Cutaneous perception identification using smartphone haptic feedback

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Abstract

The skin's ability to sense its environment is vital to activities of daily living. 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. This work presents a smartphone application for Cutaneous Hand Assessment with a Smartphone Interface (CHASI) to establish Vibrational Perception Thresholds (VPT). CHASI's vibrational output and force measurement abilities are also characterized. An 18-participant cross-sectional study, with both normative subjects and subjects with sensation impairment, compares the monofilament test with smartphone established VPT (SE- VPT). We find a high positive correlation between SE-VPT and monofilament scores (rs=0.83, p = 0.00014). We also investigate the sensitivity of our proposed SE-VPT method to the motions and forces applied to the touchscreen. We find that variations in force do not alter the practical significance of the monofilament correlation. These results further the smartphone as a potential diagnostic and monitoring tool for hand health.

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I. Introduction

Hands play an important role in activities of daily living (ADLs), 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 captured [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 (IMU) and/or Global Positioning System (GPS) to track general health metrics such as physical and mental well-being and physical activity [10] [11]. The hand has also been studied, including hand strength [12], and wrist and finger range of motion [9] [13].

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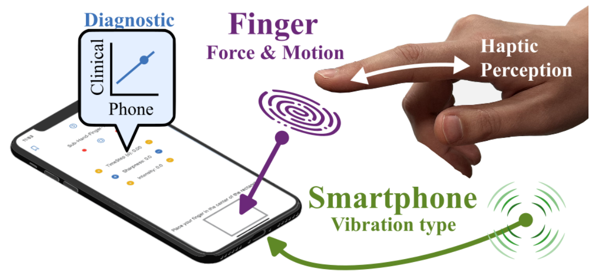

Fig. 1. This work investigates the potential that smartphones have to provide clinically relevant hand diagnostics. Here, a diagnostic metric is provided by measuring finger interaction metrics and the haptic perception of an individual to smartphone provided haptic feedback.

Specifically for the skin, vibrational perception threshold (VPT) – the lowest perceivable vibrational intensity – is an important metric for detecting sensation impairments [14]. The most widely used tool for this, the 128Hz tuning fork, however, only tests for one frequency and is subjective to the force needed to make the tool resonate [6]. 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) [15]. Most recently, Adenekan et al. (2022) furthered this work by using multiple contact points on a phone to establish an absolute intensity threshold [16]. Additionally, the work reaffirmed the tuning fork as an inconsistent clinical tool, and showed that a smartphone can deliver consistent vibrations, with a peak frequency of 230 Hz. While an important step in positioning the smartphone as a potential diagnostic tool, only a single subject was tested and therefore correlations with established clinical diagnostics could not be performed.

The current work is the first to test for correlations between smartphone established vibration perception thresholds (SE-VPT) and the monofilament test, a clinically validated skin sensitivity diagnostic metric [17] complementary to vibration testing [18]. We also uniquely explore the impact that an individual's interactions – motion of touch and applied touchscreen forces – have on establishing VPT. This cross-sectional study looks at subjects with both normative and non-normative skin sensation and hand tremors; it generates SE-VPT through a new procedure centered around a custom smartphone application called the Cutaneous Hand Assessment with a Smartphone Interface (CHASI).

A. Overview

In this work, we use an iPhone X smartphone. In Section II, the phone's force and vibrational feedback capabilities and parameters of "sharpness" and "intensity" are characterized. Section III details human subject demographics, the monofilament test procedure, and the assessment done with CHASI. Section IV reports the results of the clinical tests and smartphone trials, as well as correlation tests. In Section V we discuss how our findings inform future work to generate viable smartphone-based haptic data collection mechanisms to track impaired skin function.

II. Smartphone characteristics

A. On-screen force characterization

An iPhone X (5.7x2.79x0.3 in) running iOS 14.4.2 (Apple Inc.) with a screen resolution of 2436x1125 pixels was chosen for this study. Like most commercial smartphones it can record a user's touch position, radius of touch, and present vibrational feedback. It can sample touch input at 120Hz. It uniquely measures on-screen forces using a parallel plate capacitor [19]. Using UIKit, programmers are able to access this information as an arbitrary unit (AU) that ranges from 0 - 6.67. This allows us to test whether subjects apply different forces and its effect on vibrotactile acuity.

