

Design and Validation of a Haptic Belt

A Wearable Vibrotactile Interface to Communicate
Operating Room Problems to a Surgeon Performing
Minimally-Invasive Robotic Surgery

Leo Klunder

Design and Validation of a Wearable Vibrotactile Interface to Communicate Operating Room Problems to a Surgeon Performing Minimally-Invasive Robotic Surgery

Master Thesis

Leo Klunder

to obtain the degree of Master of Science
in BioMechanical Engineering
at Delft University of Technology,
to be defended publicly on Friday January 9th, 2026 at 2:00 PM.

Student number:	6055370
Project duration:	February 2, 2025 – January 9, 2026
Thesis committee:	Assoc. Prof. Dr. Ir. T. Horeman, TU Delft, chair
	Ir. R. Horeman, TU Delft, supervisor
	Dr. Ir. A. Hunt, TU Delft, supervisor
	Dr. Ir. J.M. Prendergast, TU Delft, external member

An electronic version of this thesis is available at <http://repository.tudelft.nl/>.



ABSTRACT

Robotic-assisted minimally-invasive surgery offers many clinical and ergonomic advantages, however, it also adds a sensory obstacle between the surgeon and the rest of the operating room (OR), limiting their awareness of ongoing issues. The surgeon's visual and auditory channels are often overloaded during procedures, motivating the need to explore haptics as an alternative communication channel. This study presents the design and validation of a wearable vibrotactile interface, created to unobtrusively communicate OR alerts to a surgeon without interfering with their primary surgical task.

A structured design methodology was followed, including requirement definition, concept generation through a morphological chart, systematic concept selection and development of a final design. The manufactured prototype consisted of a waist-mounted haptic belt, housing a 3×4 grid of wirelessly controlled vibration motors. Five distinct vibration patterns were designed using spatial and temporal encoding to represent recurrent OR issues.

The prototype was validated in a user study involving 10 participants. The experiment was divided into two sections: an isolated pattern recognition task, involving only the haptic belt, and a combined task, pairing the belt with a robotic laparoscopic trainer (AdLap). The combined task was performed through a cross-over study, in which half of the participants started with experimental runs interrupted by haptic alerts, while the other half started with runs without alerts.

Standalone recognition accuracy reached 99.3%, while combined-task accuracy remained high at 96.0%. Additionally, the alerts did not significantly degrade the primary surgical task performance.

The results show that vibrotactile feedback can be used effectively to communicate OR information during robotic-assisted surgery. Therefore, the haptic belt represents a feasible solution to improve surgeon situational awareness, with potential for future clinical integration.

Index Terms

haptic interface, vibrotactile feedback, minimally-invasive surgery, robotic-assisted surgery

CONTENTS

1	Introduction	3
2	Methods	3
2.1	Project Goal	3
2.2	Technical Requirements	3
2.3	Performance Criteria	4
2.4	Concept Development	4
2.5	Concept Selection	5
2.6	Final Design	6
2.6.1	Stimulating Element	6
2.6.2	Control Element	7
2.6.3	Additional Electrical Components	7
2.6.4	Electrical Platform - PCB	8
2.6.5	Main Physical Platform	9
2.6.6	Protection and Attachment Elements	9
2.6.7	Power source	9
2.6.8	Software	10
2.7	Information Delivery	10
2.8	Experimental Setup	11
2.8.1	Study Protocol	11
2.8.2	Performance Parameters	11
2.8.3	Software Tools	11
2.8.4	Data Analysis	11
3	Results	12
3.1	Prototype	12
3.2	Experimental Results	14
4	Discussion	16
4.1	Interpretation of Results	16
4.1.1	Prototype	16
4.1.2	Experimental Results	16
4.2	Limitations and Suggestions	17
4.3	Financial Overview	18
5	Conclusion	18
	References	18
	Appendix A: Morphological Chart	20
	Appendix B: Microcontroller Code	22
	Appendix C: Experiment Protocol	27
	Appendix D: Experiment Cheat Sheet	29
	Appendix E: Experiment Final Questionnaire	30
	Literature Research	31

1. INTRODUCTION

Robotic-assisted surgery has become an increasingly popular solution for performing precise operations. Therefore, new surgical technologies like the Da Vinci robot are being widely adopted among healthcare institutions to perform robotic-assisted procedures. In particular, the Da Vinci Xi is a robotic surgical system consisting of two main components: a docking station where the surgeon sits (the master) and a surgical instrument composed of multiple robotic arms (the slave). The surgeon uses hand controllers and foot pedals, while viewing a magnified 3D image of the surgical field, to precisely control the robotic arms inside a patient [1]. An image of the complete Da Vinci setup is shown in Fig. 1.



Fig. 1: Da Vinci Xi surgical system, composed of docking station where the surgeon operates (on the left) and controlled robotic arms (on the right) [2].

A field in which robotic-assisted surgery has brought many benefits is that of minimally-invasive laparoscopic surgery. This is a surgical technique in which the surgeon operates through small incisions in the abdomen instead of a large cut, like in open surgery. Long, slender surgical instruments and a camera, called a laparoscope, are inserted through these incisions. The camera provides a view of the internal organs on a monitor, while the surgical tools allow for precise movements, causing minimal trauma to the surrounding tissue [3]. Compared to the traditional procedure, robotic-assisted laparoscopic surgery (RALS) offers better precision and control [4] and better ergonomics for the surgeon [5], while minimizing trauma, post-operative pain and recovery time for patients [6]. Despite all these benefits, during RALS the surgeon is visually separated from the patient and the rest of the operating room (OR) staff. So, while this setup improves surgical accuracy and reduces physical strain, it also acts as a barrier between the surgeon and the OR environment. The surgeon's full attention is directed toward the console, making it harder for them to be aware of events happening around them in the room. Additionally, the OR is a very noisy environment during operations, which causes further stress and sensory overload to the surgeon, who is already focused on a highly cognitively demanding task [7]. Information about recurring issues in the OR often reaches the surgeon through sound alarms which get quickly adapted to and ignored. For this reason, a new information transfer channel is being explored in

recent years, haptic feedback. Naturally, the main application of haptic feedback has been to restore haptic sensation for the surgeon's upper limbs, either through force feedback or reproduction of the sense of touch, with various performance benefits [8]. However, we think that haptic feedback could also be used as a channel to deliver external information in a comfortable, non-invasive way, without interfering with the surgeon's task. Communicating OR alerts through touch could improve the surgeon's awareness, while avoiding their visual and auditory channels. For this specific application, tactile signals have been proven to obtain higher accuracies compared to force stimulations [9].

Therefore, this study presents a new device to improve a surgeon's awareness, by communicating OR issues without interfering with existing sensory channels and the procedure itself. The specific problem statement was formulated as follows:

"Surgeons performing robotic-assisted minimally invasive surgery do not have a reliable and unobtrusive way to receive critical OR information through sensory channels other than vision or hearing, which are already occupied or overloaded. As a result, important events may go unnoticed, leading to potential safety risks."

2. METHODS

This section explains the design process behind the conception of the final prototype and validation experiment. Starting from the project goal, the problem was translated into a list of technical requirements and performance criteria. The device was then decomposed into functional elements, to which multiple solutions were found, creating a morphological chart. Using the chart, three initial designs were developed and compared based on the performance criteria. The best design was then defined in detail, in order to be fabricated. Lastly, an experiment protocol was designed to validate the performance of the final prototype.

2.1. Project Goal

In light of the problem statement, the project goal was formulated as follows:

"Designing and validating a wearable haptic interface to communicate operating room problems through touch, to a surgeon performing minimally-invasive robotic-assisted surgery."

2.2. Technical Requirements

- 1) The device should be wearable on a body part, thus fully portable, eventually with the exclusion of the power source. Additionally, the device should be wearable by the surgeon while being seated.
- 2) The device should be secured in place on the selected

body location with minimal to no relative movement of the stimulating elements with respect to the skin. This is to guarantee consistent and reliable signal delivery.

- 3) The device should weight less than 1 kg, which is comparable to wearing a heavy piece of clothing [10]. This is to make it comfortable to wear for extended periods of time.
- 4) The device should be thinner than roughly 3 to 5 cm on crucial components and thinner than 1 cm on the main platform. This is to be easily wearable even under clothing and to avoid excessively protruding elements that could cause discomfort and structural instability.
- 5) Relative positioning between the stimulating elements should be over the minimum distance for which the human body is able to distinguish two stimuli as being spatially separate, for any specific body location. This is called two-point discrimination threshold.
- 6) The dimensions of a single stimulating element of the device should stay under the two-point discrimination threshold, to allow placing of multiple elements next to each other even when using the minimum distance.
- 7) The total number of stimulating elements should stay between 3 and 16 (corresponding to 4 x 4 grid). This is to allow for moving stimulation patterns to be delivered, without having too many elements to power. Additionally, this range is consistent with previous findings of a literature review done in preparation for this study [11].
- 8) The placing of the stimulating elements should be as intuitive as possible, ideally in straight lines, structured grids or on body landmarks.
- 9) The device needs to have clear feedback on its functioning, meaning it needs to show to the operation room staff which stimulating elements are activating at any given moment for the surgeon.
- 10) The device should be easily worn and removed within 30 s.
- 11) The device should be fully separate and independent from the robotic surgical station.
- 12) Wearing the device should not hinder the range of motion of the surgeon while operating with the robotic surgical station.
- 13) When active, the device should not negatively influence the performance of the surgeon during the operation.
- 14) The device needs to be functional for at least the entire duration of a procedure or shift, indicatively 8 hours.
- 15) The device needs to operate at low voltages, under 50 V, which is generally considered a safe threshold for the human body [12].
- 16) Materials of the device need to be skin-safe.
- 17) The device should cost under € 250 to be manufactured, in order to be accessible to any healthcare institution.

2.3. Performance Criteria

To evaluate and compare different designs, a set of performance criteria was chosen. The criteria are listed below in order of importance:

- **Saliency:** it refers to the clarity of the signal that the device transmits. In fact, the main function of the device is to deliver haptic alerts. Therefore, the most important performance metric is how clear and effective the information transfer is.
- **Intuitiveness:** here it is meant as both the intuitiveness of the signal and the intuitiveness of the interface itself. Specifically, the alerts need to be easy to understand and the device needs to be easy to use. Intuitiveness of a system is an important factor in determining how likely it is going to be adopted.
- **Comfort:** the device is designed for prolonged use by a subject who is already performing a highly cognitively demanding task. Therefore, the device itself should be as physically comfortable as possible, not to add further fatigue.
- **Compactness:** since the interface is meant as wearable, it needs to be as light and compact as possible, in order not to impede the surgeon's primary task.
- **Adaptability:** intended as both the range of different signals which the interface can produce and the range of different subjects by which it can be adopted.
- **Manufacturability:** the device needs to be easily and cheaply produced with commonly available parts.

2.4. Concept Development

Taking into consideration the goal of the project and the technical requirements, a list of sub-functions that the device needed to fulfill was identified. Subsequently, for each one of these partial system functions, multiple possible solutions were found through previous literature research findings and additional brainstorming. The entire set of sub-solutions created a morphological chart, which was then used to generate initial design concepts. The complete morphological chart can be seen in Appendix A. In particular, by selecting one solution from each sub-function, a route through the morphological chart could be traced that led to a complete system. This process was repeated three times to generate three initial concepts.

One concept was designed for reliability of signal delivery, one for compactness and one for intuitiveness. The three main concepts are as follows:

- 1) **Haptic Belt - Reliability:** The first concept is designed around a belt of flexible material as the main platform. The belt is strapped with velcro around the waist area and features a flat grid of small vibration motors, placed in contact with the lower back through an insulation layer of flexible material. In total, 12 motors are arranged in a 3 x 4 matrix, located symmetrically

with respect to the sagittal plane of the body. Through activation of these motors in specific patterns on the grid, different vibration alerts can be given to the user. All the electrical components are housed in a closed box on the back side, together with the entry for external wired power supply. The system can be connected to wirelessly to input commands. Additionally, to give feedback on which actuators are firing, a matching grid of LEDs is placed on the outer layer of the device. A sketch of the device can be seen in Fig. 2.

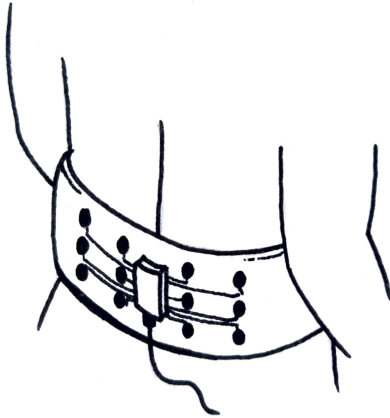


Fig. 2: Sketch of the Haptic Belt concept.

- 2) **Smart Armband - Compactness:** The second concept is conceived as an armband that stretches the user's skin to communicate the alerts. The main platform is a compression sleeve placed on the upper arm, with 12 slim smart material actuators. These actuators are made with a Shape Memory Alloy that deforms when run through by current, and are placed in direct contact with the skin to be able to stretch it. The actuators are arranged circumferentially around the arm, in 3 stacked circles of 4 actuators each, having one actuator per cardinal direction of the arm (front, back, left and right). Activation of these actuators in pre-defined patterns can deliver distinct alerts. The system features a small rechargeable battery and wireless connectivity, as the first design, making it fully portable. LEDs are used to give feedback on which actuators are firing. Fig. 3 illustrates the concept.
- 3) **Vibration Vest - Intuitiveness:** The third concept is designed as a vest with vibration motors directly integrated into the cloth. To be comfortable and not impede the surgeon's movement, it is meant as loosely fitting clothing to be worn on top of the typical operation room clothes. The vest features 11 total voice coil actuators, placed far apart from each other, scattered on various body landmarks. Specifically, 2 actuators are placed close to each shoulder, 3 are in line on the spine going from neck to waist, 2 are on the sides of the torso, 2 on the pectoral muscles and 2 on the sides of the abdomen. The actuators are activated individually, given

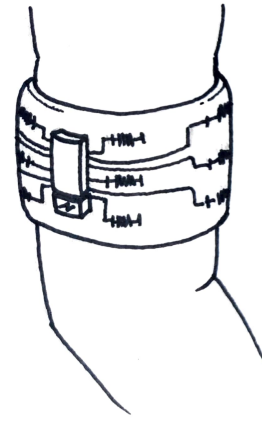


Fig. 3: Sketch of the Smart Armband concept.

their sufficient spacing, and deliver single vibration alerts. For the actuator feedback, a small screen is placed on the upper back, together with the housing for the main electrical components. Signal reception is again done through wireless connectivity. A visualization of the design is shown in Fig. 4.

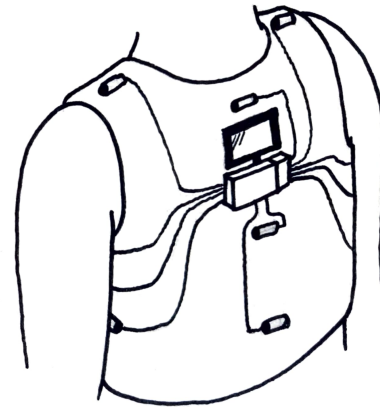


Fig. 4: Sketch of the Vibration Vest concept.

2.5. Concept Selection

The three concepts generated through the morphological chart were assessed using a Harris profile, in order to select the design to be further developed. The Harris profile was based on the performance criteria in their order of importance. The results of the evaluation are shown in Fig. 5.

The Vibration Vest concept, although scoring very high on intuitiveness and comfort, needs to sacrifice saliency due to not guaranteeing a tight fit. In addition, it is the largest design and is fairly complex to manufacture. The Smart Armband concept scores well on saliency, but, being based on skin-stretch, the information transmission is less clear than vibration for alert-style signals. Additionally, the system is heavily dependent on keeping a consistent direct contact with the skin, hindering

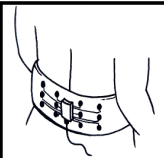
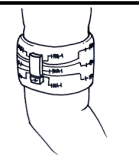
	Haptic Belt				Smart Armband				Vibration Vest			
												
Performance Criteria	--	-	+	++	--	-	+	++	--	-	+	++
Saliency												
Intuitiveness												
Comfort												
Compactness												
Adaptability												
Manufacturability												

Fig. 5: Harris Profile evaluating and comparing the three initial concepts.

its comfort. Nonetheless, it remains extremely compact and reasonably intuitive. The Haptic Belt concept is designed to provide a consistent and clear vibration signal, therefore scores the highest on saliency and also scores well on intuitiveness. It sacrifices a bit of comfort compared to the Vibration Vest and a bit of compactness compared to the Armband, but remains well balanced for most criteria. For this reason, the Haptic Belt concept was deemed the best and was developed into a detailed design.

2.6. Final Design

The final design consists in a waist-mounted haptic belt. It includes twelve coin-type eccentric rotating mass (ERM) vibration motors, arranged in a 3 x 4 flat grid. The grid is placed symmetrically on the lower back of the user, spanning roughly the entire width of the torso. Each motor is also paired with an indicator LED, which lights up simultaneously to the motor activation. The system can be controlled wirelessly through a microcontroller and is powered via USB-C by an external wired power source. Commands are sent to the haptic belt over a local network. The commands can fire individual actuators or trigger a pre-programmed sequence of actuators, creating specific stimulation patterns. The entire device is placed on a stretchable neoprene band, strapped at the front with velcro.

The location of the lower back was chosen for placing the actuators because it is a big and mostly flat area of sensitive skin, which can be easily accessed and doesn't interfere with the surgeon's arm movement or posture.

2.6.1. Stimulating Element

The choice of stimulating element drives the entire build design, since it is the core element that ultimately needs to interact with the user. The chosen stimulation element was a compact coin-shaped ERM direct-current (DC) motor. ERMs

work by spinning an unbalanced mass attached to the central shaft of their brushed DC motor. The rotation of this mass generates vibrations, dependent on the rotation frequency of the motor.

The specific model chosen for the prototype was a 10 mm $\varnothing$ x 3 mm height ERM motor provided by TinyTronics [13]. The motor has a nominal operating voltage of 3 V, at which it has an average current draw of 65 mA. The rated rotation speed is 12000 ± 2500 RPM and weighs only about 1 g. Fig. 6 shows the structure of the chosen coin ERM motor.

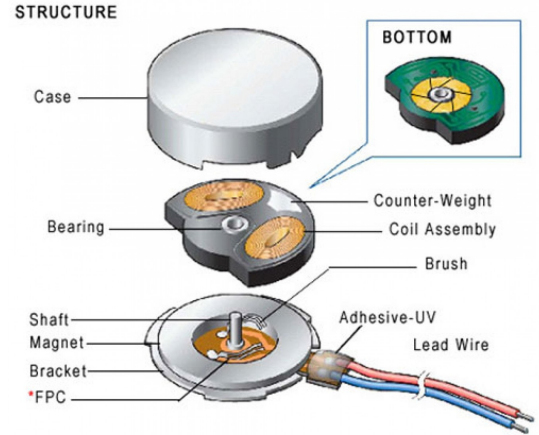


Fig. 6: Exploded view of the coin-shaped ERM vibration motors from TinyTronics, used as stimulation elements for the final design [13].

This choice was motivated by ERM motors being very compact, inexpensive, easy to connect, power efficient and able to generate vibrations of the necessary frequency and amplitude. In fact, Pacinian corpuscles, the main mechanoreceptors that sense skin vibration, have their peak sensitivity at around 200 Hz [14], which equates to 12000 RPM. ERM motors remain the simplest and most effective solution for tactile applications. This is confirmed in literature as well, where this type of motor was the most common actuation technology used to generate vibratory feedback [11].

In total 12 vibration motors were placed in a 3 x 4 flat matrix. This was done to have at least 3 motors in each planar direction, in order to generate an effect similar to tactile apparent motion [15], by activating the motors in a linear sequence. In the horizontal direction, 4 motors were placed instead of 3 to avoid putting vibration motors in the center along the spine. This was done for two main reasons: the electrical box would have been ideally placed in the center, so it would have been best to avoid putting vibration motors under it; due to the anatomy of the back muscles and the presence of the spine, the central line is less clearly perceivable than the sides [16]. Thus, splitting the central column of a 3 x 3 grid into two columns at the sides of the spine produces the chosen 3 x 4 layout. Following the technical requirements, the spacing between actuators was set at 5 cm in the vertical direction, and at roughly 7 cm in the horizontal direction. Therefore, the total footprint of the actuator matrix was designed as 10 cm x 20

cm. See Fig. 7 for a representation of the actuator grid.

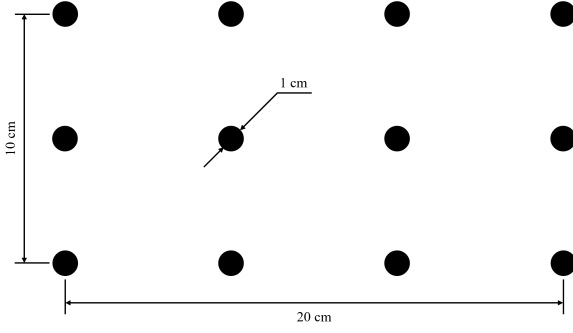


Fig. 7: Proportionally accurate representation of the layout of the 3 x 4 actuator grid, as positioned within the haptic belt prototype.

2.6.2. Control Element

The control element is the second most important component of the design, needed to precisely control the activation of the motors. The choice of microcontroller for the final design was a Raspberry Pi Pico 2 W. This particular board exposes 26 multi-function 3.3 V general purpose (GPIO) pins, with 24 of them capable of pulse-width modulation (PWM) control, which exceeds the minimum requirement of 12 motor control channels and leaves capacity for additional peripherals if needed. The board is compact, with a footprint of 21 x 51 mm, and is based on the RP2350 microcontroller, which offers strong computational capacity at low power consumption. It also features wireless connectivity, with both WiFi and Bluetooth available to connect to the microcontroller and send commands [17]. Furthermore, the Pico 2 W is relatively cheap, easily available and can be programmed with common languages like MicroPython. A picture of a Raspberry Pi Pico 2 W can be seen in Fig. 8.

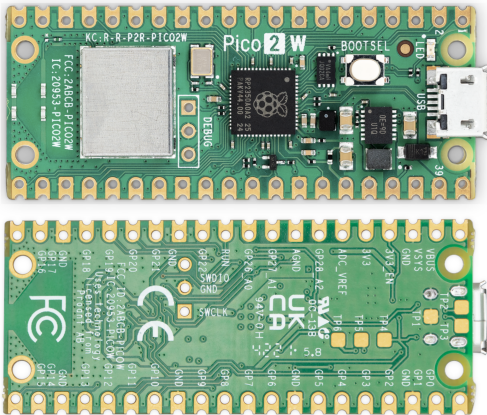


Fig. 8: Picture of the front and back of a Raspberry Pi Pico 2 W board [17].

Other considered choices for the microcontroller (Arduino Uno, ESP32-based boards) were either less compact or less capable and intuitive. Overall, for this specific application,

the Raspberry Pi Pico 2 W presented the most balanced combination of wireless capability, availability of GPIO pins, size, and ease of development.

2.6.3. Additional Electrical Components

For the system to function properly, some additional electrical components were needed between the control and controlled element. Specifically, between every output pin of the microcontroller board and the corresponding ERM motor, a MOSFET and diode were placed to supply adequate current and protect the controller.

An SOT-23 N-Channel MOSFET was chosen to interface the 3.3 V GPIO pin of the Pico 2 W board with the higher current load from the ERM motor. The MOSFET acts as a low-loss electronic switch that allows the microcontroller to activate the motor using only a small gate current while supplying the motor from an external power line. The specific MOSFET that was used supports up to 5.2 A and exhibits a low $R_{DS(on)}$ of 27 m Ω (at 4.5 V) [18], ensuring minimal conduction losses at the motor's operating current ($\approx 60 - 100$ mA). A flyback diode was also required in parallel with each ERM motor to safely dissipate inductive voltage spikes generated when the motor was switched off. In particular, an SS14 Schottky diode was chosen due to its low forward voltage drop of 0.55 V at 1 A and fast switching [19]. A series gate resistor of 510 Ω was selected to limit the instantaneous GPIO pin current and control switching speed. The resulting peak gate current is:

$$I_{gate} = V_{pin} / R_{gate} = 3.3 \text{ V} / 510 \Omega \approx 6.5 \text{ mA} \quad (1)$$

where V_{pin} is the microcontroller pin voltage and R_{gate} is the series gate resistance. The peak gate current is safely below the maximum current that should be drawn from a single GPIO pin of a Raspberry Pi Pico [20]. The MOSFET gate-charge based switching time is approximately:

$$t_{switch} = \frac{Q_{gate} \cdot R_{gate}}{V_{pin}} = \frac{11.7 \cdot 10^{-9} \text{ C} \cdot 510 \Omega}{3.3 \text{ V}} \approx 1.8 \mu\text{s} \quad (2)$$

where Q_{gate} is the MOSFET gate charge. The resulting switching time is acceptable for a PWM frequency of 1–2 kHz (thus switching period of 500 – 1000 μs). Finally, a gate pull-down resistor of 10 k Ω was selected to ensure that the MOSFET stayed off during microcontroller resets. Therefore, the MOSFET passive discharge time results in:

$$t_{off} = 3 \cdot \tau_{off} = 3 \cdot R_{pull} \cdot C_{iss} = 3 \cdot 10000 \Omega \cdot 927 \cdot 10^{-12} \text{ F} \approx 28 \mu\text{s} \quad (3)$$

τ_{off} is the MOSFET time constant, R_{pull} is the pull-down resistance and C_{iss} is the input capacitance of the MOSFET. The discharge time was considered as the time in which the MOSFET discharged below 5% of its full voltage, roughly equal to 3 times its time constant. The resulting discharge time is fast enough for most safety needs. The MOSFET's leakage current is:

$$I_{bleed} = V_{pin}/R_{pull} = 3.3V/10000\Omega = 0.33mA \quad (4)$$

which is sufficiently low.

With all these selected additional electrical components, the electrical scheme for one motor driving unit is as shown in Fig. 9. This structure was used 12 times, connecting 12 pins of the microcontroller board to the respective ERM motors.

