Minimizing Sensory Habituation in Nerve Stimulation Through Strategic Temporal Stimulation Patterns

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***Abstract*—Transcutaneous nerve stimulation (TNS) has the potential to restore sensory feedback in upper-limb prosthetic users. However, its effectiveness is limited by habituation, which is a reduction in the perceived stimulation intensity with prolonged use. This study investigated TNS parameter optimization to maintain consistent sensation, focusing on median and ulnar nerve stimulation through a high-density 2 $\times$ 5 electrode grid positioned on the upper arm. Through a systematic evaluation of six experimental conditions varying in block duration, rest intervals, and stimulation patterns, we identified optimal stimulation parameters that significantly reduced habituation while maintaining robust sensory feedback. The most effective protocol demonstrated 37.87% higher sensitivity than the standard protocol while maintaining a low decay rate (0.09 $\pm$ 0.02). During the main protocol, force output stabilized after the initial adaptation and remained significantly above baseline ($p < 0.0001$). Notably, we observed nerve-specific responses to stimulation parameters, with the median nerve showing significantly heightened sensitivity to parameter variations compared with the ulnar nerve ($p = 0.0267$). These findings offer a promising approach for maintaining stable sensory feedback in neuroprosthetic applications, with the potential to improve user experience and device adoption. The identified stimulation condition, which features 1-minute blocks and strategic rest intervals, lays the groundwork for more effective TNS-based sensory feedback systems in clinical applications.**

***Index Terms*—Sensory habituation, peripheral nerve, sensory adaptation, sensory feedback, transcutaneous nerve stimulation (TNS).**

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I. Introduction

TRANSCUTANEOUS nerve stimulation (TNS) is a promising noninvasive technique for restoring sensory feedback in upper limb prosthetics and managing neurological conditions. Sensory information plays a critical role in the motor control of biological limbs and bionic limbs [1]. When the intrinsic sensory pathway is blocked, artificial somatosensory feedback can be delivered externally by sensory nerve stimulation through both invasive and noninvasive approaches [2], [3], [4], [5]. Although invasive stimulation methods have shown considerable promise in research settings, they require surgical electrode implantation, limiting their widespread clinical adoption. Additionally, invasive approaches can lead to a quick onset of fatigue based on implantation location [6]. Noninvasive nerve stimulation offers an accessible alternative, eliciting haptic sensations in the hand using surface electrodes placed on the skin near the median and ulnar nerves that could restore tactile sensation in the hand [3], [7], [8]. Beyond evoking basic tactile sensations, advancements in TNS have demonstrated the ability to convey richer sensory information. Studies have successfully employed TNS to enable the recognition of object properties, such as shape and texture [39], [40], provide feedback on grasp force and slippage [8], [41], and convey pain-like sensations [42].

TNS evokes various sensory percepts, including vibration, pulsing, and paresthesia-like tingling sensations, in different hand regions [7]. However, the clinical effectiveness of TNS is limited by habituation, a decrease in perceived stimulation intensity over sustained stimulation, even when stimulation parameters remain constant [9], [10]. Habituation reflects fundamental properties of the central and peripheral sensory nervous system. The sensory nervous system automatically adjusts its sensitivity to reduce responsiveness to ongoing stimulation, while maintaining sensitivity to changes in stimulation patterns [11]. This adaptation occurs through peripheral and central mechanisms, leading to increased detection thresholds and reduced perceived intensity of suprathreshold stimuli [12], [13]. This phenomenon is particularly evident in vibrotactile stimulation, where prolonged exposure leads to progressive perceptual and neuronal desensitization [13], [14]. This challenge is particularly significant for prosthetic applications, where consistent sensory feedback is crucial during prolonged use of prostheses.

Current commercial prosthetic devices lack natural sensory feedback during object interactions and neural control of the prosthetic movements [4], [15]. Sensory feedback is essential for dexterous motor control and plays a critical role in prosthetic embodiment and user acceptance of prosthetic devices. Its absence contributes to impaired motor adaptation, poor device usability, and elevated cognitive load, thereby reducing long-term engagement with neuroprosthetic devices [28], [29]. Restoring artificial sensory feedback improves functional outcomes and fosters ownership of the prosthesis, highlighting the importance of restoring somatosensation in amputees. This sensory deficit contributes to high abandonment rates of 40–60% among prosthetic users [16], [17]. To control the prosthetic devices dexterously and adaptively, sophisticated prosthetic limbs need sensory feedback rather than relying only on pre-programmed gestures [15]. Without reliable sensory connections, prostheses remain tools, rather than true limb replacements.

Research on various neuromodulation techniques has highlighted the importance of stimulation parameters. Studies of transcranial magnetic stimulation (TMS) and transcranial direct current stimulation (tDCS) have demonstrated that variations in pulse frequency, duration, and intensity significantly influence therapeutic outcomes [18]. Specifically, in TNS, higher pulse frequencies (e.g., 100 Hz) may reduce habituation compared with lower frequencies (e.g., 4 Hz) [19]. The duration and magnitude of the applied current also play crucial roles in maintaining the long-lasting effects [18]. Additionally, biphasic stimulation through electrode arrays may help maintain a more consistent sensation by creating highly specific electrode fields that can target different nerve fibers [10].

