Smartphone-Based Vibration Perception Threshold Measurement on Multiple Body Sites

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***Abstract*—Tactile perception plays an important role in activities of daily living, and it can be impaired in individuals with medical conditions. The most common tools used to assess tactile sensation, the Semmes-Weinstein monofilaments and the 128 Hz tuning fork, have poor repeatability and resolution. Long term, we aim to provide a repeatable, high-resolution testing platform that can be used to assess vibrotactile perception through smartphones without the need for an experimenter to be present to conduct the test. We present a smartphone-based vibration perception measurement platform and compare its performance to measurements from standard monofilament and tuning fork tests. We conducted a user study with 21 healthy adults in which we tested each tool on the hand, wrist, and foot, to assess how well our smartphone-based vibration perception thresholds (VPTs) detect known trends obtained from standard tests. The smartphone platform detected statistically significant changes in VPT between the index finger and the foot and also between the feet of younger adults and older adults. Our smartphone-based VPT had a weak, positive correlation to tuning fork-based VPT. A long-term objective of this work is to develop an accessible smartphone-based platform that can be used to measure disease progression and regression.**

***Index Terms*—smartphone, vibration, tactile, perception**

I. Introduction

Tactile perception, including vibrotactile perception, plays a critical role in enabling humans to perform various sensorimotor tasks such as object manipulation, navigation, and playing sports [1]–[4]. We even use vibrotactile perception to balance during walking, a pervasive activity of daily living [5]–[9]. Many underlying health conditions including diabetes, chemotherapy, and direct injuries to the body can impair our tactile perception [10]. Given our reliance on tactile perception, deficits in perceiving tactile cues can have devastating consequences. Assessing tactile perception can help us understand disease progression and recovery, especially in response to treatment.

Manuscript received XXXXXX XX, XXXX; revised XXXXXX XX, XXXX; accepted XXXXXX XX, XXXX. Date of publication XXXXXX XX, XXXX; date of current version XXXXXX XX, XXXX. This article was recommended for publication by Associate Editor XXXXXXXXXXXX and Editor-in-Chief XXXXXXXXXXXX upon evaluation of the reviewers' comments.

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This work was supported in part by a grant from the Precision Health and Integrated Diagnostics Center at Stanford, the National Science Foundation Graduate Fellowship Program, and the Stanford Graduate Fellowship Program.

Frequent use of vibration perception testing occurs during routine screenings of people experiencing peripheral neuropathy. The most common clinical diagnostics for peripheral neuropathy are the Semmes-Weinstein monofilament exam and the 128 Hz tuning fork exam [11]. Although these exams provide important information on tactile ability, they have some limitations in the resolution of data they are able to provide. Tuning forks often provide inconsistent vibrations due to differences in how the clinician strikes the fork [12]. Monofilaments also suffer from variations in force delivered due to variations in clinician application and overuse [13]. Also, when used in many clinical settings, both of these tools only measure a binary response (‘*yes, can feel*’ or ‘*no, cannot feel*’) to a single provided stimulus.

Given the rise of smartphones with high quality vibration actuators, there has been a rising interest in conducting mobile haptics experiments [14]. We conducted preliminary work which showed that smartphone vibrations are more repeatable than tuning fork vibrations and that vibration perception threshold could be reliably measured using a custom application employing a staircase algorithm [15]. Also in 2022, Torres et al. [16] characterized smartphone vibrations and explored if smartphone-based vibration perception thresholds correlate with monofilament-based pressure thresholds in the index finger. Several researchers have also worked toward validating the use of smartphone vibrations for diagnosing diabetic peripheral neuropathy. May et al. [17] showed that vibrations generated from a mobile phone could be used to detect diabetic peripheral neuropathy, and that the most accurate testing location was the first metatarsal head (a bony prominence in the big toe). Jasmin et al. [18] found that a vibration-based smartphone application has a moderate to strong correlation to tuning forks in classifying participants as experiencing neuropathy or not experiencing neuropathy, and that the interrupter reliability using the smartphone application is high. While these studies are important steps towards developing an improved measurement tool, they suffer from various limitations including confounding factors in the study design, non-autonomous smartphone vibration perception data collection (reliance on an experimenter to physically conduct the exam), and the use of a binary measurement (yes/no) as opposed to a continuous, numerical value.