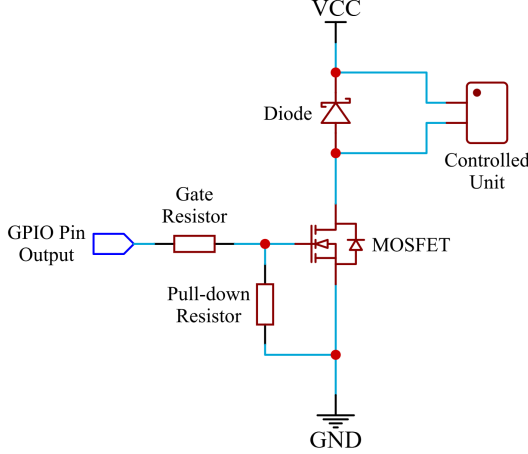


Fig. 9: Electrical scheme of one motor driving unit of the final design, placed between a pin of the Pico 2 W board and an ERM motor. Here VCC indicates the main supply voltage and GND indicates the ground.

Additionally, to give feedback on motor activations, an LED was added next to each ERM motor. Specifically, a generic 3 mm red LED was connected in parallel to each motor, to be activated simultaneously. Each LED was given an inline resistor of 150Ω , sized to limit current under the maximum rated current of 20 mA. The electrical scheme of the complete end controlled unit of ERM motor plus LED is shown in Fig. 10.

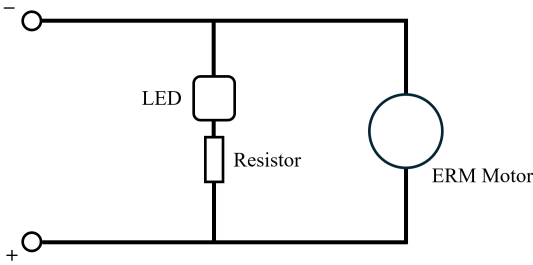
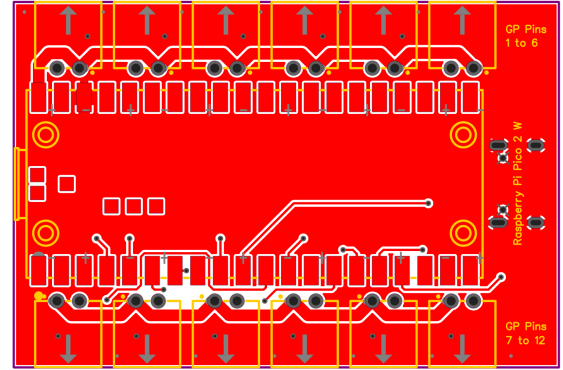


Fig. 10: Electrical scheme of the controlled elements of the final design, consisting of an ERM motor and an LED connected in parallel.

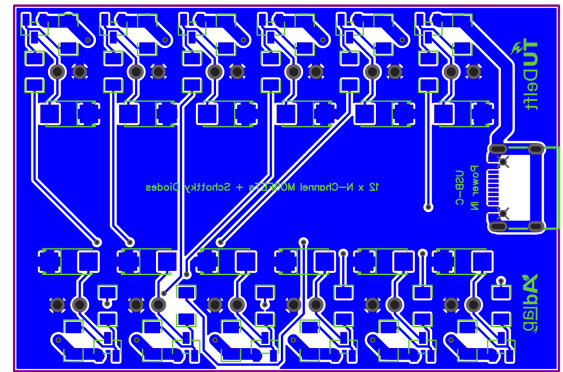
2.6.4. Electrical Platform - PCB

Most of the electrical scheme of the system was designed to be surface-mounted on a PCB. Only the end controlled units (motors + LEDs) were excluded, because they needed to remain flexible to be ultimately mounted on the wearable platform of the belt. Starting from the electrical scheme, a custom PCB was designed using the Easy-EDA editor [21]. The final PCB layout was organized as double-sided: on one

side, the microcontroller board and 12 right angle through-hole connectors were placed, 6 on each side of the board; on the other side, all the smaller surface-mounted components (MOSFETs, diodes and resistors) and the USB-C port were placed. All components were carefully organized to minimize the total footprint of the PCB, make the layout as symmetrical as possible, minimize the length of electrical paths between single components and make the PCB easily manufacturable. The electrical paths for single motor control units were kept at the standard thickness of 0.254 mm. The copper trace thicknesses for the main voltage supply (VCC) and ground (GND) paths were dimensioned using the IPC-2152 standard [22] to withstand the maximum current of the system. For a maximum rated current of 92 mA for the motors and 20 mA for the LEDs, the maximum cumulative current drawn from the system equated to roughly 1.4 A. Therefore, for 1 oz copper thickness and 10 °C temperature rise, a 1.3 mm trace width was selected for VCC and GND. A copper pour was put on both sides of the PCB to reduce loop areas, improve thermal dissipation and make the system more electrically robust in general. The total footprint of the resulting PCB layout was 61.0 x 40.9 mm. Images of the designed PCB can be seen in Fig. 11.



(a)



(b)

Fig. 11: Layouts of a) the top layer and b) the bottom layer of the final PCB design, taken from the EasyEDA editor.

2.6.5. Main Physical Platform

For the main physical wearable platform, a neoprene belt was chosen. Neoprene was selected because it is already commonly used in sportswear. In fact, as a material, it is light, soft, skin-safe, moderately transpiring and flexible enough to wrap tightly around the waist. At the same time, it provides enough stiffness to attach hardware on it while still allowing movement. It can also be easily modified with holes or stitching, making it a good platform for fast prototyping.

For the final design, two different layers of neoprene were used, to allow routing of electrical wiring between them. This would protect the user from direct contact with electrical components and keep the belt surface smooth and more visually appealing. Specifically, a neoprene belt of 3 mm thickness was chosen as the main platform wrapping around the waist. The outer side of this neoprene layer was designed to hold the electrical box and the LEDs. A second neoprene layer of 1 mm thickness was put on the inner side of the device, between the actuators and the user. The 12 motors would be attached to this sheet, enclosing them between the two flexible layers. For this reason, the second sheet was chosen to be thinner, not to dampen vibrations from the motors excessively.

2.6.6. Protection and Attachment Elements

A 3D model for the central electrical box was designed in SolidWorks to be later 3D-printed. This box was needed to protect and firmly hold in place the PCB assembly. The design was split into two parts, a bottom holder for the PCB and a top lid. A simple sliding fit was used to couple the two components without additional securing elements, to allow easy access to the PCB and microcontroller if needed. Specifically, the lid was designed to slide in from the top and be held in place by gravity and a sufficiently tight tolerance between the two parts. Instead, the bottom PCB holder was designed to be secured to the neoprene belt with regular nuts and bolts. A screenshot of the 3D models of the two electrical box components is shown in Fig. 12.

Additionally, a 3D model for an ERM motor holder was created. This holder was designed to keep the actuator in the middle pressed against the inner neoprene sheet of the belt. In particular, the profile of the holder was drawn to leave the ERM motor partially sticking out of it once placed in it. This was done to get the actuator to "bulge" out of the neoprene layer of the belt, theoretically improving the contact between the motor and the belt user. 6 holes were modeled around the holder to be able to stitch it to the neoprene sheet. A view of the ERM motor holder model can be seen in Fig. 13.

2.6.7. Power source

The system was powered through a 5 V USB-C port, attached to the bottom part of the PCB, when putting the electrical box vertically. The power was supplied by an external wired source, namely a laptop connected through USB. However, the system can be powered interchangeably with a rechargeable battery (e.g. a powerbank) to make it fully portable. This

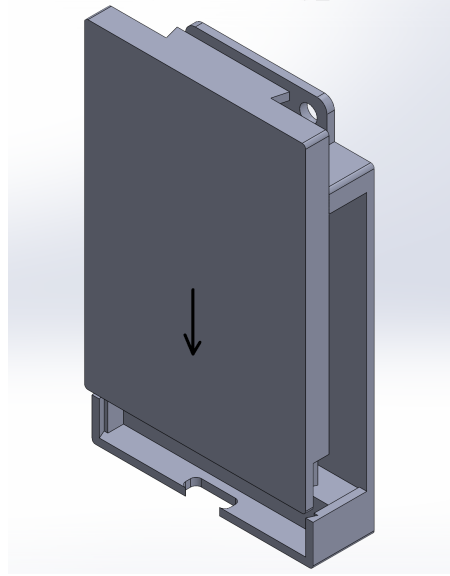


Fig. 12: Isometric view of the 3D model of the PCB holder assembly. The top lid slides into the bottom part and is held in place via geometric fit. The screenshot is taken from SolidWorks.

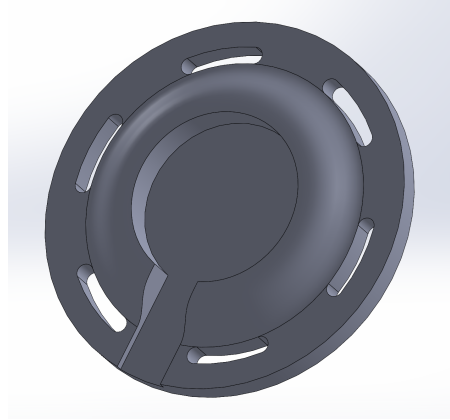


Fig. 13: View of the SolidWorks 3D model of the ERM motor holders.

would only require redesigning the central electrical box cover to hold a battery as well.

The power consumption of MOSFETs and diodes is negligible, and a Raspberry Pi Pico wireless adds approximately 80 mA of current drawn at 5 V when actively sending requests to a web page [23]. Therefore, under maximum-load conditions, the total current drawn from the system still is roughly 1.4 A. Thus, the maximum power consumption of the system equates to approximately 7 W. Considering a regular 5 V 5000 mAh powerbank and a conservative 80% efficiency, even under worst-case assumptions, the runtime of the device would be:

$$runtime = \frac{capacity}{current} = \frac{0.8 \cdot 5 Ah}{1.4 A} \approx 2.9 h$$

and this is with all actuators running continuously, which very rarely would happen since the device is meant to alert the user occasionally. While idle, with only the microcontroller active,

the system runtime would be in the multiple tens of hours. Therefore, a regular use case scenario would easily cover an 8-hour shift, even with a rather small battery.

2.6.8. Software

The code mounted on the Raspberry Pi was written in MicroPython. For this purpose, the Thonny application interface was used to access the microcontroller. The code allows for wireless control of the twelve vibration motors, individually or in pre-programmed activation patterns. Specifically, the microcontroller hosts its own WiFi access point and serves an embedded HTML landing page. This web interface is then connected to the actual motor activation commands, in order to control the device from the interface itself. The web page also provides a configurable PWM-based intensity selector, which scales motor output between 1 and 100% duty cycle. Incoming commands are received over HTTP and processed asynchronously using MicroPython's *uasyncio* function, to make commands non-blocking between each other. Motor-driving pins are mapped individually to the physical 3×4 motor grid, plus five haptic patterns can be selected. The full MicroPython code is provided in Appendix B.

2.7. Information Delivery

The haptic belt communicates information through vibrotactile stimulation. Therefore, the aim was to design a set of vibration patterns or tactile icons (in short "tactons") that were easy to perceive and distinguish. Clear perceptibility was achieved by choosing an actuator with the right frequency and amplitude of stimulation, these being roughly 200 Hz for frequency and 0.8 - 1 g for amplitude of vibration, according to literature trends [11]. Additionally, to keep their stimuli clearly separate, the actuators were placed at a distance greater than the two-point discrimination threshold of the back, which was found to be between 2 and 5 cm, according to different studies [16][24][25]. Pulse-width modulation with a frequency of 1 kHz was used to keep the vibration intensity controlled, balancing perceptibility and comfort of the stimulus. An initial value of 70% duty cycle was chosen as a good compromise, in order to have high enough intensity of vibration, low annoyance of stimulus and generally lower electrical stress on the system. Although PWM was used to drive the motors, intensity variation was not used as a distinguishing feature between tactons, as differences in amplitude are less reliably perceived than differences in timing and spatial distribution [26]. Moreover, intensity was not changed to avoid haptic intensity illusions, which could potentially cause mislocalization of stimuli [27]. Therefore, all tactons were designed to be delivered at the same chosen intensity.

Instead, the two main strategies used to differentiate patterns were spatial and temporal encoding. Each tacton was defined by a unique location or timing of motor activations, chosen to be easily distinguishable. Regarding spatial encoding, tactons were created with two approaches: either static location cues,

where a tacton activated motors only on one specific region of the belt, or sequential cues, in which a tacton triggered a short sequence across adjacent positions to create a directional sensation. The actuators at the sides of the grid were the most utilized (every pattern activated them), while the central columns mostly acted as connection between the sides for a moving pattern or vibration reinforcement for a pattern which used the side columns as well. Therefore, lateral differentiation was preferred to vertical differentiation. This was motivated by both the fact the horizontal resolution of the back is higher than its vertical resolution and by the fact that the spine acts as an anchor that lowers sensitivity to vibrotactile stimulation in central part of the back [28]. Regarding temporal encoding, different activation timings were used to distinguish patterns that were partially overlapping in space. All patterns were designed to last 1 second in total, except for one which lasted 2 seconds, in order to avoid being too similar to another pattern.

Finally, simplicity of patterns was viewed as an important feature, to keep the information transfer as intuitive as possible. For this reason, actuators were arranged in a simple, symmetric, flat grid and activation patterns always involved full lines of motors activating simultaneously. Diagonal lines and complex shapes were avoided, since they are more difficult to interpret or get perceived as simpler shapes along the cardinal directions anyway [29].

Taking into account all the considerations, five different tactons were designed with the following details:

- 1) Continuous static activation of the entire left column for 1 second.
- 2) Continuous static activation of the entire right column for 1 second.
- 3) Sequential activation of entire columns from left to right and then back from right to left for 0.25 seconds each (2 seconds in total).
- 4) Sequential activation of entire rows from bottom to top for 0.33 seconds each (1 second in total).
- 5) Activation of the entire grid 5 times in short bursts of 0.1 seconds, separated by 0.1 seconds of rest (1 second in total).

Since the function of the haptic belt is to alert a surgeon of problems happening in the operating room, each tacton was mapped to a recurrent clinical issue in the OR, chosen following an interview with a surgeon. In sequence, corresponding to the five described tactons, the chosen problems to be conveyed through the belt were:

- 1) Open door in the OR.
- 2) Issue with the power source of the surgical robot.
- 3) Issue with the patient being operated.
- 4) Issue with the surgeon's docking station.
- 5) Collision hazard of the teleoperated robotic arms with the OR staff.

For an intuitive visualization of the 5 vibration patterns, refer to Appendix D.

2.8. Experimental Setup

An experiment was designed to validate the performance of the final prototype, when used alone and in the intended scenario, paired with a robotic-assisted surgical docking station. In this case, the docking station was emulated by a surgical training controller named AdLap [30]. This system has two maneuverable manipulators, each controlling a virtual robotic laparoscopic grasper in a simulation. The programmed task is to pick and place colored marbles in matching bowls. The system also features two armrests, made to support the weight of the user's arms, improving ergonomics. An image of the full AdLap system can be seen in Fig. 14.

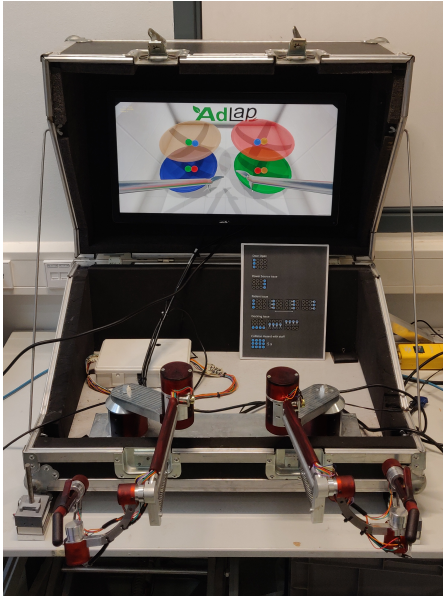


Fig. 14: Setup of the Advanced Laparoscopy (AdLap) surgical trainer, used during the experimental validation study.

The main objective of the experiment was to assess the ability of the haptic belt to deliver easily recognizable alerts and the effect of using the belt on the cognitively demanding task of performing teleoperated surgery.

2.8.1. Study Protocol

The experiment consisted of two main parts:

- 1) A first block regarding the haptic belt alone. This included an initial familiarization with the device, done by letting the subjects sense individual motor locations and the five vibration patterns. After this first intuition check, a recognition test on the vibration patterns was performed.
- 2) A second block in which the haptic belt was used together with the AdLap system. After one familiarization run with the surgical trainer, subjects performed 6 marble sorting runs in total. Half of these runs were occasionally interrupted by vibration alerts coming from the belt. Participants were randomly assigned to one of two groups: Group 1, doing no alerts runs first, or Group

2, doing runs interrupted by alerts first. This crossover was designed to balance potential order effects between the two belt feedback conditions.

All procedures followed the approved Human Research Ethics Committee (HREC) protocol [31]. Participants were recruited voluntarily as novices among students from Delft University of Technology and gave written informed consent before taking part.

Upon arrival, participants were briefed about the purpose of the study, the involved hardware and what was expected of them. The haptic belt was placed around their lower back and adjusted to ensure symmetrical alignment of the motor grid and good contact with the skin. Participants were asked to wear a single layer of light clothing to improve tactile perception and mimic the thickness of the gown worn by surgeons during operations. Appendix C lists the full detailed protocol, with the instructions followed during the validation experiment. A flowchart to visualize the study protocol is also shown in Fig. 15.

2.8.2. Performance Parameters

The main performance parameter for the haptic belt was the recognition accuracy for each vibration pattern (correct, incorrect or no-hit). Instead, for the AdLap controller, the performance parameters that were registered were the time (s) to complete the marble sorting task and the number of collisions of the virtual robotic arms detected by the simulation. A subjective description of the vibration patterns was also recorded from the test subjects, in order to check how intuitively the patterns were felt before knowing their details. Additionally, at the end of the session, participants were asked to fill in a questionnaire using a NASA TLX 5-point scale [32]. Ratings included: comfort of the haptic belt, perceived annoyance of the vibrations, ease of identifying patterns during the recognition test, ease of identifying alerts during the AdLap task, perceived usefulness of the belt in a real surgical setting. The final subjective questionnaire used during testing can be seen in Appendix E.

2.8.3. Software Tools

The experiment used three software components:

- The haptic-belt control panel for delivering stimuli.
- The AdLap simulation environment for the marble sorting task, which automatically logged the controller desired performance metrics.
- A custom data-logging script to randomize the stimulus sequence and timestamps for the different sections of the experiment, and to record subject responses.

2.8.4. Data Analysis

Data from the haptic belt were organized and analyzed to create confusion matrices for the 5 vibration patterns. From these matrices, the recognition accuracy of individual patterns and the average accuracy could be derived. Performance metrics from the surgical trainer were tested using the Shapiro-Wilks

3. RESULTS

3.1. Prototype

The full prototype of the haptic belt was successfully built following an iterative development process. The final result met all specified requirements, as detailed in Table I. Regarding the actual build, the custom PCB was ordered and manufactured through JLCPCB. The small bottom layer components were assembled automatically, while the top layer components (Raspberry Pi board and connectors) were soldered by hand. The final manufactured and assembled PCB is shown in Fig. 16.

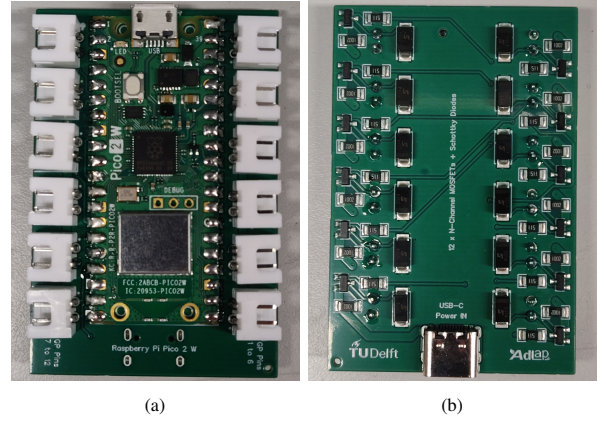


Fig. 16: Pictures of the a) top and b) bottom sides of the manufactured and fully assembled PCB.

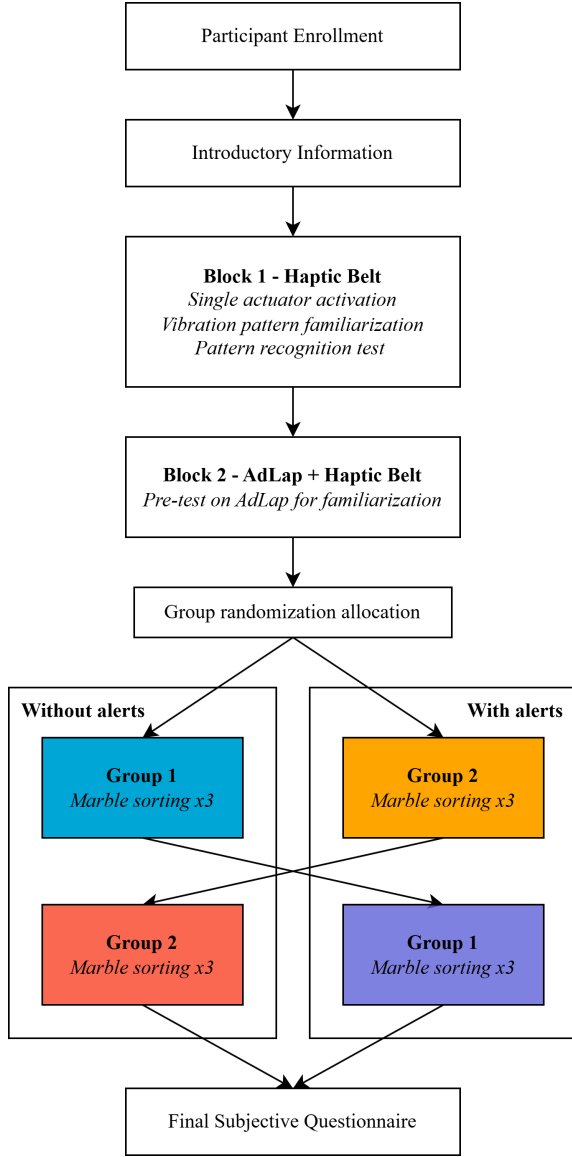


Fig. 15: Flowchart of the validation experiment structure, with depiction of the crossover study done in block 2.

test to check for normality of the data. A paired t-test was used if the data were normally distributed, while a Wilcoxon Signed Rank test was used if the data were non-normally distributed. Two datasets, for runs with alerts and without alerts, were compared to find statistically significant differences. Within each dataset, participants were grouped, and only average metrics for successive trials were analyzed. Considering this succession of trials, the first and last run of the grouped datasets were compared to find learning effects. Subjective ratings were analyzed using the same statistical framework. A significance level of $p < 0.05$ was used throughout. All data analysis was done using the scientific Python programming language.

All flexible end elements (ERM motor plus LED pairs) were prepared individually. Wires were cut to the right length to fit the motor grid dimensions. First the inline resistors were soldered to the positive end of the LEDs, then the LEDs and ERM motors were soldered in parallel. All connections were isolated with heat shrink tubing. Lastly all wires were heated up and bent to reach the correct position, and the ERM motors were placed inside their holders. A picture of the one the fabricated end elements can be seen in Fig. 17.

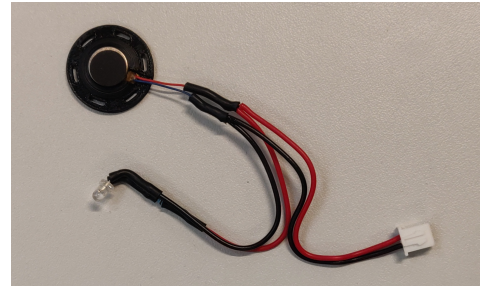


Fig. 17: Picture of one of the fabricated flexible end elements, consisting of an ERM motor wired in parallel with an LED.

The protective components (PCB housing and motor holders) were 3D-printed with fused deposition modeling (FDM) technique, using black PLA and a 0.4 mm nozzle. Printing settings were kept at a standard 0.15 mm layer height and 15%

TABLE I: Fulfillment of Technical Requirements

Req. N°	Fulfillment	Result
1	Met	The device is wearable around the waist also while being seated.
2	Met	The device is secured in place with minimal allowed relative movement.
3	Met	The device weighs less than 1 kg.
4	Met	The device is thinner than 3 cm on the central electrical box and thinner than or roughly 1 cm thick everywhere else.
5	Met	Relative distance between the actuators is equal to or over 5 cm, which is over the minimum required distance of 2 – 5 cm.
6	Met	The dimensions of the actuators are around 1 – 1.5 cm, thus well below the maximum allowed dimensions.
7	Met	The total number of stimulating elements is 12.
8	Met	Actuators are intuitively placed in a square 3 x 4 grid.
9	Met	The interface gives clear feedback on which motors are activating at any given moment by flashing corresponding LED lights, visible on the back of the belt.
10	Met	The device can be easily worn and removed within 30 s.
11	Met	The device is fully separate and independent from the robotic surgical station.
12	Met	The interface doesn't interfere with the surgeon's range of motion while operating.
13	Met	According to experimental results, the device doesn't significantly degrade surgical task performance.
14	Met	If powered with a 5000 mAh powerbank, the battery life of the device would well exceed a regular 8 hour shift.
15	Met	The device operates at low voltages of around 5 V.
16	Met	Materials of the device are skin-safe.
17	Met	The device costs around € 50 to produce, which is well under the desired limit of € 250.

infill. Due to the 3D-printing tolerances and small defects, the designs of these components were iteratively refined, to improve fit, cable routing, and ease of assembly. A neoprene sports band was used as the main platform and modified to fit the final design. Specifically, the belt was cut to the required dimensions, holes were made to attach the electric box module and LEDs, and two slits were cut at the sides of the PCB assembly for cable passage. Each ERM motor was stitched onto the inner neoprene layer of the belt. Fig. 18 shows the final placement of the motor grid on the inner neoprene sheet.

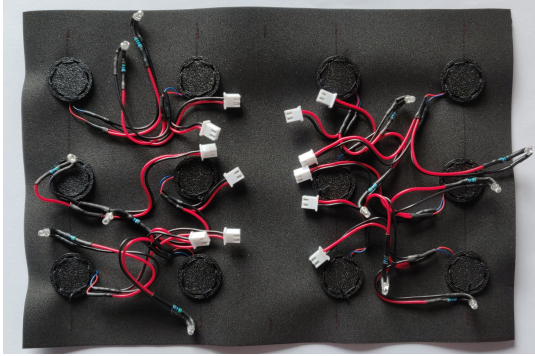


Fig. 18: Picture of the final assembly of the ERM motor grid on the inner neoprene layer of the haptic belt.