We characterize the AU to provide a force analog by placing calibrated weights on the phone's touchscreen and recording the internal software readings. All measurements are taken at the location where participants interact with the screen during this human subject study. Figure 2(a) shows the relationship between the AU and force, up to 3.73 N (6.55 AU) with an R^2 of 0.99. This relationship is used to transform the AU to Newtons for subsequent analyses.

B. Haptic vibration characterization

For vibrotactile feedback, the iPhone X uses a linear resonant actuator placed at the bottom left of the phone to create vibrational oscillations, the frequency of which can be adjusted using AC voltage input. Using SwiftUI and CoreHaptics, programmers can adjust the transient haptic feedback by varying two unitless input parameters from 0 to 1: *intensity*, comparable to vibration "strength," and *sharpness*, comparable to vibration "crispness."

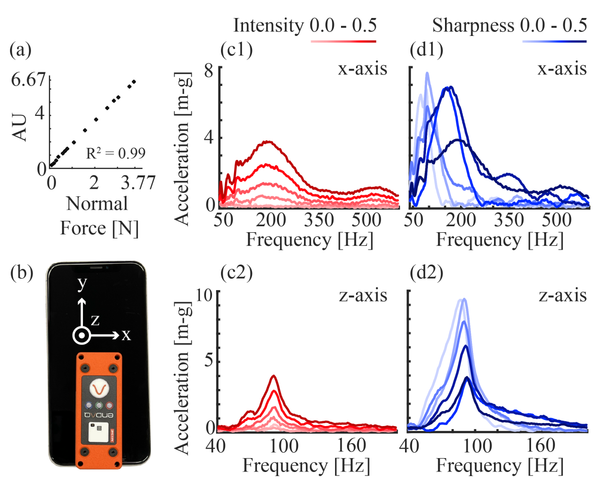

Fig. 2. (a) Force characterization curve shows the internal force reading with the applied normal force in newtons. Curve is highly linear with R^2 = 0.99. (b) Experimental setup for characterizing haptic vibrations and sensor axis. (c-d) Vibration characterization of varying intensities (holding sharpness at 0.5) and varying sharpness (holding intensity at 0.5) of the x and z-axis.

To characterize these parameters, we measure the vibrations of the phone using a 3-axis piezoelectic/digital capacitance vibrational sensor (S4-E25D40, enDAQ) as shown in Figure 2(b). The sensor is adhered to the screen of the phone during testing, and intensity and sharpness are varied separately. In all tests, vibration in the $\hat{y}$ direction is negligible, as defined in Fig. 3(c). A summary of Fast Fourier Transform (FFT) results are shown for $\hat{x}$ and $\hat{z}$ in Figure 2 for (c) intensity and (d) sharpness. First, intensity was increased in 0.1 increments to 0.5, while holding sharpness at 0.5. The primary $\hat{x}$ acceleration amplitude at 180 Hz increased from 0.4 to 3.7 m-g (milli-g-force) (c1), while the primary $\hat{z}$ acceleration amplitude at 90 Hz increased from 0.6 to 4.0 m-g (c2). When sharpness was increased in 0.1 increments to 0.5, holding intensity at 0.5, both frequency and amplitude changed. The primary $\hat{x}$ frequency shifted from 90 Hz to 187 Hz with a decreasing peak amplitude of 6 to 3 m-g (d1). It also spanned a larger frequency range at higher sharpness. In $\hat{z}$, the primary 90 Hz acceleration amplitude reduced from 9 to 3 m-g (d2). Duration of the vibration is taken as the time the magnitude of the y_T-z_T signal increased above 0.05 m-g. The duration of the intensity signal increases from 2.82 milliseconds to 24.96 milliseconds, while the duration of the sharpness signal decreases from 57.68 milliseconds to 26.26 milliseconds.

III. Experimental methods

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. Participants self-selected into two subgroups, those with normative hand function and those with non-normative hand function. A total of eighteen participants took part in the study. Five participants self-identified as having a manual physical disability or condition. Of these, three indicated they had multiple sclerosis (MS) of which two had hand tremors, one as having a spinal cord injury (SCI), and one as having arthritis. The participant with arthritis, at the time of testing, however, did not feel their condition impacted their hand function. A breakdown

TABLE I
PARTICIPANT DEMOGRAPHICS, N = 18

Gender	Female	10
	Male	8
Age	Adult (18-60)	15
	Older adult (over 60)	3
Ethnicity / Race	Black or African American	1
	Hispanic or Latinx	4
	Asian	6
	White	9
Dominant Hand	Right	16
	Left	2
Hand condition	Arthritis	1
	MS (with hand tremor)	3 (2)
	SCI	1

