

Multi-Sensory Brachial Prosthetic Using Electric Signals

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The current problem with modern brachial prosthetics is that the majority do not have combined touch sensors that can detect more than one sense. This paper proposes a sensor that can detect two senses, pressure and texture, and combine them into one electric signal that is sent to the user. Firstly, the prosthetic uses sensors to detect the user's pressure on an object and texture of the object. Then, the information is converted into an electrical signal, which stimulates the radial nerve to send the brain sensory information. Simulation graphs demonstrate that four combinations of pressure and texture yield distinct electrical signatures. High-pressure scenarios result in shorter intervals between pulses, while rough textures correlate with higher voltages. Users can theoretically distinguish between these combinations based on signal strength and pulse frequency. This study presents a promising, non-invasive method of providing dual-sensory feedback in brachial prosthetics using electric signals. It lays the foundation for developing more advanced prosthetic systems that restore critical aspects of the sense of touch.

Keywords: Prosthetics, electric stimulation, tactile sensors, haptics, texture detection, pressure detection

Introduction

Background and Context

Advancements in brachial prosthetics have led to a variety of sensory technologies aimed at restoring tactile perception for amputees¹⁻³. Early systems primarily provided single-modal feedback, such as pressure or vibration, delivered through electrotactile or vibrotactile stimulation. For instance, Antfolk et al.¹ demonstrated that single-channel electrotactile feedback could convey pressure information, allowing users to detect contact events but unable to represent more complex tactile features like texture or combined modalities.

More recent research has focused on multi-modal sensory feedback, integrating pressure, texture, and proprioceptive information to enhance tactile richness⁴⁻⁶. Technologies such as e-skin^{2,3} can detect pressure and texture simultaneously; however, these systems often require invasive interfaces or sophisticated signal processing to transmit the information to the nervous system. Non-invasive dual-modality systems^{4,5} show promise in combining somatotopic and substitute feedback channels, yet they are limited in providing continuous, naturalistic, and fully distinguishable sensations, restricting their practical usability for amputees⁷⁻⁹.

The knowledge gap is clear: current non-invasive systems either deliver only a single sensory modality, or invasive systems that provide multi-modal feedback pose safety, accessibility, and surgical risks. No existing approach provides a safe, fully non-invasive method that encodes multiple tactile modalities simultaneously into interpretable signals^{10,11}. Our

approach uniquely addresses this gap by developing a non-invasive system that simultaneously encodes both pressure and texture into a single electrical pulse train delivered via surface electrodes^{12,13}. By combining the two modalities into one controllable signal, our system offers richer, more distinguishable tactile feedback without requiring surgical implantation. This positions our work as a novel and practical solution for next-generation, multi-sensory prosthetic interfaces^{14,15}.

Problem Statement and Rationale

The lack of tactile sensation in individuals with upper-limb amputations significantly impairs their ability to interact with the environment, limiting tasks such as object manipulation, grip adjustment, and spatial navigation^{4,11,16}. While prosthetic technology has advanced, most existing systems either deliver single-modal feedback (e.g., pressure-only electrotactile stimulation) or require invasive interfaces to provide multi-modal feedback^{5,6,17}.

Single-modal non-invasive approaches allow users to detect basic contact events but fail to replicate the full complexity of tactile experience, such as the perception of texture combined with varying pressure. Invasive systems, while capable of multi-channel feedback, introduce substantial surgical and safety risks, restricting accessibility and practical adoption^{6,10,18}.

This creates a critical gap in the current state of prosthetic sensory feedback: no existing system provides a non-invasive, multi-modal solution capable of simultaneously encoding both pressure and texture into a single signal inter-

pretable by the human nervous system^{8,19}. Addressing this gap is essential to restore more naturalistic tactile perception and improve the functional use of prosthetic limbs^{20,21}.

Significance and Purpose

Integrating multi-sensory feedback into prosthetic devices represents a major advancement in rehabilitation technology^{4,7,9,22}. By restoring tactile sensations, users can better perceive object properties such as texture, compliance, and surface roughness, leading to more precise manipulation and improved interaction with their environment²³.

The purpose of this study is to develop a non-invasive system that encodes both pressure and texture into a single electrical pulse train delivered via surface electrodes, providing continuous, distinguishable, and interpretable sensory feedback^{12,13,24}. The significance of this research lies in its potential to bridge the sensory gap for amputees, offering a more intuitive interface between the user and prosthetic limb. Comprehensive feedback may enhance user satisfaction, improve prosthetic adoption, and support more effective rehabilitation outcomes^{25,26}.