Accordingly, the purpose of the current study was to evaluate the degree of sensory habituation response to sustained nerve stimulation with various temporal patterns. We established that a certain combination of stimulation parameters (2-minute stimulation blocks with 1-minute rest intervals, using 2-second stimulation pulse trains with 1-second rest) would enable sustained perception of TNS-induced sensations over a one-hour period. We hypothesized that systematically reducing these temporal parameters would reveal a threshold below which habituation would occur more rapidly. Specifically, we predicted that (1) shortening the stimulation durations while maintaining rest intervals will preserve the strength of sensation, (2) reducing rest intervals will accelerate habituation, and (3) continuous stimulation without rest periods will lead to complete habituation, characterized by an exponential decay in perceived sensation intensity. Building on the established principles of electrical nerve stimulation, we assessed the strength of sensory responses to various parameter combinations while considering the critical balance between stimulation effectiveness and tissue safety. This systematic approach allowed us to identify the minimal conditions necessary for maintaining stable sensory feedback, which is critical for practical applications in prosthetics and rehabilitation.

II. Methods

A. Participants

A total of ten neurologically intact adults (age range 20 to 40 years old, 2 females) participated in the transcutaneous nerve stimulation study. All participants provided informed consent. The protocol was approved by the Institutional Review Board of the Pennsylvania State University (Approval Number:STUDY00022392).

B. Apparatus

The participant's arm was prepared using a three-step process to ensure optimal electrode-skin contact. First, the medial surface of the left upper arm was cleaned with a 70% isopropyl alcohol wipe and allowed to dry before gently abrading the skin with an abrader pad with pumice to remove the thin layer of dead skin cells. Finally, we re-cleaned the area with another alcohol wipe and allowed it to dry, ensuring a clean and dry surface before applying electrodes.

A 2×5 grid of 10 round electrodes (10 mm diameter) was positioned along the medial portion of the upper arm beneath the short head of the biceps brachii, targeting the median and ulnar nerves. The electrodes were arranged in a configuration parallel to the underlying nerve pathways and spaced approximately 1.5 cm apart (Fig. 1(a)). Foam padding and a custom plastic vice were used to apply inward pressure to the electrode grid to ensure consistent contact with the skin. Each electrode was connected to a switch matrix (Agilent Technologies, Santa Clara, CA) for flexible routing of electrical signals between any electrode pairs.

An 2-channel programmable stimulator (STG4002, Multichannel Systems) was used to generate and control the stimulation patterns. A constant pulse frequency of 150 Hz and pulse width of 200 μs per phase were used throughout the experiment, and these parameters were selected based on earlier studies demonstrating their effectiveness in evoking stable, localized haptic sensations via TNS [8], [20]. These parameters remained constant to allow a systematic investigation of how temporal structures (i.e., block duration and inter-train rest intervals) influenced sensory habituation without confounding variability from other stimulation parameters.

The stimulation pulses were charge balanced square waves. By sequentially activating different electrode pairs, we first identified viable combinations that could selectively recruit distinct populations of nerve fibers innervating the palmar side of the left hand for experimental investigation. We used a custom MATLAB interface to facilitate electrode pair selection and adjustment of the stimulation parameters.

In the main experiment, we identified two sets of electrode pairs that elicited sensations on the palmar side of the hand in relatively similar locations (e.g., for both pairs, participants reported a tingling sensation in the ring and pinky fingers). One pair was selected for the experiment, with the second pair available as a backup in case the sensation ceased during the experiment. Of note, the primary pair was used for all participants with no need to switch to the backup pair for any participants.

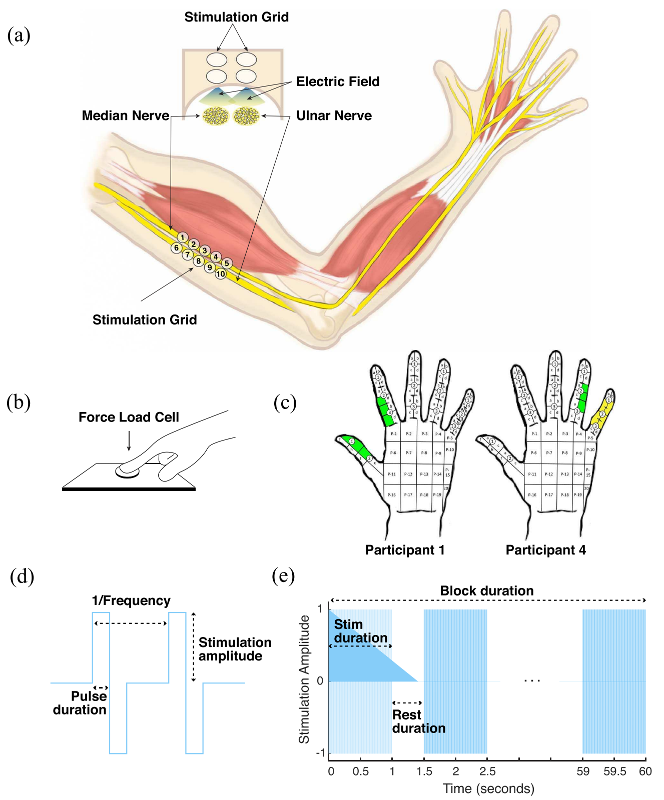

Fig. 1. Experimental Setup. (a) Schematic illustrating the placement of the electrode grid on the left upper arm, highlighting the stimulation of both the median and ulnar nerves. (b) Diagram of the index finger of the right hand pressing onto a load cell, which was used to measure the participant's perceived strength of stimulation. (c) Hand maps for two representative participants (Participants 1 and 4), showing the regions of perceived sensation on the palmar surface in response to nerve stimulation. The colors indicate sensation intensity, with green representing low intensity and yellow indicating moderate intensity. (d) Biphasic stimulation pulse parameters showing the relations between pulse duration, stimulation amplitude, and frequency. (e) Representative stimulation train showing the temporal pattern of stimulation and rest periods within each stimulation block.

