Skin Sensitivity Assessment Using Smartphone Haptic Feedback

Wilson O. Torres, Michael E. Abbott, *Member, IEEE*, Yuqing Wang, and Hannah S. Stuart, *Senior Member, IEEE*

Abstract*—*Goal: **This work presents a smartphone application to assess cutaneous sensory perception by establishing Vibrational Perception Thresholds (VPTs). Cutaneous sensory perception diagnostics allow for the early detection and symptom tracking of tactile dysfunction. However, lack of access to healthcare and the limited frequency of current screening tools can leave skin sensation impairments undiscovered or unmonitored.** ***Methods:*** **A 23-participant cross-sectional study in subjects with a range of finger sensation tests Smartphone Established VPTs (SE-VPTs) by varying device vibrational intensity. These are compared against monofilament test scores, a clinical measure of skin sensitivity.** ***Results:*** **We find a strong positive correlation between SE-VPTs and monofilament scores (r_s = 0.86, p = 1.65e-07).** ***Conclusions:*** **These results demonstrate the feasibility of using a smartphone as a skin sensation screening tool.**

***Index Terms*—Cutaneous sensation, Haptics, Smartphone.**

***Impact Statement*—We use a smartphone to obtain skin sensitivity measurements comparable with the monofilament test. This motivates work to enable at-home assessments of cutaneous perception to screen for tactile dysfunction.**

I. Introduction

HANDS are instrumental in activities of daily living, such as cooking and dressing, and are vital for education, work, and recreational activities [1]. Skin sensation plays an important role in hand functionality [2], allowing individuals to react to the stimuli felt by the hand, manipulate small objects, and/or preform writing tasks [1], [3]. When this functionality is compromised, as can occur in individuals with multiple sclerosis (MS) or rheumatoid arthritis (RA) [4], [5], additional functions may be impaired, such as grasping large objects or sensing injury [6], [7]. Unfortunately, upper extremity sensation issues are rarely reported [1] and may not be screened due to a physician's lack of time with patients or the sometimes-prohibitive cost of healthcare [6], [8]. Certain conditions can exacerbate this; RA, for example, has clinically relevant hand symptoms that can fluctuate daily and are consequently not always captured during clinical visits [9]. An accessible and regular way of measuring skin sensation is therefore needed.

The ubiquitous nature of smartphones equipped with powerful internal sensors uniquely position these devices with the means to fill this void. Various studies have leveraged smartphone sensors, such as the internal measurement unit and global positioning system to track general health metrics such as physical and mental well-being and physical activity [10], [11]. Measurements of the hand have also been collected, including hand strength [12] and wrist and finger range of motion [9], [13].

Specifically for the skin, vibrational perception threshold (VPT) – the lowest perceivable vibrational intensity – is an important metric for detecting sensation impairments [14]. There are different ways to measure this functionality, like using a vibration sensitivity tester such as a biothesiometer. This tool can stimulate the skin with discrete and controlled vibrational amplitudes, but is not widely used in practice due to its cost and the need for specialized training [15], [16]. Another tool used is the 128 Hz tuning fork, but the amplitude of vibration varies with the force used to make the tool resonate [6]. The monofilament test is a more widely used sensitivity screener with reliable readings and, while it is not a direct measure of vibration sensation, poor performance on this test relates to neurosensory deficit; the monofilament test is capable of measuring severe neuropathy [17], [18]. Additional work has shown correlations between VPTs obtained with a biothesiometer and the perception of a 5.07 monofilament level when diagnosing diabetic neuropathy [19].

As smartphones are built to provide rich vibrational haptic feedback, they have been the source of investigation as a way of replicating clinical tools. May et al. (2017) demonstrated that a 25 Hz smartphone vibration applied to the foot was better at detecting diabetic nephropathy than common clinical skin sensitivity tools. Reliability of this method was confirmed by Jasmin, et al. (2021) [20]. Recently, Adenekan et al. (2022) furthered this work by using multiple contact points on a phone to establish a single VPT in someone's hands [21]. Additionally,

Manuscript received 29 June 2023; revised 21 September 2023 and 25 October 2023; accepted 25 October 2023. Date of publication 30 October 2023; date of current version 7 November 2023. The work of W.O. Torres was supported by Hearts to Humanity Eternal (H2H8) Association Graduate Research Gift. This work was supported by the Johnson & Johnson Women in STEM^{2}D under Award #051062. The review of this paper was arranged by Editor Bjoern Michael Eskofier. *(Corresponding author: Hannah S. Stuart.)*

The authors are with the Embodied Dexterity Group, Department of Mechanical Engineering, University of California Berkeley, Berkeley, CA 94720 USA (e-mail: wilson_torres@berkeley.edu; michael_abbott@berkeley.edu; yuqingwang@berkeley.edu; hstuart@berkeley.edu).

