Design of a Haptic System for Sensory Feedback in Pediatric Prostheses

Paul Khoury
Limbitless Solutions Inc.
University of Central Florida, Orlando, FL

Abstract

Children with congenital limb differences often experience high prosthesis rejection rates due to limited functionality and lack of sensory feedback. Additionally, they often face difficulties interacting with their environment, particularly dexterous object manipulation and touch-based exploration. This creates a need for prosthetic systems that provide tactile information. This project proposes a vibrotactile array that provides intuitive sensory feedback to users of the Limbitless prosthetic arm. The design aims to communicate to the user when the fingers of their prosthetic arm make contact with an object or surface. The system circumvents the need for additional sensor hardware by inferring contact from the motors' current draw. Upon contact, the system delivers brief vibrotactile cues to the user, adhering to an event-driven sensory feedback control (DESC) paradigm. Vibrations are produced by an array of four vibration motors arranged circumferentially around the upper arm, preserving the spatial dimensionality of the information. Testing will consist of a two-part study evaluating participants' ability to (I) localize haptic signals—identifying which motors on the armband are active at a given time—and (II) interpret vibratory stimulation on the arm as corresponding to stimulation of predefined regions of the hand. These assessments will gauge the prototype's effectiveness in delivering intuitive sensory feedback for prosthetic applications and inform future design iterations. High accuracy in distinguishing signals is anticipated, consistent with findings reported in related studies. However, successful interpretation of the spatial mapping may require cognitive restructuring and training.

1 Motivation

I joined Limbitless because I need my work to have a meaningful, positive impact on people's lives. The desire to develop life-enhancing technologies as an engineer has long guided my career trajectory. My prior industry experience in medical device manufacturing and my prior research experience in computational biomechanics modeling were the previous manifestations of these principles. However, I wanted to involved in more patient-oriented work than previous opportunities had allowed, so when I came across the Limbitless REU, I felt compelled to apply.

Upon my joining, I was assigned to the Haptics Team 2 project team. We were tasked with developing a wearable tactile feedback interface for prosthetic users. The initial goals were to improve the usability of the Limbitless arm by providing vibrotactile feedback that conveys grasp force and contact geometry. This builds on my previous experience working on a wearable assistive device to help individuals with visual impairments navigate indoor spaces by mapping environmental depth data onto an array of vibration motors. My focus for this project is to investigate tactile display strategies and then develop spatio-temporal feedback schema that improves user awareness and control. This new proposed feature aims to enhance the functionality of the device in the hope of reducing user rejection rates.

2 Background

Somatosensory feedback from the hand is critical for one's ability to manipulate held objects [1]. Without sensory feedback from the hand, people tend to apply excessive grasping force to prevent the slippage of held objects [2]. Not only is this inefficient, it risks damaging delicate objects as well. For amputees with hand prostheses, artificial somatosensory feedback can improve dexterity [3]. Without haptic feedback, prosthesis wearers tend to compensate by relying on visual and auditory stimuli such as the visible compliance of a soft object being squeezed or the motor sounds from a robotic hand [4]. However, reliance on these cues often increases the cognitive load on patients [5], especially as compared to haptic feedback, which lends itself most intuitively to motor control. In addition, van der Riet notes that "When someone loses a hand through amputation they not only lose their ability to manipulate objects but also their ability to explore their environment." [6] This aspect is often overlooked in the literature, which tends to focus on the practical side of prosthetic use, while overlooking the more personal and delightful dimensions of a user's experience. Furthermore, several studies have found that incorporating haptic feedback into a prosthetic limb positively affects the users' sense of confidence in their use of their prosthesis, their sense of connection to their prosthesis, and a sense of embodiment or wholeness – all of which are important subjective experiences that positively contribute to prosthetic acceptance rates [4]. For those with an acquired limb difference, haptic feedback has also been shown to reduce phantom limb pain [7, 8, 9]. Indeed, haptic feedback is a feature that is highly requested by many prosthesis-wearers. [10, 11]

2.1 Dimensions of Somatosensation

Building on this foundational knowledge, the literature review was extended to explore the biological basis of somatosensation and to examine existing tactile interface designs. Human somatosensory experience is very rich, comprising several different dimensions or senses: contact (or touch), pressure, vibration, shear force, and shape discrimination [12]. The sense of touch is triggered when fingers make contact with surfaces or objects. Pressure sensitivity allows individuals to modulate their grip force appropriately, ensuring objects are held securely without being damaged. Vibrational feedback enables the differentiation between various surface textures, providing information about material properties. Thermal perception contributes both to material recognition and emotional connection, as individuals who have lost limbs frequently express longing to experience the warmth of human contact [12]. Shear detection along the skin's surface helps identify when objects might slip from grasp and aids in distinguishing between materials with different friction properties. Lastly, spatial discrimination enables people to detect boundaries, distinguish between sharp and blunt edges, and interpret patterns such as those found in Braille. The biological underpinnings enabling human tactile sensation are various subcutaneous mechanoreceptors, including "Merkel disks, Meissner corpuscles, Pacinian corpuscles, Ruffini endings, Krause end bulbs, and free nerve endings." [13] Each responds to a different – but not necessarily completely unique or separable – range of stimuli, whether that be a range of distances of skin displacement, a range of forces, or a range of vibration frequency [14, 15].

3 Strategies for Tactile Feedback

In the design of haptic sensory feedback systems, the most advanced solutions aim for modality-matching and somatotopical-matching. Modality-matching entails presenting a sensation in the same way it was detected. Thus, in a modality-matching feedback system, each sensation must be communicated by the corresponding type of tactile actuator, i.e. a pressure could be conveyed by a pusher that deforms the skin, temperature by a Peltier element that heats up, etc. [13] On the other hand, somatotopical-matching means that the brain perceives the senses to originate from the sensor's location. In practice, this is achieved by actuating the sensory display onto the site of the afferent neurons that correspond to the target location on the hand [16]. Available literature demonstrates this approach primarily in patients who have undergone targeted reinnervation procedures, wherein severed or injured nerves are rerouted after limb amputation or injury[17, 18]. While theoretically any physical sensation could be generated by electrically stimulating the appropriate nerve at the appropriate location, current scientific understanding of neurology remains insufficient to implement this. Additionally, this approach would be among the most invasive options. In contrast, sensory substitution, where neither modality matching nor somatotopical matching are attempted, has emerged as a more straightforward approach. For example, contact information from the hand could be represented by vibrotactile stimulation on the abdomen. Such a solution is noninvasive and relatively more manageable while still approximating valuable feedback.