The experiment began by applying a starting stimulation amplitude of 1.5 mA, which was then increased at 0.2-0.3 mA intervals. This was performed until either a haptic sensation was reported in the participant's right hand or discomfort was felt at the surface of the skin electrode. If no haptic sensation was reported, a new pair of electrodes was chosen and the process was repeated. Once a haptic sensation was reported for a given electrode pair, the stimulation amplitude was further increased at 0.1 mA intervals. This continued until either discomfort was reported or motor activation (muscle movement) was observed in the participant's hand or wrist. The fine 0.1 mA step size was used to accurately determine the sensation threshold of each participant.

The sensation threshold was defined as the minimum stimulation amplitude that elicited a clearly perceptible haptic sensation in the target hand region (e.g., tingling or pulsing) without inducing discomfort or visible motor activation [8]. The participants indicated when they first perceived a distinct, reproducible hand-based sensation (rather than at the arm or electrode site). The

TABLE I
ELECTRODE PAIRS AND SENSATION THRESHOLDS FOR EACH PARTICIPANT

Participant #	Electrode Pair (C-A)	Evoked Sensation Region	Sensory Threshold (mA)
1	3-5	I & M	4.2
2	1-4	I & T	3.4
3	3-10	R & P	3.0
4	6-8	R & P	3.5
5	1-8	R & P	4.3
6	2-8	R	2.7
7	4-8	I & M	3.3
8	2-8	R	3.2
9	6-10	I, M & R	5.0
10	1-3	I & T	1.5

For each electrode pair, C = Cathode, and A = Anode.
For evoked sensation, I = Index, M = Middle, R = Ring, T = Thumb.

final amplitude was selected to be suprathreshold for sensation but just subthreshold for motor activation, remaining constant throughout the experiment. This approach is consistent with previous studies [8].

Once this threshold was established, that amplitude was used as a constant throughout the remainder of the experiment, maintaining the stimulation below the motor activation threshold. The stimulation threshold values for each participant are depicted in Table I.

The participant's right hand was used to interact with a force load cell (LCM201-100 N; Newark Electronics, Chicago, IL, USA). Participants were instructed to use the same finger that perceived the sensation (or their dominant finger if multiple fingers were involved) to apply pressure to the load cell in response to the perceived haptic sensations. This approach allowed for a direct correlation between the stimulation and a participant's tactile perception. Force data from the load cell were recorded using a separate interface throughout the experiments, enabling the real-time monitoring of the participant's tactile feedback, as expressed through finger pressure.

C. Paradigm

The experiment consisted of six distinct conditions, with each condition defined by variations in the four primary factors: Block Duration, Block Rest, Stimulation Duration, and Stimulation Rest (Table II). Block duration refers to the time during which a series of stimulation trains was delivered (ranging from 1 to 2 min in non-continuous conditions). Block rest represents the interval between consecutive blocks during which no stimulation was applied (0–1 min). Within each block, the stimulation duration defines the length of each stimulation train (1–2 s), whereas the stimulation rest indicates the time interval between consecutive stimulation trains within the same block (0.5 to 1 s). These parameters systematically varied across experimental conditions to investigate their effects on sensory habituation.

The parameters for the main stimulation protocol were determined by pilot testing aimed at identifying temporal patterns that

TABLE II
EXPERIMENTAL CONDITIONS FOR TNS PARADIGM

Condition	Block #	Block Duration (min)	Block Rest (min)	Stimulation Duration (sec)	Stimulation Rest (sec)
1	1 - 20	2	1.0	2	1.0
2	21 - 23	1	1.0	1	1.0
3	24-26	1	1.0	1	0.5
4	27 - 29	1	0.5	1	0.5
5	30	continuous	0.0	1	0.5
6	31	continuous	0.0	continuous	0.0

reduced habituation over prolonged stimulation. While the 60-minute target reflects the protocol design goal to sustain sensation without complete habituation, not all pilot variations underwent continuous hour-long tests. Instead, shorter sessions helped select a protocol with a sufficiently low decay rate, indicative of prolonged perceptual persistence. For all experimental conditions, the stimulation amplitudes were individually calibrated prior to data collection to produce a clear, comfortable, and comparable baseline sensation intensity across participants and conditions. Although no formal psychophysical discrimination tasks were employed to equate the baseline sensory thresholds, this approach helped ensure fair comparisons between conditions. Future studies could incorporate objective psychophysical measures to validate and refine stimulation parameter selection. The number of trials varied across conditions and was not held constant, as each condition was designed with different blocks and rest durations rather than matched total session lengths. Only Condition 1 was tested over a full 60-minute session to evaluate longer-term habituation, whereas Conditions 2–6 were intentionally shorter to examine how specific reductions in temporal parameters impacted perceptual stability.

Condition 1, which served as the main block, comprised 20 trials. The parameters for this condition were chosen through piloting to enable one hour of stimulation without complete habituation. Conditions 2-4 each contained three trials and were designed to compare the evolution of tactile perception intensity when stimulation parameters were adjusted to reduce the duration and rest periods. Conditions 5 and 6 were single-trial conditions that were specifically designed to induce habituation, in which the sensation disappeared at the end of the stimulation. The structured variation in stimulation patterns was intended to modulate sensation strength and to investigate the potential onset of habituation under different temporal configurations of sensory input.

