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Contaminant Resistant Pin-Based Tactile Display*

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***Abstract*— Pin-based tactile displays have now been in use for more than forty years. One shortcoming, however, is their susceptibility to contaminants that jeopardize the operation of the delicate actuating mechanisms, necessitating costly periodic maintenance. We propose to cover such displays with a Gore-Tex protective layer to block the contaminants from reaching the sliding surfaces. The feel of the dots, however, is affected. We showed the correlation through tribological and perceptual experiments that certain pin shapes could restore the tactile feeling experience of standard braille pins.**

I. Introduction

Pin-based tactile displays have served the visually impaired community well since the invention of piezoelectric refreshable braille in the nineteen-seventies [1]. These displays, however, are vulnerable to dust, liquids, dirt, and other contaminants deposited by the skin during repeated contact with the display. These contaminants lodge themselves in the interstitial space between the bore and the shaft of each pin, leading to seizure of the mechanism. In the course of the creation of a next generation full page, compact tactile display design, we set out to address to this critical problem. In doing so we help to reduce operating expenses, such as the expensive and tedious periodic maintenance costs. There has been considerable research in alternative actuation techniques, including electro-active polymers or dielectric gels, which might eventually solve this problem by eliminating the need for sliding contacts in the pin mechanisms [13]. The results, however, have been disappointing because of low performance factors such as response rate, energy usage, deflection, strength, and resilience to wear following repeated contact with the skin's abrasive *stratum corneum*; hence, these techniques have not yet reached a sufficient level of practicality. While work on more compact and more efficient piezoelectric actuators is ongoing, we aim at producing a high-density, cost-effective tablet-type display for use by the blind and visually impaired community in the short term. Toward this end, we investigated the option of covering pin-based displays with a thin Gore-Tex membrane to protect the point mechanisms from contaminants. If successful, the maintenance of the display would essentially reduce to the periodic replacement of the protecting membrane. In this quest of minimizing the tactile feeling loss on Gore-Tex membraned braille pins, we decided to investigate the variants and invariants during active touch to braille pins. Moreover, we conduct two sets of experiments – tribological and perceptual – to analyze and categorize effects of different pin shapes and surface conditions.

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II. Background: The Gore-Tex Membrane

Gore-Tex is a woven polymer membrane that is made of bundles of stretched, thin polytetrafluoroethylene (PTFE) fibrils. It is biocompatible and has found applications in medicine, such as vascular grafts and other synthetic tissues, clothing, sealants, and so on. It is a very flexible fabric, yet it is abrasion resilient and shares with the *stratum corneum* the property of being hydrophobic and providing protection against aqueous liquids (water repellant). In addition, Gore-Tex promotes the directional migration of water when sandwiched with another polymeric fabric. Covering a tactile display with a Gore-Tex membrane is appealing, because it dramatically reduces the periodic maintenance costs of tactile displays. However, the Gore-Tex protection cover might also modify the tactile sensation provided by the Braille pins. We, therefore, looked for a method to restore the original feeling of standard pins once covered by a membrane. The glabrous skin of the fingertips mediates tactile sensations through several populations of mechanoreceptors located superficially at the interface of the epidermis and the dermis and is associated with the deeper connective tissues of the finger [2]. The interaction of a finger sliding on a Braille pins elicits a variety of mechanical events that can be characterized by the bulk response of the frictional forces at play at the interface between the pin head and the skin [3], resulting in a complex interaction in which the tangential component appears to play a major role [4]. We hypothesized that the analysis of the dynamic characteristics of the tangential interaction force component would be strongly correlated with the perceptual experience derived from scanning braille pins. Prior research with virtual braille strongly supports this idea [5].

