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Scalability of the Size of Patterns Drawn Using Tactile Hand Guidance

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Scalability of the Size of Patterns Drawn Using Tactile Hand Guidance

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Abstract— **Haptic feedback for handwriting training has been extensively studied, but with primary focus on kinematic feedback. We provide vibrotactile feedback through a wrist worn sleeve to guide the user to recreate unknown patterns and study the impact of vibrational duration (1, 2, 3 seconds) on pattern scaling. User traces a line at 90° angles, while attempting to maintain a constant speed, in the direction of the motor activated till a different motor activation is perceived. Shape and size are two features of good letter formation. Study performed on three subjects showed the ability to utilize four vibrotactile motors to guide the hand towards correct shape formation with high accuracy (> 95%). The overall size of the letter was observed to scale linearly with the vibrational duration. Implications for utilizing the vibrational feedback for handwriting correction are discussed.**

Keywords-wearable haptics; tactile sleeve; handwriting; letter size and shape; tactile hand guidance.

I. INTRODUCTION

Handwriting is an important lifelong skill that can be challenging to acquire for children with learning disabilities and post-stroke patients with agraphia. Tracing, copying, and completing paper worksheets, with the help of corrective auditory feedback, remains the common mode of teaching this skill. Providing haptic feedback in addition to the audio-visual format has shown to improve visuo-motor skills (a prerequisite to handwriting training) [1]][2], character retention [3] and the overall handwriting quality [4]. Several haptic guidance methods have been developed for handwriting training [1][3][5]-[11], with their suitability depending on the complexity of the task. For example, partial haptic guidance may be better suited for medium complexity letters/handwriting tasks, while disturbance haptic guidance for high complexity letters and full haptic guidance for the low complexity letters [8]; and combining the different haptic guidance methods over the training period has been more effective than utilizing either of them alone [9]. These systems while benefiting the sighted can also provide the visually impaired an accessible means of learning to write/sign their name [12][13].

Owing to its ready availability to the research community, Phantom Omni has been the primary platform for developing these systems [1][3][5]-[11][13]. Although Phantom Omni based handwriting training has shown to be effective, it is still not a common training tool in classrooms. Their bulk and tethered nature, requiring allocated workstations in addition to their cost, might be a hinderance in their widescale adaptability. Utilizing similar force feedback principles of hand guidance, other ergonomically focused stylus systems like RealPen [14] and KATIB [15] are currently being developed. While technologically promising, they are not cost-effective options yet.

Meanwhile, there is growing research in utilizing tactile feedback for hand movement guidance [16]-[24]. These systems employ inexpensive vibrators/motors to develop affordable wearable solutions that could be easily accessible to the educators, as well as the research community. We are investigating the efficacy of vibrotactile wearable system for handwriting training. To this effect, we provide a brief overview of the vibrotactile hand guidance methods that have been investigated.

In a large trial study, Matscheko et al. [16] achieved higher information transfer rate by placing tactors around the wrist vs. placing them in a grid on the dorsal side, while also demonstrating a lower impact of distraction load. They concluded that wrist worn tactile systems should place tactors around the wrist instead of in a grid form. They attributed the reduced accuracy (in the latter case) to space restriction of placing the grid beneath "the watch face" area while meeting the two-point discrimination requirement of about 38mm. Most systems have followed this guideline for motor placement with the motor type, number, or actuation method being the differentiators.

Sergi et al. [17] used four Direct Current (DC) motors to provide tactile feedback on the four quadrants (dorsal, volar, radial, ulnar sides) of the wrist for angular directional guidance of the entire forearm in performing 2-Degree Of Freedom (DOF) tasks and showed an increased accuracy by including the tactile feedback in comparison to visual alone. Causo et al. [18] utilized 6 vibrating disk motors worn on a stationary arm for posture correction of the other arm in a 3D space with each axis being assigned to two motors. The user is supposed to move their wrist (and then elbow, and later forearm) towards the direction of increasing vibration till a maximum vibration is felt indicating the correct final position. Salazar et al. [19] arranged six vibrational motors at equal distances around the wrist circumference for wrist guidance in 2D space using phantom sensation illusion (produced by simultaneously actuating two adjacent motors resulting in a perceived stimulus at their midpoint). Hong et al. [20][21] developed different wristbands for angular path finding/tracing in 2D surface, one with four vibrating disk motors placed along four quadrants of the wrist (like Sergi et al.) and the second with an additional four motors placed in between these, totaling to eight motors around the wrist. They found the 4-motor wristband to be faster, more accurate and preferred over the 8-motor design. They also performed comparative study between activating single motor vs. providing illusions by activating two adjacent motors and found that participants could non-visually trace paths more quickly and accurately using the single motor activation design.