Condition 1, encompassing trials 1-20, had the longest block duration of 2 min, with a 1-minute rest between blocks. Each stimulation train in this condition lasted for 2 s, followed by a 1-second rest between the stimulation trains. Conditions 2 and 3 (trials 21-26) reduced the block duration to 1 min while maintaining the same block rest; however, Condition 3 decreased the stimulation rest to 0.5 seconds. Condition 4 (trials 27-29) further reduced the block rest to 0.5 minutes. The final two conditions introduced continuous stimulation: Condition 5 (trial 30) maintained discrete 1-second stimulation trains with 0.5-second rests but without rest between blocks, whereas Condition 6 (trial 31) implemented continuous stimulation without any rest periods. In conditions 5 and 6, the participants were instructed to verbally indicate when they no longer perceived sensation. This time was manually recorded and subsequently used for the data analysis. This progressive design transitioned from longer, more spaced-out stimulations to more intense, continuous stimulation patterns and aimed to systematically explore the effect of varying these parameters on the perception of stimulation strength. Between each stimulation condition, 5 min of rest was provided to ensure that the sensation had recovered.

Early, middle, and late epochs were defined based on the ordinal position of the stimulation trains within each block (e.g., first 4, middle 4, and last 4), rather than by absolute time. This approach enabled consistent within-condition comparisons, although it did not equate to identical time windows across conditions with different durations.

D. Data Analysis

Force data from the load cell were recorded at 1000 Hz and imported into a custom MATLAB script for processing. For comparison across subjects, force values for all participants were normalized by the maximum recorded force from each subject, expressing values as a percentage of the maximum (resulting in all values between 0 and 1).

The force response to each stimulation train exhibited a sudden-change profile, with distinct changes in force observed in response to intermittent stimulation patterns within conditions containing rest periods between stimuli. To quantify the force response for each stimulation train, we identified the peak force and calculated the average of ten data points before and after the peak. This process generated a single representative value for the force response of each stimulation train. For example, in Condition 1, which lasted 120 s with a combined stimulation duration and rest period of 3 s, this method yielded 40 data points per block for analysis (corresponding to 40 stimulation trains within the block).

For Condition 6, which involved continuous stimulation without rest periods, we employed a different approach to define the start and end points of the force response. The first data point was identified as the moment when the force data surpassed a nonzero threshold, indicating the onset of a detectable tactile response. The last data point was determined as the moment when the force returned to zero, signifying cessation of the response. This method allowed us to capture the full duration of the force response during continuous stimulation from its initiation to its complete decay, which was not possible using the peak-based method employed in the other conditions.

All force data in each condition for each participant were averaged to generate a single force profile for each condition per participant. These force profiles were then analyzed by fitting a linear fit using MATLAB's `polyfit` function (first-degree polynomial), and the corresponding coefficients were computed. Additionally, an exponential decay was fitted to the data, defined as:

$$\mathrm{expDecay}(b, x) = b_1 \cdot e^{-b_2 \cdot x} + b_3$$

where b_1, b_2, and b_3 are the parameters of the model. Fitting was performed using the MATLAB function `lsqcurvefit` with initial parameter estimates based on the maximum and minimum force values in the data. To assess the fit quality, the residual sum of squares (RSS) was calculated for both linear and exponential models. The model with the lower RSS was considered to be a better fit for each participant's force profile. The comparison between the linear and exponential fits allowed for the selection of the model that better captured the decay patterns in the force data, reflecting how participants' tactile perceptions changed over time in response to the stimulation.

E. Statistical Analysis

Statistical analyses were conducted using custom MATLAB scripts to quantify changes in force (i.e., perceived stimulation strength). Repeated-measures analysis of variance (ANOVA) was used to evaluate overall differences across conditions. Post-hoc paired *t*-tests with Bonferroni corrections were applied for pairwise comparisons between specific conditions. Additionally, a two-way repeated measures ANOVA was performed to examine the interactions between the condition and nerve type. For all statistical tests, a *p*-value of 0.05 was used as the threshold for significance. Results are presented as mean $\pm$ standard error of the mean (SEM).

III. Results

To assess the optimization of transcutaneous nerve stimulation parameters to reduce habituation, we explored the effects of stimulation duration and rest periods on perceived stimulation strength, measured as the force output on a load cell. Our analysis focused on understanding how different stimulation patterns affect the rate of change in the perceived stimulation strength. We examined factors such as block duration, rest interval between blocks, duration of stimulation train within each block, and rest interval between individual stimulation trains.

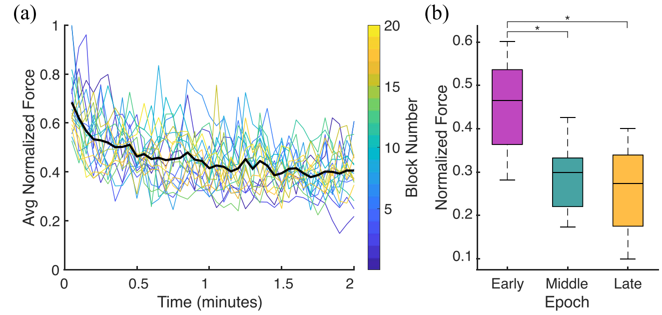

Fig. 2. Changes in perceived stimulation strength over time for Condition 1. (a) Normalized force output over time for a representative participant across 20 stimulation blocks. Colored lines represent individual blocks, with the color scale indicating block number (1-20). The black line shows the smoothed average across all blocks. (b) Box plots summarizing normalized force across all participants (n = 10) and all 20 blocks of the main condition, grouped into three epochs: Early, Middle, and Late stages of the block. The boxes show the interquartile range, with the median represented by the horizontal line. Whiskers extend to the minimum and maximum values, excluding outliers.