In this work, we build upon our preliminary work by testing the feasibility of an application designed to measure smartphone-based vibration perception thresholds at different sites on the body (hand, wrist, and foot) in a healthy, age-diverse population. We also assess how the smartphone-based vibration perception thresholds (VPTs) correlate to both tuning fork vibration perception thresholds and monofilament force perception thresholds at these locations. Our main goal is to confirm that smartphones can be used for vibration perception measurements and capture similar trends as currently used methods. In Section II, we describe our methods in characterizing, designing, and administering the smartphone-based VPT, performing the tuning fork and monofilament exams, and conducting a user study and accompanying analyses. We then discuss the study results in Section III and key takeaways and future work, such as testing our smartphone application on various patient populations and expanding this application to additional types of smartphones, in Section IV.

II. Methods

A. Measurement Methods

1) Smartphone VPT Exam: We developed an iOS application that controls Apple's Core Haptics parameters ("hapticIntensity" and "hapticSharpness") and autonomously implements a staircase algorithm (reversals = 8) to measure vibration perception threshold. Prior work by Yoshida and Kiernan, et al. [19] characterized the acceleration outputs at various locations on the phone; their results indicate that the output accelerations occur at a constant frequency of 230 Hz and that there is a positive, nonlinear relationship between the amplitude of the output acceleration and commanded "hapticIntensity" value when "hapticSharpness" is held constant at 1 and "hapticIntensity" is varied between 0.1 and 0.3. We further characterized this nonlinear relationship when "hapticSharpness' is held at a constant 1 and "hapticIntensity" is varied between 0 and 1 (Fig. 1). Despite this minor nonlinearity, we designed our staircase algorithm to output a continuous vibration for 0.1 seconds with the "hapticSharpness" set at 1.0 and the "hapticIntensity" varying with each step. This results in repeatable vibrations of varying amplitude with a constant frequency of 230 Hz which the users can respond to quickly and easily (Fig. 1). We chose to use "hapticSharpness" = 1 (230 Hz) since the Apple iPhone XS Max (our phone model) uses linear resonant actuators that are tuned to operate at "hapticSharpness" = 1 (230 Hz). Using a different "hapticSharpness," results in noisy vibration acceleration waveforms.

The vibration amplitude starts small ("hapticIntensity" = 0.05) and increases with a step size of 0.05 until the vibration is detected by the user. At this point, the user says '*yes*' to indicate detection, the spoken '*yes*' is interpreted by the app using "Speech" (Apple's voice recognition framework), and a reversal is recorded in the app. The vibration's amplitude then decreases with a step size of 0.05 until the user can no longer detect the vibration (does not provide a spoken '*yes*' response). Then, another reversal is recorded, the vibration's amplitude increases again, and the staircasing of the "hapticIntensity" values continues until eight reversals are complete. Once complete, a CSV file containing the trial data is exported and stored in Google Firebase. The vibration perception threshold is calculated by averaging the "hapticIntensity" values at the eight reversal points (where the reversal point is the average of the value of the response that triggered a reversal and the value of the response prior to the reversal) as shown in Fig. 1. Time intervals between vibrations for each trial were randomly selected to reduce bias (ranging from 3-6 s), and responses had to occur within 2.5 seconds of the vibration in order to be recorded as a true positive response (as this is the upper end of haptic response times reported in literature [20], [21]).

We measure vibration perception threshold at six locations of interest: the index finger pad, the back of the index finger, the pinky finger pad, the outer wrist, the inner wrist, and the big toe pad (Fig. 2). These locations were chosen both for both clinical relevance and ease of smartphone placement [22]. For each participant, smartphone-based VPT measurements are collected five times at each location, so that we can report the participant's average smartphone-based VPT at each location.

All smartphone-based measurements are collected on an Apple iPhone XS Max. Participants sit in a chair during the entire exam. For the finger and wrist locations, the phone is placed on a pillow that is placed on a desk. For the foot location, the phone is placed on a pillow, that is placed on the floor. To prevent participants from relying on hearing instead of feeling, to identify vibrations, participants wear headphones playing their preferred music. All but two participants listened to a Disney Hits playlist. Because the smartphone data collection component of the experiment took around an hour for most participants, we did not use white noise, which was found to make participants drowsy during piloting.