Regardless of whether the system provides modality-matched feedback or relies on sensory substitution, haptic displays can be variously realized. Mechanotactile feedback systems—such as pushers, squeeze belts, pin arrays, or pneumatic actuators—physically deform the skin and are typically best suited for modality matching, particularly in conveying pressure or force. However, there are trade-offs to consider, including bulkiness and challenges with wearability and hygiene. Vibrotactile feedback, on the contrary, is more versatile. It is commonly used not only to represent tactile sensations but also to convey abstract or symbolic information. Its advantages lie mainly in its miniaturizability and the wealth of research around it, stemming from its use in consumer technologies such as mobile devices and VR/AR systems. In many applications, both mechanotactile and vibrotactile systems are implemented as arrays to confer a spatial dimension to the feedback.

Evidently, multiple solutions exist, each with limitations. However, some offer more favorable trade-offs. A successful design is not one that can communicate all sensory dimensions within a single system (as far as current research indicates, this has not yet been achieved). Rather, a successful design is one that, given the constraints—size, weight, technical feasibility—prioritizes effectively. At the same time, a good design balances several other considerations related to the user experience—for example, that haptic feedback should be conveyed in a way that is "intuitive, informative, and [minimizes] information overload" [19].

Below is an extensive, tabulated overview of existing literature featuring studies that physically developed prototypes for a haptic feedback system. Some designs included are not primarily intended for sensory feedback, but are still germane—as inspiration often comes from unexpected and diverse sources, especially in a task as interdisciplinary as this.

Table 1: Summary of Relevant Haptic Feedback Studies

Reference	**Modality**	**Info Conveyed**	**Array Dim.**	**Config.**	**Location**	**Relevant Findings**
Witteveen et al., 2012 [20]	Vibrotactile	Grasping Force/Slip (Progressive Spatial Encoding Scheme)	1×8	Circumferential	Forearm	Improved performance in virtual object holding task.
Van der Riet et al., 2013 [6]	Vibrotactile	Intensity, Modality	1×4	Circumferential	Upper Arm	High spatial and intensity discrimination; lower accuracy with more channels.
Witteveen et al., 2015a [21]	Vibrotactile	Grasping Force	1×1	Single Actuator	Residual limb	No significant difference compared to circumferential linear array.
Witteveen et al., 2015b [21]	Vibrotactile	Grasping Force/Hand Aperture	1×8	Circumferential	Forearm	Improved grasping performance vs. no-feedback.
Kerdegari et al., 2016 [19]	Vibrotactile	Directional (Progressive Spatial Encoding)	1×7	Horizontal	Forehead	Head-mounted displays intuitive for navigation; high accuracy.
Clemente et al., 2015 [5]	Vibrotactile	Contact	1×2	Effectively single motor	Upper Arm	Useful for fragile object manipulation; stimulation site may not be important.
Guemann et al., 2019 [22]	Vibrotactile	Unmapped	1×6	Circumferential vs. Longitudinal	Upper Arm	Circumferential config. w/ prop. spacing best for discrimination; shorter pulses reduce discomfort.
Antfolk et al., 2013 [23]	Vibro vs. Mechanotactile	Force, Spatial	1×5	U-shape	Forearm	Mechanotactile outperformed vibrotactile in spatial discrimination.
Erbas & Guclu, 2024 [24]	Vibrotactile	Intensity, Modality	Dual 1×2	Horizontal	Upper Arms	14 discrete events recognized with low-medium accuracy.
Besharatzad et al., 2024 [25]	Vibrotactile	Force	1×2	Multi-motor (nominal)	Upper Arm	Amputee reached 93.3% accurate force control with training.
Xu et al., 2024 [26]	Vibrotactile	Pressure, Spatial, Symbolic	1×5	Circumferential	Upper Arm	High accuracy in dynamic/static discrimination; rolling motion conveyed.
Choi & Kim, 2019 [27]	Vibrotactile	Intensity, Spatial	6×8	2D Array	Touch Panel	Beat-phenomenon-based haptics effective for simulating textures.
Jones et al., 2006 [28]	Vibrotactile	Symbolic Navigation Commands	4×4	2D Array	Torso vs. Forearm	Patterns recognized with near-perfect accuracy on torso (forearm).
Jones et al., 2009 [29]	Vibrotactile	Symbolic Navigation Commands	3×3	2D Array	Torso vs. Forearm	Military signals mapped to torso had up to 98% recognition.
Kim et al., 2010 [12]	Multimodal	Contact, Pressure, Vibration, Shear	N/A	Multifunction Device	Not Wearable	Effective texture discrimination; shear increased confusion.
Kyung et al., 2007a [30]	Vibrotactile	Texture	1×1	Single Actuator	Handheld	Reasonably effective in texture display.

Reference	Modality	Info Conveyed	Array Dim.	Config.	Location	Relevant Findings
Kyung et al., 2007b [30]	Mechanotactile (Pins)	Texture, Spatial	3×3	2D Array	Handheld Pen	Distributed pressure cues improved accuracy (~90%).
Barontini et al., 2023a [31]	Vibrotactile	Contact, Spatial	1×2	Circumferential	Upper Arm	Subjects identified objects through contact + exploration.
Barontini et al., 2023b [31]	Mechanotactile (Belt)	Grip Force/Aperture	1×1	N/A	Upper Arm	Force feedback preferred over position; effects varied by user.
Barontini et al., 2023c [31]	Multimodal	Force, Contact	N/A	Complex	Upper Arm	Multichannel feedback not clearly beneficial.
Wijk et al., 2020 [4]	Mechanotactile (Pneumatic)	Pressure, Spatial	1×4	Reinnervated site-matched	Forearm	Improved sense of touch and embodiment; performance unchanged. PLP alleviated in most.