III. Experiment 1: Tribological Insights

A. Experimental Setup

Covering tactile displays with the Gore-Tex membrane offers benefits related to lower maintenance costs. However, it might also modify the tactile feeling in an unwanted way. To examine if and how using Gore-Tex affects the tactile feeling of braille cells, we conducted a tribological experiment in which we measured interaction forces of a sliding finger using an apparatus with different pins and different covers. The apparatus we developed is capable of collecting high-resolution data from tangential and normal forces along a lateral sliding axis [6]. An aluminum braille plate with a braille pin slot was mounted on the friction force transducer. Our experimental setup recorded the finger slide over the aluminum plate with no inclination on the platform. The aluminum braille plate was 20cm long, which is necessary to reach constant friction force and sliding speed. A braille slot secured the pin height to the constant 0.7mm. This height was chosen due to the standard commercialized braille pin height that the Braille Authority has recommended and actual users are familiar with [7]. The immovable braille pins were mounted to the braille slot on the aluminum braille plate as shown in Fig. 1. However, normal cases of finger interaction on a braille cell are different. Standard commercialized piezo actuated braille pins can be varied from 17 to 30cN [8] [9]. In our experimental setup, we decided to use a fixed pin instead because we wanted to gather more exaggerated tactile force data.

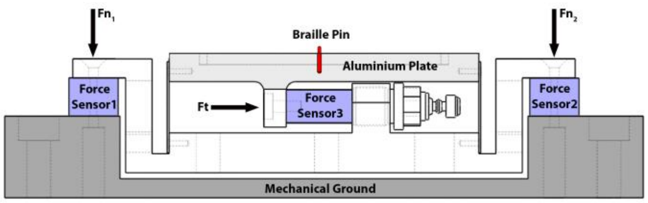

Figure 1. Experimental Setup Layout

The apparatus measured finger interaction forces as the finger moved over the braille pin. By using a low friction aluminum plate, we isolated the friction forces of the braille pin. The braille pin was positioned in the middle of the aluminum plate. This created a particular and distinguishable tangential force shape. In order to identify tangential force patterns for each pin, we prepared six different pin designs shown in Fig. 2. The first of these designs is the universally standardized braille pin (pin#S).

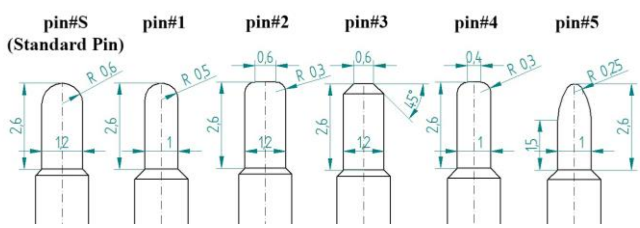

Figure 2. Standard Pin Design and 5 New Designs (mm)

B. *Participant and Experimental Design*

One participant (male, 26) participated in the experiment. Our experiment 1 had a 2 (surface: Gore-Text vs. No Gore-Tex) x 6 (pin design: pin#S vs. pin#1 vs. pin#2 vs. pin#3 vs. pin#4 vs. pin#5) within subjects factorial design.

C. *Procedure*

Finger mechanics are highly dependent on large variety of parameters (e.g., age, sex, skin, moisture level etc.). In addition, touch mechanics can cause essential physical invariants. Knowing that these different varieties of parameters might play a role in tactile perception, we were focusing on invariants in a simplified yet repetitive experiment.

During the study, the participant slid his finger over the platform. For each of the 12 conditions, the participant slid 40 times over the pin always using the same finger. As the sliding could be considered as an active touch with only one-directional recordings, there were different values for speed and normal force pairs. An example of tangential force raw data can be seen in Fig. 3. Our focus however is the bi-modal profile shape on top of the plot.

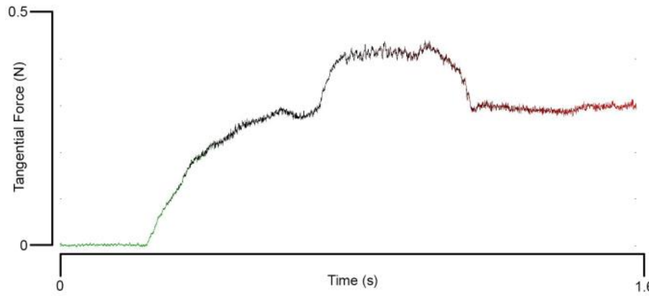

Figure 3. Raw Force Data Sample from Measurements

D. *Results*

After the data collection, we compared the respective tangential force evolution curves during scanning on the braille pin. The acquired data were matched to interaction parameters such as speed and normal force for each individual pin. Then we mathematically constructed a character graphic for each pin using Gaussian Interpolation Process [10]. Collecting data among different types of pins revealed that each pin had a unique tangential force curve, see Fig. 4 and Fig. 5. The blue lines in Fig. 4 and Fig. 5 show the interpolated data from 40 independent experiments, while red lines in Fig. 4 and green lines in Fig. 5 show the Gaussian-filtered data.