2) Tuning Fork Exam: We use a 128 Hz clinical tuning fork (CynaMed) to test the same six body parts as the smartphone (Fig. 2). Participants sit in a chair during the entire exam. For the finger and wrist locations, the hand/wrist is placed on a pillow that is placed on a desk. For the foot location, the foot is placed on a pillow, that is placed on a coffee table. The experimenter strikes the tines of the tuning fork on her knee and then places the base of the tuning fork on the body of the participant. Prior to collection, participants are touched with a vibrating tuning fork so they could get a sense of what it feels like and so that they understand that the sensation is not painful. Participants wear a blindfold so that they can not see when the tuning fork makes contact with their body, but do not wear headphones as the sound of the tuning fork vibrations are not easily discernible. Participants are instructed to say "start" when they start feeling a vibration and "stop" when they no longer feel any vibrations. A digital watch displaying seconds is used to measure the amount of time that the participant feels the vibration. The experimenter notes the second when the participate says "start" and also the second when the participant says "stop" and then records the difference in seconds, mimicking methods used in clinical settings. At each body part, tuning fork vibration perception time is measured five times. The times are then averaged, so that each participant's average perception time at each of the body parts is reported.

3) Monofilament Exam: We use a 20-piece Semmes-Weinstein monofilament set (Touch Test Sensory Evaluators,

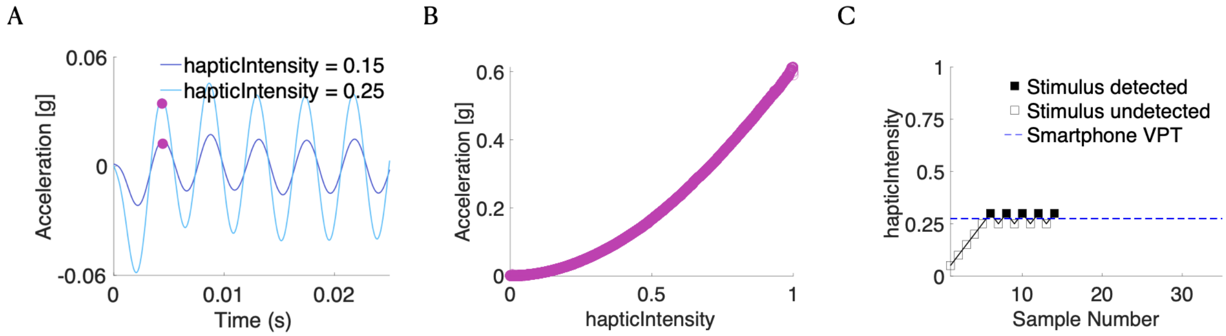

Fig. 1. (A) Sample smartphone filtered vibration waveform data for hapticIntensities of 0.15 and 0.25 using the setup described in detail in [15] and [19]. (B) Peak accelerations of the waveforms for each hapticIntensity (indicated with pink points in (A)). (C) Sample perception data for one trial of the smartphone VPT exam showcasing the staircase method.

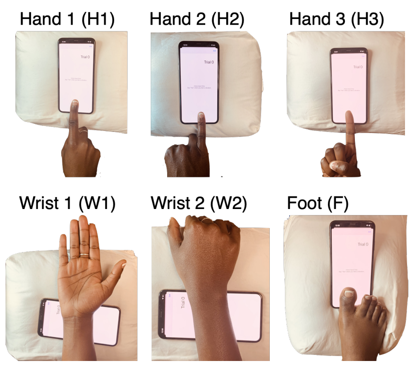

Fig. 2. The six body locations tested with all three measurement methods. The smartphone was placed on a pillow and participants were asked to contact the phone as shown in this figure. During the monofilament and tuning fork tests, participants sat in a chair, and a pillow resting on a desk or coffee table allowed participants to comfortably support their limbs.