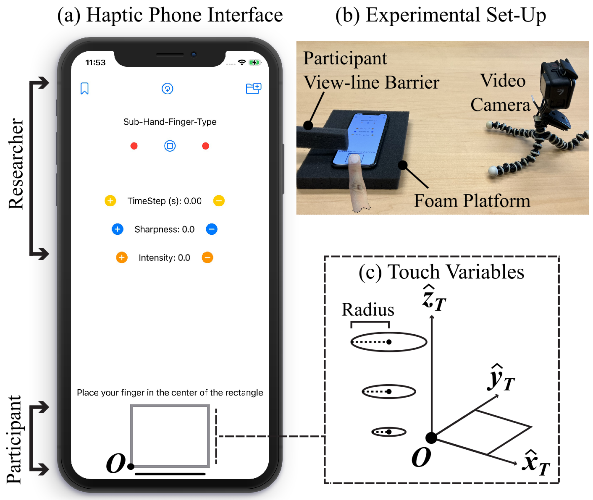

Fig. 3. (a) CHASI has interaction areas for both researcher (top) and participant (bottom). (b) A participant places their dominant index finger on the phone during tests. Haptic settings are obstructed via a view-line barrier and the phone sits on a foam pad. All phone interactions are recorded with a video camera for reference. (c) The phone measures participants' on-screen position of touch (x_t and y_t), as well as the touch radius (z_t).

of demographics for all subjects can be be found in Table I. Participants 12, 15 (MS) and 17 (SCI), completed the clinical assessment, but were unable to complete the phone sensation task as directed, so we only analyze smartphone sensation result from fifteen subjects. All work was performed under the UCB Internal Review Board approved protocol #2021-06-14449.

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, 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.

C. Haptic Smartphone Assessment

CHASI was made with SwiftUI/UIKit and is pictured in Figure 3 (a). It allows the researcher to initiate vibration events, and change the intensity and sharpness levels using the top half of the interface. The bottom portion of the interface has a 2.46 cm by 2.46 cm participant interaction area. Figure 3 (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 were opening an application on their own smartphone. Then they are exposed to a haptic event and verbally reported their perception. Verbal data was recorded by the researcher and all sessions were video recorded for reference. The subjects lift and replace their finger in between each haptic event. Throughout the interaction the phone also records the position (x_T, y_T), radius (z_T), and pressing force (F_T) of a user's applied touch. Position is the distance relative to the point O along $\hat{x}_T$ and $\hat{y}_T$ defined in Figure 3 (c). The radius of touch is analogous to vertical displacement in the $-\hat{z}_T$ direction, as the finger deforms against the screen's surface. Phone data is stored locally on the smartphone and exported for analysis at the end of the session.

In order to establish intensity-based SE-VPT and sharpness-based SE-VPT, intensity or sharpness is varied from 0.0 - 0.5 in increments of 0.1 while holding the other constant at 0.5. Increments are randomly conducted in either increasing or decreasing order. If the parameter order is increasing, the first detected vibration is recorded; for confirmation, the same level is repeated as well as the previous and following levels. If the parameter order is decreasing, the same procedure is employed, but the last detectable vibration is recorded instead. When the repeated tests do not confirm expected outcomes, subsequent and previous levels are tested again. This procedure was chosen as it resembled the monofilament test but with the additional replication procedures. We alternate between intensity and sharpness SE-VPT trials until we performed three of each (six total trials) per subject.

To mitigate possible confounding issues that multiple skin sensation sites could have on VPT [20] [21] [22] [23], thresholds are established via a singular dominant index fingertip rather than simultaneously on multiple fingers. To reduce the likelihood of vibrations felt via other pathways: (1) the participant is instructed to only contact the phone with the one finger and avoid touching any of the set up with any other part of their body 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 not audible by participants so noise cancelling headphones were not deemed necessary.

IV. Results

A. Clinical test results

Each participant is categorized into either a normative hand functionality group (Norm) or a non-normative hand functionality group (NN), based on their monofilament score. Figure 4 (a) shows the result of the monofilament test, with the delineating normative score shown as a horizontal line [24] [25] [26]. The test shows that participant 18 has an impaired score, yet self-reported as Norm, while participant 11 has arthritis and a Norm score.