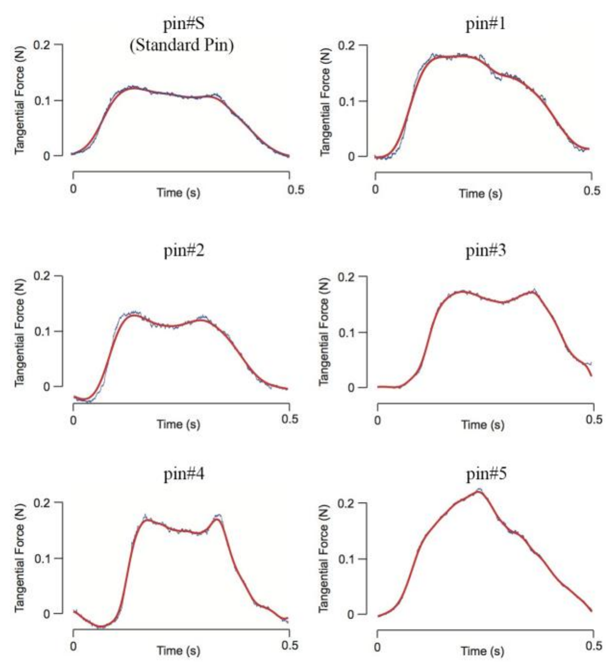

Figure 4. Tangential Force Curves for Six Pin Designs

The tangential force curves of all six pins can be seen in Fig. 4. We can see there that each pin has its own individual curve characteristics. Pin#5 is rather distinctive, while the others have bimodal plot shapes. Fig. 5 shows tangential force curves of all six pins with the Gore-Tex membrane cover. As can be seen there, pin#1 and pin#5 under the Gore-Tex membrane both have similar tangential force curves to the standard pin with no cover.