Objectives

The primary objective of this simulation-based feasibility study is to design and evaluate a non-invasive system capable of delivering both texture and pressure sensations to users of brachial prosthetics²⁷. Specifically, we aim to develop and evaluate a non-invasive two-parameter coding strategy in which texture is mapped to stimulation amplitude and pressure is mapped to inter-pulse interval^{28,29}. We hypothesize that electrical signals for four tactile states (high/low pressure and rough/smooth texture) will be discriminable, and that stimulation parameters to be used will be within prespecified neurostimulation safety limits³⁰.

Scopes and Limitations

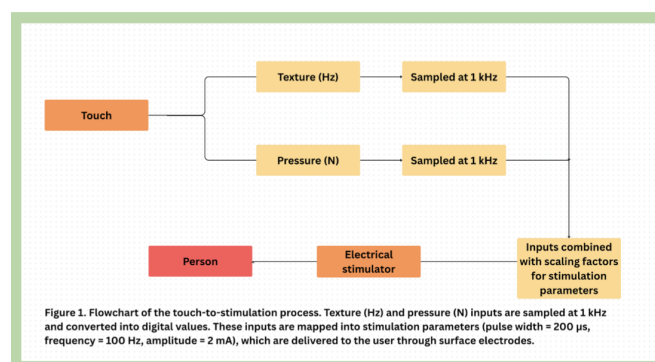
The study will use simulated tactile data to represent rough/smooth textures and high/low pressures³¹. Massagers and pressure sensors will act as stand-ins for surface electrodes, allowing controlled adjustment of intensity and pulse timing³². Commercial sensors capable of simultaneously measuring pressure and texture are not readily available, requiring guidance from mentors and technical experts^{33,34}. For ethical and safety reasons, initial experiments are simulation-only. While this system cannot fully replicate natural touch, it provides major sensory feedback critical for interaction with objects. Transition to actual electrical patches will occur only after simulation validation.

Theoretical Framework

This approach is grounded in neurohaptics and bioelectricity, drawing on principles of transcutaneous electrical nerve stimulation (TENS)^{10,12,13}. TENS delivers controlled electrical pulses through the skin to stimulate peripheral nerves, enabling tactile perception non-invasively. By encoding tactile information into pulse amplitude (pressure) and timing (texture), the system converts real-world interactions into signals interpretable by the nervous system.

Methodology Review

This study is a simulation-only feasibility study designed to evaluate the non-invasive encoding of both pressure and texture into electrical pulse trains for brachial prosthetic users. Tactile data are simulated to represent four distinct conditions combining high and low pressure with rough and smooth textures, reflecting common material interactions such as sandpaper or plastic. Pressure and texture are mapped to separate dimensions of a single waveform: texture is encoded as pulse amplitude (V), with rough surfaces producing higher voltages, while pressure is encoded as inter-pulse interval (ms), with higher pressures producing shorter intervals. These two parameters are combined in a single signal, allowing simulated perception of both pressure and texture simultaneously.



METHODS

Research Design

This is an experimental study for which the users exert a variety of forces on objects with varying roughness. The brachial prosthetics have sensors on the fingertips to collect information regarding the texture of the object and the pressure the user exerts through similar methods as products such as Ossala's findings ((A. Ossala, Prosthetic limbs could have artificial skin that really feels. Popular Science. (2015).)) and

Hyunhyub Ko's artificial fingerprints ((H. Armitage, New artificial fingerprints feel texture, hear sound. Science. (2015))). The information is digitized and transformed into varied electric waveforms and then sent to the electric patches that attach to the end of the prosthetic that comes into contact with the residual limb of the user. The electric waves exert on the user in a voltage maintained at 10-40 V and less than 10 mA RMS. The electric waves are varied in intensity and in the intervals between each pulse train.

Texture and pressure are combined by translating them into two separate dimensions of a single electrical signal. Texture is translated into the amplitude (V) of the signal, whereas rough surfaces produce higher voltages. Pressure is translated into the time interval between pulses (ms-s), whereas higher pressures produce lower time intervals. The two parameters are joined in one waveform so that the user perceives both roughness (via stimulation intensity) and pressure (via stimulation frequency) simultaneously.

We predicted that the brain would map voltage amplitude to "roughness" because high voltages correspond to stronger and more irregular stimulation, in the same way that rough surfaces produce more vigorous mechanoreceptor response. Pressure was coded as pulse interval because mechanoreceptors generally elevate firing rate with rising force. Such a mapping is in accord with established neurophysiological constraints and is in accord with prior electrotactile studies showing that amplitude and frequency can be perceived as distinct sensory dimensions^{14,15}.