Then, the two layers of neoprene were sewn together at the top and bottom borders, enclosing all the wiring while leaving the sides accessible for easy replacements. Finally, the electric box was fixed with 4 standard M3 nuts and bolts at the corners, the PCB was put in place and all end elements were connected to the central hub. A picture of the final assembled prototype is shown in Fig. 19.



Fig. 19: Picture of the final assembled prototype of the Haptic Belt system.

A complete bill of materials (BOM) was compiled, and the total material cost for one device was calculated to be around € 50. Refer to Table II for the detailed BOM. The finished haptic belt had a compact form factor with the following final dimensions: height of approximately 14.5 cm, thickness of approximately 2.5 cm on the central electrical box and thickness from 3 mm to 1 cm around the waist. The total weight of the prototype was 195 g. Ease of use was achieved through the velcro strap on-off system and the wireless control interface. A screenshot of the web interface is provided in Fig. 20.

This prototype was used during the validation study described in subsection 2.8. Fig. 21 shows the full experimental setup for a test subject using the AdLap manipulator while wearing the haptic belt around their waist.

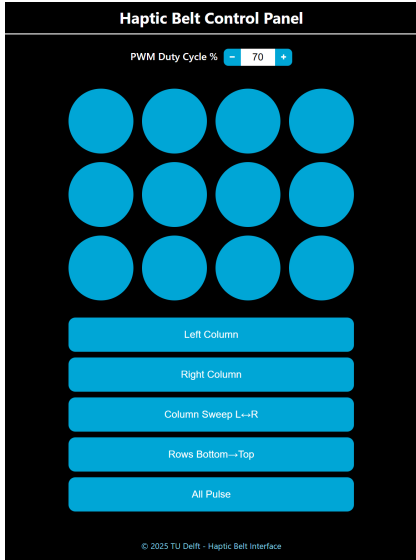


Fig. 20: Web landing page with the control panel for the Haptic Belt.

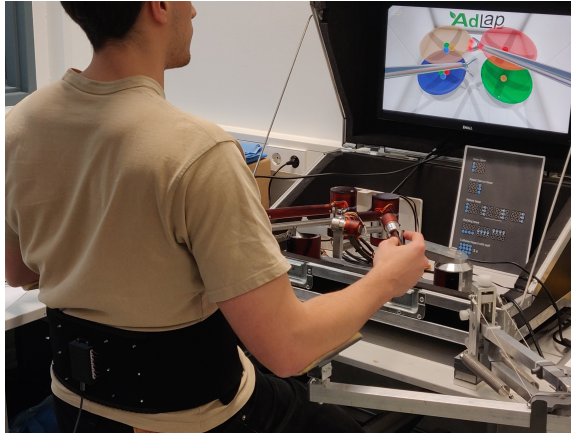


Fig. 21: Picture of the complete experimental setup, as used during the validation study. In the picture, the subject is operating the AdLap manipulators while wearing the Haptic Belt prototype.

3.2. Experimental Results

A total of 10 students participated in the validation experiment. Results from the initial intuitive pattern identification task were as follows:

- *Pattern 1 - Left column:* The first pattern was recognized by most participants as a stationary activation of the entire left column of the grid. One participant only felt the bottom left motor activating.
- *Pattern 2 - Right column:* The second pattern was recognized by most participants as a stationary activation of the entire right column of the grid. One participant only felt the bottom right motor activating. One participant described it as the activation of both columns on the right side. One participant described it as the activation of the right middle motor.
- *Pattern 3 - Left to right:* The third pattern was recognized by most participants as a sequential activation of motors

TABLE II: Bill of Materials

Component	Quantity	Total (€)	Cost
Custom PCB	1	0.34	
PCB components + partial assembly	1	4.68	
Raspberry Pi Pico 2 W	1	6.50	
JST-XH 2p Compatible PCB Connector Male - 90°	12	1.20	
JST-XH 2p Compatible Female Connector with Cable	12	5.40	
ERM Vibration DC Motor	12	10.80	
150 Ω LED series resistor	12	0.60	
Red LED - 3mm Clear	12	1.20	
Neoprene Sports Belt	1	9.99	
Lasercut Neoprene Sheet - 1 mm 50x50 cm	1	7.65	
M3 nut and bolt	4	0.20	
Heat Shrink Tubing	-	~ 0.10	
3D-printed parts	14	~ 2.00	
Total		50.66	

from left to right and back. One participant commented on feeling the sweep from left to right mostly on the edges of the grid. One participant felt a more complex activation pattern, going from bottom left to right middle to top left.

- *Pattern 4 - Bottom to top:* The fourth pattern was recognized by most participants as a sequential activation of motors from bottom to top of the grid. In 4 separate occasions, the vertical movement of the pattern was described as being felt only on the sides of the grid. One participant felt a "T-shaped" pattern, going from bottom to middle to the outside top.
- *Pattern 5 - All pulsating 5 times:* The fifth pattern had the most variability in perception from subjects. 3 participants correctly identified a pulsating pattern of the entire grid of actuators. One participant felt only the middle and top rows activating. One participant felt only one row pulsating. 4 participants described it as a pulsating pattern only on the sides of the grid. One participant described it as a pulsating pattern with unclear height.

For the recognition test on the vibration patterns when using the haptic belt alone, the results are summarized in the confusion matrix in Fig. 22. 4 out of 5 patterns had a 100% recognition accuracy, with only pattern 5 being mistaken for pattern 4 once. The resulting average recognition rate was 99.3% (total sample size $n = 150$).

Results for the recognition of vibration patterns during the combined task (haptic belt paired with the AdLap system) are summarized in the confusion matrix in Fig. 23. 4 out of 5 patterns had a 100% recognition accuracy. Pattern 4 was mistaken for pattern 5 twice. The resulting average recognition rate was 96.0% (total sample size $n = 50$).

Results from the data analysis of the performance metrics

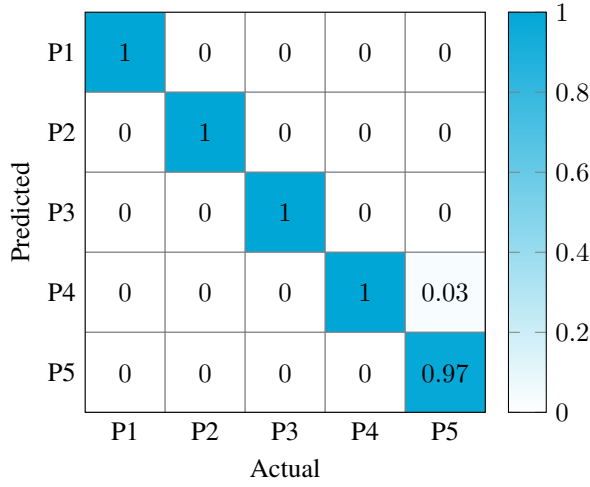


Fig. 22: Confusion matrix for the 5 vibration patterns during the recognition test. P1, P2 stand for "Pattern 1", "Pattern 2", etc., following the sequence presented in subsection 2.7. The columns correspond to the actual signals, while the rows correspond to the participants' predictions. The individual cells list the prediction percentage of a pattern compared to the total number of actual signals ($n = 30$ per pattern).

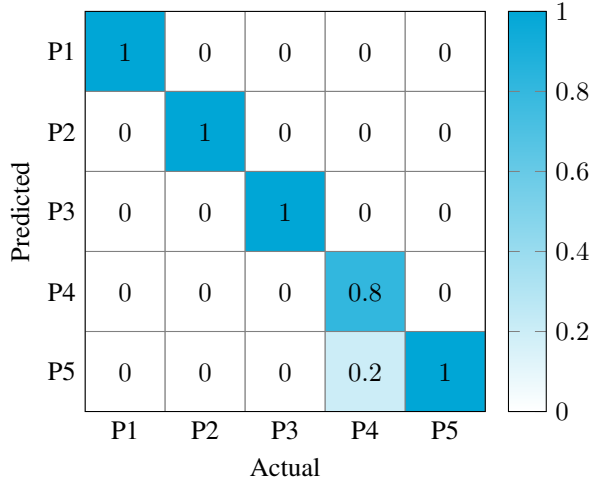
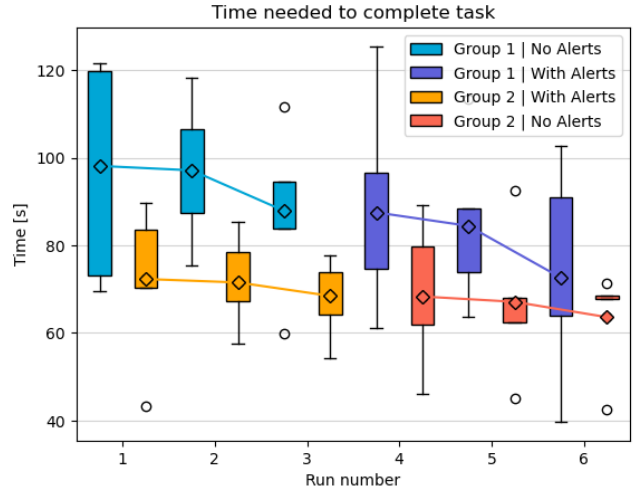


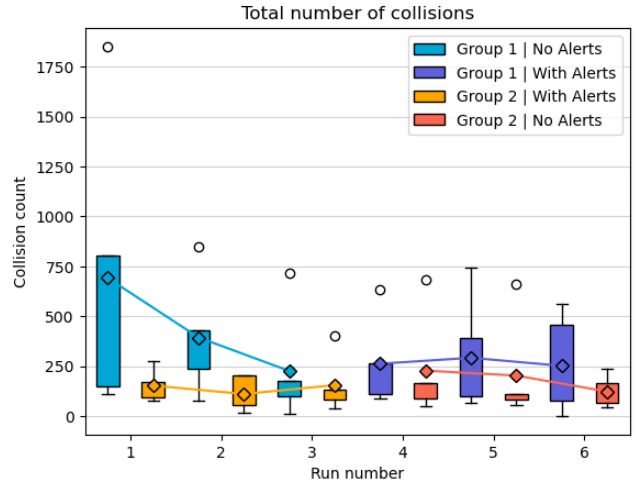
Fig. 23: Confusion matrix for the 5 vibration patterns during the combined test of haptic belt plus AdLap controller. P1, P2 stand for "Pattern 1", "Pattern 2", etc., following the sequence presented in subsection 2.7. The columns correspond to the actual signals, while the rows correspond to the participants' predictions. The individual cells list the prediction percentage of a pattern compared to the total number of actual signals ($n = 10$ per pattern).

registered by the AdLap system are shown in Fig. 24. There was a clear trend downwards in the time needed to complete the marble sorting task between the first and last runs for both groups. For the no-alert condition, a general decrease in total number of collisions was also observed between the first and last runs. On the other hand, runs with alerts didn't show a steady decrease in collisions. In both completion time and number of collisions, and for both groups, no performance disruption was observed when switching from alerts to no alerts or vice versa.

Fig. 25 compares the performance parameters of all runs combined from the two groups. No significant difference



(a)



(b)

Fig. 24: Boxplots of a) completion time and b) collision count for the 6 consecutive runs performed by participants with the AdLap during the validation experiment. All participants are grouped. Runs are divided between the two conditions (i.e. presence of alerts or no alerts) and the two groups (i.e. no alerts first for group 1 or alerts first for group 2). Mean values are highlighted with diamond markers and connected with lines. Outliers are represented by circle markers.

was found between the two conditions when looking at the combined data pool.

Results from the final subjective questionnaire are shown in Fig. 26. Subjects scored the final prototype very high on comfort, pleasantness of vibration and perceived usefulness in a real scenario. Mean scores, adjusted to a 0 to 100 scale, were 88, 86.5 and 84, respectively. The device scored lower, although still high, in ease of recognition of the alerts, both in the standalone and combined tasks. The average ease of recognition score during the standalone recognition test was 83, while the average score for the combined task was 76.5. Although these two average effort values are different, no significant overall difference was found between the two datasets.

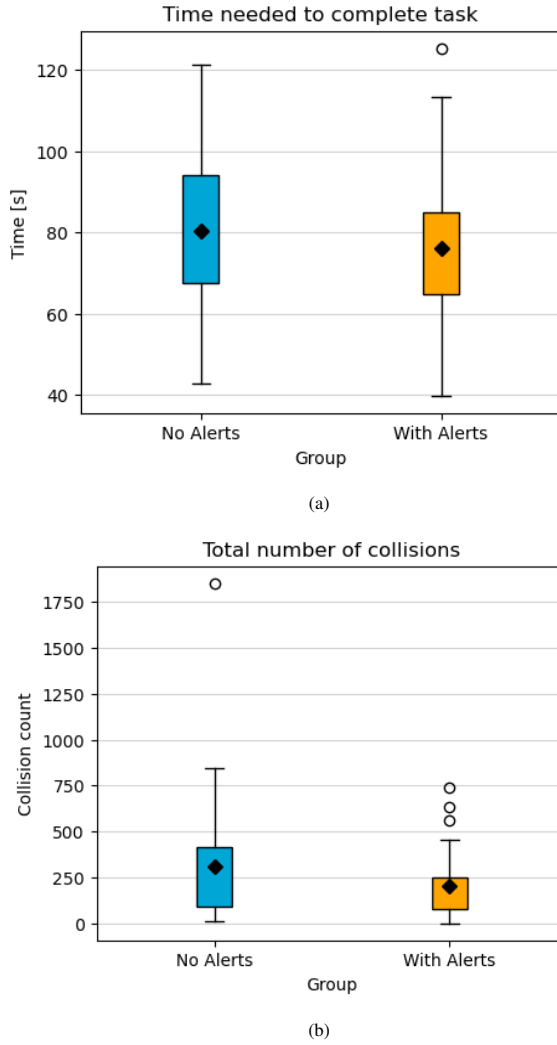


Fig. 25: Boxplots of a) completion time and b) collision count of all experimental runs grouped together. Runs are divided between the two conditions (i.e. presence of alerts or no alerts). Mean values are highlighted with diamond markers. Outliers are represented by circle markers.

4. DISCUSSION

In this section, the results are discussed to assess whether the requirements were met and whether the performance of the proposed solution was satisfactory. After that, limitations of the design and validation study are listed, together with recommendations for future improvements. Finally, a financial overview is given.

4.1. Interpretation of Results

4.1.1. Prototype

The prototype met all requirements and functioned as intended. In particular, the most important physical requirements of weight, compactness, power consumption and ease of use were successfully achieved. Small variations in vibration intensity were observed between the motors, probably due to manu-

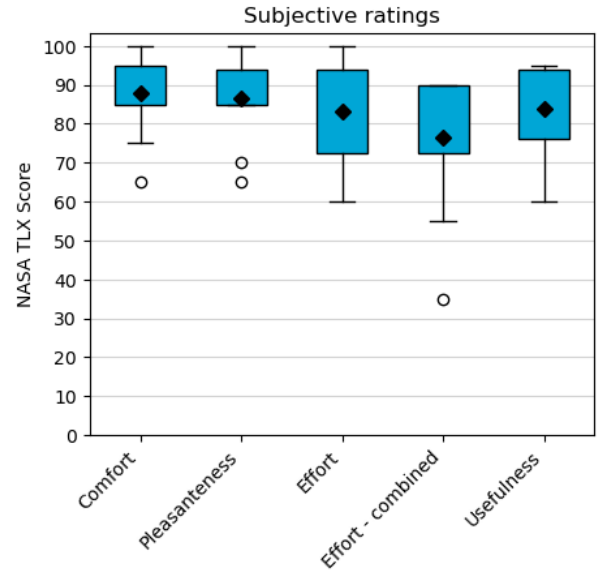


Fig. 26: Boxplots of the NASA TLX scores from the final subjective questionnaire of the validation experiment. From left to right, the columns correspond to comfort of the belt, pleasantness of the vibration, ease of recognition of the alerts when using the belt by itself, ease of recognition of the alerts during the combined task and perceived usefulness of the device. Scores are adjusted on a 0 to 100 scale. Mean values are visualized with diamond markers. Outliers are represented by circle markers.

facturing variations and the manual nature of the prototype assembly process. Additionally, the electrical wires of two ERM motors snapped during testing in the same weak spot, close to the parallel connection with the LEDs. This suggests the need for a stronger connection or a more reliable way of wiring the end components together, while maintaining the flexibility of the system. Nonetheless, the damaged end elements were easily replaced, which was proof of good modularity of the system.

4.1.2. Experimental Results

The initial intuitive descriptions of the vibration patterns revealed that certain patterns were not perceived uniformly across participants. The two simplest and most spatially separated patterns (pattern 1 and 2) were correctly identified in almost every case, with only the number of active motors being more problematic to distinguish. Instead, the more complex patterns revealed to be much more difficult to intuitively understand without knowing their structure beforehand. Pattern 3, the sequential activation of column from left to right, was still very intuitive, while pattern 4 and 5 lead to greater confusion. This aligns with the horizontal resolution of the back being higher than its vertical resolution, given that a pattern that made full use of the horizontal range of the grid was better perceived than a counterpart utilizing the vertical range of the grid. Additionally, pattern 4 was usually clear in its directionality, but in nearly half of the cases participants reported not clearly feeling the center of the motor grid. Pattern 5 had even greater perceptual confusion, again not related

to its sequencing but more related to the exact positioning of the stimulus. This suggests that large-area synchronous activations may not always be perceived as intended, and should be slightly offset as literature suggests. A general trend was noticed across the study: patterns that focused on actuating the sides of the grid were intuitively perceived, while patterns which utilized the central part of the grid were more difficult to interpret. The two central columns of the actuator matrix were in general less perceivable than the sides, confirming previous literature findings. The initial test results show the need for a brief familiarization and training with the vibration patterns before actual use in a real clinical scenario.

Even though the more complex patterns were revealed to be not highly intuitive, the standalone recognition test demonstrated that these patterns were still highly distinguishable between each other. Four of the five vibration patterns were recognized with 100% accuracy, with only one of the patterns being confused once, resulting in an overall recognition accuracy of over 99%. This result confirms that the chosen stimulation principles, in terms of frequency, location, resolution and modality of actuation, were effective in producing clear and easily distinguishable vibration patterns. The use of simple patterns with no diagonal lines, the use of mostly the sides of the motor grid, activation of full lines of motors and spatial and temporal discrimination between patterns all contributed to keeping the saliency of the stimuli very high. These choices were consistent with existing literature and were confirmed to be effective for the haptic belt's main goal.

Even when paired with a challenging task, like operating the AdLap surgical training tool, the haptic belt still performed well. Average recognition accuracy remained high, though slightly reduced at around 96%. This is expected, given the higher cognitive load and the divided attention between recognizing the vibration alerts and the marble sorting task. Nonetheless, the result proves that the haptic belt concept can be applied to a real scenario in which it needs to occasionally grab to attention of the surgeon and alert them of an ongoing issue while operating.

In accordance with the intuition test, the two patterns that were confused the most were pattern 4 and 5, the row activation from bottom to top and the fast pulsating pattern activating the entire motor grid. In fact, in both the standalone and combined tasks, these two patterns were confused for each other. This was probably due to the slight similarity in the activation characteristics of the two patterns. As demonstrated by the intuition test, participants based their discrimination choice mainly on the side motors activating, and the difference between 5 short bursts of all motors and 3 sequential bursts across the same motors wasn't enough to guarantee perfect recognition.

Analysis of participants' task performance using the AdLap showed a clear learning curve for group 1, in both completion time and collision count. For group 2, a similar downward trend was observed for completion time, although times were generally lower than the ones of group 1. Number of collisions for group 2 didn't clearly decrease. However, here collisions

started low already and stayed consistently low throughout the experiment. Given the small size of the groups, it is possible that group 2 had a generally higher skill in operating VR/AR systems, which was reflected in the results. Most importantly, though, when switching task conditions (i.e. going from runs interrupted by alerts to no alerts or vice versa), both groups didn't show any performance decrease. This indicates that the haptic belt did not significantly affect the overall performance of the surgical task. This is also confirmed when grouping together all runs for the two conditions: no significant difference in performance for completion time or collision count is seen between alert or no alert runs taken as a whole.

The questionnaire results were consistent with the objective performance data. Participants rated the belt highly in terms of comfort (88/100), pleasantness of vibration (86.5/100) and perceived usefulness (84/100). The choice of using neoprene to keep the system flexible and the focus on making the device lightweight and compact all contributed to the highly rated comfort. The level of vibration was also well tuned. All participants felt comfortable with the chosen intensity. These scores all indicate that the system could easily be adopted and be useful in a real setting. Subjects also rated the alerts as easy to recognize, both when using the haptic belt alone (83/100) and during the combined task (76.5/100). As expected, given the divided attention, the combined task scores were generally lower, although the difference was not statistically significant. Many participants explicitly mentioned that the two recognition tasks were comparable in difficulty, confirming that the haptic belt feedback didn't clash with existing sensory channels.

Overall, the results show that the manufactured prototype achieved the project goal of delivering salient, unobtrusive alerts, without drastically impacting the performance of the primary surgical task.

4.2. Limitations and Suggestions

Several limitations affected the results of the study:

- *Limited modularity*: Although most of the device was easily accessible and replaceable, some components (e.g. electrical connections between motors and LEDs, stitching between the motors and the neoprene sheet) were permanently installed or stitched together. Future iterations of the system should try to make all electrical connections and motor attachments more flexible, in order to obtain a fully modular design that doesn't need to be fully replaced when broken.

- *Motor-skin contact variability*: Although the belt was tightened and the motor assembly was designed to maximize contact interaction, individual differences in torso shape likely affected vibration saliency. Future versions of the design could improve the tensioning mechanism and the fit of the motor attachments on the skin.

- *Lack of preliminary sensitivity analysis*: Participants were not pre-screened for vibrotactile threshold differences. Only a subjective perception of clarity and comfort of the vibration

was considered. While vibration intensity was adjustable, the study lacked a systematic way to normalize the intensity across subjects. Future studies should try to implement an objective measure of saliency to get less variable results.

- *No full autonomy*: The prototype was designed and tested with a wired external power source and was not fully portable, which would be preferred in a real scenario to avoid cables being in the way. Additionally, commands were given manually during the tests. The actual system should be tied to automatic problem detection sensors to make it fully autonomous.

- *Not fully optimized stimulus*: Definition of vibration patterns was not fully optimized in terms of precise activation timings and intensity modulation. New approaches could be used by fine-tuning vibration onsets, fine-tuning vibration of single actuators (instead of having the same intensity for all) and taking advantage of haptic illusions to improve perception.

- *Small experimental sample size*: The number of stimuli, in the combined task specifically, was limited. Due to the fact that alerts needed to be sporadic to mimic realistic OR conditions, each participant received only 5 total alerts during the AdLap task. Moreover, the total number of participants ($n = 10$) was not enough to find truly significant results for the AdLap performance metrics. Future studies should include a larger participant pool or make the participants perform longer tasks to create bigger data sets.

- *Lack of realism*: Participants were not trained surgeons but novices, in both surgery and vibrotactile interfaces. The prototype was not tested in combination with a commercially available robotic-assisted surgical station but with a substitute system (i.e. the AdLap trainer with a virtual simulated task). Additionally, the room conditions of the test lab were different (less sensory overwhelming) than a real operating room. Future studies should be performed in a real setting, with experienced surgeons using a Da Vinci robot, to assess how the belt performs in its intended setting.

4.3. Financial Overview

According to the complete BOM, the total material cost of the prototype was around € 50, with the main expenses being for the platform material (approx. € 18), the ERM motors (approx. € 11) and the PCB assembly (approx. € 18 in total).

Based on a standard 3x markup price, the estimated selling price would be around € 150, to cover manufacturing, labor and logistics. Even with the implementation of automatic sensors, the total price could comfortably stay under the initially required maximum of € 250. Therefore, the device would be easily accessible to most healthcare institutions.

5. CONCLUSION

This study presented the design, manufacturing and validation of a wearable haptic belt intended to unobtrusively communicate operating room issues to surgeons performing

minimally invasive robotic-assisted procedures. Following a structured design process, from requirement definition and concept generation to prototyping and experimental testing, a functional vibrotactile interface was realized that met all key technical requirements.

The final prototype demonstrated high saliency and reliability in delivering vibrotactile stimuli, with standalone recognition accuracies exceeding 99% and combined-task accuracies remaining high at 96%, even under increased cognitive load. Participants consistently rated the system as comfortable, intuitive, and potentially useful in a real clinical setting. Importantly, the haptic belt did not significantly affect surgical task performance, indicating that it could effectively convey information without competing with the surgeon's visual or auditory attention.

While several limitations were identified, the results support the feasibility of using vibrotactile communication as an additional information channel in robotic-assisted surgery. With further refinements in ergonomics, modularity and stimulus design, a system of this kind could develop into a complete product, capable of improving a surgeon's awareness in the operating room.