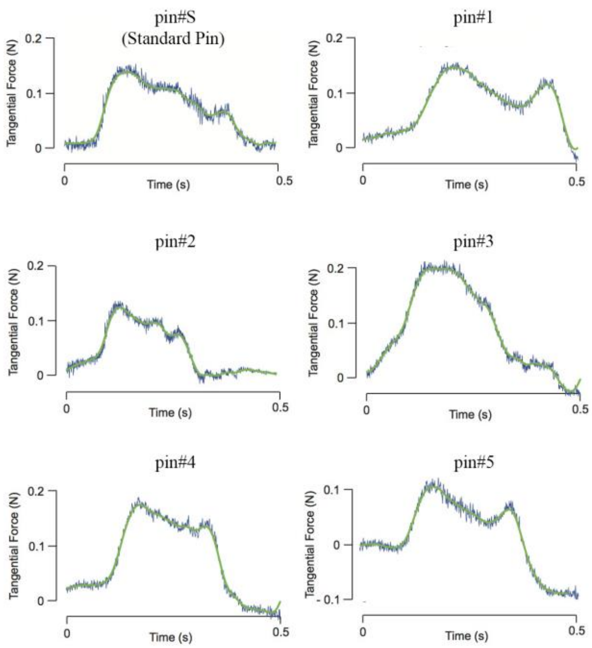

Figure 5. Tangential Force Curves for Six Pin Designs with Gore-Tex

E. Conclusion

The standard pin design has been in use since the seventies, thus the blind community is quite familiar with it and along the years has found it to be most effective [7]. The tangential force curves generated in Fig. 4. clearly represent the physical shape of each individual pin designed for this study. When put under the Gore-Tex membrane, however, their characteristics changed. It is thus a reasonable aim to attempt to find a pin design, which, once covered by a Gore-Tex membrane, would give similar curves to the standard pin. When comparing the curves in Fig. 4 and Fig. 5, we can see that the Gore-Tex layer added high-frequency noise to the curves. However, the slow-varying characteristics on the time scale of 10ms and higher are quite evident. Interestingly, the covered pin#1 and pin#5 approximated quite well the bi-modal profiles of the bare standard pin. Our experiment showed that velocity and normal force affect signal amplitude and width. However, tangential force has a characteristic shape, which can be used to categorize pins and even corresponds to the actual physical shape of the pins. Our aim is not to optimize the tactile perception of the pins but to find similar tangential bi-modal characteristics within a different physical shape. Therefore, we decided to conduct a second experiment in which we manipulated tactile feeling of the pins.

IV. Experiment 2: Perceptual Insights

The findings of the tribological experiment are promising. However, more research is needed to empirically investigate the effects of pin designs and surface conditions on braille-reading performance. Similar studies have been carried out in the past [11]. However, using the physical correlates of scanning Braille pins to find optimized pin designs is new. Braille displays are extremely expensive. On top of trying to reduce their cost, we are working on improving the existing technology to have a better, longer life span. Aim of our second experiment is to analyze braille-reading behavior among a group of effective braille readers. Our perceptual experiment investigates the effects of different pin designs (pin#S vs. pin#1 vs. pin#5) and surfaces (Gore-Tex vs. no Gore-Tex) on the reading performance of visually impaired people. More specifically, we examine which pin and surface combination is the best to minimize the haptic tactile sensation difference between tactile displays with or without Gore-Tex. Based on the findings on our tribological experiment 1, we decided to focus only on pin#S, pin#1, and pin#5 in this experiment. The insights gained from this experiment are essential to ensure a smooth transition for users when they will switch to next generation haptic displays.

A. Experimental Setup

In order to get measurable data, we designed a setup that allowed us to track participants' finger movements while reading. The experimental setup included a camera, a microphone, and a refreshable braille display. Moreover, a computer software was designed to give inputs to the braille display and to collect outputs (i.e., finger movements, voice response) from the participant. The camera was installed right above the braille display to examine the positions of the participant's fingers. Motion tracking markers were placed on the fingernails of the participant. Using the tracking markers, the experimental setup could determine when the participant was hovering above which cell. The braille display consisted of six individual braille cells with four active braille pins in each cell. In total, the braille display had 24 active braille pins. The pins could show the first ten letters of the braille alphabet (a, b, c, d, e, f, g, h, i, j), which could be refreshed at a rate of 20 Hz. This gives us a million possible meaningless distinct words. Narrowing down letter variety reduces pin costs and also helps maximizing participants' concentration and reading performance. The pins inside of the braille display were changeable (to standard pin, pin#1 and pin#5). Moreover, the display was capable to work with or without Gore-Tex.

B. Participants and Experimental Design

Ten participants aged 14-53 years (M = 23.4, SD = 12.2) participated in the experiment. Participants were recruited by contacting different associations for the visually impaired in whole Europe. Of all the contacted associations, a German and a Dutch association were willing to help recruiting participants. Two participants were recruited via the German association and eight via the Dutch association. 70% of our participants were male and 90% was blind. Table 1 shows all sample characteristics. The experimental design was a 2 (surface layer: Gore-Tex vs. no Gore-Tex) x 3 (pin design: pin#S vs. pin#1 vs. pin#5) within-subjects factorial design. To avoid order effects, the six conditions were counterbalanced using the Latin Square method. The sequences of the braille characters were pseudo randomly generated. Therefore, it is acceptable to assume that their effects were similar. Even though we recognized that every letter would provide different parameters on analysis depending on the fact that some braille characters are considerably harder to react than others we assume the difference is negligible.