Fig. 2 depicts the evolution of perceived sensation strength in response to the TNS during Condition 1, which featured the longest block duration (2 min) with a 1-minute rest between blocks. Each stimulation pulse lasted for 2 s, followed by a 1-second rest.

Fig. 2(a) shows data from a representative participant, clearly demonstrating the observed trend. The lines are color-coded to represent the progression of block numbers (1–20), with the black line showing the smoothed average. A general trend was evident: the force initially decreased sharply within the first few time points, gradually stabilizing as the blocks progressed. The results suggested an initial drop in the perceived sensation but did not decrease to zero, indicating that some sensation could still be perceived, even after prolonged stimulation.

Fig. 2(b) summarizes the data from all ten participants, showing box plots of the average normalized force across three epochs: the early, middle, and late stimulation stages. The early epoch reflected the average of the first four stimulation trains, the middle epoch was the average of the middle four, and the late epoch was the average of the last four. The force dropped significantly from the early to middle epochs but stabilized in the late epoch, remaining well above a zero force value. This stabilization suggested that, across participants, the perceived sensation strength did not fully diminish by the end of the 2-min stimulation block, implying some level of sustained sensation throughout the blocks.

Analysis of force production across trials revealed a significant effect of time on the normalized force (repeated-measures ANOVA: $F(2, 18) = 37.497$, $p = 3.814\text{e-}07$), indicating substantial changes in force output as participants progressed through the task. To further investigate these changes, we compared

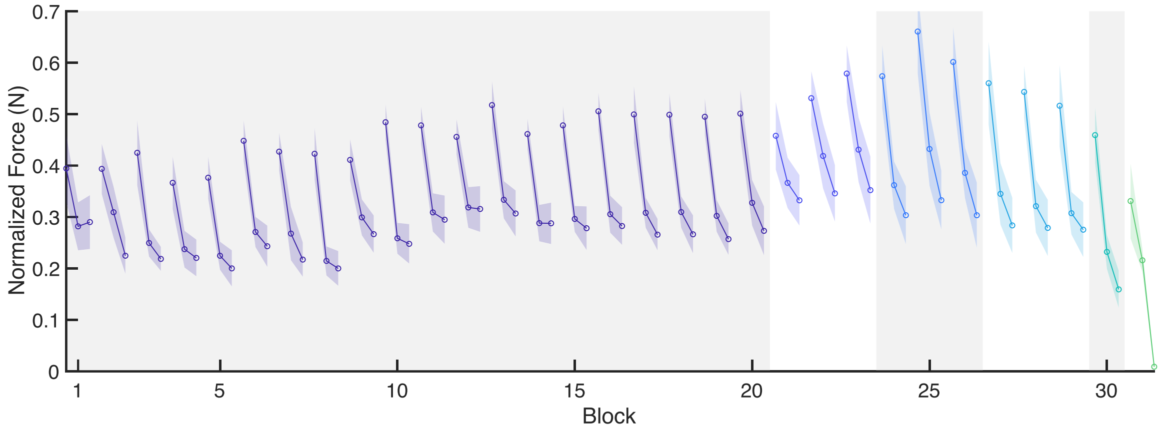

Fig. 3. Changes in normalized force across blocks. The plot shows the averaged normalized force across participants for each block, with the data separated into three distinct epochs: early, middle, and late. Shaded regions represent the standard error of the mean.

force production across three epochs: Early, Middle, and Late. Post-hoc paired t-tests revealed a significant decrease from Early to Middle epochs ($t(9) = 6.7875$, $p = 0.0001$) and from Early to Late epochs ($t(9) = 6.0905$, $p = 0.0002$), whereas no significant difference was found between the Middle and Late epochs ($t(9) = 2.2926$, $p = 0.0476$; not significant after Bonferroni correction). These results suggest that the most substantial reduction in force occurred between the Early and Middle epochs, with the force output stabilizing in the latter part of the stimulation block.

To assess whether participants maintained force production above zero, we conducted a one-sample t-test to compare the late epoch to zero. The results showed that the force production in the late epoch (mean $= 0.2579$) was significantly above zero ($t(9) = 8.3754$, $p = 1.5318\text{e-}05$). These results indicated that despite the observed decrease, participants maintained significant force production above zero levels throughout the task.

Normalized force measurements exhibited distinct patterns of reduction across the trial blocks when averaged across the participants (Fig. 3). In blocks 1–20, we observed a rapid decline in the normalized force, which was particularly pronounced from the early to middle phases within each block. In contrast, blocks 21–29 exhibited a more gradual and consistent reduction in force over time with smoother transitions between the three epochs of each block. Notably, in block 30, the force drop was sharper, whereas block 31 demonstrated complete decay, with forces approaching zero. This progression, from an initial sharp decline to a gradual reduction, and ultimately to complete force decay, represented a dynamic relation between the block structure and the participant's force output in response to stimulation.