North Coast Medical, Inc.) to assess light force perception. Filaments range from 0.008 grams-force to 300 grams-force. To assess light force perception at each of the six body parts (Fig. 2), we begin with the monofilament deemed normal for that location (0.07 grams-force for hands and dorsal feet, 3.61 grams-force for the plantar feet) [23]. Participants sit in a chair during the entire exam. For the finger and wrist locations, the hand/wrist is placed on a pillow that is placed on a desk. For the foot location, the foot is placed on a pillow, that is placed on a coffee table. Prior to collection, participants were touched with a sample monofilament so they could get a sense of what it feels like, and so that they understand that the stimulus is not painful. Participants wear a blindfold so that they can not see when the monofilament makes contact with their body, but do not wear headphones as the stimuli are inaudible. We then follow the protocol provided with the monofilament kit, mimicking how the procedure would be performed by clinicians [23]. The participants are instructed to say “yes” anytime they feel the filament touching them. If the participant feels the monofilament, we decrease the monofilament evaluator size, otherwise we increase the monofilament evaluator size. Once the participant does not feel a monofilament size (three times in a row for evaluator sizes 1.65 to 4.08 or one time in a row for evaluator sizes 4.17 to 6.65), we record the minimum evaluator size that they could feel as their monofilament threshold for that location. If the participant does not feel the starting monofilament, we increase the evaluator size until the subject can feel it and then record that evaluator size as their monofilament threshold for that location.

TABLE I
PARTICIPANT DEMOGRAPHICS, N = 21

Sex assigned at birth	Male	8
	Female	13
Age	Older Adults (over 50)	6
	Younger Adults (18-50)	15
Race/Ethnicity	American Indian / Alaska Native	1
	Hispanic / Latino	2
	Black / of African Descent	3
	Asian	6
	White	10
	Other (Brazilian)	1

B. *User Study Design*

1) Participants: Twenty-one adult participants with no known history of diabetes or other disorders linked to peripheral neuropathy completed this study. Participant demographics are displayed in Table I. This study was approved by the Stanford University Institutional Review Board under Protocol 22514, and written consent was provided by all participants. Prior to completing the study, participants completed a pre-survey that inquired about demographic information as well hobbies or injuries that may impact touch sensitivity at the hands or feet.

2) Procedure: Participants completed a two-day protocol with a one-hour session each day. The same time block was used for each day. Monofilament and tuning fork perception data were collected in the same session on one day and smartphone perception data was collected in the session on the other day. The ordering of the sessions was randomized, and the ordering of the monofilament and the tuning fork data collection within the session was also randomized. For each given modality, the ordering of the body parts tested was randomized. All perception measurements were collected on the participant’s dominant side body parts.

C. *Statistical Analyses*

Perception data obtained from the smartphone, tuning fork, and monofilaments are presented as both individual and group-level data. Smartphone, tuning fork, and monofilament thresholds for subjects 1,17, and 21 were removed due to the

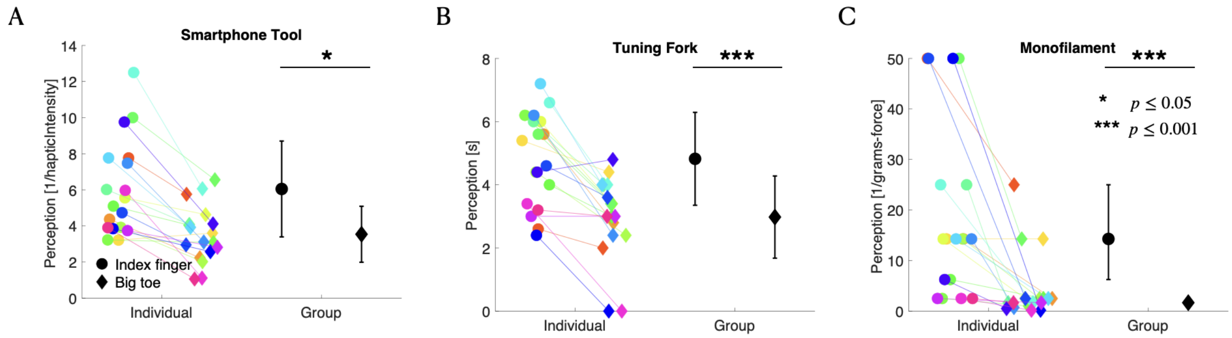

Fig. 3. Perception thresholds at the index finger and the big toe for measurement method. Individual thresholds (left) as well as group mean and standard deviation (right) are shown for the smartphone (A) and tuning fork (B). Individual thresholds (left) as well as group median and 25th and 75th quantiles (right) are shown for the monofilaments (C). All three modalities detect statistically significantly lower touch perception at the big toe than at the index finger.