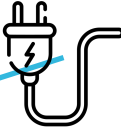
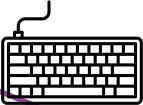
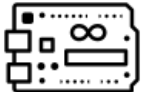
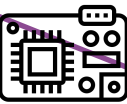
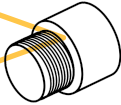
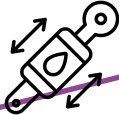
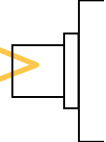
REFERENCES

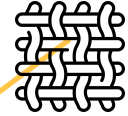
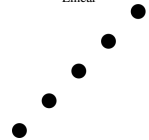
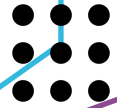
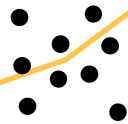
- [1] Intuitive Surgical, [Da Vinci Xi Robotic Surgical System](#), [Online]. Accessed: 2025-11-18.
- [2] Gravità Zero, [Il robot Da Vinci Xi al Policlinico Federico II di Napoli](#), [Online]. Accessed: 2025-11-18.
- [3] Cleveland Clinic, [Laparoscopy](#), [Online]. Accessed: 2025-11-18.
- [4] A. Zihni et al., [Comparison of precision and speed in laparoscopic and robot-assisted surgical task performance](#). *The Journal of surgical research*, vol. 223, pp. 29–33, 2018.
- [5] H. Cooper, H. M. Lau, and H. Mohan, [A systematic review of ergonomic and muscular strain in surgeons comparing robotic to laparoscopic approaches](#), *Journal of Robotic Surgery*, vol. 19, no. 1, p. 252, 2025.
- [6] J. Dwivedi and I. Mahgoub, [Robotic Surgery - A Review on Recent advances in Surgical Robotic Systems](#), 2012.
- [7] C. Leitsmann et al., [The Silent Operation Theatre Optimisation System \(SOTOS\(©\)\) to reduce noise pollution during da Vinci robot-assisted laparoscopic radical prostatectomy](#). eng, *Journal of robotic surgery*, vol. 15, no. 4, pp. 519–527, 2021.
- [8] I. E. Rassi and J.-M. E. Rassi, [A review of haptic feedback in tele-operated robotic surgery](#), *Journal of Medical Engineering & Technology*, vol. 44, no. 5, pp. 247–254, 2020.
- [9] A. F. Jouybari, M. Franza, O. A. Kannape, M. Hara, and O. Blanke, [Tactile spatial discrimination on the torso using vibrotactile and force stimulation](#). eng, *Experi-*

- mental brain research, vol. 239, no. 11, pp. 3175–3188, 2021.
- [10] Shipping Storm, [Approximate Weight of Goods](#), [Online]. Accessed: 2025-11-04.
 - [11] L. Klunder, [An Overview of Wearable Tactile Feedback Interfaces for Active Transfer of Non-Tactile Information](#), 2025.
 - [12] B. A. Karimi and W. Niazi, [Voltage and electrical safety](#), *Journal of Mechanical, Civil and Industrial Engineering*, vol. 6, no. 3, pp. 62–71, 2025.
 - [13] TinyTronics, [Small Vibration DC Motor 2.5-4V](#), [Online]. Accessed: 2025-11-07.
 - [14] K. O. Johnson, [The roles and functions of cutaneous mechanoreceptors](#), *Current Opinion in Neurobiology*, vol. 11, no. 4, pp. 455–461, 2001.
 - [15] S. J. Lederman and L. A. Jones, [Tactile and Haptic Illusions](#), *IEEE Transactions on Haptics*, vol. 4, no. 4, pp. 273–294, 2011.
 - [16] J. van Erp, [Vibrotactile spatial acuity on the torso: effects of location and timing parameters](#), in *First Joint Eurohaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems. World Haptics Conference*, 2005, pp. 80–85.
 - [17] Raspberry Pi Ltd, [Raspberry Pi Pico 2 W Datasheet: An RP2350-based microcontroller board with wireless](#), 2024.
 - [18] LCSC Electronics, [HUASHUO AO3400A](#), [Online]. Accessed: 2025-11-08.
 - [19] LCSC Electronics, [SUNMATE Elec SS14](#), [Online]. Accessed: 2025-11-08.
 - [20] Deepblue Mbedded, [Raspberry Pi Pico W pinout diagram GPIO guide](#), [Online]. Accessed: 2025-11-08.
 - [21] EasyEDA, [Online PCB design & circuit simulator](#), [Online]. Accessed: 2025-11-08.
 - [22] IPC-2152 – Standard for Determining Current-Carrying Capacity in Printed Board Design released, *Circuit World*, vol. 36, no. 1, 2010.
 - [23] J. Geerling, [The Raspberry Pi Pico W brings WiFi for \\$6](#), [Online]. Accessed: 2025-11-12.
 - [24] H. C. Stronks, D. J. Parker, and N. Barnes, [Vibrotactile Spatial Acuity and Intensity Discrimination on the Lower Back Using Coin Motors](#), *IEEE Transactions on Haptics*, vol. 9, no. 4, pp. 446–454, 2016.
 - [25] M. F. Nolan, [Quantitative Measure of Cutaneous Sensation: Two-Point Discrimination Values for the Face and Trunk](#), *Physical Therapy*, vol. 65, no. 2, pp. 181–185, 1985.
 - [26] C. Lim, G. Park, and H. Seifi, [Designing Distinguishable Mid-Air Ultrasound Tactons with Temporal Parameters](#), in *Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems*, 2024.
 - [27] I. Makarov et al., [The haptic intensity order illusion is caused by amplitude changes](#), *ACM Transactions on Applied Perception*, vol. 21, no. 1, pp. 1–18, 2024.
 - [28] A. M. L. Kappers and M. A. Plaisier, [Guidance for the Design of Vibrotactile Patterns for Use on the Human Back](#), in *Haptics: Science, Technology, Applications*, 2022, pp. 39–47.
 - [29] A. M. L. Kappers, J. Bay, and M. A. Plaisier, [Perception of Vibratory Direction on the Back](#), in *Haptics: Science, Technology, Applications: 12th International Conference, EuroHaptics 2020, Leiden, The Netherlands, September 6–9, 2020, Proceedings*, 2020, pp. 113–121.
 - [30] NWO, [AdLap Systems: A versatile modular Advanced Laparoscopy robot platform with fully reusable cableless instrument actuators with interaction force sensing](#), [Online]. Accessed: 2025-11-17.
 - [31] Delft University of Technology, [Human Research Ethics](#), [Online]. Accessed: 2025-11-17.
 - [32] S. G. Hart and L. E. Staveland, [Development of NASA-TLX \(Task Load Index\): Results of Empirical and Theoretical Research](#), in *Human Mental Workload*, ser. Advances in Psychology, vol. 52, North-Holland, 1988, pp. 139–183.
 - [33] Flaticon, [Vector Icons and Stickers](#), [Online]. Accessed: 2025-11-07.

APPENDIX A

MORPHOLOGICAL CHART

SUB-FUNCTIONS							
Power Source	Rechargeable Battery 	Throw-away battery 	Wired external power source 				
Signal Reception	Wireless external input 	Wired external input 	Automatic Sensors 				
Signal Processing	Raspberry Pi 	Arduino 	ESP 				
Stimulating Elements	Coin motors (ERMs, LRAs) 	Servomotors 	Voice coils 	Fluidic actuators (hydraulics / pneumatics) 	Smart materials (piezoelectric, EAPs, SMAs, MR fluid actuators) 	Electrodes 	Innovative hybrid actuators (electrohydraulic, airflow) 
Stimulation Type	Vibration 	Skin-stretch 	Indentation 	Electro-stimulation 			
Interaction Element	Direct contact 	Insulation layer / Casing 	Secondary element / Distancer 				
Main Wearable Platform	Vest 	Belt 	Sleeve (on a limb) 	Band (wristband, ankleband) 	Footsole 	Helmet 	

Securing Mechanism							
Signal Patterning							
Feedback							

APPENDIX TABLE I: Morphological chart visualizing the options for the various sub-functions of the device [33]. The blue line connects the chosen functional elements for the first design. The purple line connects the chosen functional elements for the second design. The yellow line connects the chosen functional elements for the third design.

APPENDIX B

MICROCONTROLLER CODE

```
1 import network
2 import machine
3 import uasyncio as asyncio
4 import ure
5
6 # -----
7 # Wi-Fi Access Point Configuration
8 # -----
9 ap = network.WLAN(network.AP_IF)
10 ap.config(essid='HapticBeltWLAN', password='raspberrry')
11 ap.active(True)
12 while not ap.active():
13     pass
14 print("AP active. Connect to http://192.168.4.1")
15
16 # -----
17 # Pin Mapping (3x4 Grid)
18 # -----
19 # Physical layout:
20 # [3, 2, 8, 9]
21 # [5, 4, 10, 11]
22 # [6, 7, 13, 12]
23 pin_numbers = [3, 2, 8, 9, 5, 4, 10, 11, 6, 7, 13, 12]
24
25 pins = []
26 for p in pin_numbers:
27     pwm = machine.PWM(machine.Pin(p))
28     pwm.freq(1000)
29     pwm.duty_u16(0)
30     pins.append(pwm)
31
32 led = machine.Pin("LED", machine.Pin.OUT)
33
34 # -----
35 # Global State
36 # -----
37 DEFAULT_INTENSITY = 32768 # 50%
38 current_intensity = DEFAULT_INTENSITY
39 current_task = None
40
41 # -----
42 # Utility Functions
43 # -----
44 def all_on(intensity=None):
45     val = intensity if intensity is not None else current_intensity
46     for pwm in pins:
47         pwm.duty_u16(val)
48
49 def all_off():
50     for pwm in pins:
51         pwm.duty_u16(0)
52
53 async def blink_led(duration=0.2):
54     led.value(1)
55     await asyncio.sleep(duration)
56     led.value(0)
57
58 async def single_actuator(idx, intensity=None):
59     val = intensity if intensity is not None else current_intensity
60     pins[idx].duty_u16(val)
61     asyncio.create_task(blink_led())
62     await asyncio.sleep(0.2)
63     pins[idx].duty_u16(0)
64
65 # -----
66 # Vibration Patterns
67 # -----
68 async def Pattern_1(): # Left column
69     for i in [0, 4, 8]:
70         pins[i].duty_u16(current_intensity)
71         await asyncio.sleep(1)
72     all_off()
73
74 async def Pattern_2(): # Right column
75     for i in [3, 7, 11]:
76         pins[i].duty_u16(current_intensity)
77         await asyncio.sleep(1)
78     all_off()
79
```



```

80 async def Pattern_3(): # Column sweep LR
81     columns = [
82         [0, 4, 8],
83         [1, 5, 9],
84         [2, 6, 10],
85         [3, 7, 11]
86     ]
87     # Left → Right
88     for group in columns:
89         for i in group:
90             pins[i].duty_u16(current_intensity)
91             await asyncio.sleep(0.25)
92         for i in group:
93             pins[i].duty_u16(0)
94     # Right → Left
95     for group in reversed(columns):
96         for i in group:
97             pins[i].duty_u16(current_intensity)
98             await asyncio.sleep(0.25)
99         for i in group:
100             pins[i].duty_u16(0)
101
102 async def Pattern_4(): # Rows Bottom → Top
103     rows = [
104         [8, 9, 10, 11],
105         [4, 5, 6, 7],
106         [0, 1, 2, 3]
107     ]
108     for group in rows:
109         for i in group:
110             pins[i].duty_u16(current_intensity)
111             await asyncio.sleep(0.33)
112         for i in group:
113             pins[i].duty_u16(0)
114
115 async def Pattern_5(): # All pulse
116     for _ in range(5):
117         all_on()
118         await asyncio.sleep(0.1)
119         all_off()
120         await asyncio.sleep(0.1)
121
122 patterns = [Pattern_1, Pattern_2, Pattern_3, Pattern_4, Pattern_5]
123
124 # -----
125 # Task Manager
126 # -----
127 async def run_exclusive(coro):
128     global current_task
129     if current_task:
130         current_task.cancel()
131     try:
132         await current_task
133     except asyncio.CancelledError:
134         all_off()
135     current_task = asyncio.create_task(coro)
136
137 # -----
138 # HTML Interface
139 # -----
140 full_html = """\
141 HTTP/1.1 200 OK
142 Content-Type: text/html
143
144 <!DOCTYPE html>
145 <html lang="en">
146 <head>
147 <meta charset="UTF-8">
148 <meta name="viewport" content="width=device-width, initial-scale=1">
149 <title>Haptic Belt Control Panel</title>
150 <style>
151     body {
152         font-family: 'Segoe UI', sans-serif;
153         background: #000;
154         text-align: center;
155         margin: 0;
156         padding: 0;
157         color: white;
158     }
159     h2 {
160         background: #000;
161         color: white;
162         margin: 0;
163         padding: 15px 0 10px 0;
164         font-size: 1.7em;

```

```

165     font-weight: 700;
166     border-bottom: 2px solid white;
167 }
168 .controls {
169     margin: 20px auto;
170     display: flex;
171     align-items: center;
172     justify-content: center;
173     gap: 10px;
174 }
175 .controls label {
176     font-weight: 500;
177     font-size: 1.1em;
178     color: white;
179 }
180 .intensity-wrapper {
181     display: inline-flex;
182     align-items: center;
183     border: none;
184     border-radius: 8px;
185     overflow: hidden;
186     margin-top: 5px;
187 }
188 .intensity-wrapper input {
189     font-size: 1.1em;
190     width: 60px;
191     text-align: center;
192     border: none;
193     padding: 5px 0;
194     color: #000;
195     background: #ffffff;
196     -moz-appearance: textfield;
197     outline: none;
198 }
199 .intensity-wrapper input::-webkit-inner-spin-button,
200 .intensity-wrapper input::-webkit-outer-spin-button {
201     -webkit-appearance: none;
202     margin: 0;
203 }
204 .intensity-wrapper button {
205     font-size: 1.1em;
206     font-weight: bold;
207     width: 30px;
208     height: 30px;
209     border: none;
210     background-color: #00a6d6;
211     color: white;
212     cursor: pointer;
213     transition: background 0.2s, transform 0.1s;
214 }
215 .intensity-wrapper button:hover {
216     background-color: #80D3EB;
217     color: #0C2340;
218 }
219 .intensity-wrapper button:active {
220     background-color: #0076c2;
221     transform: scale(0.95);
222 }
223 .grid {
224     display: grid;
225     grid-template-columns: repeat(4, 1fr);
226     gap: 15px;
227     padding: 20px;
228     max-width: 500px;
229     margin: 0 auto;
230 }
231 .extras {
232     display: grid;
233     grid-template-columns: repeat(1, 1fr);
234     gap: 10px;
235     padding: 10px 20px 30px;
236     max-width: 500px;
237     margin: auto;
238 }
239 .grid button {
240     aspect-ratio: 1 / 1;
241     width: 100%;
242     font-size: 0;
243     border: none;
244     border-radius: 50%;
245     background-color: #00a6d6;
246     transition: background 0.2s, transform 0.1s;
247 }
248 .grid button:hover {
249     background-color: #80D3EB;

```

```

250     transform: scale(1.05);
251   }
252   .grid button:active {
253     background-color: #0076c2;
254     transform: scale(0.95);
255   }
256   .extras button {
257     width: 100%;
258     padding: 20px;
259     font-size: 1.1em;
260     border: none;
261     border-radius: 12px;
262     background-color: #00a6d6;
263     color: white;
264     font-weight: 500;
265     transition: background 0.2s, transform 0.1s;
266   }
267   .extras button:hover {
268     background-color: #80D3EB;
269     color: #0C2340;
270   }
271   .extras button:active {
272     background-color: #0076c2;
273     transform: scale(0.98);
274   }
275   footer {
276     margin: 20px;
277     font-size: 0.9em;
278     color: #80D3EB;
279   }
280 </style>
281 </head>
282 <body>
283
284 <h2>Haptic Belt Control Panel</h2>
285
286 <div class="controls">
287   <label for="intensity">PWM Duty Cycle %</label>
288   <div class="intensity-wrapper">
289     <button id="minus"></button>
290     <input type="number" id="intensity" min="1" max="100" value="50">
291     <button id="plus"></button>
292   </div>
293 </div>
294
295 <div class="grid">
296   <button data-idx="0"></button>
297   <button data-idx="1"></button>
298   <button data-idx="2"></button>
299   <button data-idx="3"></button>
300   <button data-idx="4"></button>
301   <button data-idx="5"></button>
302   <button data-idx="6"></button>
303   <button data-idx="7"></button>
304   <button data-idx="8"></button>
305   <button data-idx="9"></button>
306   <button data-idx="10"></button>
307   <button data-idx="11"></button>
308 </div>
309
310 <div class="extras">
311   <button data-idx="0">Left Column</button>
312   <button data-idx="1">Right Column</button>
313   <button data-idx="2">Column Sweep LR</button>
314   <button data-idx="3">Rows Bottom→Top</button>
315   <button data-idx="4">All Pulse</button>
316 </div>
317
318 <footer>© 2025 TU Delft - Haptic Belt Interface</footer>
319
320 <script>
321 function getIntensity() {
322   let val = parseInt(document.getElementById('intensity').value);
323   if (isNaN(val) || val < 1) val = 1;
324   if (val > 100) val = 100;
325   return val;
326 }
327 function postWithIntensity(path) {
328   const intensity = getIntensity();
329   fetch(path + '?intensity=' + intensity, { method: 'POST' });
330 }
331 document.getElementById('plus').addEventListener('click', () => {
332   let input = document.getElementById('intensity');
333   let val = parseInt(input.value) || 1;
334   if (val < 100) input.value = val + 1;

```

```

335 });
336 document.getElementById('minus').addEventListener('click', () => {
337     let input = document.getElementById('intensity');
338     let val = parseInt(input.value) || 1;
339     if (val > 1) input.value = val - 1;
340 });
341 document.querySelectorAll('.grid button').forEach((btn) => {
342     btn.addEventListener('click', () => {
343         postWithIntensity('/press/' + btn.dataset.idx);
344     });
345     btn.addEventListener('touchstart', () => {
346         postWithIntensity('/press/' + btn.dataset.idx);
347     });
348 });
349 document.querySelectorAll('.extras button').forEach((btn) => {
350     btn.addEventListener('click', () => {
351         postWithIntensity('/extra/' + btn.dataset.idx);
352     });
353     btn.addEventListener('touchstart', () => {
354         postWithIntensity('/extra/' + btn.dataset.idx);
355     });
356 });
357 </script>
358 </body>
359 </html>
360 """
361
362 # -----
363 # Web Server Handler
364 # -----
365 async def handle_client(reader, writer):
366     global current_intensity
367
368     request_line = await reader.readline()
369     if not request_line:
370         await writer.aclose()
371         return
372     request = request_line.decode()
373     while await reader.readline() != b"\r\n":
374         pass
375
376     # Parse intensity (if provided)
377     match_intensity = ure.search(r"intensity=(\d+)", request)
378     if match_intensity:
379         pct = int(match_intensity.group(1))
380         pct = max(1, min(100, pct))
381         current_intensity = int(pct * 655.35)
382
383     # Handle POST requests
384     if "POST" in request:
385         match_gpio = ure.search(r"POST /press/(\d+)", request)
386         match_extra = ure.search(r"POST /extra/(\d+)", request)
387         if match_gpio:
388             idx = int(match_gpio.group(1))
389             if 0 <= idx < len(pins):
390                 print(f"Single Motor: index={idx}, GPIO={pin_numbers[idx]}")
391                 await run_exclusive(single_actuator(idx))
392         elif match_extra:
393             idx = int(match_extra.group(1))
394             if 0 <= idx < len(patterns):
395                 print(f"Pattern {idx+1} triggered")
396                 await run_exclusive(patterns[idx]())
397         await writer.awrite("HTTP/1.1 204 No Content\r\n\r\n")
398         await writer.aclose()
399         return
400
401     # Serve HTML GUI
402     await writer.awrite(full_html)
403     await writer.aclose()
404
405 # -----
406 # Main Loop
407 # -----
408 async def main():
409     server = await asyncio.start_server(handle_client, "0.0.0.0", 80)
410     print("Listening on http://192.168.4.1 ...")
411     while True:
412         await asyncio.sleep(1)
413
414 try:
415     asyncio.run(main())
416 finally:
417     asyncio.new_event_loop()
418

```

APPENDIX C

EXPERIMENT PROTOCOL

Preparations

- Connect the haptic belt to USB-C power source and launch its control panel.
- Set PWM intensity to 70% and check correct functioning of vibration on haptic belt.
- Turn on the AdLap controller, launch the AdLap application and calibrate the system.
- Load experiment data logging software.
- Prepare informed consent paper.
- Randomly assign subject to Group 1 (no alerts first) or Group 2 (alerts first).

Subject arrival

- Greet subject, read the informed consent introducing the study and obtain signature on consent paper.
- Secure the haptic belt snugly around the subject's lower back. Ensure that the motor grid is placed symmetrically and that the motors make good contact with the skin. The subject preferably needs to wear only one layer of light clothing (e.g. a t-shirt).
- Adjust the height of the stool and the resistance of the armrests. Write down the settings.
- Ask the subject if the entire setup is comfortable.

Block 1 - Haptic Belt Familiarization and Recognition Test

1.1 - Actuator localization

Recite: "The device has 12 vibration motors in total, arranged in a 3 by 4 rectangular grid. I will now activate them one by one starting from the top left and ending at the bottom right, to give you a feeling for where they are located and what their intensity is."

- One by one, activate each motor briefly.
- Ask the subject if the vibration intensity is comfortable and clearly perceivable.
If no: adjust PWM vibration intensity.
If yes: proceed to next phase.
- Write down the settings

1.2 - Pattern intuition check

Recite: "I will now present to you five different vibration patterns, without any prior knowledge of them. After each one I would like you to describe where you felt the motors activate, how many times and if the pattern was stationary or moving. This is done to see how intuitive these patterns are."

- Present each of the 5 vibration patterns once in a random order and record the subject's description.

1.3 - Mapping introduction

Recite: "I will now give you a cheat sheet that shows the 5 vibration patterns. Every pattern is meant to alert the user about a specific problem in the operating room. I will now play the patterns one by one while explaining their meaning. This is the first pattern. It signals [OR meaning]. Etc..."

- Hand out the cheat sheet with vibration pattern visualizations and associated meanings in the operating room.
- For each pattern: play it once, show its label on the sheet, and explain aloud what it means.
- After every pattern has been shown, play them all once more.
- Ask the subject if everything is clear or if any of the patterns need to be played again, then proceed to actual test.

1.4 - Recognition test

Recite: "You will now perform the actual recognition test for the haptic belt. One of the 5 vibration patterns will be played randomly 15 times. After each one, please try to guess out loud what is the problem in the OR that is being signaled. After your reply and your answer is recorded, the next pattern will be played. You will have the cheat sheet available at all times if you need a reminder of the patterns' meanings."

- Manually present 15 total stimuli, 3 per pattern, in a randomized order.
- For each stimulus: wait for subject to say aloud the pattern's associated OR problem; record subject's reply; play next pattern.
If no reply is given (no-hit), wait 5 to 10 seconds and continue along the pattern sequence.
- No direct feedback needs to be given to the subject during this phase.

Block 2 – AdLap Controller Familiarization and Test

2.1 - Controller familiarization

Recite: “You will now be introduced to the AdLap system, a minimally-invasive surgical training tool. The controller has two maneuverable joysticks, each controlling a virtual robotic arm in the simulation you see in front of you. You can move around the endpoint of the arms and open and close the graspers. The system also has two armrests to support your arm weight. The simulated task is to pick colored marbles and drop them in the matching basket. You can now familiarize with the system by performing one trial run before the test. Try to feel how the system moves, how all the joints rotate and how the simulation detects collisions.”

- Make subject perform one trial run of the pick-and-place task with 6 marbles to sort in two colors. Let the subject familiarize with the system’s behaviour.

2.2 - Final test

Recite: “You will now perform the final test of the experiment. This will be divided into two blocks: in the first block you will perform a marble sorting run 3 times **with no added feedback**, in the second block you will perform 3 runs again but **with added occasional alerts from the haptic belt**.” [switch the two according to group]

- 6 total runs with the AdLap controller divided in two blocks:
3 run
- Order depends on group assignment (1 = no alerts first; 2 = alerts first).
- Each run has 8 marble pick-and-place actions to be performed.

No-alert runs

Recite: “In these first three runs no alerts will be played, so focus on the pick-and-place task, sorting the marbles as quickly as possible and trying to avoid collisions of the virtual robotic graspers.”

- Make subject perform 3 controller runs.
- 1-2 min break between runs.
- Automatically record performance metrics from the AdLap controller: time to completion, path length of virtual robotic arms and number of collisions.

Alert runs

Recite: “The following three runs will occasionally be interrupted by a vibration alert coming from the belt. Each run will have at least one alert, possibly two if timing allows it. Each alert indicates something happening outside your view in the operating room. Whenever you feel a vibration alert, acknowledge it by saying out loud what the problem in the OR is, as you previously did in the recognition test. You will have the cheat sheet at your disposal if needed.”

- Make subject perform 3 runs with haptic belt active.
- For each run: deliver a vibration alert at a randomly assigned time between 20 and 60 seconds into the run; deliver an eventual second alert at least 1 minute after the first one (timeframes to be adjusted according to the subject’s expected completion time seen from the test run).
- Make sure that each subject receives at least 5 total alerts across all 3 runs, showing each pattern at least once (with patterns shown in a random order).
- 1-2 min break between runs.
- Automatically record performance metrics from the AdLap controller.

Final Questionnaire

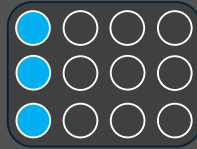
Ask to give subjective ratings, graded on a NASA TLX 5-point scale, for how:

- Comfortable the haptic belt was.
- Annoying the vibration was.
- Easy it was to recognize the vibration patterns when using the belt alone.
- Easy it was to recognize the alerts when using the belt in combination with the AdLap controller.
- Useful they think the haptic device might be for a surgeon in a real scenario.

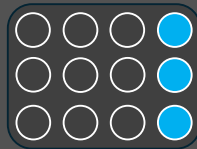
APPENDIX D

EXPERIMENT CHEAT SHEET

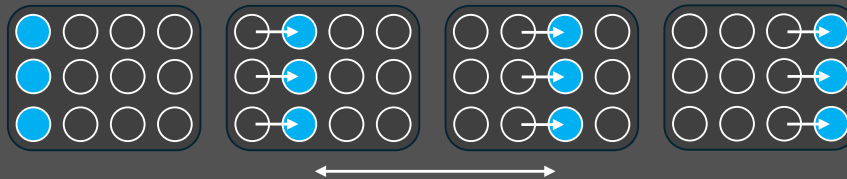
Door Open



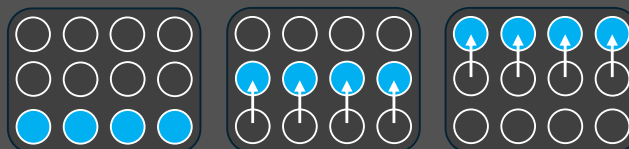
Power Source Issue



Patient Issue



Docking Issue



Collision Hazard with staff

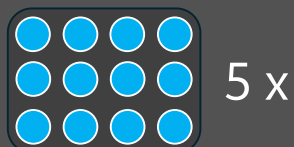


Fig. 27: Cheat sheet used during the validation experiment. The document shows a visualization of the vibration patterns and their connected meaning.

APPENDIX E

EXPERIMENT FINAL QUESTIONNAIRE

Final Subjective Questionnaire

How comfortable was the haptic belt?