4 Constraints and Prioritization

Given the broad spectrum of solutions proposed and tested in the literature, the unique limitations specific to this context required careful consideration. These constraints would inform critical design decisions for the wearable device, including modality selection, the number of tactors and their configuration (shape, size, and spacing), sensation characteristics such as intensity, and optimal body placement. Two key factors were unique to this application: (1) the demographics of the intended users—pediatric patients, most of whom have congenital limb differences—and (2) the preexisting Limbitless arm architecture and software. The fact that users of the Limbitless prosthetic arm are congenital amputees necessarily excludes somatotopically matched solutions, as there is no prior sensory map to align with. It also limits the available control strategies; these users typically have fewer, less differentiated EMG signals to work with. As it stands, the current prosthetic arm offers only open and close grip, which is controlled with a threshhold-based myoelectric control policy. A multi-gesture mode is in development, but it will include, at most, two additional gestures. Critically, there is no variable force control in the current system. In addition, implementing new sensors is not a development priority in the short-term, largely due to a lack of framework or workflow to accommodate routing additional wiring through the fingers. This forces dependence on motor current monitoring, where current overdraw from increased motor torque indicates object contact, as the only feasible feedback mechanism. In the mid to long term, the development of sensory inputs becomes more of a priority; plans for this are outlined in the Future Work section. Under present conditions, the system operates with five binary input signals representing contact or no contact for each finger. This limitation in the dimensionality of input data is one of the most significant design drivers for the entire project. Generally speaking, it is incongruous to map a small number of inputs onto a larger or higher-dimensional set of outputs. One can reduce or increase granularity, but inflating dimensionality is difficult to justify. Thus, due to the nature of the inputs present, a linear finger-mapped array should be used instead of a rectangular array model.

Another consideration is that if a 2D arrayis selected, there is consequently a shift from feedback that can be processed neurally as sensation into a symbolic language system that must be explicitly learned. This is a significant leap in cognitive load. According to Zheng and Meister [32], the brain can process sensory information at a rate of approximately 1 Billion bits/second, whereas higher-order cognitive tasks like language comprehension are processed at just 10 bits/second. Therefore, the conversion of feedback into linguistic form would result in substantial processing delays; this conflicts with the project's goal to minimize cognitive demands on prosthesis users and should therefore be avoided.

Furthermore, there is a lack of empirical support in the literature for the use of rectangular arrays in this context. While some applications of rectangular haptic arrays do exist, they are largely limited to military domains—used to convert visual or gestural signal commands into vibrational equivalents [29]. In these cases, language is already the underlying information being transmitted, so the translation into a symbolic vibrational language makes sense. Braille is another apt example of this kind of appropriate use[33, 34]. However, applying a linguistic framework to represent raw sensory data is inefficient. It bloats the information and dramatically increases cognitive load without clear benefit.

There are also spatial considerations. An array will inherently have a larger footprint on the skin. In contrast, bands can be relatively inconspicuous and can even be realistically fashioned into an aesthetic or wearable form. A large patch, sticker, or waistband required for a rectangular array can be clunky and limiting—it could interfere with sitting, movement, or general comfort. Having a linear array within a band is the most practical and user-friendly choice.

The main counterargument that would favor a 2D array is that rectangular arrays offer more potential combinations—e.g., a 3x3 array allows for 9! possible configurations compared to, say, a linear 1x5 array. However, even 5! represents a substantial number of unique signal patterns. Should there be a future need to make the band-style array forward-compatible with an arm capable of collecting richer information, the signal space would remain sufficiently robust to accomplish this effectively.

Another benefit of an array would be to convey textures or tactile patterns, but for short-term, the Limbitless arm lacks the facilities to sense and process that sort of input.

Overall, the linear finger-mapped array is better aligned with the nature of the inputs, more compatible with the brain's sensory processing capabilities, and avoids the unnecessary abstraction of data into a linguistic format. The rectangular array, while potentially powerful in specific symbolic use cases, introduces unnecessary complexity and bottlenecks for the current needs.

5 Design

5.1 Device Design

Based on the previously discussed constraints, the project will proceed with the decision to utilize a linear vibrotactile array on the arm—specifically on the upper arm, since the residual forearm is typically covered by the socket in transradial amputees. In the determination of the number of vibrors to use, the anatomy of the human upper arm provides guidance and soft constraints. Guemann [22]found that circular arrangements of tactors elicited better discrimination and localization scores than longitudinal ones. He posited that this was because stimulating distinct dermatomes – regions of skin connected to different spinal nerves – can enhance the brain's ability to distinguish between tactile sensations. Thus, to maximize clarity and localizability, tactors should be placed on separate dermatomes. There are five dermatomes around the human upper arm (see Fig. 1), so in principle, five or fewer tactors should be utilized.

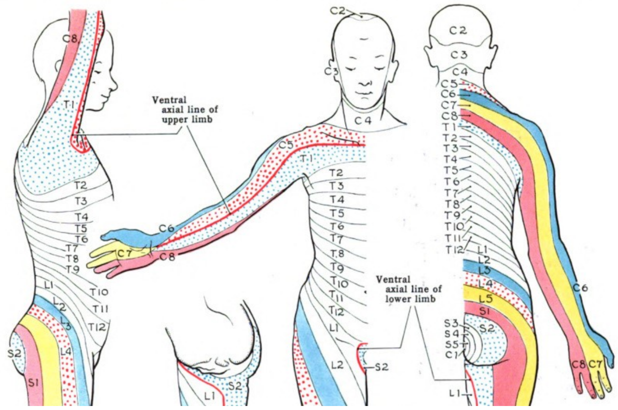

Figure 1: Dermatome Map. Retrieved from [35]

Another constraint to recall is that the target users of the Limbitless bionic arm are children. The mid-upper arm circumference (MUAC) of a 5-year-old typically falls around 17.28 cm (SD 0.73) [36]. Given that average two-point discrimination on the upper arm is between 3 and 4 cm [37][38], this suggests it is possible fit approximately four evenly spaced vibrors along the arm. This entails the pooling of at least signals into a single output, but that is acceptable. Very few gestures require fine control of every individual finger. For example, the pinky and ring fingers have limited independent movement due to shared flexor muscles and tendons. This anatomical coupling often leads to them being grouped in many motor actions; coupling them in haptic feedback design would be precedented. This approach is further supported by informal user feedback, where such grouping was independently suggested unprompted, demonstrating its intuitive logic. These considerations were evaluated quantitatively using a concept matrix, which challenged and ultimately validated the design decisions. The results supported both the single tactor and the linear array, which scored highest. Ultimately, the decision was made to proceed with the linear array design because the single tactor configuration seemed too limited for long-term goals. Looking ahead, the research team has more ambitious plans that involve integrating external sensors, and a multi-tactor setup provides a more scalable platform for communicating richer feedback. Additionally, Kyung et al. [30] found that feedback delivered through a linear array (as opposed to a single tactor) enabled faster and more accurate identification of patterns and textures. This is likely because array configurations allow for some degree of shape discrimination and directional sensing, even if the resolution is relatively low.