We then performed parameter sensitivity analysis to quantify the response to varying stimulation conditions (Fig. 4(a)). We calculated the percentage change in the mean force relative to the main condition (Condition 1) for each participant. The results revealed a distinct pattern: Conditions 2, 3, and 4 demonstrated higher force values (i.e., perceived sensation strength), with condition 3 exhibiting the highest force value ($37.87\% \pm 18.51\%$, mean $\pm$ SEM). In contrast, Conditions 5 and 6 showed

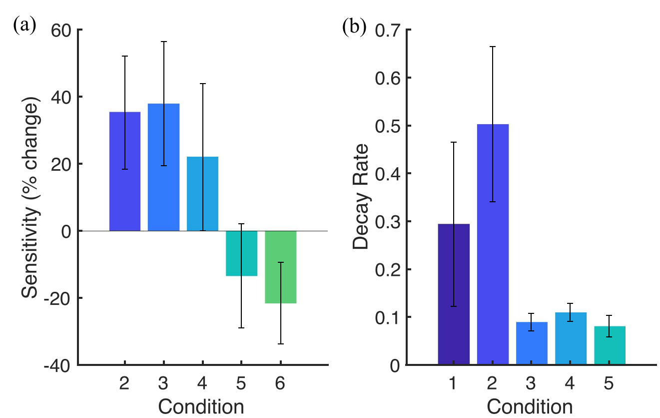

Fig. 4. Parameter sensitivity and decay rate analysis across stimulation conditions. (a) Sensitivity analysis showing the percentage change in the mean force relative to Condition 1. Positive values reflect increased force production, whereas negative values indicate a reduction in the force. (b) Exponential decay rates for conditions 1–5 (condition 6 was the best fit for a linear model). Higher decay rates indicate a more rapid decline in force over time. Error bars represent the standard error of the mean.

lower force values, with Condition 6 yielding the lowest force ($-21.55\% \pm 12.18\%$).

To characterize the temporal dynamics, we performed linear and exponential decay regressions using the RSS to determine the optimal fit. Fig. 4(b) shows that the exponential decay rate had marked differences between conditions, with Conditions 1 and 2 exhibiting significantly higher decay rates (0.29 ± 0.17 and 0.50 ± 0.16, respectively) compared to Conditions 3, 4, and 5 (0.09 ± 0.02, 0.11 ± 0.02, and 0.08 ± 0.02, respectively).

Notably, Condition 3 demonstrated two advantageous characteristics: 1) stronger forces relative to the main blocks (Condition 1), indicating enhanced sensation strength, and 2) a lower decay rate, suggesting sustained sensation intensity over time. This combination of heightened sensitivity and temporal stability makes Condition 3 particularly promising for potential clinical applications.

We also compared the sensation strengths of the ulnar and median nerves across the six stimulation conditions

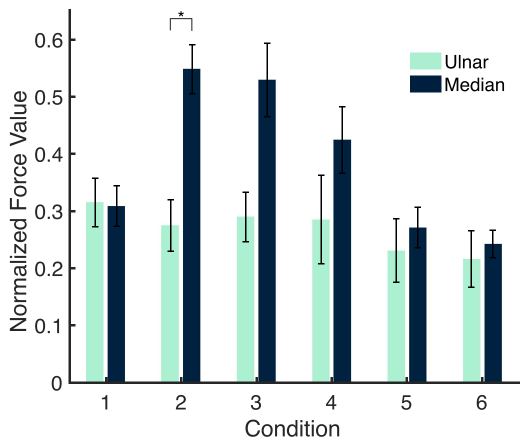

Fig. 5. Comparison of ulnar and median nerve stimulation across stimulation conditions. Normalized force values (mean $\pm$ SEM) for the ulnar (light green) and median (dark blue) nerves across six experimental conditions. * indicates significance.

(Fig. 5). Among the 10 participants, five received ulnar nerve stimulation, and the other five received median nerve stimulation. This analysis revealed distinct differences between the two nerves. Notably, the ulnar nerve showed relative stability under all conditions, maintaining normalized force values between 0.2 and 0.3. In contrast, the median nerve exhibited greater sensitivity to the experimental manipulations, with normalized force values ranging from 0.25 to nearly 0.55, showing pronounced peaks in conditions 2 and 3. This differential response pattern suggested that the median nerve was more susceptible to modulation by varying the stimulation parameters. In contrast, the ulnar nerve maintained a more consistent force production regardless of the condition. A two-way ANOVA revealed a significant interaction between the condition and the nerve ($F(5,48) = 2.80$, $p = 0.0267$). The interaction effect suggested that the influence of the stimulation conditions on the normalized force varied depending on the nerve being stimulated, potentially indicating differential nerve responses to the stimulation conditions used in this study. Post-hoc t-tests were conducted to compare the differences between the ulnar and median nerves across the stimulation conditions, with a Bonferroni correction applied to account for multiple comparisons. The results indicated a significant difference in Condition 2 ($p = 0.002$). These findings highlighted both nerve-specific differences and the sensitivity of the experimental conditions in modulating the force output.

IV. Discussion

Our study aimed to evaluate the degree of sensory habituation in response to sustained nerve stimulation using various temporal parameters. Our results highlight that several temporal patterns in TNS can lead to sustained sensation intensity, thereby minimizing sensory habituation, a key outcome of sensory feedback systems in upper-limb prosthetics. This supports our initial hypothesis regarding the relationship between stimulation parameters and sensory adaptation. Our overall study outcomes provide critical insights into optimizing the TNS parameters to maintain consistent sensory feedback, with important implications for sensory prosthetic applications.

A. Parameter Optimization and Habituation Dynamics

The most notable finding was the identification of an optimal protocol (Condition 3) that demonstrated both enhanced sensitivity (37.87% higher than baseline) and reduced habituation (decay rate of 0.09 ± 0.02). This condition, characterized by shorter stimulation blocks with brief rest intervals, showed a significantly lower habituation rate than the longer blocks used in Condition 1, validating the role of rest intervals in sustaining sensory feedback. These findings suggest that shorter stimulation blocks interspersed with brief rest periods can help to sustain sensory perception by allowing periodic recovery from sensory adaptation. These observations align with recent findings on temporally structured stimulation strategies that enhance naturalness and mitigate perceptual fading. For example, temporally asynchronous paradigms reduce adaptation effects and improve perceptual stability [30], whereas stimulation schemes based on just-noticeable-difference models modulate temporal patterns to minimize habituation [31]. Our approach contributes to this growing body of work by offering a protocol that balances stimulation and rest to preserve sensory responsiveness over an extended period.