This article has supplementary downloadable material available at https://doi.org/10.1109/OJEMB.2023.3328502, provided by the authors.

Digital Object Identifier 10.1109/OJEMB.2023.3328502

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the work reaffirmed the tuning fork as an inconsistent clinical tool. In Yoshida, et al. (2023), a smartphone delivers consistent vibrations with frequencies up to 230 Hz and is used to show how physical and cognitive activities raise VPTs [22]. In these prior studies in the hands, subjects with skin impairment are not yet recruited such that correlations between smartphone established VPTs (SE-VPTs) and established clinical diagnostics have not yet been performed, as depicted in Fig. 1.

Evaluating correlation with clinical tools is an important step in establishing the smartphone as an accessible and practical skin sensitivity test to supplement current clinical methods. The current work is the first to test for correlations between SE-VPTs and the monofilament test, chosen for its wide clinical use. We also allow natural interactions with the phone screen, where users can press the phone with different amounts of force, varying both between individuals and trials. This type of interaction is important for future adoptability, as requiring precise pressing forces would add an additional barrier for use. We, therefore, uniquely explore the impact that an individual's applied touchscreen forces have on feeling the smartphone's vibrational signals. This cross-sectional study looks at subjects with varying levels of skin sensation and generates SE-VPTs through a custom smartphone application. We utilize a modified method of limits protocol during human subjects testing, which allows for faster trials and accelerated threshold testing.

II. Materials and Methods

A. Smartphone Test Bed

An iPhone X (5.7 × 2.79 × 0.3 in) running iOS 14.4.2 (Apple Inc.) with a screen resolution of 2436 × 1125 pixels was chosen for this study. Like most commercial smartphones it can record a user's touch position and radius of touch at 120 Hz, as well as present vibrational feedback. It additionally measures on-screen forces using a parallel plate capacitor [23], which allows us to consider applied forces during our testing. Characterization of this sensor can be found in the supplementary material.

III. Experimental Procedure

A. Participant Population

Individuals over the age of 18 were recruited from the University of California, Berkeley (UCB) and the local community through digital flyers. Individuals with known bone fracture or surgery in the hands were excluded. A total of twenty-six participants took part in the study; twenty-one self-identified as having normative hand function and five participants identified as having a hand condition that may affect finger sensation. Of those with self-reported conditions, three indicated they had MS (of which two have hand tremors), one had a spinal cord injury (SCI), and one had arthritis. Severity of condition was not collected. A breakdown of demographics for all subjects can be be found in Table I.

Three participants are excluded from the study. One normative participant did not follow researcher's instructions, one of the MS participants had hand tremors severe enough to prevent them from maintaining constant contact with the screen, and the SCI participant had severe sensation deficit and could not feel any smartphone vibrations even at the phone's maximum settings. We therefore analyze sensation results from twenty-three subjects (n = 23). All work was performed under the UCB Internal Review Board approved protocol #2021-06-14449.

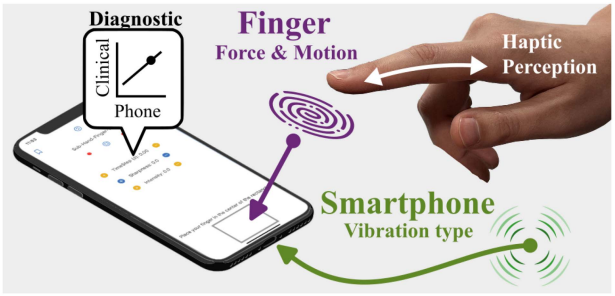

Fig. 1. This work investigates the potential smartphones have to provide clinically relevant hand diagnostics. Here, a diagnostic metric is provided by measuring fingertip haptic perception of smartphone vibrations.

TABLE I
PARTICIPANT DEMOGRAPHICS, N = 26

Gender	Female	13
	Male	13
Age	Adult (18-60)	18
	Older adult (over 60)	8
Ethnicity / Race	Black or African American	2
	Hispanic or Latinx	5
	Indegenous American	1
	Asian	7
	White	15
Dominant Hand	Right	24
	Left	2
Hand condition	Arthritis	1
	MS (with hand tremor)	3 (2)
	SCI	1

B. Clinical Cutaneous Sensation Assessment

Cutaneous skin sensation is measured for all participants using a monofilament test (Jamar Retractable Monofilaments, Performance Health) on a participant's dominant index fingertip with their hand resting on a table. The test starts with the thinnest monofilament level, 1.65, which is pressed against the fingertip until it buckles. This is performed three consecutive times, and if the participant feels any of the three presses, the monofilament level is recorded as their monofilament score. If the participant does not feel any of the three presses, the next monofilament level is tested. A score of 2.83 or lower is considered normative.