5.2 Vibration Design

With the physical design of the mechanism now characterized, the communication protocol and feedback "language" must be defined. This encompasses the waveforms, timing, and patterns of its vibrations. For binary signals, such as contact information, Erbas and Guclu [24] argue that discrete feedback is more effective than continuous feedback for communicating contact. In a discrete feedback model, if contact is made, instead of vibrating for the entire time that contact is held, it only vibrates once, initially, when the contact is first made (an instance of a state change, in this case from Off to On). This paradigm is known as discrete event-driven sensory feedback control (DESC) [39]. This approach is promising, as its alternative -continuous feedback- requires significant “processing power by the related systems and increases cognitive load during the tasks” [24]. DESC is intuitive because it aligns with the common experience: conscious perception of static tactile contact diminishes over time, except when encountering extreme, unusual, or dynamically changing textural properties.

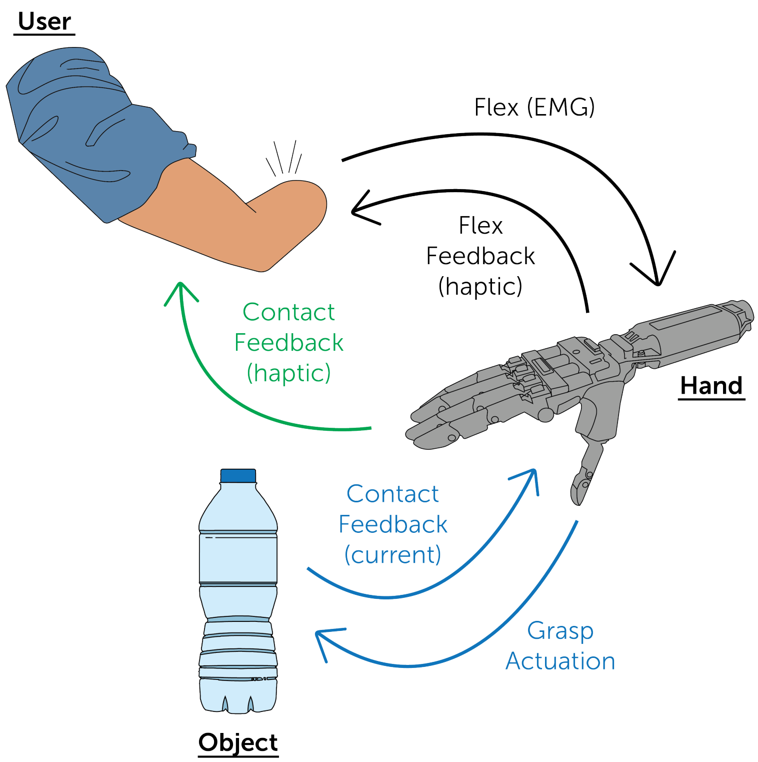

Figure 2: Control flow diagram. Credit: Gianna Vargas, 2025.

Towards the aim of developing more naturalistic sensory feedback, Tyler [1] demonstrated that modulating electrical stimulation in wavelike patterns transformed typical tingling sensations into natural feelings of pressure that patients could readily recognize. The research team did not study if the success of this method also was applicable to vibrotactile stimulation, but the results are interesting and invite further exploration on the topic. The frequency of stimulation is another critical parameter, which is fortunately well-studied. Pacinian corpuscles respond to high-frequency vibrations, roughly 40–800 Hz. Meissner corpuscles are sensitive to lower-frequency vibrations and are stimulated at frequencies below 100 Hz. Within these ranges of vibration frequency, 250 Hz is identified as frequency at which human skin is most perceptually sensitive [40] . Furthermore, Kajimoto et al. [41] found that a 200 Hz signal activated Merkel receptors and evoked a pressure-like sensation, whereas frequencies below 100 Hz evoked sensations more consistent with flutter or low-frequency vibration. The pressure-like sensation evoked by 200 Hz presents an interesting opportunity for quasi-modality-matched feedback, where the vibrational stimulus suggests a pressure-like feeling to match the pressure it is meant to represent.

6 Experimentation

6.1 Materials

For the initial prototype, a system was constructed using LilyPad "Vibe Board" vibration motors from SparkFun Electronics®. These motors were selected due to their availability, relative affordability, simplicity, and ease of integration. In particular, they feature holes designed for threading conductive materials, as they are intended for wearable technology applications. The vibrators are sewn into a velcro armband such that each motor is positioned approximately 90 degrees apart around the wearer's arm, ensuring stimulation of distinct dermatomes. Each haptic motor is controlled by an Arduino® Nano ESP32 microcontroller. The controller connects to a TCA9548A I2C multiplexer to enable communication with up to eight identical I2C address devices through a single microcontroller. The multiplexer connects to four motor drivers (SparkFun Electronics® Haptic Motor Driver - DRV2605L), each of which controls one haptic motor. The motor drivers allow for more precise, programmable motor control and includes built-in waveforms for testing. A full PCB schematic detailing the circuit is included in the Appendix (fig.6).

6.2 Experimental Methods

To evaluate (1) participants' ability to localize vibrotactile stimuli delivered via an armband, and (2) the intuitiveness of different mapping schemes between vibror locations and hand representations, the following study is proposed.

6.2.1 Part 1: Vibrotactile Stimulus Localization

Participants will wear an armband equipped with four evenly spaced vibration motors (vibrors) on their non-dominant arm. Their task is to identify which vibror(s) are active during each trial.

All possible combinations of the four vibrors (e.g., only the 1st active, 1st + 3rd active, all four active, etc.) will be presented, with the number of simultaneously active vibrors ranging from one to four.

Each pattern will be tested multiple times (e.g., three repetitions per pattern), presented in order of increasing number of active vibrors. This progressive ordering is intended to help participants become familiar with the armband's functionality. Participants will use a visual interface to indicate which vibrors they perceive to be active. The accuracy of identification will be the primary measured outcome.