VibroSleeve [22] proposed placement of 16 vibrating disk motors on a sleeve worn around the forearm (a row of four motors on each forearm quadrant: dorsal, ventral, medial and lateral) for arm guidance in 3D Cartesian space. In a test where they examined the user's ability to correctly identify the stimulation side (top/bottom/left/right), they simultaneously activated all the four motors on that side for 500ms before requesting participant response resulting in 100% accuracy. They aimed to study the perceived direction of motion using movement illusion generated by the sequential stimulation of motors, from the proximal to distal end of the forearm for forward motion (or vice versa for backward motion). They also utilized Amplitude Modulation (AM) where the intensity of the previous motor was reduced before the activation of the next motor in the sequence. While they found highest directional accuracy (85-90%) and subjective ease of interpretation in the AM pattern representation method, this was also the only activation sequence where they had provided a break (100ms) between the activation of successive motors. Hence, it is inconclusive whether the increased direction recognition was due to the AM pattern or the difference between continuous activation vs. with breaks, or even due to the introduction of movement illusion.

StrokeSleeve [23][24] design utilized two sleeves (worn on the wrist and biceps respectively), each embedded with four eccentric mass motors for hand guidance and movement training. The arm motion was tracked, and upon detecting a deviation from the desired trajectory, visual and vibratory feedback was provided. They found that vibratory feedback significantly reduced the angular error in motion during the training, especially for simpler tasks. Although they did not observe a significant angular error reduction during their retention trials, they attributed this to the short training period and the meaninglessness of the motions performed reducing the intrinsic motivation to memorize the trajectories.

In vibrotactile hand guidance research area, there are limited studies in utilizing tactile wearable systems for handwriting training. A few exceptions are Morikawa et al. [25][26] and Narita et al. [27][28] that utilize wrist worn pressure presentation device for calligraphy training. They use two levers mounted on the wrist to provide stimulations (gentle taps) to correct the user's hand position along the horizontal direction, for self-training. They do not provide any vertical direction feedback.

Towards the goal of developing wearable vibrotactile handwriting training system, this study investigates the ability to utilize a sleeve for guiding the user towards the correct form (shape) and size/scale of different characters. Therefore, vibrations are provided at different spatial locations on a forearm (representing the direction of desired motion), and participants are asked to draw unseen patterns on graph paper (with grids) as the only visual guide.

Appropriate form and size are key features of good letter formation [29]. Focusing on the proper sizing of the letters (prior to the form) has shown to improve letter form and handwriting legibility [30]. Hence, this work aims to study the applicability of utilizing a vibrotactile sleeve embedded with four motors for presenting the correct form of select letters from English, Arabic and Malayalam (a south Indian language) that are hidden from the user. We investigate the ability of using vibrotactile cues for controlling the size of each of these letters.

This paper demonstrates the preliminary results of utilizing tactile feedback for controlling the form and size of letters drawn by the user. In Section II, an overview of the vibrotactile sleeve is provided, section III lists the scope of this study, section IV describes the experimental setup for data collection, section V explains the results, and section VI concludes with a summary and future work.

II. BACKGROUND

The sleeve and the system architecture being utilized in this study has been presented in prior works [31][32] with a learn-to-write software that tracks pen movement (based on a webcam input) as the user tries to trace a pattern displayed on the screen. If the pen deviates from the pattern being traced, motors embedded within the sleeve provide vibrational feedback guiding the user's hand in the correct direction. Different arrangements of the motors on the sleeve were considered and the accuracy of perceived location and user response time were investigated to identify the best location for motor placement [32]. A summary of the sleeve design is provided below for completeness.

A. Motor placement

Since four motor wristbands were found to be accurate and intuitive for hand guidance in 2D space [21], our hardware utilizes four mini vibrating disk motors. Only a single motor is activated at a time, thus enabling faster response by reducing the cognitive load/confusion introduced by providing illusions [19]. The activated motor represents one of the four directions (up, down, left, or right) of desired motion.