How pleasant was the vibration?



How easy was it to recognize the vibration patterns when using the belt alone?



How easy was it to recognize the alerts when using the belt in combination with the AdLap controller?



How useful do you think the haptic belt might be for a surgeon in a real scenario?



Fig. 28: Final questionnaire of the experiment, using a 5-point scale NASA TLX grading system.

An Overview of Wearable Tactile Feedback Interfaces for Active Transfer of Non-Tactile Information

Leo Klunder - 6055370

Abstract—This literature review investigates wearable tactile feedback interfaces designed to actively convey non-tactile information through touch. While haptic technologies are increasingly used across fields such as medicine, robotics and virtual reality, most applications focus on restoring or simulating physical touch. This review focuses instead on interfaces that deliver abstract or higher-order information, such as navigation cues, alerts, and symbolic signals, using tactile stimuli, in order to find typical design choices. Following a systematic search and filtering process based on PRISMA guidelines, 38 prototypes were analyzed and categorized by stimulation method: mechanical (vibration, skin-stretch, indentation, or multiple) and electrical. The analysis revealed a strong preference for vibration-based mechanical interfaces, opposed to a lower representation of skin-stretch, indentation, and electrical stimulation devices. Common design trends included simplicity and intuitiveness of stimulus distribution, and a focus on directional cue delivery. The review highlights the limited versatility of current actuation technologies and identifies future opportunities in developing more flexible tactile systems, capable of transmitting a broader range of non-tactile information.

1. INTRODUCTION

The skin is a powerful communication channel, capable of sensing a wide range of physical stimuli such as light touch, pressure, vibration, stretch, heat and pain [1]. Yet, even while being the human body's largest sensory organ, it is often underutilized in most communication applications [2], where visual and auditory feedback dominate instead. This is due to the higher complexity and perceived importance of information that vision and hearing are able to convey over the sense of touch [3][4]. Therefore, researchers are increasingly turning to haptic feedback as an additional way to deliver information, not only purely touch-related but also of higher order, in an effort to take better advantage of this sensory platform.

Haptic feedback can generally be divided into two types: tactile or cutaneous and kinesthetic or proprioceptive [5]. Tactile feedback is generated by stimulating skin mechanoreceptors: Merkel cells, which react to sustained indentation and detect shape and texture, Meissner corpuscles, sensitive to low-frequency vibrations, contact slip and sudden forces (in general dynamic skin deformation), Pacinian corpuscles, sensitive to high-frequency vibrations and Ruffini endings, sensitive to skin stretch [6]. On the other hand, kinesthetic feedback comes from receptors in muscles and tendons: muscle spindles, sensitive to muscle fiber length and contraction velocity, and

Golgi tendon organs, sensitive to muscle force [7]. All these receptors work together to give us a rich sense of touch and body position awareness.

Haptic interfaces are devices specifically designed to stimulate these receptors. They artificially recreate an otherwise missing touch or force sensation, or convey some external information through this artificial stimulation. Many different types of haptic interfaces have been developed over the years, in terms of stimulation type, conveyed information and applications. A first distinction can be made looking at the type of delivered feedback. Tactile interfaces target the skin's mechanoreceptors and usually try to recreate a touch sensation (e.g. surface shape or texture [8]), via mechanical or electrical stimulation of these receptors. On the other hand, kinesthetic interfaces are focused on the musculoskeletal system's movement and usually try to recreate a force sensation (e.g. presence of an obstacle [9] or a grasping force on the hand [10]), by applying a force themselves or offering some type of resistance. A further distinction can be made between active and passive haptic interfaces. Active interfaces directly stimulate the user to generate the desired sensation (like a vibrating wristband to give alerts [11]). Passive interfaces, instead, adapt to user inputs and only react to specific actions (like a fingertip display to simulate softness sensation [12] or a manipulator with impedance control to simulate collisions [13]).

Used technologies range from widely available electromagnetic actuators, like servo motors and eccentric rotating mass motors, to piezoelectric motors to hydraulics and pneumatics to smart materials, like shape memory alloys and dielectric elastomers [14].

The fields these interfaces are becoming increasingly relevant in are also varied: from medicine (remote surgery [15], motor rehabilitation [16]) to robotics (teleoperation [17], drone guidance [18]) to sensory substitution (feedback for prostheses [19] or for visually impaired users [20]) to recreation (more immersive virtual reality experiences [21]). In all these contexts, touch can be used to convey data that is either missing or carried by a different sensory channel, making the complete system feel more intuitive.

Within this vast field of research, haptics have been naturally adopted to convey or restore simple tactile information. Instead, not equal effort has been put into developing haptic interfaces that deliver more complex non-tactile information, such as navigation cues, alerts, or symbolic signals. This type

of interface is especially valuable when vision and hearing, the usual sensory channels for this kind of information, are unavailable or overloaded.

Therefore, the goal of this review is to give an overview of the state-of-the-art in tactile interfaces designed to deliver external non-tactile information through touch, in order to find the most common technologies and design choices used, and help the prototyping of future devices in this field.

2. METHODS

To collect relevant literature for this review, the search plan guidelines from Delft University of Technology [22] were followed, together with the PRISMA filtering method for systematic reviews [23]. The literature search was carried out using the Scopus database, chosen for its broad library of peer-reviewed publications. The database was consulted in order to find devices with a functioning and already tested prototype.

The research focused on tactile interfaces that actively convey non-tactile information through touch. While a passive interface is dependent on the user's initiative to create a contact and interact with it, an active interface needs instead to stimulate the user at any given moment without prior input. Therefore, delivering information becomes much easier if the device is by design already and always in contact with the subject. For this reason, the attribute of being wearable, thus already attached somewhere on the body, is added to the desired characteristics of the devices searched for.

In the end, according to the specified research goal of the review, the search query used in Scopus was structured around three main terms: **wearable**, **tactile**, and **interface**, connected by AND operators. For each of these terms, a range of synonyms and related terms were added to increase the likelihood of capturing all relevant studies. These additional terms were refined through an iterative process, trying to balance the inclusiveness and relevance of the results: the pool of resulting papers had to be broad enough to avoid missing important entries, but narrow enough to filter out unrelated content. The final search query was:

(TITLE("wearable" OR "*worn" OR "on-skin" AND ("tactile" OR "haptic" OR "vibration" W/2 "interface" OR "device" OR "technolog" OR "system" OR "actuator" OR "display" OR "glove" OR "vest" OR "band" OR "belt" OR "sleeve" OR "grid" OR "array" OR "feedback")) AND ABS("haptic" OR "tactile" OR "vibration" W/2 "device" OR "interface" OR "technolog" OR "system" OR "actuator" OR "display" OR "glove" OR "vest" OR "band" OR "belt" OR "sleeve" OR "grid" OR "array" OR "feedback")) AND NOT TITLE("sensor" OR "force-feedback" OR "kinesthetic" OR "stiffness")) AND PUBYEAR > 2009 AND PUBYEAR < 2026 AND (LIMIT-TO (LANGUAGE, "English"))).

The term "sensor" and terms related to the kinesthetic side of haptic interfaces ("kinesthetic", "stiffness" and "force-

feedback") were excluded from the title field with the AND NOT operator. This was done to avoid including studies on passive sensing or force-based interfaces, which were outside the scope of this review. A complete and more easily readable list of all the terms used in the search query can be found in Table I. The first three columns of the table list the three main blocks of terms put in series with an AND (terms within a column are put in parallel with an OR operator), while the fourth column lists the excluded terms put in series to first three blocks with an AND NOT. A publication year filter (2010–2025) was added at the end of the query to focus only on recent developments in the field. For this, a time window of 15 years was considered as a good balance to capture trends of the past decade without going too far back in time. Finally, a language filter (English) was also added to mirror the author's proficiency and general use of English in scientific publications.

The search returned 369 automatic entries, on which a finer selection process was carried out. After removing 4 duplicate entries, 365 records were screened based on their titles: entries that did not mention an active tactile interface in the title were excluded, together with papers focusing on sensors and kinesthetic feedback that were not automatically filtered, leaving 309 papers. Abstracts were then reviewed, and studies that focused on tactile sensory substitution and restoration (e.g. prostheses with tactile feedback to simulate lost touch sensations), or operator tactile exploration (e.g. feeling surface texture or softness) were excluded. Instead, only devices that focused on conveying higher-order non-tactile information were included, reducing the pool to 84 papers. The full texts of these papers were screened for a detailed description of the device design specifications and functional parameters. Out of the 84 papers, 46 that lacked major information about design choices were excluded. In the end, 38 articles were included in the final review. A diagram illustrating the complete PRISMA selection flow can be seen in Fig. 1.

TABLE I: Search Query Terms

Attribute	Field	Subject	Exclusions
Wearable	*Tactile	Interface*	Sensor*
Worn	Haptic	Device*	Force-feedback
On-skin	Vibration*	Technolog*	Kinesthetic
		System*	Stiffness
		Actuator*	
		Display*	
		Glove*	
		Vest*	
		Band	
		Belt*	
		Sleeve*	
		Grid*	
		Array*	
		Feedback*	

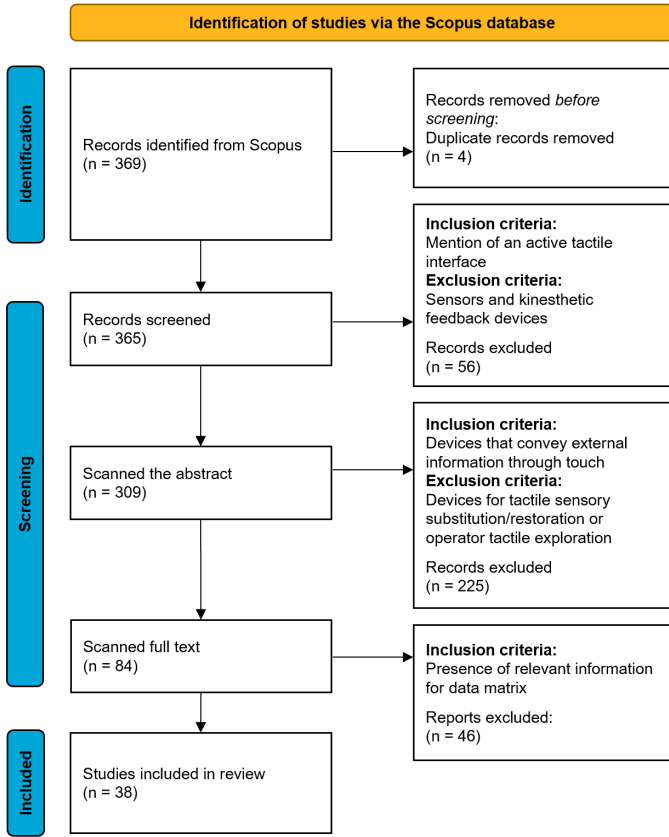


Fig. 1: PRISMA flow diagram illustrating the complete filtering process to select the papers to be included in the review.

3. CLASSIFICATION

From the selected papers, information about functioning principles, technologies, design details and applications was extracted and used to fill a data matrix, which can be seen in its entirety in the Appendix. Given the large amount of information stored in the data matrix, a classification is needed to group concepts together and present results concisely. For this purpose, different classifications are possible. The most intuitive one is based on the stimulation mechanic, i.e. the way the device interacts with the skin's mechanoreceptors. Other possibilities include the actuation technology, the type of delivered information and related feedback method, and finally the body location / pattern of actuators of the device, so the positioning and distribution of stimulus on the body.

In the end, due to better coherence within sub-groups compared to other division methods, the chosen classification is stimulation type. This results in two main categories: 1) mechanical stimulation and 2) electrical stimulation. In fact, the two main ways a haptic interface can interact with the skin's mechanoreceptors consist in either 1) giving an external mechanical stimulus that the receptors are able to register and transform into an electrical signal to be sent to the brain or 2) directly stimulating the mechanoreceptors with an electrical input that simulates the effect of a mechanical stimulation

[24]. The mechanical category is subsequently divided into more specific sub-categories that focus on only one type of mechanical stimulation. These are vibration, skin-stretch, indentation and a sub-category for devices that are capable of doing multiple types of mechanical stimulation. The electrical category is further divided into deep and superficial electrical stimulation. A schematic overview of the defined classification can be seen in Fig. 2.

In the following sections, each category and subcategory are further explored using examples found in literature. Specifically, the review gives insights about encountered actuation technologies, operational parameters, the preferred types of transferred information, the modality in which this is done (i.e. specific feedback details) and the preferred locations and distributions of tactile stimuli on the human body.

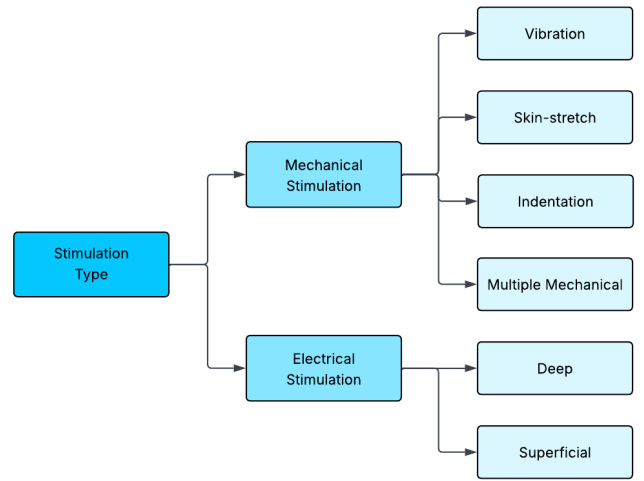


Fig. 2: Diagram illustrating the classification of the results according to the stimulation mechanic.

4. MECHANICAL STIMULATION

Mechanical stimulation is achieved by haptic interfaces through the use of a mechanical actuator, which is put (directly or indirectly) in contact with the user's skin. The actuator displaces the skin with a desired frequency, intensity and direction, triggering the mechanoreceptors that are sensitive to that particular type of stimulus. The three main stimulation types, which mechanical haptic interfaces can be divided in, are: vibration (specifically high frequency), skin-stretch and indentation. Subsections A, B and C are dedicated to these three groups respectively. Instead, subsection D is dedicated to devices that are able to do multiple of the three listed mechanical stimuli.

4.1. Vibration

Vibration is by far the largest subcategory within mechanical

stimulation and the most widely adopted stimulation modality for wearable haptic interfaces in general. This trend is also reflected in the pool of selected studies for this review, with 24 out of 38 total included devices relying on this functioning principle to interact with the human body.

The most common actuation technology used to generate vibratory feedback were small electromagnetic motors, particularly eccentric rotating mass (ERM) motors. ERM motors typically work by spinning an unbalanced mass attached to the shaft of a direct current brushed motor. As the offset mass rotates, its centripetal force is asymmetric, resulting in a net centrifugal force, which causes a displacement of the motor. With a high number of revolutions per minute, the motor is constantly being displaced and moved by these asymmetric forces, which are perceived as a vibration. The frequency and amplitude of the vibration are controlled by adjusting the motor's rotational speed, typically through modulation of the input voltage or using a pulse-width modulation (PWM) duty cycle. Two main form factors of ERM motors are commonly found in literature:

- Coin-shaped ERM motors, where the motor and eccentric mass are enclosed in a flat, disk-like housing; a popular model for this type of actuator is a Precision Microdrive 310 Series ERM motor, as the ones use in the design of BuzzWear [11] and EdgeVib [25]; typical dimension for these actuators are around 10 mm for the diameter and 3 mm for thickness.
- Cylindrical ERM motors, where the motor and mass are housed in a more elongated, tubular casing; these seem to be preferred for applications around the waist and lower back area, like in the directional cue waistband developed by Hao and Song [26] and in the character delivering back array by Janidarmian et al. [27]; cylindrical ERM motors typically have a smaller diameter compared to coin-shaped ones (6 to 8 mm), but they are longer (from 10 to 20 mm).

Fig. 3 shows examples of these two types of ERM motors. Typical operational voltage ranges were from 2 to 5 V [28] and operational vibration frequencies varied from 10 to around 200 Hz, with the most utilized range being between 170 and 200 Hz, in order to best match the peak sensitivity of Pacinian corpuscles [6]. For example, Lee and Starner used a 175 Hz frequency to produce a "strong" 0.71 g amplitude vibration and a second 133 Hz for a "weaker" 0.43 g amplitude vibration [28], Ibrahimov et al. varied the frequency between 100 and 200 Hz [18], Liao et al. used a 170 Hz resonant frequency [25], Szczerba et al. used a 200 Hz frequency producing a 1.25 g amplitude vibration [29]. Some interfaces utilized a lower frequency range, like the tactile foot sole designed by Tachiquin et al. [20] and the MoveTouch motor guidance bracelet [30], both operating at 10 to 55 Hz. Maximum vibration amplitudes were almost always around 0.75 to 1 g.

In addition to ERMs, some devices used alternative vibration actuators:

- Piezoelectric actuators (TDK Electronics PowerHap 2.5 g) were employed by Lee and In in their wrist-worn

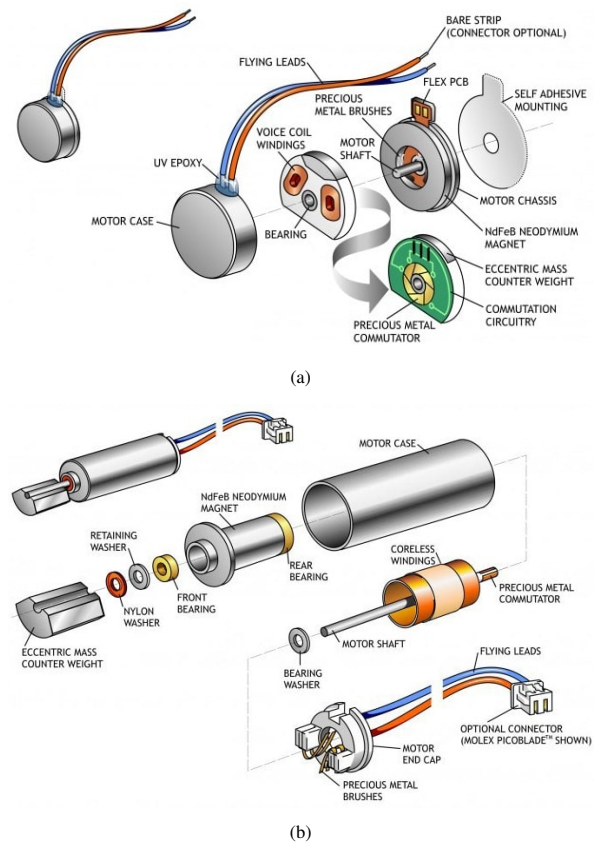


Fig. 3: Examples of a) ERM coin-shaped motor and b) ERM cylindrical motor from Precision Microdrives [31].

vibrotactile device for orientation [32]. Piezoelectric actuators take advantage of the inverse piezoelectric effect to change in length when an electrical voltage is applied. PowerHap actuators, in particular, are based on a multilayered piezoceramic center plate with inner copper electrodes. When activated, the plates only expand minimally in one axis, but, due to constant volume restrictions, they contract simultaneously in both other axes. Two stainless steel cymbals are then attached at both sides of the center plate, acting as displacement amplifiers; see Fig. 4 for reference. Therefore, providing an alternate current at a desired frequency to the actuator creates a corresponding vibration. The specific model used in this case had dimensions of 9 x 9 x 0.55 mm, an operating voltage of -10 to 60 V and a peak vibration amplitude of 2.5 g.

- Voice coil actuators (Tactile Labs Haptuator Mark II) were used by Culbertson et al. in their WAVES haptic interface for motion guidance of the hand [34]. Voice coil actuators are direct current linear actuators, composed of a permanent magnet suspended inside an electromagnetic coil. Current flowing through the coil generates a magnetic field that interacts with the permanent magnet, creating a force that displaces the magnet itself. The force vector can then be reversed by changing the polarity of current flowing through the coil, which, if

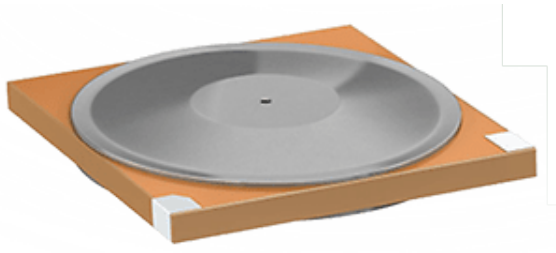


Fig. 4: TDK Electronics PowerHap 2.5 g piezoelectric actuator, with two stainless steel cymbals on the sides on a piezoceramic plate (in orange) [33].

done repeatedly at high frequency, creates a vibration. In the specific case of WAVES, voice coil actuators were used to generate asymmetric vibration by moving the magnet unevenly along the axis of the actuator. This was achieved by giving as input a step-ramp current pulse which pushed the magnet quickly in one direction and then slowly returned it to its starting position. These asymmetric vibrations would create a salient pull sensation in a specified direction, giving an intuitive way to display guidance cues. The actuators in question had total dimensions of $9 \times 9 \times 32$ mm and a characteristic frequency of 110 Hz. A picture of the WAVES voice coil actuator can be seen in Fig. 5.

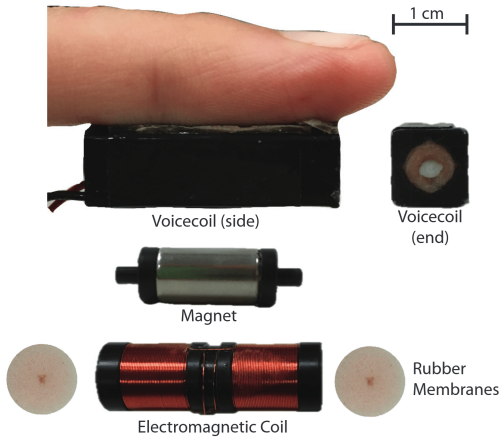


Fig. 5: Voice coil actuator strapped to the index finger, as used by Culbertson et al. [34].

- Tactile transducers (Tactaid VBW32) were used by Gopalai and Arosha Senanayake in a postural correction waist interface [35], with very similar operating parameters as ERM motors: 5-12 V voltage range, PWM duty cycle input and a 250 Hz resonant frequency. Tactile transducers are also a type of voice coil actuator, commonly compared to bass shakers that, instead of producing low frequency bass sound through a diaphragm, transmit low-frequency vibrations to an external body.
- An innovative variation on a voice coil actuator was implemented by Ozioko et al. in their wearable haptic fingertip interface named Tacsac [36]. This electromagnetic

actuator employed a flat, flexible, spiral coil, interacting with a permanent magnet on top of it, which acted as the skin contactor, all encased in soft polydimethylsiloxane. The actuator had a total diameter of 15 mm (10 mm spiral coil diameter) and was capable of generating vibrations between 10 and 200 Hz, with a resonant frequency of 60-70 Hz, at which the maximum off-plane displacement was 0.377 mm. The voice coil was paired with a capacitive sensing layer so that the system could both send and receive vibration messages. Images of the actuator can be seen in Fig. 6.

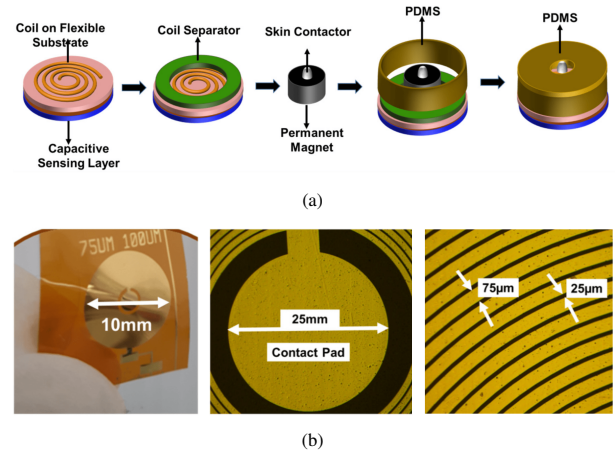


Fig. 6: a) Schematic representation of the structure of the Tacsac spiral voice coil actuator. b) Pictures of the flexible coil that was integrated in the actuator [36].

Body location and distribution for the vibration actuators varied significantly across literature examples and were influenced by the specific application. Most interfaces were placed somewhere on the upper part of the body, with the arms being the preferred location. Hong et al. placed 12 actuators, equally spaced on two lines on both sides of the arm, spanning the arm length [37], Lee and In placed 8 actuators around the forearm in 2 consecutive circles of 4 (equally radially distributed) [32], Vibrosleeve used 16 actuators in 4 strips of 4, parallel to the arm axis and equally spaced around the forearm as well [28], MoveTouch [30], EdgveVib [25] and BuzzWear [11] had actuators placed around the wrist, 5 in-line on the volar side, 4 in a 2×2 grid on the dorsal side and 3 in a flat triangular layout on the volar side, respectively. For the hand, Shin et al. placed 9 vibration motors, of which 5 were on every second finger phalange, 2 on the knuckles and 2 near the wrist [38], Luzhnica and Veas used 6 actuators on the back of the hand as well, one on every second finger phalange and one on the back of the palm [39], WAVES was composed of 9 actuators positioned on the phalanges of the first three fingers [34]. Included fingertip interfaces were Tacsac, with one actuator on the tip of the index [36] and DronePick, with one actuator per fingertip [18].

After the arms, the waist and lower back area was the next most common region for actuator placement. If the feedback to be delivered was simply binary, like in the case

of a postural correction alert, only 2 actuators were needed: Gopalai and Aroscha Senanayake placed one actuator at the front and one at the back of the waist [35], while Xu et al. placed the two actuators at the sides (left and right of the waist at approximately the L4/L5 level) [16]. Instead, if the device needed to deliver multiple different cues, like different directions, an array of actuators was placed linearly around the waist or in a grid on the lower back: Hao and Song placed 12 vibration motors equally radially distributed around the waist [26], Janidarmian et al. developed a 3 x 3 grid of actuators for the lower back [27], Dharma et al. placed 60 ERM coin motors in 5 x 6 matrices on the front and back of the torso [40], Srikulwong and O'Neill implemented both a waist interface with 8 equispaced actuators and a 3 x 3 back array interface, ultimately landing on the belt configuration to design their TactNav navigation system [41].