C. Smartphone Application and Use During Trials

The smartphone application interface is made with SwiftUI/UIKit and is pictured in Fig. 2(a). It allows the researcher to initiate vibration events using the top half of the interface. This transient haptic feedback can be modified by varying two

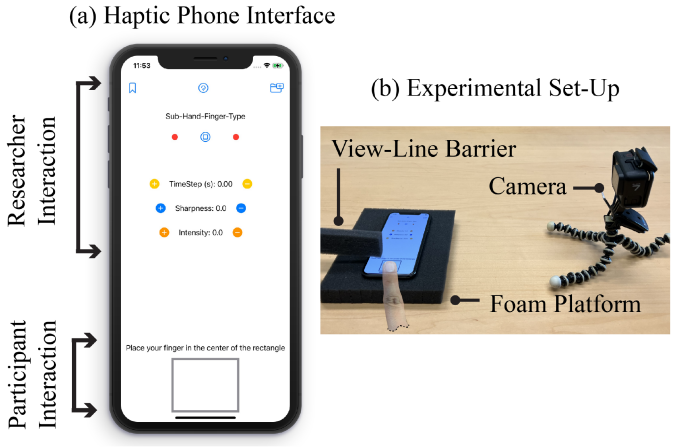

Fig. 2. (a) Smartphone app has interaction areas for both researcher (top) and participant (bottom). (b) A participant places their dominant index finger on the phone during tests. Haptic settings are obstructed via a view-line barrier and the phone sits on a foam pad. All phone interactions are recorded with a video camera for reference.

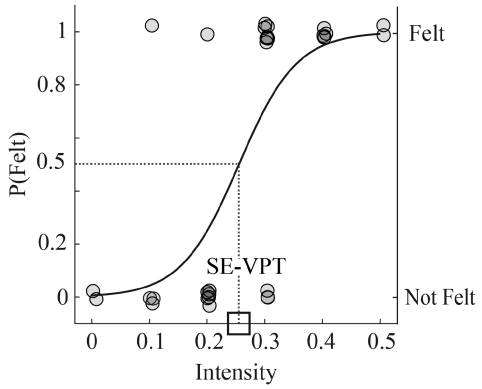

Fig. 3. Sample psychometric curve created using a binomial logistic regression model. Participant's response to each testing is overlaid. SE-VPT is obtained as the stimulus intensity at the 0.5 probability P(Felt) mark.

unitless input parameters from 0 to 1: *intensity*, comparable to vibration "strength," and *sharpness*, comparable to vibration "crispness." Characterization of these signal parameters can be found in supplementary materials. The bottom portion of the interface has a 2.46 cm by 2.46 cm participant interaction area. This location is chosen to maintain a close proximity to the haptic motor, located to the bottom left of the phone, and to mimic a button familiar to users during normal smartphone interactions (e.g. a common location for a "home" button).

To mitigate possible confounding issues that multiple skin sensation sites can have on VPTs [24], [25], [26], [27], testing is conducted only on the dominant index fingertip. To reduce the likelihood of vibrations felt via other sensory pathways: (1) the participant is instructed to contact the phone only with one finger and avoid touching any of the set up with another body part during haptic events, (2) participants are asked to close their eyes before the activation of the vibration, (3) a view-line barrier is used to prevent the participant from seeing the parameters on the researcher's side of the application, and (4) the phone rests on a foam platform to dissipate vibrations against the table. The vibrations are inaudible to participants so noise cancelling headphones were deemed unnecessary.

Fig. 2(b) depicts the view of the subject. For a given trial, the subject is first asked to place their dominant index finger on the bottom square by tapping and holding as if they are opening an application on their own smartphone. Then they are exposed to a haptic event and verbally report whether they perceived the event. Verbal data is recorded by the researcher and sessions are video recorded for reference when possible. The subjects lift and replace their finger in between each haptic event. Throughout the interaction the phone also records the pressing force of a user's applied touch. Phone data is stored locally on the smartphone and exported for analysis at the end of the session.

Between haptic events, intensity is varied from 0.0-0.5 in increments of 0.1 while holding sharpness constant at 0.5. Increment size is chosen as the smallest increase allowed by the smartphone software. In a pilot test, a sharpness level of 0.5 was determined as sufficiently high for perception. Additional changes to the sharpness parameter with a fixed intensity level did not change the perception of vibration signals. Therefore, only intensity level changes are analyzed in this work. Before starting testing, participants familiarize themselves with the maximum intensity level. If a participant is unable to feel this vibration, the maximum level tested is increased by 0.1; this only occurred with one participant who completed the study with the maximum level increased to 0.6.

