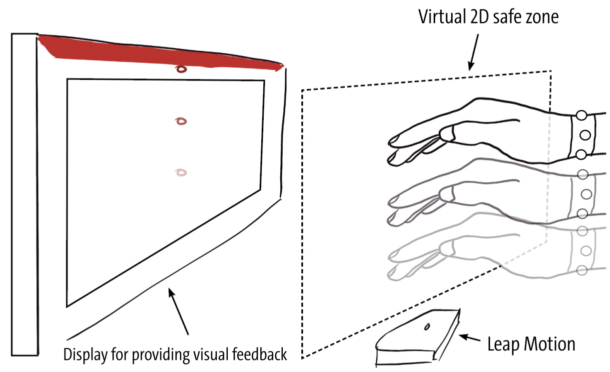

Figure 3: Experimental study setup with a monitor and leap motion.

3.3 Procedure

3.3.1 Polarities. For evaluating vibration polarities and simulating a safe zone, the participant's hand position was tracked and displayed with a visual cursor on a monitor in front (see Figure 3). We asked the participant to trace a white line that shaped a rectangle close to the four borders with the cursor. This line-tracing task was instructed to keep the participant busy with an assignment. As soon as the patient deviated with the cursor from the line towards the borders of the display, they left the safe zone and, accordingly, received the feedback both on the screen and in the wristband. On the screen, the software presented red bars at the safe zone's borders. VTF, in turn, was provided via one of the wristband's four vibration motors.

Following the literature review's findings about feedback metaphors, we selected three different VTF conditions: attractive, repulsive, and an additional *all-motors* feedback. *Attractive polarity* was played on the opposite side of the side that crossed the safe zone, thereby mimicking a pulling sensation. Thus, if the participant crossed the zone's left border, the motor in the wrist's right side was activated. *Repulsive polarity*, in turn, was provided on the same side to feel like a pushing sensation. Finally, *all four vibration motors* involved activation of all the motors when the safe zone was crossed. It produced a simple "ON/OFF" sensation as a warning signal without any spatial information. Furthermore, the sensation was stronger because four motors (instead of only one) were activated at the same time.

We repeated this task with each participant three times. Each time a different one of the three VTF modes was presented as a warning signal. For each participant, the order of presented VTF modes was randomized. After experiencing each feedback mode, we interviewed the participants to gain insights on their experience. In addition, we devised a questionnaire that collected quantitative and qualitative data about each participant's subjective experience. The questions explored the following topics.

Understanding (Q1) : How easy/difficult was it for you to understand what the vibration feedback means? (1 very helpful; 5 not helpful at all)

Detection – overall (Q2) : How helpful was the vibration feedback to detect that you touch the outer borders? (1 very helpful; 5 not helpful at all)

Detection – directions (Q3) : How helpful was the vibration feedback to detect which side of the outer border you are touching - left, right, top, bottom? (1 very helpful; 5 not helpful at all)

Mental demand (Q4) : How mentally demanding or tiring was it for you to interpret the vibration feedback? (1 low; 5 high)

(Un-)pleasantness (Q5) : How un-/pleasant was the use of vibration feedback? (1 not pleasant at all; 5 very pleasant)

Vibration intensity (Q6) : How would you rate the vibration intensity? (1 too weak; 5 too strong)

Overall experience (Q7) : How did the vibration feedback feel for you in general? (open-ended)

Overall preference (Q8) : Which type of vibration feedback did you prefer? (1st, 2nd or 3rd mode)

For Q1–Q6, we used Likert-scales from 1 to 5 to measure subjects' responses. Q8 was asked after all three modes had been presented.

3.3.2 Saltatory Pattern. As an alternative to the polarity feedback, we presented the salatory (rotational) vibration pattern to each participant via the wristband. This vibration pattern which created a sensation of rotation along the wrist consisted of two consecutive sequences. In each sequence, four adjacent motors vibrated successively. Each of them vibrated for 500ms each time followed by an interval of 250ms. The participant was, then, asked to perform a spontaneous arm/wrist movement in response to the played feedback pattern.