The legs, although less represented, had also some examples of applications in literature: Stock et al. placed 4 equispaced actuators around the ankle for their FEEDI navigation prototype [42] and Chen et al. used 4 vibration motors as well, evenly distributed along the anterior hemisphere of the ankle, for their gait retraining interface [43]; both Tachiquin et al. [20] and Kammoun et al. [44] developed foot sole haptic displays with 4 ERM motors positioned at the four cardinal directions to give wayfinding cues.

Even less frequent but notable placements include:

- A neck interface called HapticPointer by Matsuda et al. [45] with 16 in-line vibrotactors equispaced around the neck to transmit direction information.
- A head interface integrated into glasses by Szczerba et al. [29] with one vibration motor per temple for automotive route guidance.
- An interface integrated into standard industrial loosely-fitting workwear, with 13 actuators spread across the body next to various joints and anatomic references with thin skin, created by Lins et al. to deliver posture awareness warning [46].

Fig. 7 shows some examples of the mentioned haptic interface prototypes for different body locations.

Despite the great variability of positioning and distribution of the tactile stimuli on the body, a common characteristic could be seen across the majority of devices, being that the number of actuators was kept as low as possible and their pattern as simple as possible. In fact, the number of actuators rarely exceeded 10 to 12, with the haptic interface by Dharma et al. [40] being the big outlier with 60 individual actuators, and the distribution of actuators was nearly always done in a simple line or grid, or by placing one tactor per anatomical reference (e.g. one actuator per finger [18][39]).

Spacing between actuators within an array was kept around 2 to 3 cm in areas with finer tactile two-point discrimination, like the wrist [30][25], and around 5 cm for less sensitive areas, like the torso [27]. When a radial spacing was used, the usual angular resolution would be 90° between actuators around a limb or big part of the body [42][32], with the most resolved tactile displays arriving at a maximum of 30° between

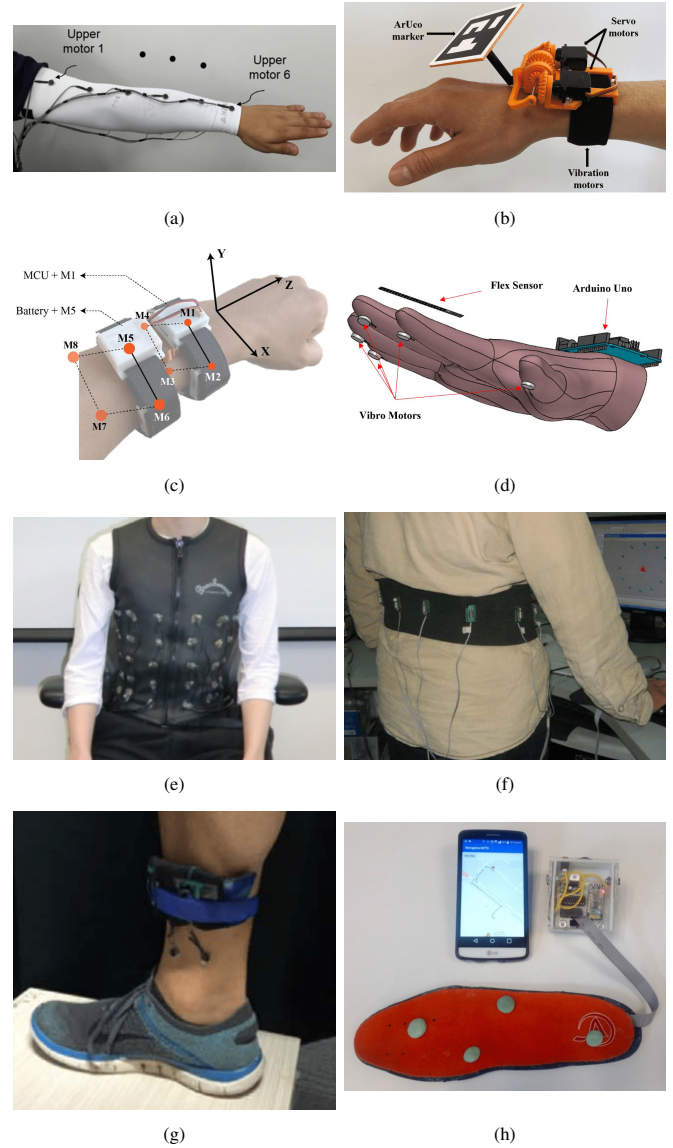


Fig. 7: a) Arm sleeve interface by Hong et al. [37]. b) MoveTouch wrist interface [30]. c) Forearm interface by Lee and In [32]. d) DronePick fingertip interface [18]. e) Haptic vest by Dharma et al. [40]. f) Waist belt interface by Hao and Song [26]. g) Ankle interface by Chen et al. [43]. h) Foot sole interface by Tachiquin et al. [20].

consecutive actuators [26], and even in these cases the most salient directions would remain the main four around that body part.

Regarding the type of transferred non-tactile information, the most common application was giving directional cues, with a total of 10 devices. These focused on either automotive navigation [29], teleoperation [18] or guidance of visually impaired people [20]. Other encountered relevant applications were:

- motor guidance of limbs, for rehabilitation purposes [28] or for human-robot interaction safety [30];
- biofeedback corrective alerts, mainly for posture and balance control [16];
- textual communication through touch, either with morse

code [36] or by directly delivering alphanumeric characters [25], and even musical tones for pitch training [38].

The way in which information was delivered, thus the specific feedback parameters, also strongly depended on the application. Spatial encoding was usually done with the activation of a single actuator, where the activated location on the body corresponded to a spatial direction relative to the user (e.g. directions around the waist for guidance of visually impaired [41]), a direction relative to an external teleoperated body (e.g. direction of a target relative to a drone [18]) or a position on an external body (e.g. wing deflection of a UAV displayed on the arm [37]). Motor guidance of limbs was usually done with a pattern activation of the actuators, in order to create a tactile illusion of motion on the skin that signaled the direction in which to move the body part [30]. More abstract information was also delivered through a sequential activation of actuators to create stroke patterns (e.g. recreating the stroke patterns to draw alphanumeric characters [27]) or by activating multiple actuators at once and encoding a specific character, note or concept to that combination of actuators. The temporal characteristics of the stimuli varied from 50 ms vibration pulses [29] to 2 sec constant vibration signals [38], with an average of around 200-250 ms. Time intervals between sequential activations were anywhere from 0.5 sec for more warning-style information [20], to being partially overlapped in the case of creating a smooth continuous stroke pattern [43]. In general, intensity modulation was also used to signify severity (e.g. higher intensity for more severe posture violations [35]) or just to create more distinct tactile patterns to be recognized [11].

4.2. Skin-stretch

The second most common mechanical stimulation approach after vibration is skin-stretch, with 5 devices included in this review taking advantage of this mechanic. Skin-stretch is based on deforming the skin laterally, therefore triggering Ruffini endings. This often produces a very salient stimulus, which has been proven to be even more effective than vibration on some parts of the body, like the forearm [47].

The preferred actuation for skin-stretch interfaces were servo motors. While for vibration the actuator itself was generating the stimulus, here the actuator was used to move a secondary element, which in turn was put in direct contact with the user's skin. A typical approach would involve using servo motors to pull flexible fabric straps wrapped around a limb or torso. Pulling the straps would then stretch the skin in one direction or squeeze it, generating intuitive cues like a navigation direction. Kayhan and Samur [48] developed a haptic waist belt interface with 2 servo motors (Hitec HS311) actuating latex straps on both sides of the waist to give directional cues to visually impaired runners. The strap would get pulled proportionally to the desired steering angle, to signify the direction in which the user would have to move. KhalilianMotamed Bonab et al. [49] also created a skin-stretch

haptic interface using fabric belts actuated by two brushless DC servo motors (Maxon DCX22S), and positioned it around the forearm, to give motor guidance cues to the hand (for modulating the opening and closing of the hand in particular). In both configurations the pair of servos were put on opposite sides of the body part with their axis parallel to the body part's axis and were connected with a pulley to a strap, in order to provide bidirectional stretch or a squeeze stimulation (if the two servos rotated in opposite directions). Fig. 8 shows these two skin stretch haptic interfaces using actuated fabric belts.

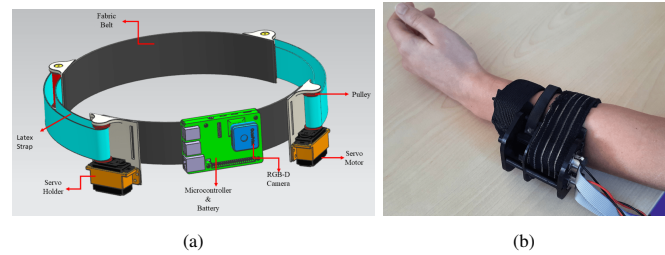


Fig. 8: ?? 3D model of the skin-stretch haptic interface with actuated fabric belts around the waist by Jayhan and Samur [48]. ?? Prototype of skin-stretch haptic interface with fabric belts around the forearm by KhalilianMotamed Bonab et al. [49].

A lateral skin-stretch interface by Kuang et al. [50] also employed servo motors. In this case, two linear servos (VS-19 Linear Pico Servomotors) actuated a 2D Cartesian-like structure with a spherical tactor placed on the forehead to give position information. The structure can be seen in Fig. 9.

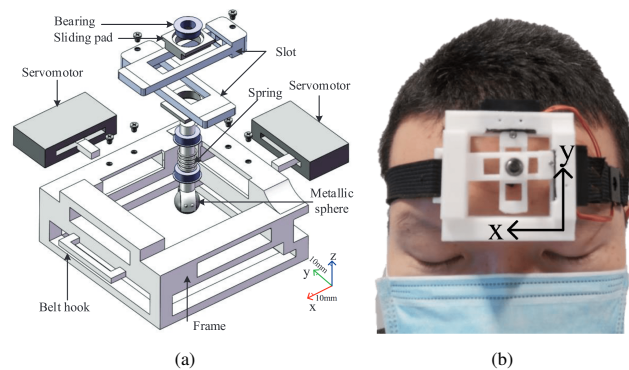


Fig. 9: ?? Exploded 3D model of the lateral skin-stretch interface by Kuang et al. [50]. ?? Interface prototype placed on the forehead.

Other actuation technologies encountered in literature included:

- An ultrasonic piezoelectric motor, used by Bark et al. [51] to rotate two contact pads attached to the forearm's skin, in order to intuitively deliver rotational information.
- A novel mechanism by Haynes et al. [52] using shape-memory alloy (SMA) wires, that took advantage of their shape memory effect to change in length when an electric current flowed through them. The device in question consisted of a 3D-printed planar diamond-shaped structure with two SMA coils mounted orthogonally between opposite corners, capable of expanding and contracting in the two orthogonal directions. Two corners of the

structure were then connected via adhesive pads on the skin to transmit the deformation of the wires as skin-stretch; the skin-stretch would serve as an unobtrusive notification. Fig. 10 shows a picture of the prototype placed on the forearm.

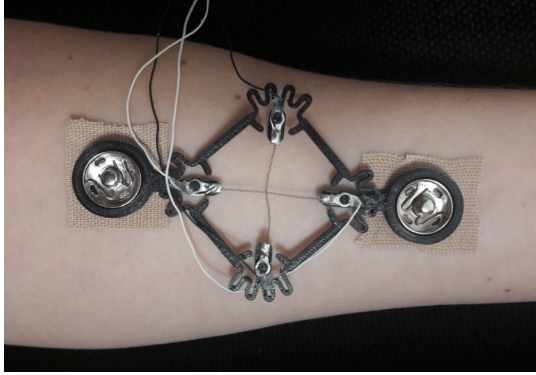


Fig. 10: Skin-stretch interface using SMA coils developed by Haynes et al. [52].

Regarding placement and distribution, the preferred location were once again the arms, with the inner and outer sides of the forearm being the most utilized. Even in the case of the tactile interface by Kuang et al. [50], for which the primary positioning was the forehead, alternative considered placements were the wrist and back of the hand. Also, all devices used only two actuators, which was the minimum number necessary to create a skin-stretch stimulus either in two orthogonal directions [52] or along the same line but on two opposite sides of a body part at once [49].

Once again, as for vibration, the main application was giving directional cues, either for navigation for blind people [48] or for motor guidance of a limb [49]. An additional spatial application was encountered in the reviewed literature, only present among skin-stretch devices: position information. In fact, the forehead interface by Kuang et al. [50] used an 8 mm spheric tactor that could move inside a 60 x 60 mm square frame to provide location feedback about the user's absolute position, while the haptic interface by Bark et al. [51] provided positional information about absolute rotations, by imparting a rotational skin-stretch on the forearm within a $\pm 45^\circ$ range.

In terms of information encoding, spatial direction was the most common modality, with the direction of skin deformation intuitively coupled to the direction to be displayed. Stretch intensity was then modulated corresponding to magnitude (e.g. bigger stretch for bigger steering angle to be taken by the user [48]) or error (e.g. a linearly modulated feedback as a function of pose/angular error [49]). Temporal encoding was less relevant, given the continuous nature of stretch stimuli.

4.3. Indentation

Indentation here is meant as any vertical skin displacement different from a vibration, thus, either a dynamic low-frequency vertical stimulus, like a short tap, or a sustained indentation,

like a long press. Therefore, the targeted mechanoreceptors are a combination of Merkel cells, which are the main afferents for localized normal pressure, and Meissner corpuscles, if the stimulus is more dynamic. In the reviewed literature, the number of haptic interfaces falling under this category is much lower than for the vibration stimulus, and even less popular than skin-stretch. In total, 3 devices were included in this review.

Encountered actuation technologies for tapping devices were similar to ones already found in previous categories:

- Van der Woude et al. [53] used one voice coil actuator to power a circular pad that tapped the user's upper arm, giving rhythm cues for improving speech fluency. Pictures of the device can be seen in Fig. 11.

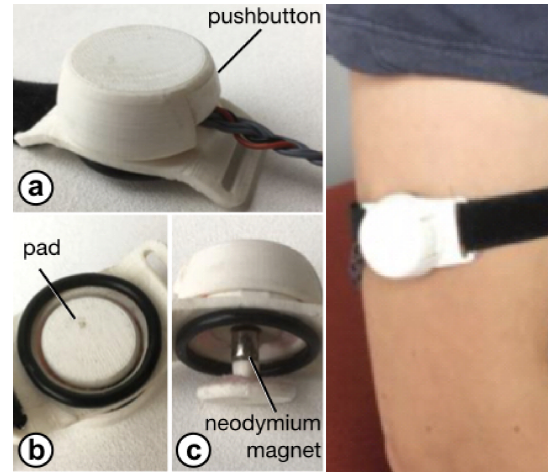
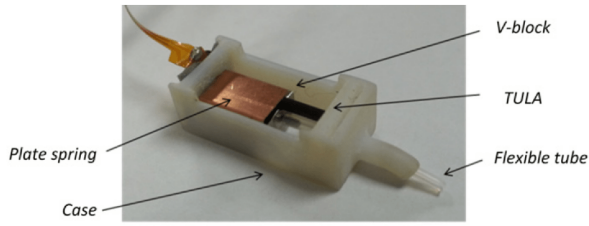


Fig. 11: Tapping interface by Van der Woude et al. [53]. On the left is a closer look at the actuation, on the right is the device strapped around the upper arm.

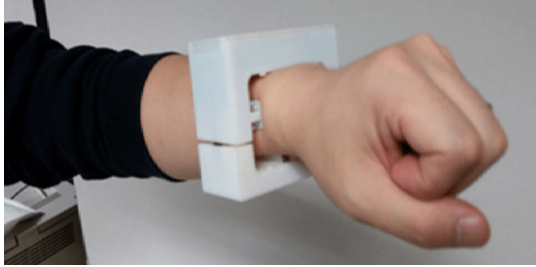
- Jin et al. [54] designed a wrist interface called VT-ware to give motor guidance cues to the arm, with 6 piezoelectric actuators (TULA50 from Piezoelectric Technology Co. Ltd.). Four actuators were equally radially distributed around the wrist and the other two were added in-line on the dorsal side of the wrist. The device can be seen in Fig. 12.

Instead, a novel actuation principle was implemented by Lee and Lee [55] in their tactile display using airflows. Here, 4 small electric air pumps (JPM32B) were mounted in a square shape of 33 mm diagonal, to be attached on various possible hairy skin locations on the body. The air jets produced by the wearable interface would recreate the sensation of sustained skin indentation without direct contact, in order to deliver directional information. Fig. 13 shows the prototype of this "non-contact" tactile interface.

Given the small number of entries, no real trend in spatial distribution of the actuators could be extracted. Nonetheless, the total number of actuators was still kept low (it varied from 1 to 6 in the included examples) and the preferred location of stimulus were once again the arms, with devices placed on the wrist [54] and upper arm [53], confirming the trend seen in previous subcategories of mechanical stimulation



(a)



(b)

Fig. 12: a) TULA module used in the VT-ware prototype [54], featuring a piezoelectric actuator to displace a flexible tube acting as skin contactor. b) Complete VT-ware prototype installed around the wrist.



Fig. 13: Airflow-based indentation tactile interface by Lee and Lee [55]. On the left is a closer look at the prototype's 4 air pumps, on the right is the device strapped around the back of the neck and wrist.

interfaces. Even for the airflow tactile display, among the 12 total considered sites, the two that were deemed the best were the dorsal side of the wrist together with the dorsal side of the neck [55]. Actuator spacing was once again around the 15 to 30 mm mark for wrist interfaces and 90° for radial distribution around the wrist, as for the vibration devices.

The most popular application was reconfirmed as giving information about directions: the airflow tactile display used two sequential 500 ms constant stimuli on two opposite side pins to signal a desired navigation direction to the user [55], while VT-ware [54] generated a single 20 ms tapping stimulus or a tactile motion illusion on the module/s that corresponded to the desired motor guidance direction (direction in which the arm needed to move).

4.4. Multiple Mechanical Stimulation Types

This subsection is dedicated to wearable tactile interfaces that were not focused on only one mechanical stimulation principle, but were designed to take advantage of multiple

feedback types at once. In particular, 3 examples found in literature were able to include combinations of vibration, indentation and stretch, either by using multiple types of specialized actuators on the same device or by using a single type of actuator that could vary its stimulation characteristics.

For the former case, MacGavin et al. [56] developed an arm tactile interface for communication between deaf-blind, which integrated 13 ERM coin motors (Tatoko vibration Coin motors) with 6 servo motors (SG90) and a thermal patch (COM11 289), making the device able to generate vibration, indentation (both tapping and long press) and heat stimuli. The ERM motors were placed in 2 x 2 matrix flat on the back of the palm, within the gaps of a vertically oriented 3 x 3 matrix; the 6 servo motors were staggered along the forearm, on top of the thermal patch. Fig. 14 shows this distribution of actuators on the resulting prototype.

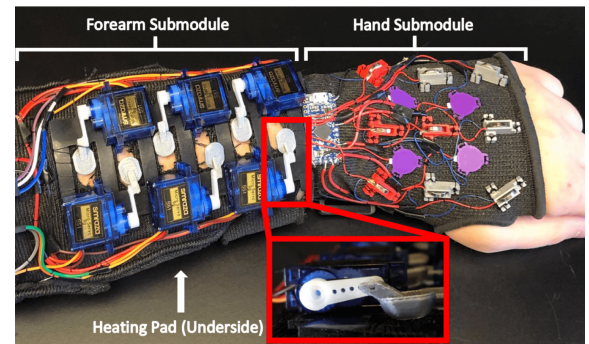


Fig. 14: Prototype of the arm tactile interface by MacGavin et al., featuring multiple types of actuators on different parts of the device [56].

For the other case, Sanchez-Tamayo et al. [14] designed a cutaneous wearable device using one electrohydraulic actuator that was capable of delivering multiple types of haptic cues. This novel actuation technology consisted in a vertical stack of 10 pouches, made from a flexible thermoplastic shell, with electrodes on both sides and filled with liquid dielectric. When a voltage was applied across the electrodes, the generated electric field interacted with the dielectric, making the electrodes to begin zipping together and displacing the liquid dielectric. This expanded the central part of the pouch and created a displacement that could be used for mechanical stimulation of the skin. The electrohydraulic actuator was capable of delivering broadband vibration from 0 to 200 Hz, sustained pressure or tapping (quickly making and breaking contact with the skin) by modulation of the input voltage value and frequency. The system used high voltages, with a maximum of 6 kV, but still ensured safety by limiting the maximum current and properly insulating the actuator pouch. The functioning principle of the actuator and its integration in the final prototype are visualized in Fig. 15.

In the third example, a family of on-skin tactile interfaces called Springlets was designed by Alhuda Hamdan et al. [57]. The researchers used the same actuation principle, shape-memory alloys, but adapted it to slight variations of the same base actuator to generate different tactile stimuli. Specifically,

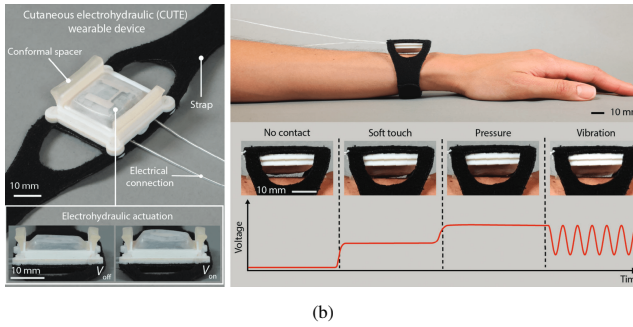
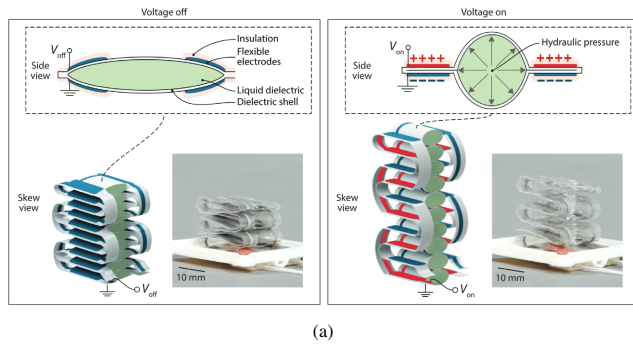


Fig. 15: a) Graphical explanation of the functioning principle of the electrohydraulic actuator by Sanchez-Tamayo et al. [14]. b) Wrist interface prototype using one electrohydraulic actuator.

6 different actuators were developed, each of them using one SMA (Toki BioMetalHelix or Dynalloy Flexinol) spring attached parallel to the skin with bi-adhesive medical tape. The base actuator structure and 6 resulting variations can be seen in Fig. 16. When current flowed through the SMA spring, it heated up and contracted, stretching the skin at the attachment points as a result. Then, by slightly changing the way the spring was attached to the skin, a wide range of non-vibratory touch sensations could be produced, mainly different types of skin-stretch (pinching, directional stretching, dragging and expanding) and indentation (pressing or pulling).

Regarding positioning, although two of the three devices were tested on multiple different hairy skin locations, the preferred placing was once again on the arms: Springlets [57] were placed on wrist and upper arm for testing and on the forearm for a motion guidance application, Sanchez-Tamayo et al. [14] placed their prototype on the dorsal side on the wrist, and the tactile interface by MacGavin et al. [56] was designed to be put on the back of the hand and forearm.

Given the great variety of feedback types and locations, applications of these devices were also various, with the main ones still being direction giving and unobtrusive notifications, as seen in previous subcategories. In particular, the electrohydraulic interface was designed to generate diverse alert cues [14] and the haptic device by MacGavin et al. [56] for "protactile" communication among deaf-blind people, specifically to signal presence and engagement between users and to give directional information. Cited applications for Springlets [57] were subtle alerts, motion guidance of the arm, chest breathing coordination (rhythm cueing), navigation and enhancement of virtual reality experiences.

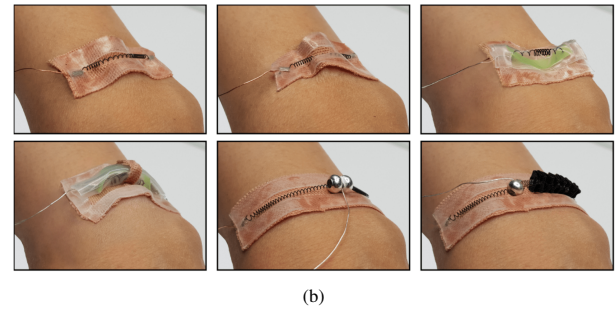
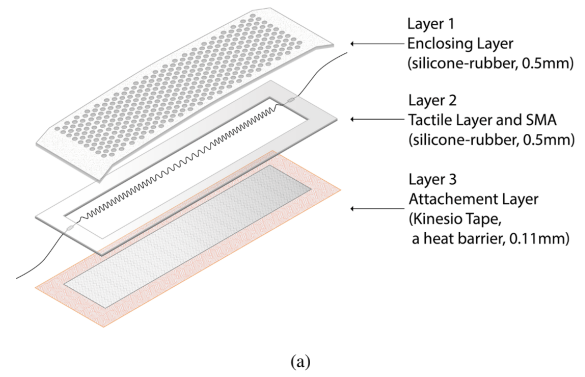


Fig. 16: a) Representation of the structure of the base SMA Springlet actuator by Alhuda Hamdan et al. [57]. b) Images of the resulting 6 variations of non-vibratory tactile interfaces.

5. ELECTRICAL STIMULATION

Electrical stimulation represents a fundamentally different approach from mechanical tactile feedback. It involves directly stimulating the nerve axons of skin mechanoreceptors via electric currents. This is done by creating an electric potential difference on the external membrane of the nerves, and when this potential exceed a certain threshold a tactile sensation is perceived as if the mechanoreceptors were stimulated mechanically [58]. Two main types of electrical stimulation can be identified, namely superficial and deep electrical stimulation. The two sub-sections A and B are dedicated to literature examples for these two stimulation mechanics. Despite its potential, electrical stimulation remains less widespread in tactile interfaces. Even for this review, only 3 total examples found in literature were included.

5.1. Superficial Electrical Stimulation

Superficial electrical stimulation involves placing electrodes on the skin's surface. The most common form of device in this sub-category used metallic electrodes arranged in high-density grids, put in direct contact with the user's skin. Nguyen et al. [59] developed a tongue-placed electrotactile display featuring 33 total copper electrodes, arranged in a round matrix with 8 rays equispaced at 45° (5 electrodes per ray plus one central electrode). The electrodes were 3 mm in diameter and covered a total area of 3 x 3 cm on the tongue. See Fig. 17 for reference.