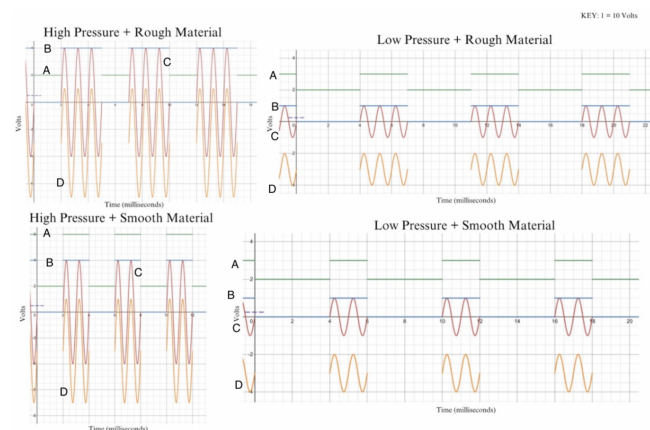
Texture was measured as surface roughness and the dynamic vibration signatures generated by sliding contact. On-prosthesis sensing employed a fingertip MEMS accelerometer (4 kHz sampling rate) to sense high-frequency vibration, a 200 Hz-sampled miniature capacitive tactile array to sense contact pressure distribution, and a 200 Hz-sampled fingertip force sensor to sense normal load. Acceleration signals were bandpass filtered (5 Hz-1 kHz), normalized for instantaneous normal force, and Fourier transformed to the frequency domain by short-time Fourier transforms to produce power spectral density features. A roughness index $R \in [0, 1]$ was determined from relative spectral power in high-frequency bands and from spatial variance of taxel readings. R was converted to stimulation amplitude via $A = A_{min} + R(A_{max} - A_{min})$, with amplitude being imposed at runtime in units of current (mA) after electrode impedance has been measured for safety constraints.

Participants or Sample

Due to limitations stated, we do not have participants for this study. The simulation models four distinct tactile conditions using artificial data corresponding to common material interactions. Examples include high-pressure interactions with

coarse materials like sandpaper and low-pressure interactions with smoother materials like plastic.

Data Collection



The graphs above demonstrate the various combinations of pressure and texture transformed into our electrical waves. Each color corresponds to a designated letter, and the combination is consistent throughout the four graphs. Line D depicts the texture wave (volts) and Line A depicts the pressure (time interval). Lines C and B show the combined feedback of texture and pressure. The texture (rough or smooth) determines the voltage of the electrical waves, ranging from 10-40 V. If the material is rougher, the voltage will increase; if the material is smoother, the voltage will decrease. The pressure determines the intervals, which vary from 500 ms - 2 s between each electrical wave. The higher the pressure, the shorter the intervals between the waves will be; the lower the pressure, the longer the intervals between the waves will be.

Variables and Measurements

The variables are the pressure and texture of the object, which converts into electrical signals. Information is sent to the user through electrical signals measured in V. The information (pressure and texture) is then converted to electrical signals. The sensor detects the pressure measured in Pa. Pascal measures the pressure and is determined by Newtons per square meter. In addition, a contact-based profilometer measures the roughness of the material.

Procedure

1. The variables of the study, texture and pressure, are decided.

2. Research was conducted regarding electrical patches, pulses, and data collection methods.
3. We reviewed the safety standards and procedures (IEEE Std 601-2018 and IEC 60601-2-10) and set the voltage to a harmless level (10-40 Volts)
4. A computer model was created for the electrical pulses.
5. We analyzed and compared the data using the visual guide.

Data Analysis

Data were analyzed using visual and numerical comparison of waveform outputs. Consistency and distinctiveness were the primary evaluation criteria. Each waveform was examined for repeatable patterns and clear differentiation from the other three conditions.

Ethical Considerations

We have already mapped out the wavelength of the electrical waves that will provide the user with the feedback of texture and pressure. For our planned testing phase, we are using massagers to simulate the function of electrical patches, or in other words, what the sensors are doing. These massagers will allow us to adjust intensity and pulse intervals safely, without delivering actual electrical stimulation. The variables controlling the massagers are based on input from pressure sensors, which measure force in Pa. However, there are currently no readily available products that can directly detect both texture (roughness/smoothness) and pressure, so we are seeking guidance from mentors and professional contacts to help program and integrate these sensors. In future trials, we will replace the massagers with electrical patches that deliver controlled electrical feedback to the user. These trials will require strict safety protocols including voltage limitations, informed consent, and IRB approval. Additional funding will allow us to access higher-quality prosthetics and resources to refine our design.

Resources and Limitations

We need to obtain a massager and profilometers to experiment with the approach of our prosthetics with electrical signals. The massagers will represent the electrical patches where we can adjust the intensity applied and the time interval between the pulses of massage. The information that will determine the two variables of the massager comes from the pressure sensors that collect information. However, there are no products that can specifically collect rough/smooth texture and pressure that are readily available on the market. Therefore, we need mentorship from our mentor and professional members to assist us

in programming the sensors. In addition, we will need a safe environment and participants to conduct an experiment for our product.