presence of too many false positives during the monofilament exam (saying they felt a touch from the filament when it was not touching them). Group level, smartphone-based data and tuning fork-based data are presented as means and standard deviations as smartphone and tuning fork thresholds are both continuous data. Group level, monofilament-based data are presented as medians and quantiles (25th and 75th) as monofilament thresholds are discrete. Figures corresponding to smartphone and monofilament thresholds use inverted units (1/"hapticIntensity" or "hapticIntensity"$^{-1}$ and 1/ grams-force or grams-force^{-1}) such that a higher threshold value corresponds to better perception across all measurement methods. However, all statistical significance tests are conducted on using the values with standard units: smartphone vibration perception threshold in "hapticIntensity", tuning fork threshold in seconds, and monofilament threshold in grams-force.

Differences in perception data at the index finger and big toe (H1 and F from Fig. 2) are calculated using paired single-sided t-tests with Bonferroni correction for the smartphone and tuning fork and a single-sided Wilcoxon signed rank test (which is the nonparametric equivalent) for the monofilament.

Differences in perception data between younger adults and older adults at the index finger are calculated using unpaired single-sided t-tests with Bonferroni correction for the smartphone and tuning fork and a single-sided Wilcoxon rank sum test with Bonferroni correction (which is the nonparametric equivalent) for the monofilament. Differences in perception data between younger adults and older adults at big toe are calculated in the same manner.

Correlations between the three modalities are performed using Pearson's correlation coefficient for smartphone and tuning fork and Spearman's rank correlation coefficient for smartphone and monofilament as well as monofilament and tuning fork to account for the discrete monofilament thresholds. While Pearson's correlations result in a line of best fit, Spearman's correlations do not result in a line of best fit because it is used to describe non-linear relationships. We also calculated Pearson correlation coefficients for the smartphone perception and tuning fork perception in older adults at each body location.

All statistical analyses except quantile calculations for the monofilament data are conducted using MATLAB 2022b. The quantile calculations for the monofilament data are performed using R (Version 4.0.3) which allows for quantiles to be calculated for discrete and non-normal data that are unsuitable for linear interpolation. We used R's type 1 quantile calculation algorithm.

III. Results and Discussion

A. Discrimination Between Hands and Feet

To investigate the resolution limits of our smartphone-based tool, we first sought to determine whether our tool could detect known trends in vibration perception differences of different body locations in healthy humans. As shown in Fig. 3A, our participants had smartphone perception value of 6.05 ± 2.65 "hapticIntensity"$^{-1}$ ($mean \pm std$) at the index finger and 3.54 ± 1.55 "hapticIntensity"$^{-1}$ at the big toe. From our statistical analysis, we found that our smartphone-based tool detected a statistically significant VPT difference between the index finger and big toe ($p = 0.005$).

For clinical comparison, we conducted these same analyses on the tuning fork perception data. Tuning fork perception values were 4.83 ± 1.47 s at the index finger and 2.98 ± 1.30 s at the big toe (Fig. 3B). Similar to the smartphone, there was a statistically significant difference between index finger and big toe ($p = 1.24 \times 10^{-5}$) in the tuning fork threshold measurements.

We conducted similar analyses using nonparametric equivalents on the monofilament perception data. The monofilament force perception values were as follows: 14.29 [6.25, 25] grams-force^{-1} ($median$ [$25th$, $75th$ $quantiles$]) at the index finger and 1.67 [1.0, 2.5] grams-force^{-1} at the big toe (Fig. 3C). We again found that there was a statistically significant difference between the monofilament threshold measurements at the index finger and at the big toe ($p = 4.70 \times 10^{-4}$).