6.2.2 Part 2: Evaluation of Embodied Coherence in Mapping Schemes

In this phase, the vibrators are mapped to specific regions of the hand to assess how naturally users associate vibrotactile stimuli with internal representations of the hand. The mapping will evaluate response speed as a proxy for intuitiveness. Response speed serves as a reliable indicator of intuitiveness because rapid acquisition occurs when new systems seamlessly integrate with existing mental models, allowing the brain to unconsciously recognize familiar patterns and eliminate the need for explicit instruction or extensive trial-and-error exploration.

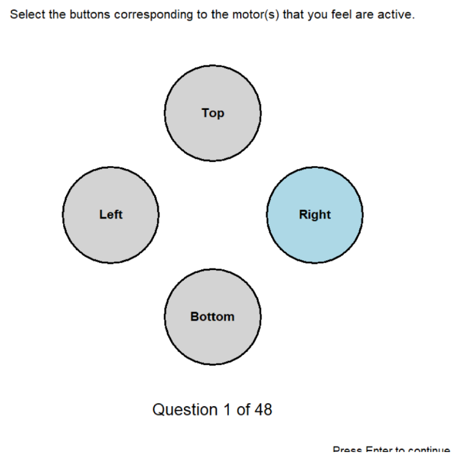

Figure 3: Testing Interface for Localization Test.

Mapping Scheme:

- Left vibror → Thumb
- Top vibror → Index finger
- Right vibror → Middle finger
- Bottom vibror → Ring + Pinky fingers

Stimulation patterns will be drawn from a limited set of gestures (e.g., whole hand grasp, pinch, point, thumb only, pinky only) and presented one at a time in randomized order. Participants will be asked to identify the gesture represented by each pattern.

Response time will be the primary measured outcome. Faster identification times in conjunction with accuracy will be interpreted as evidence of a more intuitive and congruent mapping between the vibrotactile input and the participant's internal model of the hand.

6.2.3 Part 3: Survey

At the conclusion of the armband-testing phase, participants will be asked a set of questions aiming to measure their confidence using and interpreting the system, their perception of the system overall, and perceived mental and physical exertion. Questions include original questions as well as additional survey questions from the System Usability Scale (SUS), and the NASA-TLX, which are validated surveys that assess usability of the devices and cognitive workload.

7 Future Work

Looking ahead at future iterations of the project, the haptics team has identified several goals to strive for in order to elevate tactile perception capabilities of the arm.

The immediate priority involves physically integrating the haptic feedback system with the existing Limbitless arm hardware. This integration will require consolidating the current prototype

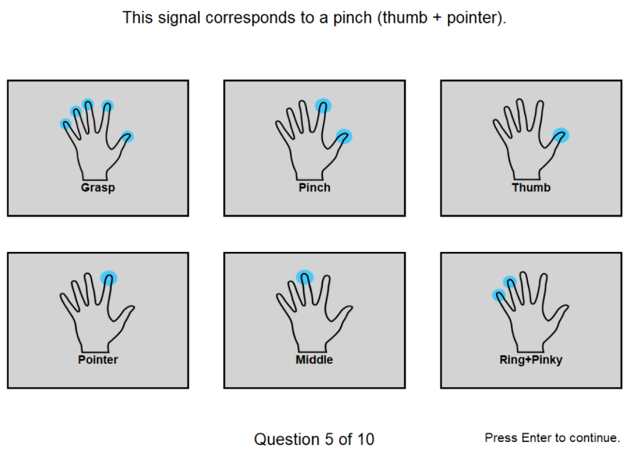

Figure 4: Testing Interface for Mapping Test.

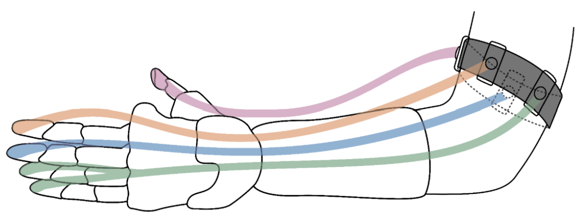

Figure 5: Mapping Scheme Correspondence Visualization. Artist's rendering. Credit: Vanessa Lopez, 2025.

electronics into a flexible PCB that can be fitted into the prosthetic device. Another critical step in the completion of this prototype is developing the signal processing algorithms needed to interpret the motor current draw from each finger actuator and establish appropriate thresholds for reliable contact detection.

As a secondary objective, incorporating pressure sensors is recommended to address the lack of inputs for the system, which has received limited attention thus far. In particular, thin film pressure sensors are highly suitable for application in the Limbitless context. Although routing the wiring through the digits will present a challenge, it is a worthwhile pursuit if tactile feedback remains a priority. The advisable sensor placement has been identified as the thumb and the upper-left, upper-right, and top extrema of the hand. This configuration is conducive to "feeling around" one's environment and tactile sensing. The decision to limit the system to four sensors was to ensure compatibility with the existing hardware architecture, requiring only the addition of new vibrations ("vibremes") to the vibrational language.

With pressure sensors, there will be the ability and the desire to communicate more complex information than binary signals through each vibrator. This would necessitate analog output ranges for expressing continuous values such as force magnitude. Witteveen et al. (2012) [20] compared various feedback modulation strategies for communicating grasp force in prosthetics—specifically amplitude, pulse frequency, and location—and found that amplitude modulation led to the best performance in an object-holding task.

A tertiary goal would be to transition to a mechanotactile armband. While this approach would result in a device with a less-slim profile, it possesses several advantages. These include delivering more comfortable sensations, more intuitive sensations due to the modality-matched feedback, and easily implementable proportional force feedback. This transition would also facilitate synergy with other haptic feedback systems (such as device feedback and flex feedback, ideally integrated on a single hardware platform) by reducing sensory confusion. When multiple vibrotactile signals are presented simultaneously, users are more likely to become confused by the myriad vibrations being presented, which undermines the goal of providing intuitive feedback. However, a approach utilizing both mechanotactile stimulation for sensory feedback and vibrotactile stimulation for flex and device feedback would have greater clarity. Research by Antfolk [23] supports this direction, finding that "pressure stimulation surpassed vibrotactile stimulation in multi-site sensory feedback discrimination." Additionally, the smaller and more localized receptive fields and finer spatial resolution of Merkel's disks (which respond to pressure stimulation) compared to Pacinian corpuscles (which respond to vibrotactile stimulation) further supports the mechanotactile approach. A separate, further-ahead objective is exploring the design from Xu et al.'s [26] 25-sensor array (5 sensors per finger), capable of conveying a pressure map. Even without active force control, this configuration can provide valuable geometric information about grasped objects through low-resolution pressure maps. While Xu et al.'s [26]design conveyed this pressure map to the user through a 5-tactor armband, a 2D 5×5 array located on the back of the torso would arguably be most apt. Finally, several other areas of improvement warrant exploration: integrating Bluetooth for improved portability by eliminating wiring, waterproofing the device to allow for washing, and developing psychophysical calibration protocols [24] to optimize device feedback for individual users.