D. Protocols for Establishing SE-VPTs

A modified version of the method of limits [28] is used in order to establish intensity-based SE-VPTs. Increments are randomly conducted in either increasing or decreasing order. When the intensity is increasing from an initial value of 0, the first detected vibration is recorded; for confirmation, the same level is repeated as well as the previous and following levels. If the intensity is decreasing from the maximum tested intensity, the same procedure is employed, but the last detectable vibration is recorded instead. When the repeated tests do not confirm expected outcomes, the researcher strategically re-tests the values that are inconsistent, as well as the previous and following levels. Three of these trials per subject are performed. This protocol for measuring perception is chosen as it can be performed in few trials (i.e., a minimum of 21 vibration events for three trials) and allows the researcher to add additional confirmation testing at relevant intervals.

We create logistic curves for each participant using logistic regression models with the intensity as a predictive factor and the probability of feeling the stimulus ($P(Felt)$) as the outcome. SE-VPT is obtained as the intensity at the 0.5 probability mark. This employed methodology adapts the method of limits by using all data points generated, not just the points during response crossover, allowing for the creation of a logistic curve without the need for additional trials. A sample model for one participant using modified method of limits can be seen in Fig. 3, overlaid atop their responses.

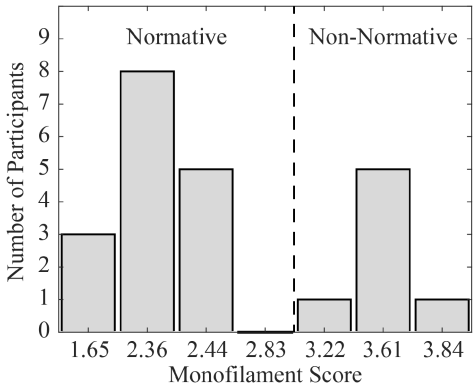

Fig. 4. Histogram of participants' discrete clinical monofilament scores, with vertical dashed line separating normative from non-normative scores (n = 23).

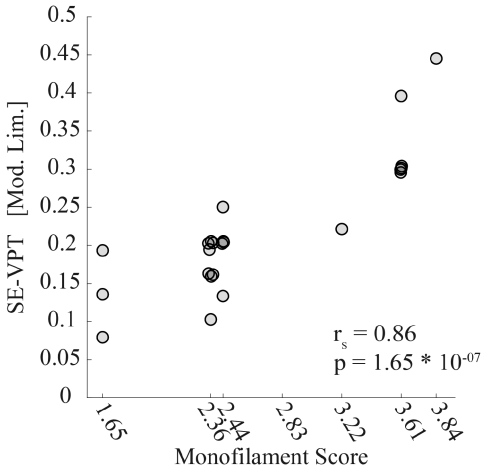

Fig. 5. Spearman's rank order correlation shows a statistically significant strong positive correlation between SE-VPT and monofilament scores (n = 23).

IV. Results

A. Clinical Test Results

The discrete monofilament scores for the study cohort are shown in Fig. 4, with the delineating normative score displayed as a vertical line [29], [30], [31]. Sixteen participants score within the normative range, while seven participants have non-normative scores. It is of note that five participants with non-normative monofilament scores self-report as having no hand condition. They are older adults, however, and age could play a role in their results as it is known to decrease cutaneous sensation [14]. One participant with a self-reported hand condition has a normative monofilament score. This data is provided only to describe the variation of the tested population, and to note how self reported sensation conditions can differ from quantitative measures of skin sensation. Our objective is to use the monofilament score as a correlate and not for impairment classification.

B. SE-VPT and Monofilament Correlation

We run a Spearman's rank-order correlation to determine the relationship between SE-VPTs and monofilament scores. There is a strong positive correlation between SE-VPTs and monofilament scores ($r_s = 0.86$, $p = 1.40 * 10^{-07}$), shown in Fig. 5. This suggests that, generally, as monofilament scores increase so do SE-VPTs.

C. Testing Applied Screen Force

Touch screen force at time of vibration varies between individuals. Twenty-two out of twenty-three participants apply forces within the expected range as described in [32], with a mean of 0.82 N $\pm$ 0.46 N. The outlier is an older adult with an average applied force of 3.35 N.