3.3.3 Multimodal Feedback. As the last part of the procedure, we compared reaction times of different sensory feedback modalities, namely visual-only vs. tactile-only vs. visual-tactile. The hand position was again tracked by the Leap Motion device. We asked the participant to move the cursor with their hand into the center of the display after which this part of the experiment was started. We asked the participant to move the cursor to one of the four main directions (left, top, right or bottom) until they reached the border. When that happened, they received feedback via one of the sensory modalities. On noticing it, they had to move back as quickly as possible into the center to wait for the next direction. We repeated this 16 times (each of the four main directions was instructed four times). This task of 16 instructed movements was executed by the participant three times. In each time, we addressed a different kind of sensory modality when they crossed the border:

- For visual-only, the participant only received visual feedback as in red bars representing the borders.
- For tactile-only, VTF was provided in the mode selected by the participant in the first task (repulsive, attractive or all-motors).
- The third condition presented both visual and tactile feedback at the same time.

In order to avoid the participants' learning effect, we randomized the distances between center and border. The prototype tracked the reaction time it took the participant to move back to the center once feedback was provided.

4 RESULTS

4.1 Polarities

Overall, the results from the questionnaire show that *patients* did not find differences in their preferences between different VTF types (see Figure 4). The only difference was in the vibration intensity, where the all-motors feedback was perceived as too strong compared to the other types, which, in turn were close to the optimal (in this case, middle of the scale).

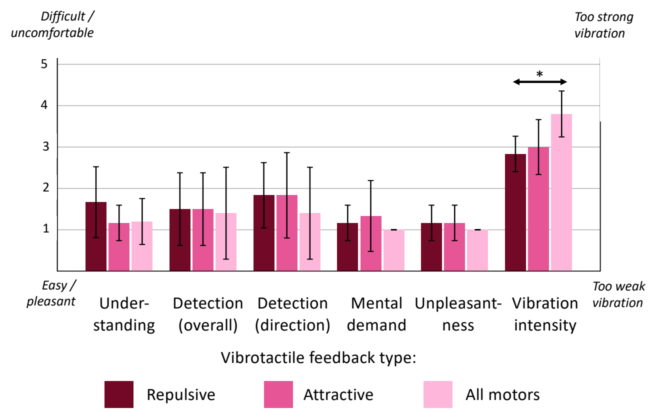

Figure 4: Averaged responses from patients, with 95% confidence intervals, for questions Q1–Q6. Lower values are better, except for vibration intensity, where 3 is the best rating. Statistically significant differences have been indicated as follows: $* = p < .05, ** = p < 0.01, *** = p < 0.001$**.**

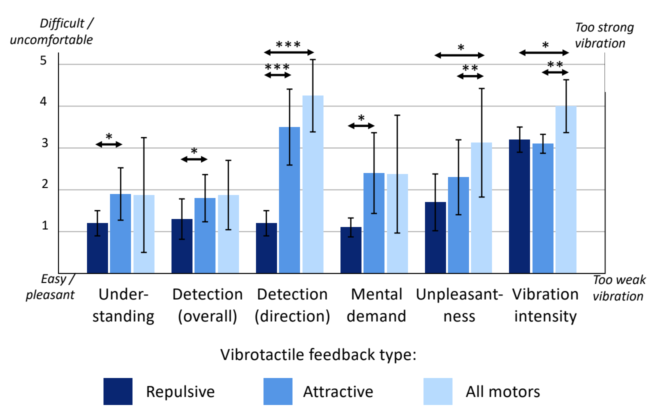

Figure 5: Averaged responses from non-patients, with 95% confidence intervals, for questions Q1–Q6. Lower values are better, except for vibration intensity, where 3 is the best rating. Statistically significant differences have been indicated as follows: $* = p < .05, ** = p < 0.01, *** = p < 0.001$**.**

Table 1: Hand movements inspired by the saltatory movement pattern.

Movement type	Number of non-patients	Number of patients
Circular arm movement	8	0
Wrist rotation (intended)	1	3
Stop-and-go movement (circular or triangular)	3	0
Lifting the arm	0	1
Swifting hand from left to right	0	1
No response	0	1

In terms of helpfulness, mental demand, and pleasantness, all three conditions received nearly the same positive rankings. This finding of similar ratings can be interpreted in two ways: either the feedback types did not differ, or the stroke patients were not able to distinguish between them. We believe that the latter was often the case: When being asked, only some of the patients told that they noticed the difference between attractive and repulsive feedback. However, even they could not tell what exactly differentiated them from each other.