Four different arrangements of motor placement on the sleeve were considered. Initially, the motors were placed around the four quadrants of the wrist (ring configuration) as recommended by literature [16]. Since the two-point discrimination on the forearm is between 25mm [33] and 38mm [34], we also performed initial testing by placing the four motors in other configurations with spacing of 50mm or more.

In top-arm configuration, two motors were placed on the dorsal side of the forearm, one near the wrist/distal region and the other 10cm apart on the proximal region, with none on the ventral side and in bottom-arm configuration both were placed on the ventral side with similar spacing as previous, with none on the dorsal side. In spaced-ring configuration, one motor was placed near the wrist on the dorsal side of the forearm and another one was placed on the ventral side near the proximal side of the forearm (10cm from the wrist motor). The other two motors were each placed on the radial and ulnar side midway between these (i.e., 50mm from the wrist).

Preliminary testing performed on three subjects on the ability to identify the activated motor showed an average accuracy of 94% using the wrist-ring arrangement and 98% using the spaced-ring arrangement. Spacing the motors on the same side (dorsal or ventral alone) also gave higher average accuracy (96%) but there appeared to be a directional bias wherein the down motor was often misidentified as the right motor. It was also observed that the spaced-ring arrangement had the fastest user response speed (average 1.02s, ranging from 0.45s to 1.6s) among the four configurations [32].

Hence, the spaced-ring arrangement was chosen for our sleeve design with a motor embedded on each side of the forearm: up motor on the dorsal side near the wrist, down motor on the ventral side near the proximal region 10mm away from wrist, left motor on the lateral side 5mm away from wrist, and right motor on medial side 5mm away from wrist.

B. *Motor Control*

Four mini vibrating disk motors by Adafruit (ADA 1201) were embedded into a fabric sleeve. The motors are controlled using ESP32 microcontroller and two dual DC motor drivers (TB6612FNG). Pulse Width Modulated (PWM) signal from the ESP32 is used to control the intensity of vibrations. In this study, the vibrational intensity is kept constant using a square waveform (50% duty cycle) at 250Hz frequency. The ESP32 is powered using a 3.7V 500mAh Lithium-ion battery.

III. SCOPE

This study evaluates the feasibility of utilizing the tactile sleeve for handwriting intervention, with the eventual goal of providing a corrective feedback to their hand in case they deviate from the alphabet/pattern they are trying to trace/draw. Hence, it investigates the following:

a) will the user be able to respond to a vibration and correct their hand movement in the desired direction, while they are attempting to draw a pattern?

b) can the user's hand move a consistent distance for identical vibrational cues (same vibrational intensity for the same time)?

The response of a user in drawing a pattern projected on their arm via the tactile sleeve, was tested to understand the accuracy, scalability, and variability in the drawn pattern as a function of tactile duration.

The study uses a wrist worn sleeve embedded with four mini vibrating disk motors, with a single motor being activated in the desired direction of movement (up, down, left, or right), thus providing 90° directional cues only. The vibrotactile sleeve was used to guide participants through blind patterns of low, medium, and high complexity, grouped based on the number of directional changes required to complete the pattern.

It was hypothesized that the participants will be able to identify the vibrational direction provided by the sleeve and trace these blind patterns with high accuracy. Also, another hypothesis was that the size of the patterns drawn will scale with the duration of vibration. Finally, it was hypothesized that shorter vibrational durations (< 3 seconds) will show higher variability in the pattern size, due to a significant portion of the duration (approx. 1 second) being used for comprehending the direction to be moved in.

IV. EXPERIMENTAL SETUP

Due to COVID-19 restrictions on large scale human subject testing, this pilot study performed initial data collection on three healthy adult volunteers, with no prior experience of using wearable haptics. All the participants were right-handed and wore the sleeve on the dominant forearm (Figure 1).

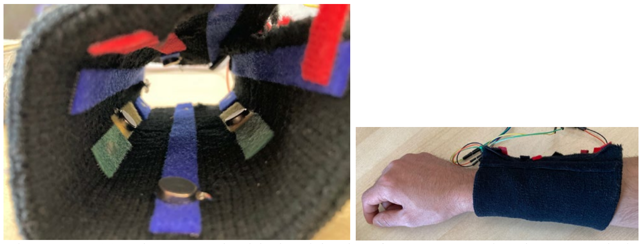


Figure 1. (a) Sleeve embedded with the four motors in the spaced-ring arrangement. (b) Sleeve worn by one of the participants.