B. Haptic Smartphone Assessment Results

Figure 4 (b) shows the percentage of haptic events felt, per discrete intensity levels tested for all trials and across all participants, along with monofilament-based Norm and NN sub-groups. Intensity saturation – being able to feel 100% of the haptic vibrations – occurs for all participants at an intensity level of 0.4 and continues for intensity 0.5. On the

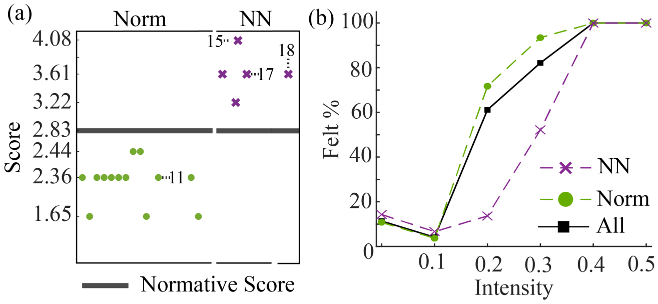

Fig. 4. (a) Participant clinical monofilament scores, with delineating normative score for Norm and Non-Norm (NN) groups (n=18). (b) Percentage felt for all phone intensity SE-VPT trials, across all (n=15) participants.

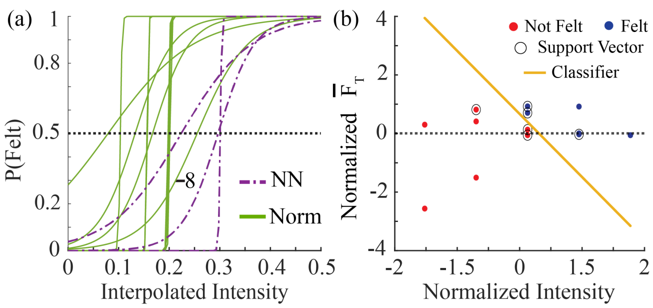

Fig. 5. (a) Logistic regression models, for all participants (n=15), of avowed/disavowed intensity levels, with SE-VPT obtained at the 0.5 probability P(Felt). (b) Sample individual participant data. Accounting for normalized average pressing force ($\bar{F}_T$) and normalized intensity levels, avowed/disavowed intensities are classified using a Support Vector Machine algorithm. SE-VPT-F_T are obtained at the x-intercept of the classifier line.

lower bound, an intensity of 0.0 and 0.1 had a felt percentage of 11.36% and 4.12%, respectively, indicating a non-zero false positive rate and that participants could not effectively distinguish the 0.0 or 0.1 intensity. Norm and NN groups follow a similar trend. At the 0.2 and 0.3 intensity levels the Norm and NN groups differ, with the NN group feeling fewer of the haptic events, a sign of possible sensation impairment.

Variations in sharpness bore almost no impact on whether a vibration was felt at a held intensity level of 0.5. The only level that did not yield 100% was at sharpness 0.0 for NN participants, who felt 91% of events. Therefore, only intensity SE-VPT are considered for the following analyses, as the particular set of sharpness SE-VPT parameters tested do not provide either within- or between-subject variability.

With the employed procedure, a subject's VPT does not always fall consistently on a single discrete intensity level. Therefore, to obtain Intensity SE-VPT, participant's responses are modeled using a binomial logistic regression, with the intensity level as the predictor variable and SE-VPT interpolated from the 0.5 probability mark. Figure 5 (a) shows the logistic regression models for each of the participants, separated into Norm and NN groups; all models are significant at a 0.05 significance level. The shape of the modeled curves indicate how contradictory participant's responses are during the intensity appraisals. A steep slope denotes that a participant has a clear distinction between which intensity levels cause them to feel a vibration, while

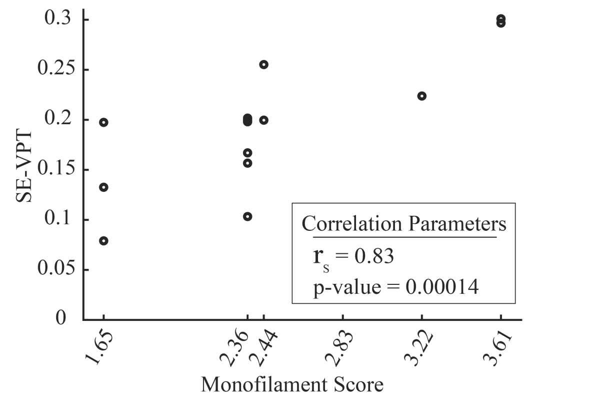

Fig. 6. Spearman's rank order correlation shows a statistically significant high positive correlation between SE-VPT and monofilament scores. (n=15)

a gradual slope indicates that participants contradict themselves at some intensity levels. Overall, the NN participants produce curves to the right of the Norm group, indicating a higher intensity SE-VPT. It is of note that participant 8 has a curve similar to the NN group; this participant stated their hands were colder than normal.