In short, all three modalities yielded data that align with previous research findings that hands are more sensitive to vibrations and force than feet [24]. The ability to replicate known trends further strengthens the hypothesis that smartphones may be able to provide high enough resolution data to classify vibrotactile perception at an even finer scale than just neuropathic or non-neuropathic.

B. Discrimination Between Younger and Older Adults

We also investigated the smartphone's ability to measure known effects of age on vibrotactile perception

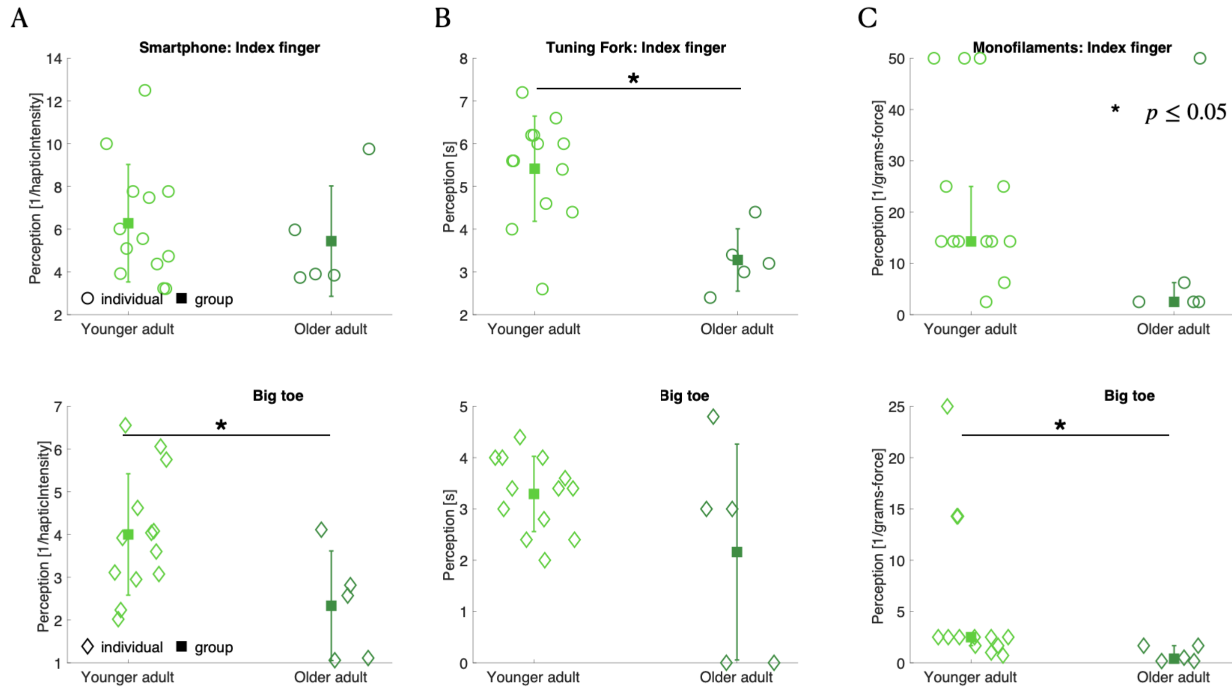

Fig. 4. Perception thresholds in younger adults (left) and older adults (right) at the index finger (top) and big toe (bottom). Individual thresholds as well as group mean and standard deviation are shown for the smartphone (A) and tuning fork (B). Individual thresholds as well as median and 25th and 75th quantiles are shown for the monofilaments (C).

(Fig. 4A). From our statistical analyses, we found that the smartphone could not discriminate between younger (6.28 ± 2.75 "hapticIntensity"$^{-1}$) and older (5.44 ± 2.58 "hapticIntensity"$^{-1}$) adults at the index finger location ($p = 0.82$), but could discriminate between younger (4.00 ± 1.42 "hapticIntensity"$^{-1}$) and older (2.33 ± 1.28 "hapticIntensity"$^{-1}$) adults at the big toe ($p = 0.02$).