To test whether touchscreen pressing force impacts participants' ability to feel a vibration, we use a binomial logistic regression to model all participants' binary responses with intensity and contact force at the time of the vibration event as predictors. The regression coefficient for contact force is 0.032, with a p-value of 0.92, while the regression coefficient for intensity is 23.28 with a p-value of $1.40 * 10^{-34}$. Force having a large p-value and small coefficient implies that the variation in natural contact force observed here does not significantly contribute to individual's response to vibration, while intensity does.

V. Discussion

The current study shows that smartphone established vibration perception thresholds, collected through a modified method of limits, may be used as a correlate of cutaneous skin sensation as measured by the monofilament test. This enables the collection of additional longitudinal at-home sensitivity data not possible with current clinical methods alone.

This data set was collected by testing subjects with a wide range of abilities. As a result, some subjects could not complete the smartphone test. Therefore, SE-VPTs, in the tested form, appear to be suitable for a subset of people. Yet, the accessible nature of smartphones could prove useful for those who can achieve SE-VPTs at home.

The modified method of limits protocol utilized in this study for establishing SE-VPTs is non-standard. We therefore provide a comparison study with a standard constant stimuli method [28], [33] in supplemental data, which indicates similar monofilament correlation results across both methods. The advantage of using the present method is to reduce the number of required tests while using all response data to generate VPTs.

While we did not vary contact force in a controlled manner, we found that most of our cohort's applied pressing force falls within ranges established with previous work [32]. This could be why we found no significant impact of touchscreen applied force on participant ability to feel phone haptic vibrations, even with an outlier participant applying larger than expected forces. Further examination is needed to understand why the outlier applied such large forces as they had a normative monofilament score. While this could be physiological, unable to be observed

with the monofilament test, it could also be behavioral. As VPTs can vary with force [34], [35], it might be necessary in future work to find a way to control applied forces. This is an important future consideration for adoption as this type of touchscreen force sensing has not been present in smartphones since 2018.

A. Limitations and Future Work

While this study represents a promising first step, transitioning into real-world application will require further investigation. Next steps include fine tuning perception measurement methodologies that are able to quickly test for perception in a self-guided way with minimal time burden to individuals. Such methods must be developed for reliability across different people and environments. For example, in the current work, subjects represent an unequal age and racial/ethnicity distribution. Future studies will focus on expanding the participant pool, as well as collecting more data on individual characteristics, such as impairment severity for non-normative individuals with specific conditions. Other variables could include smoking status, etc. to understand how these impact VPTs. We also hope to evolve the current software application to operate autonomously without the need for the presence of a researcher. Such translation will also need to take into account the various environmental factors that may alter SE-VPTs. For example, VPTs are known to have temperature dependencies [14] or can be influenced by human attention and action [22], which present areas for further examination. These real-world considerations are likely important for wide adoption.

Vibration signals may also differ between phones due to the addition of phone cases, variability in internal haptic motors, etc. Human vibration mechanoreceptors have a broad sensitivity from 5–800 Hz, with Pacinian corpuscles being responsible for high frequency vibrations and having peak sensitivity at 150–300 Hz [36], [37], [38]. The tested smartphone in this work produces a broad-spectrum of frequencies that are within this high sensitivity range. However, the phone is unable to produce specific individual frequencies. Therefore, this study is not designed to identify the individual contribution of each frequency to SE-VPT. A comparison to tools that produce more narrow frequencies, like a biothesiometer, or the use of microneurography to directly monitor nerve impulses is left to future work. The use of established vibration sensitivity testers will additionally allow for the formal testing of agreement and potential bias between clinical and smartphone enabled VPTs.

VI. Conclusion

The motivation of this work is to give people more ownership over their hand health. We present the use of a smartphone in a controlled laboratory setting as a way of establishing vibration perception thresholds that strongly correlate with the clinically relevant monofilament test. This indicates that the smartphone may one day provide users with clinically relevant measures of cutaneous sensitivity at home. Therefore, this study demonstrates the potential of the everyday smartphone to be an accessible skin functionality diagnostic and monitoring tool.

Acknowledgment

We would like to acknowledge the contributions of Anjana Saravanan to this work. Any opinions, findings, conclusions or recommendations expressed in this material are of the authors and do not necessarily reflect the views of the funding sources.

WT created the smartphone intervention. WT, MA, HS contributed to the ideation and design of the smartphone application. WT performed human subject experiments and analyzed smartphone and clinical data. MA and HS contributed to data interpretation. YW collected and analyzed data for smartphone vibration characterization. HS directed the high-level vision of the project and advised experiments conducted in this work. WT wrote the first draft of the manuscript. WT, MA, YW, and HS wrote sections of the manuscript. All authors contributed to manuscript revision, read, and approved the submitted version.

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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