TABLE I. SAMPLE CHARACTERISTICS

Parameter	M	SD	%
Demographics			
Age (range 14-53)	23.4	12.2	
Female			30
Male			70
German			20
Dutch			80
Education[a] (German)	5.0	1.41	
Education[a] (Dutch)	7.5	.71	
Impairment Characteristics			
Visual impairment (Blindness)			90
Visual impairment (Severe)			10
Years of impairment	20.6	13.62	
Braille-Reading Characteristics			
Years since braille learning	14.89	13.62	
Braille learned at school			100
Reading proficiency	6.1	.99	
Reading frequency	4.9	.32	
Reading pace	5.6	.97	
Pin pressure	3.0	1.05	
Braille-Reading Style			
Left hand			40
Right hand			20
Both hands			40

a. Due to differences in educational systems in the Netherlands and Germany there are two different education scales: Education NL scale ranging from 1 – 7 and Education GER ranging from 1 – 12, with higher scores representing higher levels of education.

C. Procedure

At the beginning of the experiment, informed consent was obtained either from the participant self (participant age 18+) or from his/her parents (participant age <18). The informed consent was prepared according to the Helsinki Declaration [12], and the study was approved by our ethical committee.

The experiment consisted of two parts and took about 30 minutes. Part 1 consisted of a reading task and part 2 of a questionnaire. At the beginning of the reading task, participants were given time to familiarize with the braille display. Participants had their own reading style, speed, dominant hand or fingers, but we did not predefine in the instructions how they should read. Instead, we ascertained these variables in the questionnaire and checked afterwards if we had to control for them in our statistical analyses. During the reading task, participants were asked to read out aloud six braille letters on the braille display. These letters were completely random, meaning that they did not form words together. We asked participants to read these letters aloud one by one and from left to right. The random allocation of the letters gave us a better indication of the reading performance of the participant, because participants could not guess the next character. After the participants had read the first six letters, we changed the braille letters into six different characters and asked participants to continue reading them from the beginning. After repeating this procedure ten times, we had 60 reading recordings per participant. Reading one condition took participants up to three minutes depending on their braille-reading efficiency. After ten swipes, participants could take a break while we were changing the setup to the next condition. Then we started over again. In order to control for the reading performance parameters, a camera and a microphone recorded participants' responses. After completing all six conditions with a single participant, we recorded a total of 360 individual letter readings we could analyze. After completing the reading task, we asked them for feedback about their experience with the braille display using a questionnaire. They were encouraged to be forthcoming about their answers. We guided participants through all the steps of the study in their own language.

E. Observational Parameters

During our experiment, we collected observational data (i.e., data captured by the camera) as well as self-report data (i.e., data collected via the questionnaire). Table II lists all the observational and self-report parameters.

TABLE II. MEASURED PARAMETERS

t_{cr}	Correct Response	Average time spend to read one braille character correctly
t_r	Response	Average time between first touch to the braille cell and first answer
t_s	Swipe Time	Average total time spend to read all the six braille characters
p_{er}	Error Rate	Percentage of incorrect answers to all answers
p_{ir}	Inconsistency Rate	Percentage of consecutive incorrect answers to all answers
P	Pleasantness	How pleasant is the use of pin/surface (1 = very unpleasant, 7 = very pleasant)
C	Comfortableness	How comfortable is the use of pin/surface (1 = painful, 7 = comfortable)

After the experiment, we interpolated performance of each subject on the stimulus for each condition. We took the standard pin data as reference point to compare different conditions. As we post-processed the data, we were able to investigate how much braille-reading performance an individual subject is losing or gaining by changing from standard pin condition to other conditions. By interpolating the multiple arrays of data, it is possible to degrade multiple trials to a single plot.

F. Self-report Parameters

In our questionnaire we measured two sets of parameters, pleasantness and comfortableness. Pleasantness and comfortableness were assessed by asking participants how they experienced the use of the different pins and surfaces. Pleasantness was measured with one seven-point Likert scale item (1 = very unpleasant, 7 = very pleasant) and comfortableness was measured with one seven-point Likert scale item (1 = painful, 7 = comfortable). In addition, a number of control variables were collected to make sure that our effects were not caused by other individual differences between participants. First, we measured demographic characteristics, such as age, gender, and education. Second, we ascertained braille-reading characteristics, such as reading proficiency, reading frequency, reading pace, pin pressure, number of years since braille learning, and place of braille learning. Finally, we determined participants' preferred reading hand. Table 1 summarizes these control variables.