Experimental Timeline

0-2 Months: Prototyping

- Sensor integration (MEMS accelerometer + 8-taxel capacitive array).
- Microcontroller coding (signal acquisition + voltage/pulse interval mapping).
- Bench stimulator selection and calibration.

3–4 Months: Bench Testing

- Model 4 tactile conditions (high/low pressure × rough/smooth).
- Signal separability validation with oscilloscope recordings.
- Safety verification of voltage/current levels on bench models (resistor skin equivalents).

5–7 Months: Pilot Human Testing (after IRB approval)

- Pilot volunteer trials (3–5 people).
- Data collection of perception regarding distinguishability of four signal conditions.
- Tune encoding strategy if needed (voltage vs interval mapping).

8-9 Months: Refinements

- Refine hardware (miniaturizing electrode patch, stabilizing the signal).
- Refine software for smooth transitions between tactile states.

Estimate Budget

Equipment	Estimated Cost
Tactile Sensors (capacitive taxel arrays and MEMS accelerometer)	\$800
Microcontroller	\$400
Electrodes	\$600
Bench/research stimulator	\$4,500
Safety equipment	\$1,200
Profilometer rental	\$600
Participant compensation	\$1,000
Technician or professional support	\$2,000

Total cost: \$11,100

DISCUSSION

Summary of Main Outcomes

The study can prove that the dual-encoding model is a feasible model to replicate tactile perception of texture and weight via electrical stimulation. The model can create distinct and consistent waveforms for each of the four tactile conditions tested through voltage amplitude and pulse interval manipulation. The study hence supports the hypothesis that tactile complex input data is able to be parsed and synthesized into electrical signals that can be interpreted. The system demonstrated reliable and unique signals that can serve as a basis for a real time feedback mechanism for prostheses.

Implications & Importance

The prospect of generating tactile perception via electrical waveforms presents game-changing opportunities for the design of prosthetic limbs. For users of prosthetics, the ability to restore tactile sense could provide an enormous boost to dexterity and facilitate an intuitive experience, decreasing cognitive overhead. However, it has wider application beyond prosthetics, including robotics, where tactile perception could enhance object handling; virtual reality, where haptics is gaining increasing demand; and physiotherapy and rehabilitation, where feedback-intensive treatment may have clinical applications. The noninvasive nature of this system would also increase its safety and clinical utility.

Relationships to Goals

In addition, the paper presents a novel dual-encoding mechanism and their proof-of-concept validation protocol to discriminate sensations of pressure and texture using variations in voltage amplitude and pulse interval. Findings of the study are consistent with the primary hypothesis, revealing that dual-parameter electrical encoding can successfully be used to transmit rich tactile signals in prosthetic devices.

Suggestions

Advancement of the research needs to be directed toward migrating from simulation to physical prototyping. Hardware should be a wearable device with integrated tactile sensors and a real-time waveform generator to provide human testing and feedback. Incorporating other modalities into the model, including vibration, temperature, and proprioceptive feedback, increases the realism. Longitudinal studies on user adaptation, cognition, and comfort over time should be conducted for real-life implementation, alongside joint efforts of medical practitioners and bio-engineers for ensuring correspondence of technical viability and medical implications.

Impediments

The main drawback with respect to this study is that it is based on simulation. In particular, biological variation; nerve response variation, skin impedance variation, psychological perception variation and user interface had not been modeled. The voltage-to-texture assumption, interval-to-pressure assumption are based on linear mapping, and may not be present in natural settings. No user interface was tested, and subjective response data could not be obtained. All these will have to be considered in further iterative design, empirical investigations and human subject validations.

Final Remarks

Highlighting a realistic step forward, the study showcases an encoded multi-sensory feedback system being reliably employed to provide a functional means of passing textured information through electrical signals. Enabling safe scaling possibilities toward prosthetic devices, the transient application of this simulation technology may soon be observed moving from a virtual to a physical setting, where adapted means of delivery could not simply signal lost sensation, but potentially replace this experience with intuitive, emotional responses.

Glossary

- Brachial Prosthetic: an artificial device that acts in place of the arm, integrating sensors and receptors.
- TENS (Transcutaneous Electrical Nerve Stimulation): non-invasive method for delivering electrical pulses to stimulate nerves
- Pulse train: sequence of repeated electrical pulses to encode information
- Inter-pulse interval (IPI): the time between two electrical pulses, measured in ms or s Amplitude: strengths of an electrical signal, measured in V
- Simulation study: a research method using computer generated or artificial-data rather than volunteers or participants
- Feasibility study: an early-stage study evaluating a proposed system

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