Similarly, Lu et al. [60] created an electrotactile display

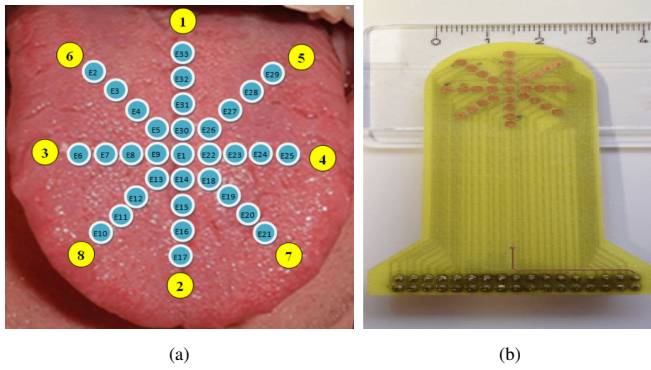


Fig. 17: a) Electrode placement on the tongue for the electrotactile display by Nguyen et al. [59]. b) Picture of the component of the fabricated prototype to be placed on the tongue.

with 64 solder tin hemispherical electrodes, arranged in a 8 x 8 square matrix. The electrode here were slightly smaller, with a 1.55 mm diameter, and covered a similar working space of 2.7 x 2.7 cm. Fig. 18 shows the prototype of this electrotactile display.

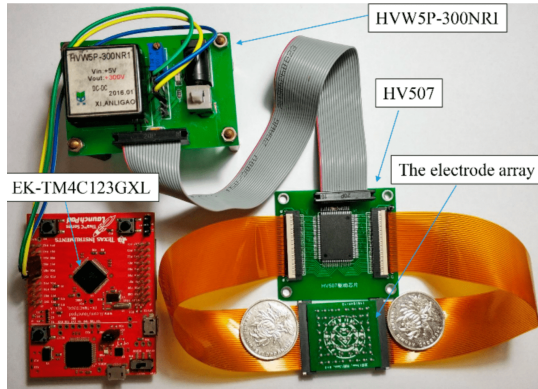


Fig. 18: Fabricated prototype of the wrist electrotactile display by Lu et al. [60].

5.2. Deep Electrical Stimulation

Deep electrical stimulation is a semi-invasive technique, in which electrodes are pierced through the first layers of skin to improve the impedance of the system and present tactile sensations at lower voltages [58]. Within this sub-category, one example found in literature was included: Tezuka et al. [58] developed an electrotactile display using titanium micro-needle electrodes that penetrated through the stratum corneum to deliver tactile sensations at low voltages. In their configuration, multiple 20 x 40 mm thin sheets of polyamide housed 7 needles each at their center (1 central needle with other 6 symmetrically around it). For a closer look at the sheet

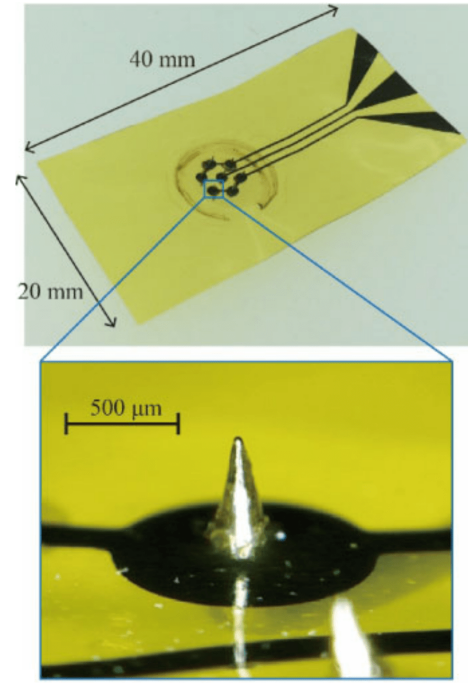


Fig. 19: Flexible sheet electrotactile display by Tezuka et al., with a zoomed detail of its titanium micro-needles [58].

device see Fig. 19.

5.3. General Considerations on Electrical Interfaces

Regarding body location, apart from the unusual tongue placement of the device by Nguyen et al., the other two devices were put on the arm. Lu et al. [60] strapped their electrotactile interface around the wrist, while Tezuka et al. [58] used 3 flexible sheets in total attached 90 mm apart from each other along the forearm, even though the sheet interface itself could be placed anywhere on the body.

As for stimulus distribution, electrical interfaces generally employed a much larger number of stimulation points compared to their mechanical counterpart, with grids of many electrodes. The first two examples used 33 and 64 electrodes, respectively, and even the third interface had a total of 21 needles piercing the skin. In fact, despite only having one active electrode per sheet (the central needle), this device still required 6 other needles per sheet to function as ground and used 3 sheets in total. Typical input voltages were given at 50 Hz with a PWM signal at 35 to 50% duty cycle [58] and their magnitude was generally low, with values around the 5 to 10 V; only Lu et al. [60] used a wide voltage range from 0 to 300 V. Spatial resolution between pins was very consistent between the three examples, sitting between the 2.3 and 3 mm.

The types of transferred information for electro-stimulation displays reflected what was found in previous categories. The tongue display was designed to convey directional cues, by giving one impact impulse at a time on the ray of electrodes

corresponding to the desired direction to be displayed [59]. The display by Lu et al. [60] did alphanumeric character delivery by sequentially stimulating consecutive electrodes on the grid, in order to trace a character (with 0.1 sec stimulation and 1.0 sec steps between consecutive electrodes). Finally, the interface by Tezuka et al. [58] conveyed generic 3-bit information with 3 patches, on which the central needle gave the electric stimulus as positive square waves.

6. HELICOPTER VIEW

The complete distribution of the devices included in this review can be seen in Fig. 20. Within this subspace of interfaces designed to deliver higher-order non-tactile information, the results showed a strong preference for mechanical stimulation (35 out of 38 devices). On the other hand, only 3 out of 38 included interfaces employed electrical stimulation. For mechanical stimulation, the heavily favorite approach relied on vibration (24 out of 35 mechanical stimulation interfaces). Skin-stretch was the second most popular approach, with 5 total devices. Indentation and multi-modal interfaces were represented by three examples each. Within electrical stimulation devices, two were designed for superficial and one for deep stimulation.

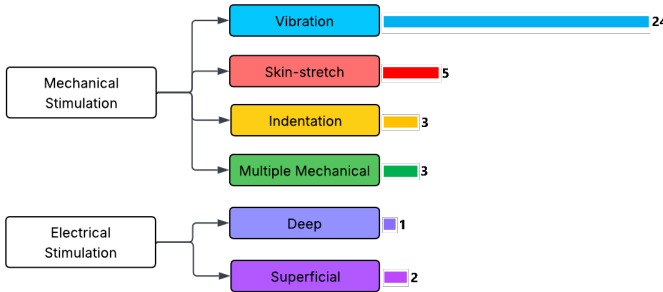


Fig. 20: Distribution of the selected devices in their respective sub-categories.

A time distribution of the publications for each sub-category is shown in Fig. 21. Vibration is present throughout the entire analyzed timespan, with a peak representation between 2017 and 2020, included. Because of the prevalence of vibration interfaces, this time window also becomes the one with the most amount of entries, considering all categories combined. Before and after this window, the number of publications per year for vibration does not exceed two. Skin-stretch interfaces tend to appear later in the timeline (4 out of 5 examples after 2018), with only one entry appearing early in 2010. The same can be said for multi-modal interfaces, which appear all from 2019 onward. Instead, the included indentation and electrical interfaces were designed generally earlier. The average publication year for these two sub-categories sits around 2016 to 2017.

Fig. 22 illustrates the spatial distribution of the entire pool of selected devices on the human body. The arms were the most represented location, with 27 out of 38 interfaces considering

them as a possible placement. In particular, the forearm and wrist were the preferred spots to put a tactile interface on the arm. The lower torso area was the second most utilized positioning, featuring five interfaces around the waist and five on the lower back. The lower leg area saw two devices strapped around the ankle and two devices placed under the foot. Finally, five devices were placed around the head area (neck, forehead, temples or tongue).

Regarding applications, the majority of devices were designed to deliver directional or positional information. In total, 25 studies cited navigation (14), limb motor guidance (7) or other more specialized positional tasks (4) as their main use case. Even the biofeedback corrective alert function, represented here by three examples, could be considered a type of directional information regarding posture and gait corrections. Another common function across categories was delivering simple unobtrusive alerts. Five interfaces cited this as their main application. Finally, the third big category of devices (8 in total) focused on the more complex task of inter-subject communication. These interfaces performed either alphanumeric character delivery (4 instances) or a different type of communication like morse code or musical tones.

7. DISCUSSION

The classification revealed a strong preference for mechanical stimulation, specifically for vibration. This is probably due to the natural association of vibration stimuli to alert warnings, making them ideal to direct the user's attention to the delivered information, together with the simplicity of integration and affordability of small vibration actuators like ERM motors. ERMs are also compact (around 10 mm diameter), thus suitable for wearable applications. They require a low power supply and are highly effective at delivering salient vibrations in a wide range of frequencies, making them good enough for most applications. Alternative actuators, such as piezoelectric or voice coil actuators, offer good performance as well, but are less employed due to being either less compact or more expensive and complex. Skin-stretch was also regarded as a viable stimulation modality, being very intuitive, pleasant and sometimes even more salient than vibration on specific body parts. Nonetheless, it was less common due to being much less flexible, since it seemed to be heavily associated with directional information. Additionally, servo motors, the most common actuation technology for skin-stretch interfaces, generally required bulkier and more complex power supplies and mechanisms to produce the skin displacement, compromising the wearability of the system as a whole. Indentation was even less prevalent. In fact, this type of haptic feedback requires actuators that produce large and controllable displacements, which, again, usually results in very cumbersome systems. Finally, electrical stimulation was also under-represented. Despite its potential for high resolution feedback, electrical stimulation is usually perceived as less

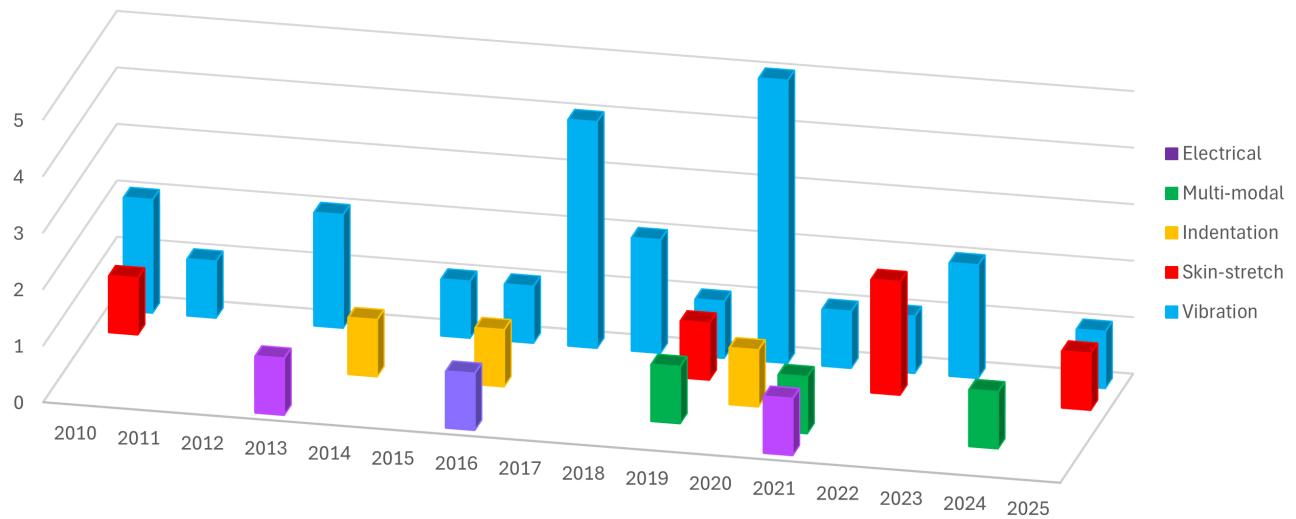


Fig. 21: Timeline of the publications included in this review, divided by stimulation sub-category. Publication year is on the x-axis, while number of publications is on the y-axis. The z-axis divides different sub-categories, listed in the legend on the right. The two electrical sub-categories are merged into one timeline (the darker purple is for the deep stimulation entry, while the lighter purple for superficial stimulation).

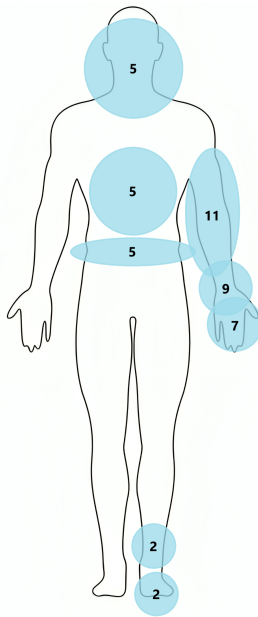


Fig. 22: Illustration of the spatial distribution of the included tactile interfaces on the human body. The sum of all positions is higher than 38 due to some interfaces being counted for multiple placements. The circles are not scaled to the number of entries they refer to, they only highlight the indicative area of interest of those devices.

comfortable and safe, sometimes even requiring semi-invasive techniques like penetrating the first layer of skin to be more effective. This, together with higher fabrication complexity and more difficult implementation (e.g. needing to find a suitable voltage threshold just for the system to function), made it less adopted than mechanical stimulation.

Time distribution results showed a general increase in entries from around 2016 to 2017, evidence for the increased interest in tactile technology research over the past decade.

Given the limited number of devices included in the review no conclusive time trends could be extracted, for smaller categories in particular. Nonetheless, to be noted is the general shift in interest towards skin-stretch interfaces and especially towards multi-modal tactile interfaces. In fact, the latter only appeared later in the selected time frame. The general trend in the past few years seems to be exploring new unobtrusive stimulation mechanics different from vibration, like skin-stretch, or combining vibration with these new mechanics to create more complex and capable systems.

Regarding device placement, the arms and torso were the most common areas across all categories, being large areas of sensitive hairy skin where an interface could be attached without overly compromising the user's mobility. In particular, the forearm/wrist turned out to be the preferred position for a wearable tactile interface, probably due to its good accessibility. Furthermore, numbers and patterns of actuators were generally kept minimal, to simplify designs and reduce cognitive load.

Applications across all categories focused heavily on directional cues, reflecting the demand for navigation aids, especially for visually impaired users or teleoperation tasks. This heavy representation of directional information was also probably caused by it being the easiest, most intuitive type of complex external information to be conveyed through touch. In fact, the tactile sense is inherently spatial, thus, directly linking an abstract direction to a "touched" direction on the body requires only one extra logical step (indeed in many examples directional information could be transferred by simply activating one actuator at a time among an array of cleverly placed actuators that covered the entire space of directions).

7.1. Limitations

The main limitation across the reviewed literature seems to be the low versatility of stimuli produced by the chosen actuation technology and the resulting lack of flexibility in possible applications for the devices, outside of their primary function. In fact, the great majority of adopted actuators were capable of creating only one specific type of stimulus, with just one example of newly designed actuator truly capable of delivering multiple types of cues, this being the actuator by Sanchez-Tamayo et al. [14]. In particular, the biggest challenge regarding actuation technology appears to be combining sustained indentation with vibration. When filtering through the papers to be included in the review, various other examples were found of innovative actuators meant for haptic devices [61][62][63], but rarely these would actually be implemented and tested in a full prototype, leaving this application to future research. On the contrary, the tested prototypes featured here generally opted for the easiest solution for actuation and dedicated more attention to the information transfer modality (testing and fine-tuning the feedback parameters within the limitations of the chosen hardware). Given that most studies focused on the easier direction-giving task, the choice of a simpler actuation was natural and was already effective for the interfaces to fulfill their function. However, this limits the adaptability of these devices if new and more complex tasks need to be performed. With a more versatile actuator to begin with, a wider spectrum of tactile profiles could be generated, not focusing merely on vibration, in turn making it easier to create distinct tactile cues and to deliver more complex information.

8. CONCLUSION

This review explored the current state of wearable tactile feedback interfaces that actively convey non-tactile information through touch. This growing field of research finds applications in assistive technology, navigation, rehabilitation, and general human-computer interaction. To achieve this, a structured literature search was conducted following the PRISMA method for systematic review filtering. Using an iteratively refined search query on the Scopus database, 369 publications were initially identified. After successive steps of title screening, abstract review, and full-text analysis, a final pool of 38 properly tested and technically described tactile interface prototypes were selected. The goal was to extract information about actuation technologies, design choices and applications.

The classification of these devices was done according to the stimulation mechanic, dividing them into various types of mechanical stimulation and electrical stimulation. Results revealed a strong preference for mechanical stimulation approaches, particularly vibration-based interfaces using small electromagnetic actuators, favored due to their simplicity, effectiveness and low cost. Skin-stretch and indentation-based

devices were also present but less common, often due to higher design complexity or limited feedback flexibility. Electrical stimulation, while promising for high-resolution feedback, was rarely used in practice due to comfort and safety concerns.

Across the reviewed devices, design trends prioritized compactness, minimal actuator count, and intuitive placement on the body, for which the preferred locations were the arms and torso. Directional cues were the most prevalent type of non-tactile information conveyed, likely because of the inherent spatial mapping that tactile displays can create. Other relevant, but less common, applications included motor guidance, biofeedback and textual communication. A significant limitation observed was the low versatility of feedback types most actuators could deliver, with a much bigger presence of highly specialized devices for one type of information and limited to one type of stimulation.

In conclusion, while researchers have already made great progress in developing wearable interfaces for complex information transfer, future progress will depend on the creation and implementation of more versatile actuators capable of delivering multi-modal feedback. This would also support the development of richer tactile patterns and broaden potential applications.

REFERENCES

- [1] S. Biswas and Y. Visell, [Emerging material technologies for haptics](#), *Advanced Materials Technologies*, vol. 4, Mar. 2019.
- [2] A. Gallace and C. Spence, [In Touch with the Future: The sense of touch from cognitive neuroscience to virtual reality](#). Oxford University Press, Jan. 2014.
- [3] H. N. Schifferstein, [The perceived importance of sensory modalities in product usage: A study of self-reports](#), *Acta Psychologica*, vol. 121, no. 1, pp. 41–64, 2006.
- [4] D. Hecht and M. Reiner, [Sensory dominance in combinations of audio, visual and haptic stimuli](#), *Experimental Brain Research*, vol. 193, no. 2, pp. 307–314, Feb. 2009.
- [5] A. Hamam, M. Eid, and A. El Saddik, [Effect of kinesthetic and tactile haptic feedback on the quality of experience of edutainment applications](#), *Multimedia Tools and Applications*, vol. 67, no. 2, pp. 455–472, Nov. 2013.
- [6] K. O. Johnson, [The roles and functions of cutaneous mechanoreceptors](#), *Current Opinion in Neurobiology*, vol. 11, no. 4, pp. 455–461, 2001.
- [7] J. C. Tuthill and E. Azim, [Proprioception](#), *Current Biology*, vol. 28, no. 5, pp. 194–203, Mar. 2018.
- [8] M. Gabardi, M. Solazzi, D. Leonardis, and A. Frisoli, [A new wearable fingertip haptic interface for the rendering of virtual shapes and surface features](#), in *2016 IEEE Haptics Symposium (HAPTICS)*, 2016, pp. 140–146.
- [9] V. R. Mercado, M. Marchal, and A. Lécuyer, [“haptics on-demand”: A survey on encountered-type haptic dis-](#)

- plays, *IEEE Transactions on Haptics*, vol. 14, no. 3, pp. 449–464, 2021.
- [10] R. Hinchet, V. Vechev, H. Shea, and O. Hilliges, [Dextres: Wearable haptic feedback for grasping in vr via a thin form-factor electrostatic brake](#), in *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology*, 2018, pp. 901–912.
 - [11] S. C. Lee and T. Starner, [Buzzwear: Alert perception in wearable tactile displays on the wrist](#), in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, 2010, pp. 433–442.
 - [12] E. P. Scilingo, M. Bianchi, G. Grioli, and A. Bicchi, [Rendering softness: Integration of kinesthetic and cutaneous information in a haptic device](#), *IEEE Transactions on Haptics*, vol. 3, no. 2, pp. 109–118, 2010.
 - [13] H. Park and J. Lee, [Adaptive impedance control of a haptic interface](#), *Mechatronics*, vol. 14, no. 3, pp. 237–253, 2004.
 - [14] N. Sanchez-Tamayo, Z. Yoder, P. Rothmund, G. Ballardini, C. Keplinger, and K. Kuchenbecker, [Cutaneous Electrohydraulic \(CUTE\) Wearable Devices for Pleasant Broad-Bandwidth Haptic Cues](#), *Advanced Science*, vol. 11, no. 48, 2024.
 - [15] C. Basdogan, S. De, J. Kim, M. Muniyandi, H. Kim, and M. Srinivasan, [Haptics in minimally invasive surgical simulation and training](#), *IEEE Computer Graphics and Applications*, vol. 24, no. 2, pp. 56–64, 2004.
 - [16] J. Xu et al., [Configurable, wearable sensing and vibrotactile feedback system for real-time postural balance and gait training: Proof-of-concept](#), *Journal of Neuro-Engineering and Rehabilitation*, vol. 14, no. 1, 2017.
 - [17] N. Diolaiti and C. Melchiorri, [Teleoperation of a mobile robot through haptic feedback](#), in *IEEE International Workshop HAVE Haptic Virtual Environments and Their*, 2002, pp. 67–72.
 - [18] R. Ibrahimov, E. Tsykunov, V. Shirokun, A. Somov, and D. Tsetserukou, [Dronepick: Object picking and delivery teleoperation with the drone controlled by a wearable tactile display](#), in *2019 28th IEEE International Conference on Robot and Human Interactive Communication (RO-MAN)*, 2019, pp. 1–6.
 - [19] K. R. Schoepp, M. R. Dawson, J. S. Schofield, J. P. Carey, and J. S. Hebert, [Design and integration of an inexpensive wearable mechanotactile feedback system for myoelectric prostheses](#), *IEEE Journal of Translational Engineering in Health and Medicine*, vol. 6, 2018.
 - [20] R. Tachiquin et al., [Wearable urban mobility assistive device for visually impaired pedestrians using a smartphone and a tactile-foot interface](#), *Sensors*, vol. 21, no. 16, 2021.
 - [21] V. Yem and H. Kajimoto, [Wearable tactile device using mechanical and electrical stimulation for fingertip interaction with virtual world](#), in *2017 IEEE Virtual Reality (VR)*, 2017, pp. 99–104.
 - [22] Delft University of Technology, [Making a search plan](#), [Online]. Accessed: 2025-04-20.
 - [23] PRISMA, [PRISMA 2020 flow diagram](#), [Online]. Accessed: 2025-04-20.
 - [24] K. Kaczmarek, J. Webster, P. Bach-y-Rita, and W. Tompkins, [Electrotactile and vibrotactile displays for sensory substitution systems](#), *IEEE Transactions on Biomedical Engineering*, vol. 38, no. 1, pp. 1–16, 1991.
 - [25] Y.-C. Liao, Y.-L. Chen, J.-Y. Lo, R.-H. Liang, L. Chan, and B.-Y. Chen, [Edgevib: Effective alphanumeric character output using a wrist-worn tactile display](#), in *Proceedings of the 29th Annual Symposium on User Interface Software and Technology*, 2016, pp. 595–601.
 - [26] F. Hao and A.-g. Song, [Design of a wearable vibrotactile display waist belt](#), in *2010 8th World Congress on Intelligent Control and Automation*, 2010, pp. 5014–5017.
 - [27] M. Janidarmian, A. Roshan Fekr, K. Radecka, and Z. Zilic, [Wearable Vibrotactile System as an Assistive Technology Solution](#), *Mobile Networks and Applications*, vol. 27, no. 2, pp. 709–717, 2022.
 - [28] D. Prabhu, M. M. Hasan, L. Wise, C. MacMahon, and C. McCarthy, [Vibrosleeve: A wearable vibro-tactile feedback device for arm guidance](#), in *2020 42nd Annual International Conference of the IEEE Engineering in Medicine & Biology Society (EMBC)*, 2020, pp. 4909–4912.
 - [29] J. Szczerba, R. Hersberger, and R. Mathieu, [A wearable vibrotactile display for automotive route guidance: Evaluating usability, workload, performance and preference](#), *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, vol. 59, no. 1, pp. 1027–1031, 2015.
 - [30] A. Alabbas, M. A. Cabrera, M. Sayed, O. Alyounes, Q. Liu, and D. Tsetserukou, [Movetouch: Robotic motion capturing system with wearable tactile display to achieve safe hri](#), in *Haptics: Understanding Touch; Technology and Systems; Applications and Interaction*, 2025, pp. 428–441.
 - [31] Precision Microdrives, [Eccentric Rotating Mass Vibration Motors – ERMs](#), [Online]. Accessed: 2025-04-20.
 - [32] M. Lee and H. In, [Novel wrist-worn vibrotactile device for providing multi-categorical information for orientation and mobility of the blind and visually impaired](#), *IEEE Access*, vol. 11, pp. 111 860–111 874, 2023.
 - [33] TDK Electronics, [PowerHap Piezo Actuators](#), [Online]. Accessed: 2025-04-20.
 - [34] H. Culbertson, J. M. Walker, M. Raitor, and A. M. Okamura, [Waves: A wearable asymmetric vibration excitation system for presenting three-dimensional translation and rotation cues](#), in *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*, 2017, pp. 4972–4982.
 - [35] A. Gopalai and S. Arosha Senanayake, [A wearable real-time intelligent posture corrective system using vibrotactile feedback](#), *IEEE/ASME Transactions on Mechatronics*, vol. 16, no. 5, pp. 827–834, 2011.