Data was collected to test the accuracy of the (a) perceived location, (b) pattern formation (shape), and (c) pattern sizing (scaling) based on the vibrational duration provided. Prior to the data collection, each subject was given 5 minutes to self-train by activating a desired motor on the sleeve using directional keys on a keyboard. The testing was performed as described below.

A. *Training*

The participants were asked to use a pen and draw straight lines in the direction of the activated motor on a graph paper (with 0.5cm x 0.5cm grids). They were provided a pattern, corresponding to English letter *f* for training.

The letter *f* was converted into square font such that it required the following pen movements to draw: 2cm towards right, 4cm up, 3cm right, 3 cm left, 2cm down, 1cm left and 2 cm right as shown (Figure 2). Each 1cm distance expected to be traced was encoded into 1s of continuous motor vibration in that direction, when presented using the sleeve. Continuous movement in one direction is considered one segment. Hence, the letter f consisted of 7 segments. The change from one segment to next is also continuous, i.e., as soon as the first 2s of vibration on the right motor are completed, the up motor starts vibrating and the participant has no prior information that the vibration location is about to change.

Initially, the participants were provided a graph paper and asked to draw the pattern based on straight movements in the direction of vibration perceived. Then, they were provided the graph paper with the letter f already drawn to the expected size/scale. They practiced tracing on this letter multiple (3-4) times while receiving the vibrations corresponding to the pattern through the sleeve.

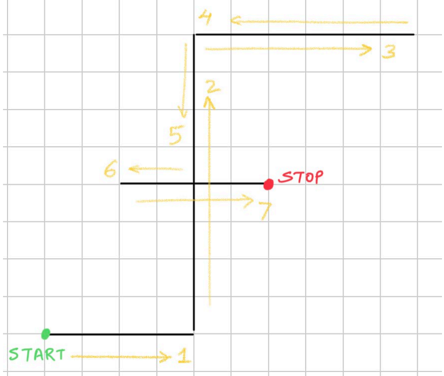


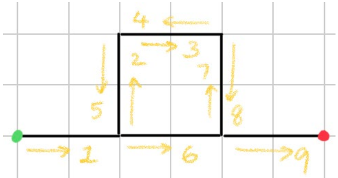
Figure 2. Letter f in square font showing the 7 segments to be drawn in the order numbered. Each grid is 0.5cm and each 1cm distance is encoded using a 1s vibrational duration/movement in that direction.

B. *Blind Pattern Drawing*

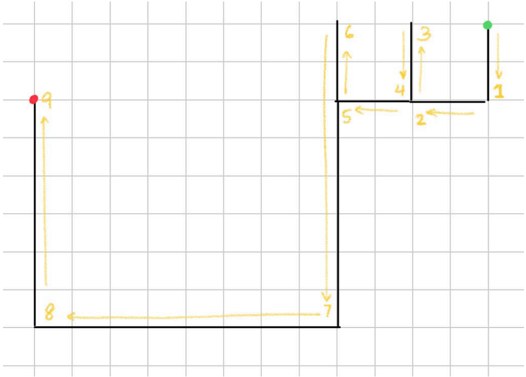
Five patterns, corresponding to English cursive letter (a), Arabic letters (s, f) and Malayalam letters (a, sh), converted into square font were randomly projected to the participant's arm through the activation of corresponding motor. Based on the number of directional changes (segments) required to complete the pattern, the patterns were grouped as low, medium, or high complexity.

English letter *a* was broken into 9 segments (medium complexity) of equal lengths in the following direction: right, up, right, left, down, right, up, down, right (Figure 3. a). The Arabic letter *s* had 9 segments (medium complexity) and letter *f* had only 6 segments (low complexity). High complexity Malayalam letters *sh* had 12 segments and *a* had 16 segments.

The shortest length (1cm) was encoded into 1s of continuous motor vibration in that direction. The low and medium complexity letters were presented at three scales: at 1s, 2s, and 3s. i.e., the same pattern was presented with 2x and 3x the duration of vibration per 1cm distance, to evaluate how the same pattern would be scaled by the participants based on modulating the vibrational duration. To avoid fatigue, the high complexity letters were only presented once to the participant at 1s scale.