Non-patients, in contrast, had differences in their responses to the same questions (Figure 5). Their ratings for repulsive feedback (i.e., moving away from the stimulus) were more positive (i.e., lower) compared to the other feedback types in different ways in all the questions, in light of pairwise post hoc within-subjects comparisons. The biggest difference was obtained in the direction detection dimension, where the benefit was statistically highly significant (**) in both of the pairwise comparisons. The differences between the attractive and all-motors feedback, in contrast, were mostly not significant: the only differences manifested in unpleasantness and vibration intensity in which case attractive feedback was considered better.

The open-ended, qualitative responses to Q7 suggest that vibration signals were helpful. This was stated in both participant groups. The patients felt, in general, positive and excited about the vibrotactile cues and reported that the signals were helpful to figure out to find their way back. They described the different polarities as "it felt nice [...] made me immediately correct the movement" (P11, patient), "exciting" (P14, patient), "pleasant and important to follow the line" (P16, patient), "surprised me in a good way" + "it was clear and easy to understand" (P18, patient). P11 (patient) described the attractive polarity as "less ticklish" and therefore "nicer" than the repulsive one.

Finally, Q8 inquired about the overall preference between the three VTF types. Patients' preferences were evenly distributed, with 1, 2 and 3 votes for repulsive, attractive and all-motors types, respectively. Non-patients, in turn, unanimously preferred the repulsive type (all 12 votes). Low participation counts prevented statistical testing, but the findings seem to suggest that different types of feedback are adequate for patients and non-patients. In addition, the uniform distribution of patients answers seems to support for inability to discern the different VTF types reliably from each other.

4.2 Saltatory Pattern

Only four out of 18 participants responded to the vibration pattern with the intended wrist rotation. Surprisingly, three out of these four individuals were stroke patients. Eight participants interpreted the vibration pattern as a circular arm movement. They executed the motion from the shoulder rather than the wrist. Three participants moved their arms in an abrupt stop-and-go way, either circularly or triangularly. The stop-and-go motion mimicked the vibrating actuators' pauses. One of the patients said that she felt the signal instructed her to lift her arm. Another one felt like "swifting" the hand from left to right as if she had a wand in her hand. Two patients had difficulties in translating the signal into a movement. It took them a few minutes to express what the signal causes in them. Nevertheless, they reported that the vibration would activate their fingers or elbow. Participants' hand movements are summarized in Table 1.

4.3 Multimodal Feedback

Finally, we wanted to investigate whether multimodal feedback (i.e., vibrotactile and visual together) would improve participants' detection of undesired compensatory movements. We found that the addition of visual feedback indeed helped the participants: The difference was statistically significant suggested by an ANOVA repeated measures test ($F(2, 30) = 6.465, p < .05$). The post hoc pairwise comparisons showed that there was no significant difference between the unimodal cues themselves ($p = .98$). Instead it was that the multimodal feedback – combining visual and tactile cues – yielded faster reaction times to correct the arm motion.

Furthermore, looking at the between-subjects factor of health condition, we observed that patients were significantly slower than those of the non-patients ($F(1, 15) = 13.289, p < 0.05$). This implies that the patients needed significantly more time to process feedback in any of the sensory modalities than the healthy subjects.

5 DISCUSSION

Stroke is a common neurological condition and its number of patients is projected to grow with an increasingly ageing population. Therefore, effective, efficient, and, particularly, patient-centric medical treatment is required. In this paper, we presented results on the perception of vibrotactile patterns for motion guidance by stroke patients and healthy participants. The ultimate goal is to build a VR-based rehabilitation system that enables patients to avoid compensatory movements during sensorimotor training by providing multimodal feedback.

In terms of the vibration polarities, the stroke patients did not have preference. Instead, they rather seemed confused about the differences. On the other hand, the non-patients clearly preferred the repulsive signals. This implies that a polarity approach may not be beneficial for arm motion guidance of stroke patients. Regarding the saltatory pattern, half of the patients executed the intended wrist rotation intuitively correct. Surprisingly, only 1 out of 12 healthy participants did so. The test on multimodal signals revealed significant shorter reaction times for the correction of arm trajectory when receiving both visual and tactile signals at the same time. Furthermore, the patients' reaction times were significantly shorter than the non-patients. However, the sample size of participants with a stroke was quite small. Therefore, the results may only give a small hint about how stroke survivors perceive vibrotactile signals.

In addition to suggesting for the benefits of multimodal feedback, the other main finding was the stark differences between stroke patients' and healthy individuals' perceptions and responses. This highlights the need for patient-centric rehabilitation approaches where patients' individual impairments are carefully taken into account when planning for rehalibitation and designing processes of (haptic) rehabilitation devices.

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