Beyond temporal structured stimulation, other optimization strategies have also emerged to reduce habituation, including dynamic encoding models, interleaved stimulation schemes, multichannel modulation, and automatic calibration techniques [32], [33], [34], [35]. These methods emphasize tailoring stimulation protocols to match perceptual dynamics, which is consistent with our findings that temporal structuring substantially affects perceptual persistence. While this study focused on temporal parameters using a single electrode pair, alternative approaches, such as frequency modulation or switching between multiple stimulation sites that could evoke the same perception, may also mitigate perceptual fading [33], [34], [35]. These complementary approaches represent promising avenues for future research on complex neuroprosthetic systems.

Such stimulation conditions align with the neural adaptation principles in TNS, indicating the potential for integration in commercial prosthetic devices, where maintaining sensation is essential for user experience and dexterity [21]. The success of this protocol aligns with previous research on vibrotactile stimulation, in which prolonged exposure has been shown to lead to progressive perceptual and neuronal desensitization [13], [14] and well-spaced stimulation periods can help preserve neural responsiveness [22]. Habituation is a fundamental sensory system property that enables efficient encoding by diminishing responses to persistent, non-salient stimuli while preserving sensitivity to novel input [11], [12]. Natural tactile adaptation occurs over seconds to minutes, depending on the receptor type and stimulus features [13], [14]. Rapidly adapting afferents show significant attenuation within seconds of continuous stimulation [13], whereas vibrotactile percepts decay over similar timescales [14]. Our findings align with these trends, particularly under continuous stimulation (Condition 6), which resulted in a rapid perceptual fading. In contrast, our temporally structured stimulation protocols preserved sensation across longer durations, suggesting that incorporating rest intervals can better match natural neural recovery dynamics and extend the usable range of sensory feedback in noninvasive systems.

Our analysis of the main protocol (condition 1) revealed a characteristic pattern of sensory adaptation that was stabilized rather than completely habituated. While significant declines were observed early, the perceived sensation stabilized at levels significantly above zero, demonstrating that parameter selection can maintain sensory perception over time. This finding is particularly relevant for prosthetic applications where consistent feedback is crucial for natural interactions with objects [4], [15], [23].

B. Nerve-Specific Responses and Clinical Implications

The differential responses between median and ulnar nerve stimulation represent a novel finding with important clinical implications. The heightened sensitivity of the median nerve to parameter variations suggests that stimulation protocols may need to be nerve specific for optimal outcomes. These differences likely reflect the underlying anatomical and physiological factors, potentially involving nerve depth, anatomical structure, or varying distances from the skin surface, that influence how stimulation is processed. This aligns with previous work on nerve-specific adaptation [24] and suggests the potential for custom TNS stimulation conditions for different neural targets. Such customization could maximize the effectiveness of applications such as prosthetics, rehabilitation, and sensory substitution systems [7], [8].

Our findings challenge the prevailing assumption that prolonged nerve stimulation inevitably leads to significant habituation [9], [10]. By analyzing habituation using exponential decay, we demonstrated that the temporal parameters of stimulation significantly influenced the rate of habituation. Specifically, shorter stimulation durations (Conditions 3–5) resulted in considerably slower decay rates compared to longer (Condition 1) and continuous (Condition 6) stimulation, indicating a delayed onset of complete habituation. This evidence suggests that manipulating the temporal features of TNS can mitigate habituation and maintain a more consistent sensation intensity, thereby offering valuable insights for optimizing stimulation protocols.

The complete habituation observed under Condition 6 (continuous stimulation) reinforces the critical importance of rest intervals in maintaining sensation intensity. This underscores the potential limitation of continuous protocols in clinical settings and highlights the need for interval-based designs for extended prosthetic use [11], [12]. This finding is particularly significant because experienced prosthesis users frequently depend on various feedback sources to effectively navigate daily activities [16], [17].

C. Positioning Within the Neuroprosthetic Landscape

While this study focused on optimizing the stimulation parameters for sustained sensory feedback, it is important to contextualize our findings within the broader neuroprosthetic landscape. Invasive peripheral nerve interfaces offer exceptional selectivity and spatial resolution by directly targeting individual nerve fascicles, thereby enabling naturalistic sensory perception and precise prosthetic control [3], [4], [6]. These systems support bidirectional communication for closed-loop control, enhancing dexterity, embodiment, and functional independence [3], [6], [43]. However, their clinical adoption remains limited because of surgical invasiveness, fibrotic tissue responses, infection risk, and long-term signal degradation [4], [6], [34]. These risks underscore the clinical need for noninvasive alternatives, such as the temporally optimized stimulation approach demonstrated in this study. Our work contributes by systematically evaluating temporal stimulation patterns and identifying strategies that preserve perceptual stability, thereby enhancing the long-term viability of noninvasive sensory feedback systems and complementing ongoing advances in both invasive and noninvasive neuroprosthetic technologies. Although our evaluations were performed in a noninvasive setting, the findings could possibly be extended to invasive systems, and further evaluation is needed to confirm this.