8 Conclusion

The system demonstrates potential as a lightweight, intuitive, and cost-effective solution for integrating low-resolution sensory feedback into devices that previously lacked haptic capabilities. The decision to proceed with a linear four-motor vibrotactile array, rather than exploring the full spectrum of possible haptic feedback modalities, prevented the project from becoming unbounded in scope. Without this constraint-driven approach, the research could have easily expanded into numerous parallel investigations of mechanotactile systems, 2D arrays, or electrical stimulation—each adding months of additional development without necessarily advancing the core objective.

The higher specific application context of pediatric prosthetics provided boundaries that enabled the project to progress. This allowed for focus on optimizing for the unique needs of children with congenital upper-limb difference. Insights derived from the proposed data collection will be used to inform subsequent iterations of the design, allowing for continuous enhancement. In addition, the alternative concepts outlined in future work are compelling paths for further research once the foundational system has been validated.

Acknowledgments

This project would not have been possible without the interdisciplinary team and alumni at Limbitless Solutions and in particular, project partner Jordan C. Dalton. The abstract for this work was co-written with Jordan C. Dalton to comprehensively include insights from both parties involved in this collaborative research effort. Special thanks to Gianna Vargas and Vanessa Lopez for their graphic design support. The support of the Paul B. Hunter and Constance D. Hunter Charitable Foundation for their philanthropic support for undergraduate research is appreciated. The support for this work was provided by the National Science Foundation REU program under Award No. 234922. Any opinions, findings, and conclusions and recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation. The author acknowledges the use of Generative AI to revise sections of this manuscript for clarity and grammar.

References

[1] D. J. Tyler, "Restoring the human touch: Prosthetics imbued with haptics give their wearers fine motor control and a sense of connection," *IEEE Spectr.*, vol. 53, no. 5, pp. 28–33, May 2016. [Online]. Available: http://ieeexplore.ieee.org/document/7459116/

[2] G. Westling and R. Johansson, "Factors influencing the force control during precision grip," *Exp Brain Res*, vol. 53, no. 2, Jan. 1984. [Online]. Available: http://link.springer.com/10.1007/BF00238156

[3] B. Güçlü, Ed., *Somatosensory feedback for neuroprosthetics.* London, United Kingdom ; San Diego, CA: Academic Press, An imprint of Elsevier, 2021.

[4] U. Wijk, I. K. Carlsson, C. Antfolk, A. Björkman, and B. Rosén, "Sensory Feedback in Hand Prostheses: A Prospective Study of Everyday Use," *Front. Neurosci.*, vol. 14, Jul. 2020. [Online]. Available: https://www.frontiersin.org/journals/neuroscience/articles/10.3389/fnins.2020.00663/full

[5] F. Clemente, M. D'Alonzo, M. Controzzi, B. B. Edin, and C. Cipriani, "Non-Invasive, Temporally Discrete Feedback of Object Contact and Release Improves Grasp Control of Closed-Loop Myoelectric Transradial Prostheses," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 24, no. 12, pp. 1314–1322, Dec. 2016. [Online]. Available: https://ieeexplore.ieee.org/document/7328737/

[6] D. Van Der Riet, R. Stopforth, G. Bright, and O. Diegel, "Simultaneous vibrotactile feedback for multisensory upper limb prosthetics," in *2013 6th Robotics and Mechatronics Conference (RobMech).* Durban, South Africa: IEEE, Oct. 2013, pp. 64–69. [Online]. Available: http://ieeexplore.ieee.org/document/6685493/

[7] C. Dietrich, K. Walter-Walsh, S. Preißler, G. O. Hofmann, O. W. Witte, W. H. Miltner, and T. Weiss, "Sensory feedback prosthesis reduces phantom limb pain: Proof of a principle," *Neuroscience Letters*, vol. 507, no. 2, pp. 97–100, Jan. 2012. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0304394011014807

[8] C. Dietrich, S. Nehrdich, S. Seifert, K. R. Blume, W. H. R. Miltner, G. O. Hofmann, and T. Weiss, "Leg Prosthesis With Somatosensory Feedback Reduces Phantom Limb Pain and Increases Functionality," *Front. Neurol.*, vol. 9, p. 270, Apr. 2018. [Online]. Available: http://journal.frontiersin.org/article/10.3389/fneur.2018.00270/full

[9] D. M. Page, J. A. George, D. T. Kluger, C. Duncan, S. Wendelken, T. Davis, D. T. Hutchinson, and G. A. Clark, "Motor Control and Sensory Feedback Enhance Prosthesis Embodiment and Reduce Phantom Pain After Long-Term Hand Amputation," *Front. Hum. Neurosci.*, vol. 12, p. 352, Sep. 2018. [Online]. Available: https://www.frontiersin.org/article/10.3389/fnhum.2018.00352/full

[10] C. Pylatiuk, S. Schulz, and L. Döderlein, "Results of an Internet survey of myoelectric prosthetic hand users," *Prosthetics & Orthotics International*, vol. 31, no. 4, pp. 362–370, Dec. 2007. [Online]. Available: https://journals.lww.com/00006479-200731040-00005

[11] H. L. Benz, J. Yao, L. Rose, O. Olgac, K. Kreutz, A. Saha, and E. F. Civillico, "Upper extremity prosthesis user perspectives on unmet needs and innovative technology," in *2016 38th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC).* Orlando, FL, USA: IEEE, Aug. 2016, pp. 287–290. [Online]. Available: http://ieeexplore.ieee.org/document/7590696/