Applied force has the potential to change VPT [27]. Therefore, we also examine a force-sensitive SE-VPT (SE-VPT-F_T). As shown in Figure 5 (b) for a single individual, the average F_T applied during the vibration event is plotted against intensity. F_T and intensity are z-score normalized. A support vector machine (SVM) algorithm classifies between felt and non-felt responses to obtain a characteristic line. Subject intensity SE-VPT-F_T is established at the x-intercept of the classifier line, the point that corresponds to the mean of the average F_T during the pressing gesture. The classifier is evaluated using a k-fold validation with 10 folds. Misclassification rates concentrate around 0.20 or lower, with the exception of participant 2, whose classification centers around 0.37, signifying adequate performance.

C. Clinical and smartphone correlations

We run a Spearman's rank-order correlation to determine the relationship between Intensity SE-VPT and monofilament scores. There is a high positive correlation between intensity SE-VPT and monofilament scores(r_s=0.83, p = 0.00014), shown in Figure 6. Only Norm subjects receive an SE-VTP score close to 0.2 or less, while only NN subjects receive an SE-VPT score of close to 0.3. However, scores between 0.2 and 0.3 appear ambiguous for classifying between Norm and NN groups in this data-set.

A Spearman's rank-order correlation is also run to determine the relationship between intensity SE-VPT-F_T and monofilament score. The SE-VPT-F_T and monofilament score has a statistically significant, high positive correlation (r_s=0.86, p = 0.00036). While the correlation coefficient increases using SE-VPT-F_T, the practical significance of the correlation does not change. A similar SVM-driven approach is conducted with z_T, independently, instead of F_T. The Spearman's rank-order correlation shows that z_T has a statistically significant correlation (r_s=0.80, p = 0.0003),

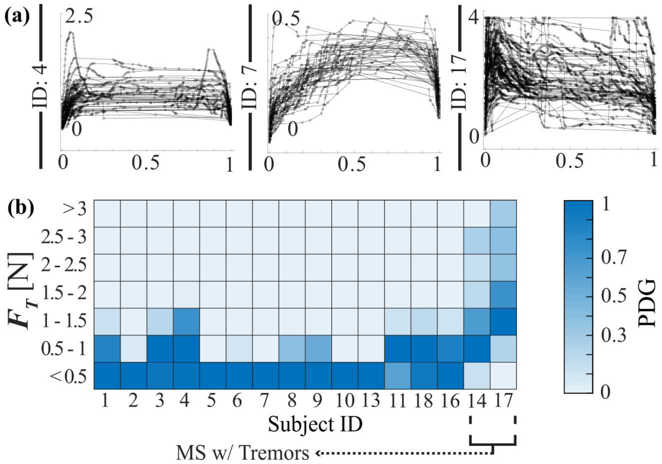

Fig. 7. (a) The force in newtons applied to the screen during all sensation tasks for subjects 4, 7 and 17. (b) A heatmap of the rate of F_T levels, as the proportion of datapoints generated by that participant (PDG).

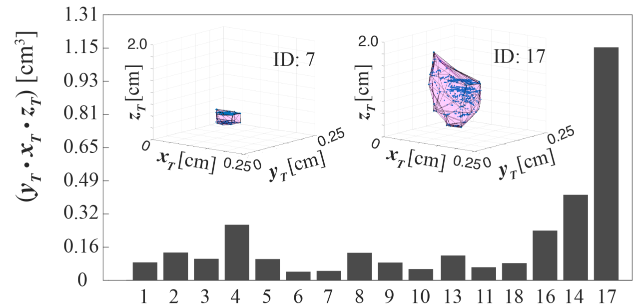

Fig. 8. The volumetric shapes created that encompass all x_T, y_T, z_T points generated for participant 7 and 17 as well as a bar graph with the volumes of these shapes for all participants.

comparable to the logistic regression based intensity SE-VPT. This is expected as z_T roughly parallels F_T.