V. Experimental Results

A. Pre-Analysis

Descriptive analyses revealed that there were some skewness and kurtosis problems in our data, which were probably due to the equally good performance of all participants. Consequently, the assumption of normality was not met and parametric tests could not be used. To remedy these problems, we performed logarithmic transformations on the data. Positively skewed variables were transformed using the logarithmic function on each of the variables. As the logarithm cannot be used on scores ≤ 0, we carried out score reflection (i.e., maximum value + 1 – variable value) on the negatively skewed variables before using the logarithmic function. Moreover, we added the constant 1 to each variable containing 0. After these transformations, most skewness and kurtosis problems were remedied. Only two of the six $\mathbf{p_{er}}$ and $\mathbf{p_{ir}}$ variables persisted in suffering from skewness problems. Therefore, results concerning these variables ought to be treated with caution. In addition, correlational analyses revealed that the performance parameters $\mathbf{t_{cr}}$ and $\mathbf{t_r}$ suffered from multicollinearity problems, because Pearson correlation coefficients were above .80 for these parameters. A closer examination of the correlation coefficients of $\mathbf{t_{cr}}$ and $\mathbf{t_r}$ showed that pin#1 probably caused the multicollinearity issues, because in most of the cases, pin#1 was highly correlated (>. 80) with pin#S. This means that the difference between pin#S and pin#1 was not great enough and that pin#S and pin#1, therefore, could not be treated as individual conditions with respect to the parameters $\mathbf{t_{cr}}$ and $\mathbf{t_r}$. To solve this multicollinearity issue, we decided to exclude pin#1 when analyzing the parameters $\mathbf{t_{cr}}$ and $\mathbf{t_r}$. As there were no multicollinearity issues related to the other parameters, pin#1 was still included in these analyses. Finally, correlational analyses showed that only the control variable reading frequency was significantly related to our dependent variables. Therefore, we included reading frequency as a covariate in all further analyses.

B. Testing Hypothesis

The mean values and standard deviations are presented in Table IV, while the results of the repeated-measure analysis of variance (ANOVA) tests are shown in Table III.

TABLE III. Results repeated-measures ANOVA

		F	***p***	η^2
$\mathbf{t_{cr}}$	Surface	3.65	.09	.31
	Pin Design	5.6	.05	.41
	Surface x Pin Design	4.56	.07	.36
$\mathbf{t_r}$	Surface	2.99	.13	.27
	Pin Design	4.88	.06	.38
	Surface x Pin Design	2.84	.13	.26
$\mathbf{p_{er}}$	Surface	0	.99	0
	Pin Design	3.22	.07	.28
	Surface x Pin Design	3.44	.06	.3
$\mathbf{p_{ir}}$	Surface	.03	.88	0
	Pin Design	3.21	.07	.29
	Surface x Pin Design	.69	.51	.08
$\mathbf{t_s}$	Surface	1.88	.21	.19
	Pin Design	3.13	.07	.28
	Surface x Pin Design	2.38	.13	.23

Our hypothesis was tested using a 3 (pin design: pin#S vs. pin#1 vs. pin#5) x 2 (surface: Gore-Tex vs. no Gore-Tex) repeated-measures GLM for each dependent variable, with pin design and surface as within-subjects factors.

The analysis with $\mathbf{t_{cr}}$ as dependent variable showed a significant main effect of pin design on correct response, $F(1, 8) = 5.60$, $p < .05$, $\eta^2 = .41$. Post-hoc Least Significant Difference (LSD) tests showed that the time to give a correct response was marginally significantly higher for the standard pin (pin#S) ($M = 2.91$, $SE = .02$) than for pin#5 ($M = 2.88$, $SE = .02$). Moreover, there was a marginally significant main effect of surface on correct response, $F(1,8) = 3.65$, $p < .10$, $\eta^2 = .31$. Pairwise LSD comparisons revealed that the Gore-Tex surface led to a higher correct $\mathbf{t_r}$ ($M = 2.94$, $SE = .02$) than the no Gore-Tex surface ($M = 2.85$, $SE = .03$). In other words, participants needed more time for a correct response with the Gore-Tex surface than with the no Gore-Tex surface. Finally, there was a marginally significant interaction effect of pin design and surface, $F(1, 8) = 4.56$, $p < .10$, $\eta^2 = .36$. As can be seen in Fig. 6, when using the Gore-Tex surface, the time participants needed to give a correct response was lower when pin#5 was used than when pin#S was used. Pin#S and pin#5 performed equally well without Gore-Tex.