[12] K. Kim, J. E. Colgate, J. J. Santos-MunnÉ, A. Makhlin, and M. A. Peshkin, "On the Design of Miniature Haptic Devices for Upper Extremity Prosthetics," *IEEE/ASME Transactions on Mechatronics*, vol. 15, no. 1, pp. 27–39, Feb. 2010. [Online]. Available: https://ieeexplore.ieee.org/document/4815425?arnumber=4815425

[13] Y. Huang, K. Yao, J. Li, D. Li, H. Jia, Y. Liu, C. K. Yiu, W. Park, and X. Yu, "Recent advances in multi-mode haptic feedback technologies towards wearable interfaces," *Materials Today Physics*, vol. 22, p. 100602, Jan. 2022. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2542529321002637

[14] A. R. See, J. A. G. Choco, and K. Chandramohan, "Touch, Texture and Haptic Feedback: A Review on How We Feel the World around Us," *Applied Sciences*, vol. 12, no. 9, p. 4686, May 2022, publisher: MDPI AG. [Online]. Available: https://www.mdpi.com/2076-3417/12/9/4686

[15] V. G. Macefield, "Physiological characteristics of low-threshold mechanoreceptors in joints, muscle and skin in human subjects," *Clin Exp Pharma Physio*, vol. 32, no. 1-2, pp. 135–144, Jan. 2005, publisher: Wiley. [Online]. Available: https://onlinelibrary.wiley.com/doi/10.1111/j.1440-1681.2005.04143.x

[16] J. S. Schofield, K. R. Evans, J. P. Carey, and J. S. Hebert, "Applications of sensory feedback in motorized upper extremity prosthesis: a review," *Expert Review of Medical Devices*, vol. 11, no. 5, pp. 499–511, Sep. 2014. [Online]. Available: http://www.tandfonline.com/doi/full/10.1586/17434440.2014.929496

[17] J. T. Henderson, Z. A. Koenig, M. Climov, and J. Gelman, "Targeted Muscle Reinnervation: A Systematic Review of Nerve Transfers for the Upper Extremity," *Ann Plast Surg*, vol. 90, no. 5, pp. 462–470, May 2023, publisher: Ovid Technologies (Wolters Kluwer Health). [Online]. Available: https://journals.lww.com/10.1097/SAP.0000000000003498

[18] K. D. OShaughnessy, G. A. Dumanian, R. D. Lipschutz, L. A. Miller, K. Stubblefield, and T. A. Kuiken, "Targeted Reinnervation to Improve Prosthesis Control in Transhumeral Amputees: A Report of Three Cases," *The Journal of Bone & Joint Surgery*, vol. 90, no. 2,

pp. 393–400, Feb. 2008, publisher: Ovid Technologies (Wolters Kluwer Health). [Online]. Available: http://journals.lww.com/00004623-200802000-00024

[19] H. Kerdegari, Y. Kim, and T. J. Prescott, “Head-Mounted Sensory Augmentation Device: Designing a Tactile Language,” *IEEE Trans. Haptics*, vol. 9, no. 3, pp. 376–386, Jul. 2016. [Online]. Available: http://ieeexplore.ieee.org/document/7452615/

[20] H. J. B. Witteveen, J. S. Rietman, and P. H. Veltink, “Grasping force and slip feedback through vibrotactile stimulation to be used in myoelectric forearm prostheses,” in *2012 Annual International Conference of the IEEE Engineering in Medicine and Biology Society*. San Diego, CA: IEEE, Aug. 2012, pp. 2969–2972. [Online]. Available: http://ieeexplore.ieee.org/document/6346587/

[21] H. J. Witteveen, H. S. Rietman, and P. H. Veltink, “Vibrotactile grasping force and hand aperture feedback for myoelectric forearm prosthesis users,” *Prosthetics & Orthotics International*, vol. 39, no. 3, pp. 204–212, Jun. 2015. [Online]. Available: https://journals.lww.com/00006479-201539030-00004

[22] M. Guemann, S. Bouvier, C. Halgand, F. Paclet, L. Borrini, D. Ricard, E. Lapeyre, D. Cattaert, and A. D. Rugy, “Effect of vibration characteristics and vibror arrangement on the tactile perception of the upper arm in healthy subjects and upper limb amputees,” *J NeuroEngineering Rehabil*, vol. 16, no. 1, p. 138, Dec. 2019. [Online]. Available: https://jneuroengrehab.biomedcentral.com/articles/10.1186/s12984-019-0597-6

[23] C. Antfolk, M. D’Alonzo, M. Controzzi, G. Lundborg, B. Rosen, F. Sebelius, and C. Cipriani, “Artificial redirection of sensation from prosthetic fingers to the phantom hand map on transradial amputees: Vibrotactile versus mechanotactile sensory feedback,” *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 21, no. 1, pp. 112–120, 2013.

[24] Erbaş and B. Güçlü, “Real-time vibrotactile pattern generation and identification using discrete event-driven feedback,” *Somatosensory & Motor Research*, vol. 41, no. 2, pp. 77–89, Apr. 2024. [Online]. Available: https://www.tandfonline.com/doi/full/10.1080/08990220.2023.2175811

[25] N. Besharatzad, T. Thurston, S. Sylwester, and V. J. Mathews, “A Standardized Vibro-tactile Sensory Feedback System For Upper-limb Prostheses,” *Annu Int Conf IEEE Eng Med Biol Soc*, vol. 2024, pp. 1–4, Jul. 2024.

[26] H. Xu, Y. Rong, J. Ren, N. Zhang, Y. Zhao, X. Yang, Z. Zhu, and G. Gu, “A Learning-Based Sensor Array for Untethered Soft Prosthetic Hand Aiming at Restoring Tactile Sensation,” *Advanced Intelligent Systems*, vol. 6, no. 10, p. 2300221, Oct. 2024. [Online]. Available: https://onlinelibrary.wiley.com/doi/10.1002/aisy.202300221

[27] D.-S. Choi and S.-Y. Kim, “Transparent Film-Type Vibrotactile Actuator Array and Its Haptic Rendering Using Beat Phenomenon,” *Sensors*, vol. 19, no. 16, p. 3490, Aug. 2019. [Online]. Available: https://www.mdpi.com/1424-8220/19/16/3490

[28] L. A. Jones, B. Lockyer, and E. Piateski, “Tactile display and vibrotactile pattern recognition on the torso,” *Advanced Robotics*, vol. 20, no. 12, pp. 1359–1374, Jan. 2006. [Online]. Available: https://www.tandfonline.com/doi/full/10.1163/156855306778960563

[29] L. A. Jones, J. Kunkel, and E. Piateski, “Vibrotactile Pattern Recognition on the Arm and Back,” *Perception*, vol. 38, no. 1, pp. 52–68, Jan. 2009. [Online]. Available: https://journals.sagepub.com/doi/10.1068/p5914

[30] K.-U. Kyung, J.-Y. Lee, and J.-S. Park, “Comparison of Force, Tactile and Vibrotactile Feedback for Texture Representation Using a Combined Haptic Feedback Interface,” in *Haptic and audio interaction design: second international workshop, HAID 2007, Seoul, South Korea, November 29-30, 2007: proceedings*, ser. Lecture notes in computer science. Berlin ; New York: Springer, 2007, pp. 34–43.