We ran the same statistical tests on the tuning fork exam data for clinical comparison. As shown in Fig. 4B, we found that the tuning fork exam could discriminate between younger (5.42 ± 1.23 s) and older (3.28 ± 0.73 s) adults at the index finger location ($p = 3.6 \times 10^{-3}$). However, the tuning fork exam could not discriminate between younger (3.29 ± 0.73 s) and older (2.16 ± 2.10 s) adults at the big toe location ($p = 0.15$).

We conducted similar analyses using the nonparametric equivalents on the monofilament perception data (Fig. 4C). The monofilament exam could not distinguish between younger (14.29 [14.29, 25] grams-force^{-1}) and older (2.5 [2.5, 6.25] grams-force^{-1}) adults at the index finger ($p = 0.14$), but could identify a significant difference at the big toe between younger (2.50 [1.67, 2.50] grams-force^{-1}) and older (0.40 [0.17, 1.67] grams-force^{-1}) adults ($p = 9.5 \times 10^{-3}$).

To summarize, the smartphone was able to replicate the known trend of older adults having worse vibrotactile perception than younger adults in the feet [25]. The monofilament exam was also able to replicate this same known trend. The modified tuning fork exam yielded unexpected results – while the tuning fork could identify perception in the older hands as worse than perception than in younger hands (Sec. III-A), it could not identify older feet having worse perception than younger feet. However, clinically, the tuning fork exam for the foot is conducted at a bony prominence of the big toe, not at the fat pad of the big toe (as we used for this experiment to directly compare to our chosen smartphone placement). Hence, this result is not necessarily in conflict with clinical expectations. To truly determine if the smartphone measurements could replicate this trend at the big toe location, one would have to find a way to adhere the smartphone to the bony prominence of the big toe and test the smartphone alongside the tuning fork at this location.

C. Correlation Between Smartphone VPT and Clinical Measurements

To better understand how our smartphone perception values correlate to clinical standards, we calculated correlation coefficients (Fig. 5). As shown in Fig. 5A, we found a statistically significant, but weak, positive correlation between the smartphone-based VPT and the tuning fork VPT ($R_p = 0.367$, $p = 9.29 \times 10^{-5}$) (Fig. 5). We also found a statistically significant, but very weak, positive correlation ($R_s = 0.230$, $p = 0.017$) between the smartphone-based perception value and the monofilament perception value (Fig. 5B). Finally, we found a statistically significant, but very weak, positive correlation between the monofilament perception value and the tuning fork perception value ($R_s = 0.250$, $p = 0.092$) as shown in Fig. 5C.

The correlations between the various touch sensitivity tools are all positive as expected, with the strongest correlation existing between the smartphone and the tuning fork. Both the smartphone and tuning fork measure vibrotactile ability, so we expect those to be more closely correlated than the monofilaments (which measure force, not vibration perception). However, the correlations are quite weak. One possible

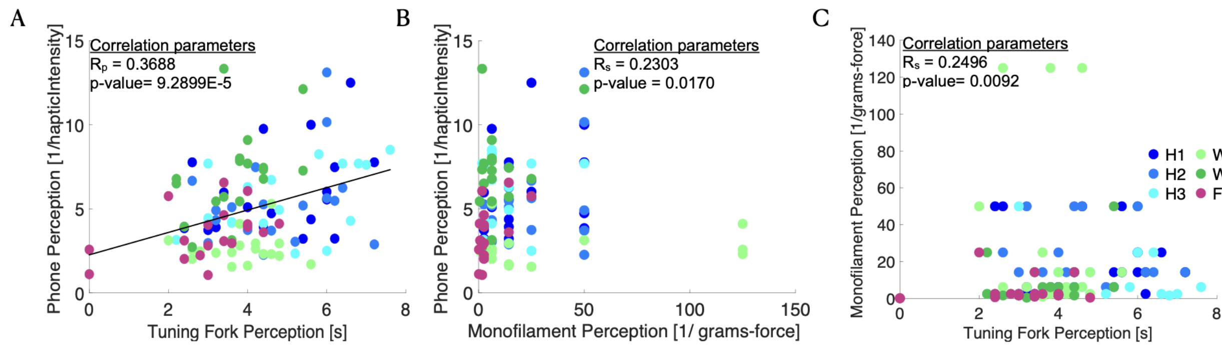

Fig. 5. Correlations between each of the measurement methods. Pearson's correlation coefficient is shown for the smartphone and tuning fork data (A). Spearman's correlation coefficient is shown for correlations between the smartphone and monofilaments data (B) and between the monofilaments and tuning fork data (C). As a reminder, (B) and (C) do not have best fit lines because Spearman's correlation is used to describe non-linear relationships.