- [36] O. Ozioko, W. Navaraj, M. Hersh, and R. Dahiya, [Tacsac: A wearable haptic device with capacitive touch-sensing capability for tactile display](#), *Sensors*, vol. 20, no. 17, 2020.
- [37] S. Hong, J. Lee, and C. Park, [Development of a wireless pilot arm-wearable haptic interface for unmanned aerial vehicle wing deflection sensing](#), *Journal of Intelligent Material Systems and Structures*, vol. 28, no. 9, pp. 1130–1139, 2017.
- [38] S. Shin, C. Oh, and H. Shin, [Tactile tone system: A wearable device to assist accuracy of vocal pitch in cochlear implant users](#), in *Proceedings of the 22nd International ACM SIGACCESS Conference on Computers and Accessibility*, 2020.
- [39] G. Luzhnica and E. Veas, [Investigating interactions for text recognition using a vibrotactile wearable display](#), in *Proceedings of the 23rd International Conference on Intelligent User Interfaces*, 2018, pp. 453–465.
- [40] A. A. G. Dharma, T. Oami, Y. Obata, L. Yan, and K. Tomimatsu, [Design of a wearable haptic vest as a supportive tool for navigation](#), in *Human-Computer Interaction. Interaction Modalities and Techniques*, 2013, pp. 568–577.
- [41] M. Srikulwong and E. O’Neill, [Wearable tactile display of directions for pedestrian navigation: Comparative lab and field evaluations](#), in *2013 World Haptics Conference (WHC)*, 2013, pp. 503–508.
- [42] S. Stock, A. Bertemes, M. Stang, M. Böhme, D. Grimm, and W. Stork, [Feedi - a smart wearable foot-band for navigation and guidance using haptic feedback](#), in *Human Interaction, Emerging Technologies and Future Applications II*, 2020, pp. 349–355.
- [43] D. Chen, M. Haller, and T. Besier, [Wearable lower limb haptic feedback device for retraining Foot Progression Angle and Step Width](#), *Gait and Posture*, vol. 55, pp. 177–183, 2017.
- [44] S. Kammoun, R. Bouaziz, F. Saeed, S. Qasem, and T. Al-Hadhrani, [HaptiSole: Wearable Haptic System in Vibrotactile Guidance Shoes for Visually Impaired Wayfinding](#), *KSII Transactions on Internet and Information Systems*, vol. 17, no. 11, pp. 3064–3082, 2023.
- [45] A. Matsuda, K. Nozawa, K. Takata, A. Izumihara, and J. Rekimoto, [Hapticpointer: A neck-worn device that presents direction by vibrotactile feedback for remote collaboration tasks](#), in *Proceedings of the Augmented Humans International Conference*, 2020.
- [46] C. Lins, S. Fudickar, A. Gerka, and A. Hein, [A wearable vibrotactile interface for unfavorable posture awareness warning](#), in *Proceedings of the 4th International Conference on Information and Communication Technologies for Ageing Well and e-Health - ICT4AWE*, 2018, pp. 178–183.
- [47] J. Biggs and M. Srinivasan, [Tangential versus normal displacements of skin: Relative effectiveness for producing tactile sensations](#), in *Proceedings 10th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems. HAPTICS 2002*, 2002, pp. 121–128.
- [48] O. Kayhan and E. Samur, [A wearable haptic guidance system based on skin stretch around the waist for visually-impaired runners](#), in *2022 IEEE Haptics Symposium (HAPTICS)*, 2022, pp. 1–6.
- [49] A. KhalilianMotamed Bonab, C. Camardella, A. Frisoli, and D. Leonardis, [A direct-drive, wearable armband device to experiment combined continuous and vibrotactile haptic feedback for guidance in motor tasks](#), in *Haptics: Understanding Touch; Technology and Systems; Applications and Interaction*, 2025, pp. 211–222.
- [50] L. Kuang, M. Aggravi, P. R. Giordano, and C. Paccchierotti, [Wearable cutaneous device for applying position/location haptic feedback in navigation applications](#), in *2022 IEEE Haptics Symposium (HAPTICS)*, 2022, pp. 1–6.
- [51] K. Bark, J. Wheeler, P. Shull, J. Savall, and M. Cutkosky, [Rotational skin stretch feedback: A wearable haptic display for motion](#), *IEEE Transactions on Haptics*, vol. 3, no. 3, pp. 166–176, 2010.
- [52] A. Haynes, M. Simons, T. Helps, Y. Nakamura, and J. Rossiter, [A wearable skin-stretching tactile interface for human-robot and human-human communication](#), *IEEE Robotics and Automation Letters*, vol. 4, no. 2, pp. 1641–1646, 2019.
- [53] W. van der Woude, D. Tetteroo, and R.-H. Liang, [Presley: Designing non-obtrusive tactile rhythmic wearable devices for improving speech fluency](#), in *Companion Publication of the 2020 ACM Designing Interactive Systems Conference*, 2020, pp. 97–103.
- [54] Y. S. Jin, H. Y. Chun, E. T. Kim, and S. Kang, [Vt-ware: A wearable tactile device for upper extremity motion guidance](#), in *The 23rd IEEE International Symposium on Robot and Human Interactive Communication*, 2014, pp. 335–340.
- [55] J. Lee and G. Lee, [Designing a non-contact wearable tactile display using airflows](#), in *Proceedings of the 29th Annual Symposium on User Interface Software and Technology*, 2016, pp. 183–194.
- [56] B. MacGavin, T. Edwards, and J. Gorlewicz, [A protactile-inspired wearable haptic device for capturing the core functions of communication](#), *IEEE Transactions on Haptics*, vol. 14, no. 2, pp. 279–284, 2021.
- [57] N. A.-h. Hamdan, A. Wagner, S. Voelker, J. Steimle, and J. Borchers, [Springlets: Expressive, flexible and silent on-skin tactile interfaces](#), in *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, 2019, pp. 1–14.
- [58] M. Tezuka, N. Kitamura, and N. Miki, [Information transfer using wearable thin electrotactile displays with microneedle electrodes](#), *Japanese Journal of Applied Physics*, vol. 55, no. 6, 2016.
- [59] T. H. Nguyen, T. H. Nguyen, T. L. Le, T. T. H. Tran, N. Vuillerme, and T. P. Vuong, [A wearable assistive device for the blind using tongue-placed electrotactile](#)

- display: Design and verification, in *2013 International Conference on Control, Automation and Information Sciences (ICCAIS)*, 2013, pp. 42–47.
- [60] X. Lu, M. Lin, S. Wang, X. Hu, H. Yin, and Y. Yan, [Experiment study for wrist-wearable electro-tactile display](#), *Sensors*, vol. 21, no. 4, 2021.
 - [61] G. Korres and M. Eid, [Design of Low-Profile Tactile Actuator with Rich Vibrotactile Stimulation For Wearable Applications](#), in *2019 IEEE International Symposium on Haptic, Audio and Visual Environments and Games (HAVE)*, 2019, pp. 1–6.
 - [62] W.-H. Park, J. W. Bae, E.-J. Shin, and S.-Y. Kim, [Development of a flexible and bendable vibrotactile actuator based on wave-shaped poly\(vinyl chloride\)/acetyl tributyl citrate gels for wearable electronic devices](#), *Smart Materials and Structures*, vol. 25, no. 11, p. 115 020, Oct. 2016.
 - [63] T. Kodama, S. Izumi, K. Masaki, H. Kawaguchi, K. Maenaka, and M. Yoshimoto, [Large displacement haptic stimulus actuator using piezoelectric pump for wearable devices](#), in *37th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*, 2015, pp. 1172–1175.

APPENDIX TABLE I: Mechanical Stimulation Interfaces - Vibration

Reference	Actuation Technology	Dimensions	Actuator Oper. Spec.	Body Location	Number/Pattern of Actuators	Spatial Resolution	Conveyed Information	Feedback Details
Hong et al. [37]	ERM coin motors	Actuator: 10 mm $\varnothing$; Device: arm-length sleeve, 20 x 10 cm (indicative) control module	PWM duty cycle input signal	Arm	12 - 6 equally spaced in-line actuators spanning the arm length, on both sides of the arm (upper and lower)	From 5 to 10 cm	UAV wing deflection information	Vibration feedback proportional to estimated wing deflection; each vibrohaptic motor represents the displacement at a specific location along the UAV wing
Prabhu et al. [28]	ERM coin motors - Adafruit Vibrating Mini Motor Discs ADA1201	Actuator: 10 mm $\varnothing$, 2.7 mm height; Device: 15 cm (indicative) sleeve and electronic module	Voltage range: 2V - 5V; Frequency range: 73-183Hz	Forearm	16 - 4 strips of 4 motors, parallel to the arm axis and equally spaced around it (one strip on medial, dorsal, ventral and lateral sides of the forearm)	90° radially between strips of motors; 30 mm between motors of the same line	Motor guidance cues for rehabilitation / training	Sequential activation of motors (at roughly 50% duty cycle / 92 Hz, for 100 ms each) to create desired vibration patterns that signify the motion that the arm needs to follow
Lee and Stamer [11]	ERM coin motors - Precision Microdrives #310-101	Actuator: 10 mm $\varnothing$, 3.4 mm height; Device: 5 to 10 cm (indicative)	0.71 g 175 Hz for "strong" feedback, 0.43 g 133 Hz for "weak" feedback	Wrist (volar side)	3 - flat triangular layout	30 mm	Unobtrusive notifications / alerts	Twenty-four directional tactile patterns by changing starting point, direction, temporal pattern and intensity; 2.25 sec duration
Liao et al. [25]	ERM coin motors - Precision Microdrive 310-113	Actuator: 10mm diameter Device: 40 x 40 mm	170 Hz resonant frequency; 5V voltage;	Wrist (dorsal side)	4 - 2 x 2 square	30 mm	Alphanumeric character delivery	500 ms vibrations with gaps of 100 ms; sequential vibration of specific motors to create vibration stroke patterns representing characters
Alabbas et al. [30]	ERM coin motors	Actuator : 10 mm $\varnothing$; Device: 5 to 10 cm (indicative)	10 - 55 Hz frequency range	Wrist (volar side)	5 in-line orthogonally to the arm's axis	2 cm	Motor guidance for human-robot interaction safety	Variation of vibration duration and sequence of activated motors to create vibration patterns to signal motor guidance commands
Lee and In [32]	Piezoelectric actuators - TDK Electronics PowerHap 2.5 g	Actuator: 15.4 mm side length; Device: 65 mm length on the forearm	-	Forearm (around)	8 - 2 consecutive circles of 4 radially distributed vibrators	90° radially around the wrist;	Directional, spatial and status cues (navigation)	Use of different vibration durations, intensities and activation patterns to create various static and dynamic tactons, in order to give directions, signal veering and warn of obstacles
Ibrahimov et al. [18]	ERM coin motors	-	PWM input signal; Vibration intensity from 100 Hz to 200 Hz	Fingertips	5 - 1 per fingertip	-	Directional cues for drone teleoperation	Vibrotactile patterns (with varying vibration intensity) representing the location of the remote object relative to the quadcopter
Ozioko et al. [36]	Voice coil actuator with flexible coil and permanent magnet	Actuator: 2.5 mm $\varnothing$ central contact pad, 10 mm $\varnothing$ coil (with 25 microns wire width); 15 mm $\varnothing$ overall;	10-200 Hz vibration frequencies; 60.70 Hz resonance frequency with 0.377 max off-plane displacement at 180 mA current	Fingertip (index)	1	-	Deaf-blind communication (through morse code)	The actuator vibrates at a desired frequency to send a morse code message to the user
Culbertson et al. [34]	Voice coil actuators - Haptuator Mark II (Tactile Labs)	Actuator: 9 x 9 x 32 mm;	110 Hz resonant frequency;	Finger phalanges, mostly on first three fingers	3 for translations (1 per direction); 6 for rotations (2 per rotation plane)	-	Motor guidance cues (3D translation and rotation of the hand)	5 ms step followed by a 15 ms downward ramp input to the actuator to create asymmetric vibration (50 Hz asymmetric vibrations); 0.25 mm skin deformation; a single actuator presents a translation guidance cue and a pair of actuators presents a rotation guidance
Luzhnica and Veas [39]	ERM coin motors - ROB-08449	Actuator: 3.4 mm $\varnothing$	2.3 - 3.6 V; 0.8 G amplitude	Hand (back)	6 - one on the back of every finger second phalange and one on the back of the palm	-	Textual skin-reading	Each character is encoded with one or two vibromotors using an overlapped spatiotemporal stimulation; 200 ms single motor vibration with 10 ms offset for two motor characters, 200 ms between letter gaps
Shin et al. [38]	ERM coin motors - Precision Microdrives model 310-101	Actuator: 10 mm $\varnothing$	-	Hand (back)	9 - 5 on every second finger phalange, 2 on knuckles and 2 near the wrist	-	Musical tone information for vocal pitch training	2 sec constant vibration of up to three actuators at a time to represent the detected musical tone; each combination of actuators corresponds to one tone from C3 to B5 (7 motors for tones and 2 for the octave)
Gopalai and Arosha Senanayake [35]	Electromagnetic tactile transducers - Tactaid VBV32	Device: 20 x 10 cm (indicative)	Use of audio amplifiers LM386N; 5-12 V operating range; PWM duty cycle input voltage; 250 Hz resonant frequency	Waist (front and back)	2 (1 on stomach and 1 on low back)	180°	Biofeedback corrective alert (trunk postural correction)	Negative feedback informing of posture violations (trunk sway) only on one side of the limb, proportional to the violation severity
Xu et al. [16]	ERM coin motors - XY-B1034-DX	Actuator: 22.5 x 20.5 x 15.0 mm (12 g weight)	1 g amplitude; 220 Hz frequency	Waist (sides)	2 (left and right sides of the torso at approximately the L4/L5 level)	180°	Biofeedback corrective alert (postural balance and gait training)	Continuous feedback with the same vibrational intensity and frequency, provided when medial/lateral trunk tilt exceeded the activation threshold and no feedback provided when trunk tilt was inside the no feedback zone (negative feedback cueing to move away from the vibration)
Hao and Song [26]	ERM cylindrical motors	Actuator: 6mm $\varnothing$, 16 mm length	4000 RPM; 1.5 V	Waist (around)	12 equally radially distributed	30° radial resolution	Directional cues for situation awareness	Constant vibration on the factor corresponding to the desired direction around the user
Srikulwong and O'Neill [41]	ERM coin motors - Solarbotics VPM2 disk motors	Actuator: 11mm $\varnothing$, 3mm height	200 Hz vibration frequency	Waist (around) or lower back	Waist: 8 - distributed linearly around the waist; Back array: 9 - 3 x 3	Waist: unequal spacing (from 50 mm to 130 mm); Back array: equal inter-spacing of 50 mm	Directional cues (navigation)	12 repetitions of signals at 50-millisecond pulse and inter-pulse duration (1.2 second total stimulus); single actuator to signal the direction for the belt, sequential activation of actuators to create haptic patterns that represent directions for the back array
Lins et al. [46]	ERM cylindrical motors - EKULIT VM 0610 A 3.0	Actuator: 6 mm $\varnothing$, 13 mm length	167 Hz vibration frequency; 3 V; 10000 rpm	Across the body	13 - next to joints and anatomic references with thin skin (neck, shoulders, elbows, wrists, lower end of shoulder blades, left and right of the lumbar spine, inner side of the knees)	-	Biofeedback corrective alert (posture awareness warning)	Pulse sequence with two or three individual pulses, each with a pulse length of 150 ms; vibration on body location at risk of dangerous posture to hint a postural change
Szczerba et al. [29]	ERM coin motors	Actuator: 10 mm $\varnothing$	200 Hz vibration frequency; 1.25 g amplitude	Head	2 (one on left one on right temple)	180°	Directional cues (automotive navigation / turn-by-turn route guidance)	Activation of a single vibrotactile motor corresponding to the desired direction; distances encoded by an increasing number of pulses when approaching closer; 50ms pulses 200ms breaks
Matsuda et al. [45]	ERM coin motors	-	14500 rpm; 0.75 g max amplitude	Neck (around)	16 - in-line equispaced	22.5° / 35 mm	Directional cues	Activation of 3 motors closest to the target direction with vibration intensity inversely proportional to the direction difference

Dharma et al. [40]	ERM coin motors - FM34F	Actuator: 12 mm $\varnothing$	3 V; 13000 rpm	Torso	60 - 5 x 12 matrix	Between 5 and 10 cm	Directional cues (navigation)	34 unique haptic patterns indicating one of four main directions; the patterns vary on vibration strength, total exposure time and sequence of activated vibrotactors
Janidarmian et al. [27]	ERM cylindrical motors -Precision Microdrive model 307-103	Actuator: 8.7 mm $\varnothing$, 25.1 mm length	-	Lower back	9 - 3 x 3 matrix	5 cm	Alphanumeric character delivery	200 ms stimulus duration, no time interval between onsets of stimuli; sequential activation of desired actuators to create a stroke that represents a character or part of it
Stock et al. [42]	ERM coin motors	-	60 mA power consumption; PWM duty cycle input voltage;	Ankle (around)	4 equispaced around the ankle (front, back, left and right)	90°	Directional cues (navigation and guidance)	Direction angle given by vibrating one or two motors at same time with weighted intensities, to represent each possible angle between the two
Chen et al. [43]	ERM coin motors	Actuator: 8 mm $\varnothing$, 2.5 mm height	-	Ankle (around)	4 actuators, placed horizontally evenly distributed along the anterior hemisphere of the leg at ankle height	Roughly 60° radially	Motor guidance for gait retraining	Binary vibrotactile feedback: a double pulse of 250 ms with a 50 ms gap between on the left or right motors; Tactile apparent motion: stimulus duration of 200 ms and interstimulus onset interval of 100 ms; pull feedback modality (move towards the stimulus) was used for both feedback strategies
Kammoun et al. [44]	ERM coin motors	Actuator: 130 mm ² contact surface	20 - 100 Hz vibration frequency range	Foot (under)	4 - positioned at 0°, 90°, 180° and 270°, flat on the foot sole	90°	Directional cues (wayfinding)	Vibration of one or two motors simultaneously to display in total 6 different directions;
Tachiquin et al. [20]	ERM coin motors - Jinlong Machinery C1030L-50	Actuator: 10 mm $\varnothing$, 3 mm height, 133 mm ² contact area	10-55 Hz vibration frequency range; delivered axial forces up to 13 mN; 400 mW max power usage	Foot (under)	4 - positioned on the tibial, lateral, and medial plantar areas	Roughly 90° around the foot sole	Directional cues (wayfinding)	Each of the four dots represents a direction; Tactile rendering method: three consecutive short vibrations (1 sec with 0.5 sec gaps) in the corresponding dot, one short vibration in the opposite dot, and again a short vibration in the corresponding dot

APPENDIX TABLE II: Mechanical Stimulation Interfaces - Skin-stretch

Reference	Actuation Technology	Dimensions	Actuator Oper. Spec.	Body Location	Number/Pattern of Actuators	Spatial Resolution	Conveyed Information	Feedback Details
KhalilianMotamed Bonab et al. [49]	Brushless DC servo motors - Maxon DCX22S	Motor: 5 cm x 2.2 cm $\varnothing$; Device: 10 cm length (indicative)	Motor torque output of 14.4 mNm	Forearm (around)	2 motors with axes parallel to each other and forearm	Axes of the two motors positioned as close together as possible	Motor task guidance cues (modulation of hand opening and closing, hand pronosupination / hand movement rehab)	Linearly modulated clench / stretch feedback as a function of pose / angular error (0.17 N/error % or 0.17 N/° error) only in one direction (negative error); Vibrotactile feedback with 20 Hz sinusoid
Bark et al. [51]	Ultrasonic piezoelectric motor	Skin-contactor: 14 mm $\varnothing$ contact pads; Device: 29 x 45 x 126 mm	0.6 Nm max torque; 15-150 deg/s speed range; 0.05 deg resolution; $\pm$ 45° of rotation range	Forearm	2 contact pads attached to the skin	26 mm	Positional information (rotations)	Rotational stretch proportional to the desired rotation to be displayed
Haynes et al. [52]	Shape-Memory Alloy wires (Toki Biomaterials)	Actuator: 3 cm (indicative) wire length; Device: 5 mm total height; 10 cm total length (indicative)	5 mm maximum stroke; 70 °C operating temperature; 5 V max input; PWM duty cycle input voltage	Forearm (inner side)	2 orthogonal wires that can expand and contract	8 cm between attachment points	Unobtrusive notifications / Body-to-body communication	Modulated voltage step input according the desired stretch strength and direction to be given for the alert
Kuang et al. [50]	Linear servo motors - VS-19 Linear Pico Servomotors	Skin-contactor: 8 mm $\varnothing$ spheric tactor in a 12 x 12 mm work space; Device: 60 x 60 x 30 mm outer frame	max. stall torque of 60 gf.cm at 3.7 VDC	Forehead (preferred) but also wrist or back of hand	2 servomotors moving 1 pin in 2 planar directions	-	Position cues (navigation)	The spheric tactor can be either left free to rotate when the pin moves, providing location feedback about its absolute position, or kept fixed, providing skin stretch about its relative displacement
Kayhan and Samur [48]	Servo motors - Hiitec HS311	Motor: 5.3 x 2 x 4.3 cm	3.1 A, 10000 mAh batteries	Waist (around)	2 motors located at left and right side of the belt with vertical axes	Motors at the two sides of the waist, roughly at 45° from the sagittal plane on the transverse plane	Directional cues (navigation for blind)	Continuous skin stretch proportional to the steering angle, on the side corresponding to the desired direction

APPENDIX TABLE III: Mechanical Stimulation Interfaces - Indentation

Reference	Actuation Technology	Dimensions	Actuator Oper. Spec.	Body Location	Number/Pattern of Actuators	Spatial Resolution	Conveyed Information	Feedback Details
Lee and Lee [55]	Airflow Actuators - JPM32B air pumps	Actuator: 1 mm $\varnothing$ nozzles on the pipes; Device: 40 x 40 x 25 mm, 1cm distance from the skin	3.5 L/min max flow rate; 74.3 m/s max airflow velocity	12 different hairy skin locations, preferred wrist dorsal and neck dorsal	4 - square shape	33 mm distance on the diagonal	Directional cues	two sequential 500 ms constant stimuli on two opposite side pins to signal a direction
Van der Woude et al. [53]	Voice coil actuator	Actuator: 21 mm $\varnothing$ circular pad	4 ohm resistance;	Upper arm	1	-	Rhythm cueing for speech fluency	92 BPM tactile rhythmic feedback
Jin et al. [54]	Piezoelectric actuators - TULA50, Piezoelectric Technology Co. Ltd.	-	50 Hz, 3mm max displacement	Wrist	6 - 4 modules equally distributed around the wrist, plus 2 modules added in-line on the dorsal side of the wrist	90° radially around the wrist; 15 mm between the three modules on dorsal side	Motor guidance cues for stroke rehabilitation	Activation of single tapping on the module that corresponds to the desired direction in which the arm needs to move; tactile motion illusion using the 3 upper modules or consecutive modules to signal forwards/backwards and rotation; 20 ms stimulus duration per module

APPENDIX TABLE IV: Mechanical Stimulation Interfaces - Multi-modal

Reference	Actuation Technology	Dimensions	Actuator Oper. Spec.	Body Location	Number/Pattern of Actuators	Spatial Resolution	Conveyed Information	Feedback Details
MacGavin et al. [56]	ERM coin motors - Tatoko vibration Coin motors; Servo motors - SG90; Thermal patch - COM11 289	-	5 V coin motors; 9 G 4.8 V servos; 37.8 °C patch;	Back of hand and forearm	13 ERM motors - 2 x 2 matrix flat against the hand within the gaps of a 3 x 3 matrix vertically oriented; 6 in-line servos	3.5 cm within grid; 2.54 cm between the two grids; servo arms 0.34 cm apart	Deaf-blind ""protactile"" communication (specifically direction giving)	Different sequential vibration patterns and tapping patterns on the grids of actuators
Sanchez-Tamayo et al. [14]	Electrohydraulic actuators	Actuator pouch: 14 x 14 mm	2.44 mm actuation stroke; 2.3 N force; 0-200 Hz vibrations (with only 14% force reduction at 200 Hz actuation compared to 1 Hz); 6 kV maximum operating voltage	Various hairy skin locations, preferred wrist	1 (dorsal side of wrist)	1 stack of 10 electrohydraulic pouches	Various functions, mostly unobtrusive alerts	Diverse tactile feedback cues depending on the actuation temporal pattern
Hamdan et al. [57]	Shape-Memory Alloy springs - Toki BioMetalHelix and Dynalloy Flexinol	Actuator: spring coil diameter from 0.4 to 3.45 mm; roughly 30-35 mm spring length; Device: roughly 25 x 50 mm sticker dimensions	20 to 245 g spring force; 150 to 3400 mA standard current;	Various hairy skin locations, preferred wrist, upper arm, shoulder, neck, chest and back	1 spring attached parallel to the skin	(in the example of navigation) 5–8 cm	Unobtrusive notifications, navigation, motor guidance	the SMA spring has its ends attached to the skin and when contracting produces the desired tactile sensation, mainly a skin-stretch in the order of 15 to 20 mm (frequency of roughly 0.1 Hz)

APPENDIX TABLE V: Electrical Stimulation Interfaces

Reference	Stimulation Technology	Dimensions	Stimulation Oper. Spec.	Body Location	Number/Pattern of Stimulation Points	Spatial Resolution	Conveyed Information	Feedback Details
Nguyen et al. [59]	Copper electrodes	Electrode: 3 mm $\varnothing$ with 1 mm insulation; Device: 3 x 3 cm total display	3 to 12 V	Tongue (flat on dorsal part)	33 electrodes in a round matrix with 8 rays equispaced at 45° (5 electrodes per ray + 1 central electrode)	roughly 3 mm	Directional cues	One impact impulse at a time (activate one ray of electrodes) corresponding to one direction
Lu et al. [60]	Solder tin hemispherical electrodes	Electrode: 1.55 mm $\varnothing$; Device: 27 x 27 mm PCB board	Adjustable voltage from 0 to 300 V; 100 Hz 35% duty cycle	Wrist	64 electrodes - 8 x 8 square matrix	3 mm	Alphanumeric character delivery	Sequential stimuli on consecutive electrodes to display characters on the matrix; 0.1s stimulation with 1.0s steps between consecutive electrodes
Tezuka et al. [58]	Titanium micro-needle electrodes	Needles: 600 microns length; Single sheet device: 40 x 20 mm	PWM 50% duty cycle; 50 Hz frequency; 6 V minimum threshold voltage	Forearm (but potentially any body location)	7 needles per sheet - 1 central and 6 symmetrically around it; 3 sheets in total along the forearm	roughly 2.3 mm between needles; 90 mm between sheets	3-bit information transfer	Electric stimulus as positive square waves on central needle (the other 6 function as the ground); every sheet can provide two stimulation patterns (two strengths) thus 1-bit info;