[31] F. Barontini, A. Obermeier, M. G. Catalano, S. Fani, G. Grioli, M. Bianchi, A. Bicchi, and E. Jakubowitz, “Tactile Feedback in Upper Limb Prosthetics: A Pilot Study on Trans-Radial Amputees Comparing Different Haptic Modalities,” *IEEE Trans. Haptics*, vol. 16, no. 4, pp. 760–769, Oct. 2023. [Online]. Available: https://ieeexplore.ieee.org/document/10273734/

[32] J. Zheng and M. Meister, “The unbearable slowness of being: Why do we live at 10 bits/s?” *Neuron*, vol. 113, no. 2, pp. 192–204, Jan. 2025. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0896627324008080

[33] L. Brayda, F. Leo, C. Baccelliere, E. Ferrari, and C. Vigini, “Updated Tactile Feedback with a Pin Array Matrix Helps Blind People to Reduce Self-Location Errors,” *Micromachines*, vol. 9, no. 7, p. 351, Jul. 2018, publisher: MDPI AG. [Online]. Available: https://www.mdpi.com/2072-666X/9/7/351

[34] K.-U. Kyung, J.-Y. Lee, and J. Park, “Haptic Stylus and Empirical Studies on Braille, Button, and Texture Display,” *BioMed Research International*, vol. 2008, no. 1, Jan. 2008, publisher: Wiley. [Online]. Available: https://onlinelibrary.wiley.com/doi/10.1155/2008/369651

[35] J. Grant, *An Atlas of Anatomy: By Regions ...*, ser. An Atlas of Anatomy: By Regions. Williams & Wilkins, 1962. [Online]. Available: https://books.google.com/books?id=bsNpAAAAMAAJ

[36] T. Edmond, A. Laps, A. L. Case, N. O’Hara, and J. M. Abzug, “Normal Ranges of Upper Extremity Length, Circumference, and Rate of Growth in the Pediatric Population,” *Hand (New York, N,Y.)*, vol. 15, no. 5, pp. 713–721, Sep. 2020. [Online]. Available: https://journals.sagepub.com/doi/10.1177/1558944718824706

[37] R. W. Cholewiak, “The Perception of Tactile Distance: Influences of Body Site, Space, and Time,” *Perception*, vol. 28, no. 7, pp. 851–875, Jul. 1999. [Online]. Available: https://journals.sagepub.com/doi/10.1068/p2873

[38] M. F. Nolan, “Two-Point Discrimination Assessment in the Upper Limb in Young Adult Men and Women,” *Physical Therapy*, vol. 62, no. 7, pp. 965–969, Jul. 1982. [Online]. Available: https://academic.oup.com/ptj/article/2727434/Two-Point

[39] R. S. Johansson and J. R. Flanagan, “Coding and use of tactile signals from the fingertips in object manipulation tasks,” *Nat Rev Neurosci*, vol. 10, no. 5, pp. 345–359, May 2009. [Online]. Available: https://www.nature.com/articles/nrn2621

[40] M. Meehan, F. Brooks, S. Razzaque, and M. Whitton, "Ieee virtual reality," *Los Angeles, CA*, pp. 141–148, 2003.

[41] H. Kajimoto, N. Kawakami, T. Maeda, and S. Tachi, "Tactile feeling display using functional electrical stimulation," in *Proc. 1999 ICAT*, vol. 133, 1999.

9 Appendix

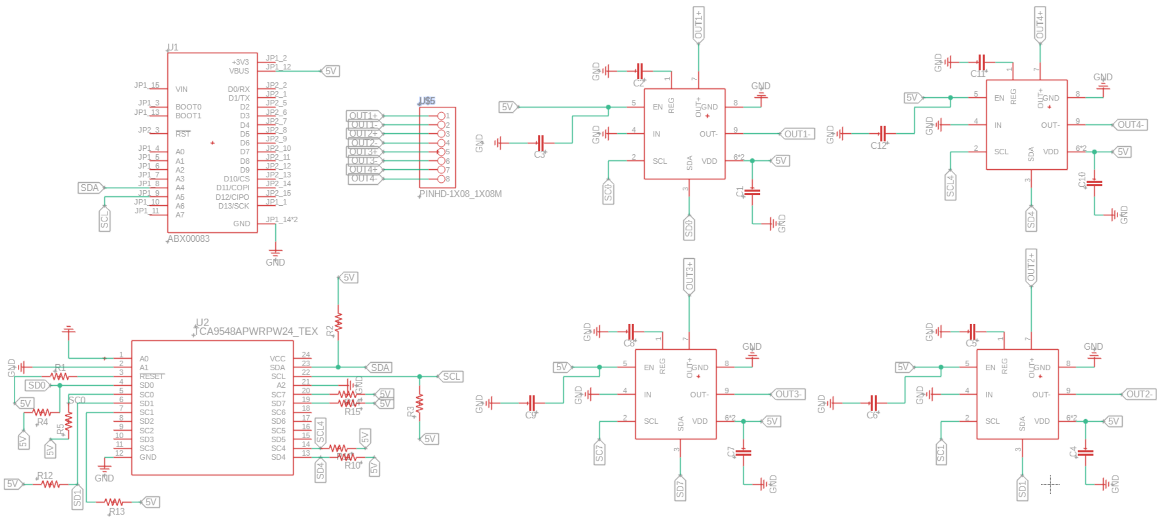

Figure 6: PCB Schematic. Credit: Nishant Ganesan, 2025.