D. Clinical Applications and Future Directions

These findings have significant implications for the development of sensory feedback systems in upper-limb prosthetics. The high abandonment rates of prosthetic devices (40-60%) might be partially addressed by implementing optimized stimulation protocols that provide more consistent and natural sensory feedback [16], [17]. By demonstrating that sensory habituation can be mitigated through the TNS temporal parameters, our study paves the way for TNS applications to improve prosthesis utiility and user satisfaction. The optimization of TNS parameters could also potentially enhance robotic rehabilitation approaches by providing more consistent and effective sensory feedback during therapeutic interventions [25]. These devices can provide real-time feedback on performance, allowing for targeted and intensive training to promote neuroplasticity. Exoskeletons and end-effector devices are the two main categories of robotic systems used in neural rehabilitation for patients with brain lesions or spinal cord injuries, each offering unique advantages to patients with varying levels of impairment [25]. The optimization of the TNS temporal parameters identified in our study could potentially enhance these robotic rehabilitation approaches by providing more consistent and effective sensory feedback during therapeutic interventions.

Future studies should investigate the practicality of implementing such optimized parameters in robotic systems to promote neuroplasticity and long-term sensory assistance. Adjustment of parameters through real-time feedback is essential for advancing this technology. Additionally, examining the interaction between stimulation parameters and different modalities of sensory feedback could lead to more sophisticated multi-modal feedback systems. The development of integrated feedback systems that combine joint kinematics, joint kinetics, and tactile pressure has great potential for enhancing the experience of prosthetic users.

Our findings demonstrate that temporal structuring of stimulation, specifically incorporating strategic rest intervals, can effectively reduce habituation during transcutaneous nerve stimulation. However, this benefit comes at the cost of interrupting continuous sensory feedback, which is a critical feature for natural and functional prosthetic use. Thus, there is an inherent trade-off between managing habituation and delivering a truly continuous sensory input. Future studies must strive to balance these competing demands to optimize both sensation stability and usability in real-world prosthetic applications. While our study focused exclusively on temporal parameters using fixed electrode placements, spatial adjustments represent a complementary and potentially more functionally relevant approach. Techniques such as electrode switching, multichannel modulation, and varying stimulation sites can distribute activation across nerve populations, which may delay habituation onset and enrich sensory feedback. Integrating temporal optimization with spatial encoding strategies is crucial for advancing the development of neuroprosthetic systems that provide robust, continuous, and functionally meaningful sensory experiences.

E. Study Limitations

Although our findings demonstrate promising approaches for mitigating sensory habituation, several important counterarguments warrant careful consideration. First, the potential for long-term habituation remains a valid concern even with optimized stimulation protocols. Although our results showed significantly reduced habituation rates in shorter time frames, the neurophysiological properties underlying sensory adaptation may still lead to diminished responses over extended periods of use [26]. This underscores the necessity for longitudinal studies examining habituation patterns over weeks or months of regular use. Additionally, there is a need to develop adaptive stimulation protocols that can dynamically adjust to changing sensory thresholds [12].

The individual variability in nerve responses presents another significant challenge for the broad application of our approach. While our study identified general patterns in nerve response characteristics, considerable variation in neural architecture and sensitivity among individuals could affect the universal applicability of specific stimulation parameters [27]. This variability underscores the importance of developing flexible and customizable protocols that can be calibrated to individual user characteristics. Future implementations may benefit from incorporating machine-learning algorithms that can learn and adapt to individual response patterns over time, potentially offering personalized parameter optimization that accounts for user-specific neural characteristics.

During the experiment setup, we systematically varied the electrode locations within a 2×5 grid to identify stimulation sites that evoked clearly localized hand sensations, targeting either the median or ulnar nerves. While the evoked sensation location varied across participants based on nerve recruitment, the electrode position remained constant within each participant during the experimental conditions. Although we observed nerve-specific differences in perceptual stability, our study was not designed to directly evaluate the effects of stimulation site location on habituation. Future studies should explore whether dynamically alternating electrode locations or nerve targets can further mitigate habituation by spatially distributing the sensory load.

We acknowledge several methodological limitations of this study. This research was conducted exclusively with neurologically intact participants, and we did not comprehensively analyze sensory responses at varying current amplitudes or during continuous stimulation. However, prior research [7], [8] demonstrated no significant differences in controllable haptic sensations between amputees and neurologically intact individuals, suggesting the preliminary applicability of our model. In clinical populations, particularly those with neuropathic conditions such as diabetic peripheral neuropathy, managing habituation poses additional challenges owing to altered sensory thresholds. Recent studies have explored adaptive stimulation strategies to address these issues [36], [37]. While our study involved neurologically intact participants, these findings highlight the translational potential and the need for future studies involving clinical populations in which sensory restoration is both more complex and more urgently needed. Future investigations will expand this research to include diverse populations, such as amputees and stroke patients, to validate and refine our approach.

Similar challenges related to sensory habituation have been reported in studies involving lower limb amputees. For instance, [38] showed that the persistence and quality of sensory feedback in the lower limb can deteriorate with continuous stimulation, underscoring the importance of optimizing temporal patterns across different limb applications. Our findings on upper-limb TNS may offer insights that are applicable to other limbs.

V. Conclusion

The optimization of TNS parameters has direct implications for the design and implementation of stable sensory feedback protocols. Our findings suggest that stimulation protocols should incorporate strategic rest periods to maintain sensation intensity and parameter selection should consider nerve-specific responses, particularly for median nerve stimulation. Shorter stimulation blocks with appropriate rest intervals may be more effective than longer stimulation periods, and real-time monitoring of sensory adaptation may guide dynamic parameter adjustments. These insights may lead to the creation of more effective sensory feedback systems, potentially enhancing the functionality of assistive devices, and increasing user acceptance.

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