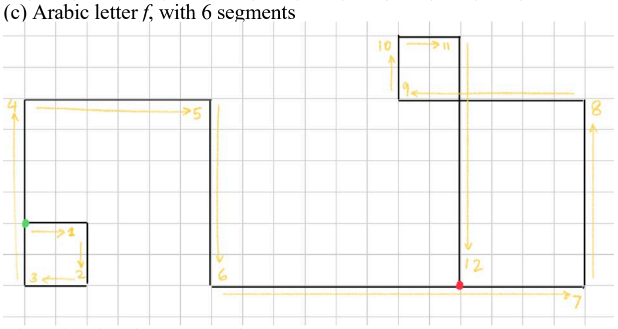


(a) English letter *a* in square font, with 9 segments

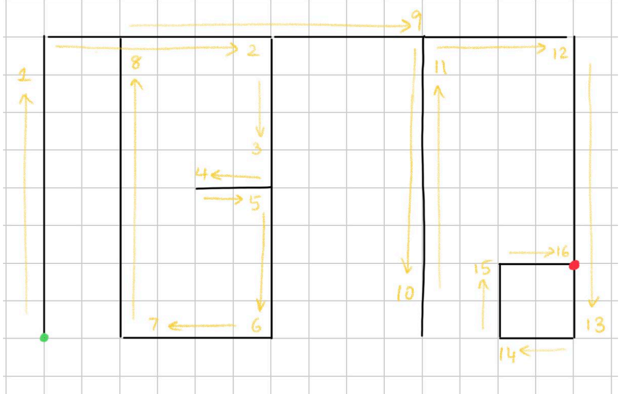


(b) Arabic letter *s*, with 9 segments

(c) Arabic letter *f*, with 6 segments



(d) Malayalam letter *sh*, with 12 segments



(e) Malayalam letter *a*, with 16 segments

Figure 3. Letters showing corresponding number of segments and their order.

The letter/pattern and the duration were randomly picked. The participants were not informed on what pattern they were being provided, although a countdown was provided to prepare them for the start of the pattern. None of the participants knew to read Arabic or Malayalam alphabets and no feedback was provided (during or after any trial) on whether the pattern was correctly drawn or not. Blind patterns were provided so that the subject's ability to identify the vibrational location and respond to changes in the vibrational direction while performing the task of tracing a pattern could be isolated from their ability to trace known/seen patterns. They were asked to try and maintain their speed of drawing but were not provided any cues during (or after) the trials to modify their speed. They were provided 2-3 minute break between each pattern.

V. PRELIMINARY RESULTS

The data was collected from three participants. Each of them drew 11 blind patterns (3 scales of 3 low/medium complex letters and 1 scale of 2 high complex letters) corresponding to 100 segments/directional changes per participant. This data was analyzed for the accuracy, scalability, and variability of drawn patterns as a function of the vibrational duration.

A. *Pattern Shape*

The participants were able to replicate the shape of the unknown pattern with a high accuracy. Pattern accuracy was measured as the movement in the correct direction for a given segment with respect to the direction presented by the activated motor. The participants drew the blind patterns with an average accuracy of 95.67% (individual accuracy of 96%, 95% and 96% per subject). This corroborates the initial measurements made on perceived location accuracy and demonstrates that subjects can distinguish and move in the direction of the vibration even while drawing patterns.

The error was either due to the subject drawing a segment in the wrong direction or missing a segment/directional change completely and continuing in the same direction. Missed segments: Two subjects missed one segment while the third subject missed two segments. Each of the missed segments were the shortest 1cm segments, though not from the same pattern and not for the same time duration.

B. *Pattern Size and Scalability*

To determine whether the participants could maintain a steady size for the segments with same vibrational duration, and how the sizing of segments with longer duration scaled – length of each of the 100 segments were measured. The segment length/size (in cm) vs. continuous tactile duration, cumulative for all the subjects, is shown in Figure 4.

As seen from the Figure 4, the size of the segments drawn by the subjects increases linearly with the increase in tactile duration. That is, the size of the patterns can be scaled linearly as a function of the tactile duration. Hence, once trained on a pattern, the user can be expected to move their arm relatively steadily for the same intensity of vibration.

It should be noted that the participants in this study were not aware of how long any of the segments were (or how long the vibration would be felt in that direction) and when a new segment (or change in direction) would occur. Thus, they could not have predicted the segment length to be drawn.