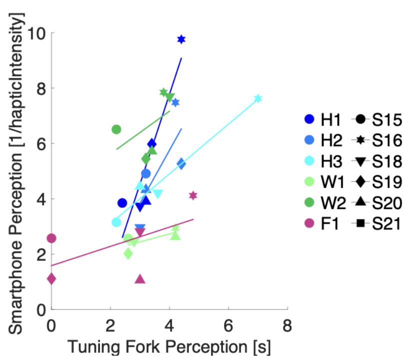

Fig. 6. Pearson's correlations between the smartphone and tuning fork perception at each tested body location in the older adult population.

TABLE II
PEARSON CORRELATION BETWEEN SMARTPHONE AND TUNING FORK IN OLDER ADULTS

	H1	**H2**	**H3**	**W1**	**W2**	**F**
R_p	0.915	0.757	0.985	0.728	0.490	0.571
$p-value$	0.0293	0.1387	0.0146	0.1636	0.4025	0.3149

reason for this result is that the tuning fork and monofilament perception values are subject to inconsistencies, such as variation in how hard the experimenter struck the tuning fork and how hard the experimenter pressed the monofilaments. Another possible reason is that half of our positions were hand positions and most of our participants were healthy young adults, which resulted in many similar perception values, not a broad range. To better assess this idea, we calculated correlations for the smartphone perception and tuning fork perception in older adults (Fig. 6) as they are thought to have more range in vibration ability. We calculated coefficients for each body location separately, and found that this resulted in much higher correlations between measures. The index finger had the strongest correlation ($R_p = 0.915$, $p = 0.0293$) while the big toe had a weaker correlation ($R_p = 0.571$, $p = 0.315$). Correlations for the other locations are found in Table II).

IV. Conclusion

Using Apple's Core Haptics Framework along with standard psychophysical methods, we developed a smartphone-based vibration perception threshold test that can be used to identify known trends in vibrotactile ability. Fingers are known to be more touch-sensitive than feet [24]. Additionally, younger adults are known to have more touch-sensitive feet than older adults [25]. Though we had the limitation of having a non-age-balanced population, our smartphone successfully identified these trends.

We also found that our smartphone-based vibration perception measures were weakly correlated to clinical tuning fork-based vibration perception measures across all participants and highly correlated to clinical tuning fork-based vibration perception measures in older adults. This is likely because there was more spread in the older adults' perception ability.

When comparing the three measures, we also found that the tuning fork performed the best in discriminating between older and younger participants' vibrotactile perception at the index finger. This is particularly interesting because the index finger is a convenient location for using our smartphone tool. A key difference between our smartphone-based vibration test and the clinical tuning fork test is that the tuning fork exam involves an element of timing (how long users perceive the vibration), whereas our smartphone application delivers vibrations with a set time and varying amplitude. Moving forward, we will explore whether a smartphone app designed to replicate the tuning fork exam by providing a vibration stimuli that decays over time, will enable us to better discriminate between vibrotactile ability of different groups at the index finger, a more convenient testing location than the big toe.

The aim of this initial work was to confirm the feasibility of the iPhone XS Max and app platform to accurately measure vibration perception thresholds. Next, we will conduct studies comparing participants with neuropathy and at different levels of risk of developing neuropathy. This will enable us to assess whether our platform can be used to measure progression and regression of nerve damage. If successful, our platform could be used to identify those at risk of developing irreversible nerve damage, and could motivate at-risk individuals to adhere to treatment and management plans. Given the ubiquitous nature of smartphones, the tool could be used both in and outside of clinics to increase access to reliable sensory diagnostic tests. However, different types of smartphones contain varying hardware and control variables. Thus, in order to make this vision a reality, future work must be done to characterize additional smartphones and expand the make and models of smartphones that can be used within our platform.

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