D. Observations of forces applied to the phone

Due to the potential influence of contact force in haptic perception and the inclusion of subjects with hand tremor, we report the touchscreen behaviors observed. During the tapping portion of the gesture, we find that participants start imparting a pressing force on the screen as soon as they make contact. They increase force until reaching their personal maximum F_T. They then typically hold steady until decreasing force during the release of the tap. For participants without tremors, consistent but individualized "signature" force profiles emerge across all trials, layering on top of each other, as seen in subjects 4 and 7 in Figure 7(a). For participants with tremors, like subject 17, force profiles instead show a larger range of variation, at times reaching the maximum value of the smartphone force sensor; this does not occur in the Norm group. The variation of force levels applied by all subjects can be seen in Figure 7 (b). We plot F_T rate as the proportion of datapoints generated (PDG) by a given subject. Participants with tremors show wider force striation when compared to the rest of the cohort.

V. Discussion

The current study shows that smartphone established VPT can be used to measure cutaneous skin sensation. The tested procedure used to obtain SE-VPT yields a high positive, statistically significant correlation with monofilament test scores. This confirms that the span of vibration intensities tested, ranging from 0.4 to 3.7 m-g at frequency of 180 Hz in the $\hat{x}$-direction and from 0.6 to 4.0 m-g in at 90 Hz in the $\hat{z}$-direction, is adequate to capture the VPT for subjects with normal and moderately reduced skin sensitivity.

Participant 18 demonstrates the potential usefulness of SE-VPT because they did not self-identify as having any hand impairment, even though they had a sensation impairment as confirmed both via the non-normative monofilament and smartphone assessment scores. This participant was an older adult, and while loss of cutaneous sensation can occur with age, it is also known to be a marker in the early stages of different neuropathies, nerve damage caused by various conditions [14]. Here, having a smartphone enabled, readily accessible and frequent cutaneous sensation diagnostic tool could give individuals, like participant 18, earlier insight into otherwise unknown hand functionality status. While promising, it is important to note that three out of the eighteen total subjects could not complete the smartphone test either because (1) they could not feel the sensations at the highest intensity tested or (2) did not follow procedure instructions. Therefore, SE-VTP, in the tested form, may not be suitable for all people.

Since contact force influences VPT [27], we tested the implication of force on CHASI using the alternative SVM-based SE-VPT-F_T. We find little change in the correlation's practical significance, indicating that force may not be an explicit requirement when using the proposed SE-VPT. This is an important consideration for adoption as this type of touchscreen force sensing has not been present in smartphones since 2018. CHASI's force data, nonetheless, measures tremor-associated inconsistencies in force control [28] in the two participants with this condition. Tremor detection can widely impact hand functionality, and its effect is often underestimated [29], making identification noteworthy.

A similar trend was discerned using the motion of a person's fingertip on the touchscreen. Figure 8 shows the 3D shape encompassing all x_T, y_T, and z_T generated points, calculated using the boundary MATLAB function with a shrink factor of 0.1. When comparing across subjects, a similar pattern to F_T in Figure 7(b) emerges, with participants with tremors having a noticeably higher calculated volumes. Further options for tremor and sensitivity diagnostic procedures utilizing such variations in motion is left for future work.

A. Limitations and Future Work

While this work shows a correlation between the monofilatment test and the intensity SE-VPT, it did not directly compare against a clinical vibration test, such as the Vibratron II, which could provide an even stronger correlation. We also did not find the Sharpness SE-VPT effective at the held intensity level of 0.5. Future work will vary sharpness levels across lower intensity levels to test for feasibility.

Various environmental factors may alter SE-VPT. For example, temperature dependencies of vibrational testing should be further examined in the CHASI assessment since VPT are known to have temperature dependencies [14]. This could explain why participant 8, who had cold hands, had a similar SE-VPT to the NN group while having a normative monofilament score.

Normative participants outnumber non-normative participants, at the same time presenting an unequal age and racial/ethnicity distribution. Therefore, results may not be fully generalizable, but reflect these other variations. The current procedure also relies on the judgment of the researcher to perform additional confirmation stimuli when there is a contradicting response to an intensity level. To strengthen the current work, future studies will focus on expanding the participant pool, and evolve the current software application to operate autonomously without any researcher input.

Despite these limitations, the ability to establish SE-VPT, and potentially identify tremors, with a singular interaction task helps establish the smartphone as a promising fingertip skin functionality diagnostic and monitoring tool that gives people more ownership over their hand health.

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