TABLE I. STATISTICS OF SIZES DRAWN FOR THE DIFFERENT DURATIONS

Duration (s)	**1**	**2**	**3**	**4**	**6**	**8**	**9**	**12**
Avg. size (cm)	0.982	1.281	2.595	3.818	6.163	8.536	9.800	14.068
Variance (cm ^ 2)	0.013	0.062	0.242	0.524	1.198	2.522	3.410	10.251
Std. dev. (cm)	0.114	0.248	0.492	0.724	1.094	1.588	1.847	3.202
Median (cm)	1	1.25	2.5	3.75	6.1	8.4	9.875	13
CV	0.116	0.194	0.189	0.190	0.178	0.186	0.188	0.228

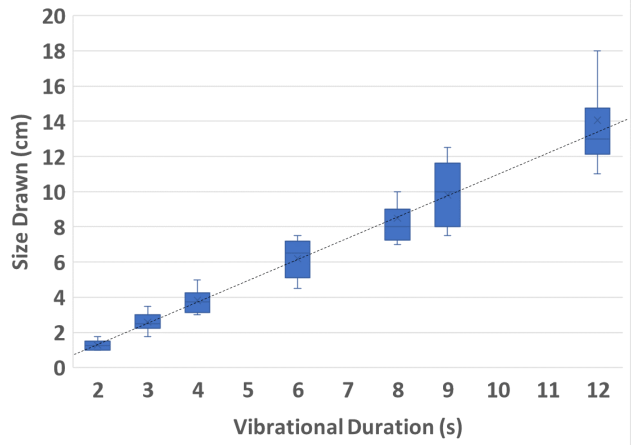


Figure 4. Cumulative data for the segment sizes drawn vs. the duration of continuous vibrational stimulation.

C. *Variability in Pattern Size*

Since the initial user response time had an average of 1s, it was hypothesized that it might be difficult to maintain a steady size for the shorter segments, due to the cognitive load of decoding the direction. However, in contrast to the assumption, as observed in Figure 4 and Table 1, the standard deviation in the drawn size for smaller segments is very low and increases as the segment length increases. Thus, as the tactile duration is increased, the error in size increases. Although the pattern scales almost linearly with tactile duration, the high variability for larger lengths indicates that when the vibrations provided continuously for a longer duration, it becomes more difficult to maintain the steady speed.

Breaking down the larger lengths into multiple shorter durations might provide a more controlled size. Considering the broken segments are independent of each other, the variance sum law (1) provides that the individual variances can be added together to determine the total variance for that segment. For example, the 12cm distance covered using 12s continuous vibrations results in a variance of 10.25cm^2. Breaking the 12s continuous vibrations into six shorter 2s continuous vibrations (σ^2_{2cm} = 0.062cm^2) with breaks in between would result in total variance of six times σ^2_{2cm} (2). Hence, reducing the overall variance to 0.36cm^2 in the 12cm length.

$$\sigma^2_{x+y} = \sigma^2_x + \sigma^2_y \qquad (1)$$

$$\sigma^2_{N.x} = N.\sigma^2_x \qquad (2)$$

where σ^2_x is the variance of segment with length x, $\sigma^2_{N.x}$ the variance of segment with length N times x, and N is the number of segments the total length is broken into.

The low variability for shorter lengths (< 5 cm) indicates the feasibility of utilizing continuous tactile durations for correcting handwriting movements that are expected to be within the short lengths.

VI. CONCLUSION AND FUTURE WORK

There is limited research on utilizing tactile feedback for handwriting training. This study shows the feasibility of utilizing a tactile sleeve to control the shape and size of blind patterns presented to the hand. A wrist worn sleeve embedded with four vibrating motors was utilized to guide the hand of three subjects. The subjects were asked to draw patterns, unknown to them, using the tactile feedback from the sleeve alone and were able to reproduce the patterns with high accuracy.

The impact of continuous vibrations on the sizing of the drawn segments was evaluated. It was observed that the segment lengths can be scaled linearly using vibrational durations. It is proposed that shorter segments, of less than 5cm, be provided using continuous vibrations. However, if longer segments need to be drawn, they can be broken into multiple small segments represented using continuous vibrations of less than 5s with a short break (eg. 100ms) between the segments. In handwriting training, the size of lines/segments drawn is usually less than 5cm and hence continuous vibrations of different time duration might be sufficient to provide the necessary scaling of the letter/pattern.

Currently, work is in progress to test this sleeve on a larger number of participants. The ability of subjects to draw more complex patterns using phantom sensations is also being explored. Future work includes testing this system on individuals with visuo-motor skills issues and/or handwriting learning disabilities. Furthermore, the impact of modulating the vibrational intensity on the handwriting patterns is yet to be studied.

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