The analysis with $\mathbf{t_r}$ as dependent variable yielded a marginally significant main effect of pin design on $\mathbf{t_r}$, $F(1, 8) = 4.88$, $p < .10$, $\eta^2 = .38$. However, post hoc LSD tests did not reveal a significant difference between pin#S and pin#5. Investigating the overall means, we generally see the trend that t_r is higher for pin#S than for pin#5. Yet, this is just a trend and needs to be treated cautiously.

Using error rate as dependent variable, we found a marginally significant main effect of pin design on error rate, $F(2, 16) = 3.22$, $p < .10$, $\eta^2 = .29$, with post hoc LSD tests indicating that pin#S led to a significantly higher error rate ($M = .42$, $SE = .08$) than pin#5 ($M = .23$, $SE = .06$). Moreover, there was a marginally significant interaction effect of pin design and surface on error rate, $F(2, 16) = 3.44$, $p < .10$, $\eta^2 = .30$. As can be seen in Fig. 7, the display with the Gore-Tex surface led to a higher error rate than the display without Gore-Tex. Moreover, when using Gore-Tex, the error rate was the lowest for pin#5 and highest for pin#S and pin#1. Pin#5 with Gore-Tex cover performed best among all conditions. Finally, we can see that there is no big performance difference between pin#5 with Gore-Tex and the bare pin#S. This implies that pin#5 with Gore-Tex might be a good replacement for the old technology. As mentioned above, these results have to be treated with caution, because two of the six error rate variables were still a bit skewed after the logarithmic transformation.

The analysis with inconsistency rate as dependent variable yielded a marginally significant main effect of pin design on inconsistency rate, $F(2, 16) = 3.21$, $p < .10$, $\eta^2 = .29$. Pairwise LSD comparisons revealed that the inconsistency rate was significantly lower for pin#5 ($M = .28$, $SE = .08$) than for pin#S ($M = .53$, $SE = .10$).

Using swipe time as dependent variable, the analysis revealed a marginally significant main effect of pin design on swipe time, $F(2, 16) = 3.13$, $p < .10$, $\eta^2 = .28$. However, post hoc LSD tests did not reveal any significant differences between the three pin designs. Investigating the overall means, we generally see the trend that swipe time is the highest for pin#S, and the lowest for pin#5 when Gore-Tex is used. Yet, this is just a trend and needs to be treated with caution.

TABLE IV. MEANS AND STANDARD DEVIATIONS FOR ALL OBSERVATIONAL PARAMETERS

Within-subjects Factors		t_{cr}		t_r	
Surface	***Pin Design***	***M***	***SD***	***M***	***SD***
w/o Gore-Tex	Pin#S	2.85	.1	2.85	.1
	Pin#1				
	Pin#5	2.85	.09	2.85	.09
w/ Gore-Tex	Pin#S	2.97	.12	2.97	.12
	Pin#1				
	Pin#5	2.91	.07	2.92	.08
Within-subjects Factors		t_s		p_{er}	
w/o Gore-Tex	Pin#S	.22	.28	.3	.39
	Pin#1	.06	.19	.06	.19
	Pin#5	.05	.15	.06	.19
w/ Gore-Tex	Pin#S	.63	.48	.76	.56
	Pin#1	.61	.32	.78	.43
	Pin#5	.41	.32	.5	.41
Within-subjects Factors		p_{ir}			
w/o Gore-Tex	Pin#S	3.59	.16		
	Pin#1	3.6	.15		
	Pin#5	3.57	.17		
w/ Gore-Tex	Pin#S	3.7	.16		
	Pin#1	3.69	.1		
	Pin#5	3.65	.12		

C. *Self-Report Data*

Next to the observational performance parameters above, we also measured participants' perception (i.e., pleasantness and comfortableness) of the display with or without the Gore-Text surface and of the different pin designs. To examine if there were any differences of participants' perception of the display with or without the Gore-Text surface, we conducted two paired-samples t-tests. The first paired-sample t-test with pleasantness as dependent variable showed that participants perceived the display with the Gore-Tex surface to be significantly more unpleasant (M = .68, SD = .19) than the display without the Gore-Tex surface (M = .08, SD = .17), $t(9) = 6.94$, $p < .001$ (2-tailed). Moreover, there was no significant difference between participants' perception of comfortableness between the display with the Gore-Tex surface and without Gore-Tex, $t(9) = .51$, $p = .62$ (2-tailed). Furthermore, we conducted two repeated-measures GLM to examine participants' perception with respect to the three different pins. Results showed that there were no significant effects of pin design on pleasantness perceptions, $F(2, 18) = 1.24$, $p = .31$, and comfortableness perceptions, $F(2, 18) = 1.06$, $p = .37$, meaning that participants did not perceive a difference between the three pins.

VI. CONCLUSION AND DISCUSSION

From our two experiments, we can conclude that the tangential force curve has a strong correlation with the phenomenal tactile perception. Thus, the primary objective of this study was satisfied. In addition, we found that pin#5 performs constantly better than other pins regarding the performance parameters. In contrast, Gore-Tex diminishes performance. However, the combination of Gore-Tex and pin#5 seems to be a promising option for replacing the bare standard pin.

Investigating how pin design and surface affect performance parameters of tactile displays is very important, given that there is an urgent need for reducing maintaining costs of tactile displays. Such an investigation is, however, difficult, and we therefore need to consider some limitations of our study. First of all, we need to consider the low sample size of our study. It is probably due to this low sample size that we only found marginally significant effects. However, our effect sizes are mostly medium sized, which is why we are confident about our findings.

Even though our research was inspired by a problem in braille displays (i.e., contaminant resistance problems), our findings are applicable to other circumstances. Such connection leads us to the more general discussion that it might be possible to create tactile sensation corrections based on the use of materials and shapes for a variety of devices. Further research should also foster the leveraging of haptic illusions for new exciting applications.

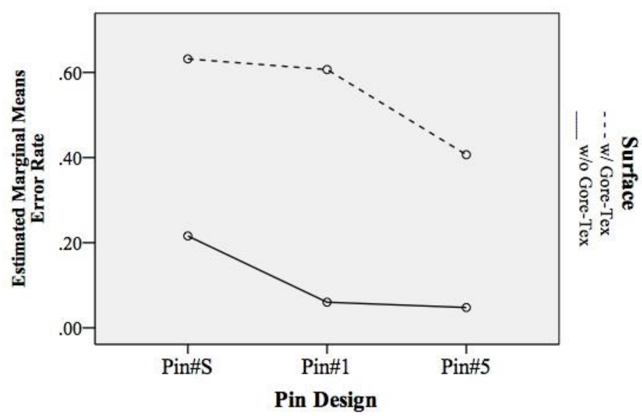

Figure 6. Interaction effect of pin design and surface on $\mathbf{p_{er}}$.

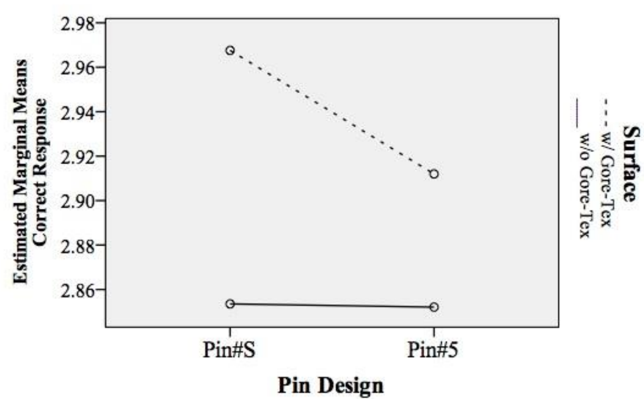

Figure 7. Interaction effect of pin design and surface on $\mathbf{t_{cr}}$.

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