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TITLE:

Tactile Semiautomatic Passive-Finger Angle Stimulator (TSPAS)

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KEYWORDS:

touch perception, tactile perception, tactile spatial acuity, working memory, tactile angle discrimination, logistic curve

SUMMARY:

Presented is the tactile semiautomated passive-finger angle stimulator TSPAS, a new way to assess tactile spatial acuity and tactile angle discrimination using a computer-controlled tactile stimulus system that applies raised angle stimuli to a subject's passive fingerpad, while controlling for movement speed, distance, and contact duration.

ABSTRACT:

Passive tactile perception is the ability to passively and statically perceive stimulus information coming from the skin; for example, the ability to sense spatial information is the strongest in the skin on the hands. This ability is termed tactile spatial acuity, and is measured by the tactile threshold or discrimination threshold. At present, the two-point threshold is extensively used as a measure of tactile spatial acuity, although many studies have indicated that critical deficits exist

in two-point discrimination. Therefore, a computer-controlled tactile stimulus system was developed, the tactile semiautomated passive-finger angle stimulator (TSPAS), using the tactile angle discrimination threshold as a new measure for tactile spatial acuity. The TSPAS is a simple, easily operated system that applies raised angle stimuli to a subject's passive fingerpad, while controlling movement speed, distance, and contact duration. The components of the TSPAS are described in detail as well as the procedure to calculate the tactile angle discrimination threshold.

INTRODUCTION:

Touch perception is a fundamental form of the sensations processed by the somatosensory system, including haptic perception and tactile perception. Passive tactile perception, as opposed to active exploration, means that the object is moved to make contact with static skin[1,2]. As in other senses, spatial resolution in tactile perception, also termed tactile spatial acuity, is usually represented by the tactile threshold, detection threshold, or discrimination threshold[2,3]. In the past 100 years, the two-point threshold has commonly been used as a measure of tactile spatial acuity[4]. However, many studies have indicated that the two-point threshold is an invalid index of tactile spatial ability because two-point discrimination (TPD) cannot exclude nonspatial cues (e.g., if two points are too close, they may locate a single afferent receptive field, which readily evokes increased neural activity) and maintain a stable criterion for responses[3–5]. Owing to the number of drawbacks of TPD, several new and promising methods have been developed as replacements, such as tactile grating orientation (GO)[3,6], two-point orientation discrimination[5], raised letter recognition, gap detection[7], dot patterns, Landolt C rings[8], and angle discrimination (AD)[9,10]. At present, because of the advantages in operating GO, as well as the spatial structure and complexity of the stimulus used, GO is increasingly used to measure tactile spatial acuity[11–13].

Although tactile GO is thought to rely on underlying spatial mechanisms, thereby yielding a reliable measure of tactile spatial acuity, it is still debated whether GO performance is partly affected by nonspatial cues[14] (e.g., intensive signs that may provide a cue to identify the difference between orientation stimuli). Additionally, GO only consists of simple spatial orientation (i.e., horizontal and vertical) tasks and primarily involves sensory processing, which limits its use when exploring the hierarchical interplay between tactile primary processing by the primary somatosensory cortex and tactile advanced possessing involving the posterior parietal cortex (PPC) and supramarginal gyrus (SMG)[15–17]. To compensate for these drawbacks, tactile AD was developed to measure tactile spatial acuity[9,10]. In AD, a pair of angles passively slide across the fingertip. The angles vary in size, and the subject needs to determine which of the angles is larger. To consistently accomplish this task, spatial features of tactile angles must be represented and stored in the working memory and then compared and discerned. Therefore, tactile AD involves not only primary processing but also advanced cognition of tactile perception, such as working memory and attention.

As in a variety of line orientation perception tests, in tactile AD the subject is presented successively with one reference angle and one comparison angle and is asked to indicate which is the larger angle[18–21]. The lines composing the angles are equal in length and symmetrically distributed along an imaginary bisector. By symmetrically changing the spatial dimensions of the lines, all types of raised plane angles can be created. Therefore, a critical advantage of this method is that the angles being differentiated have similar spatial structures. In addition, the spatial representation gained in the AD is more sequential than that gained in GO. However, the AD threshold provides evidence that tactile spatial acuity is sufficient to allow spatial discrimination between objects[22]. Furthermore, the tactile spatial perception of the angle may be experienced from point to line and finally form a two-dimensional plane angle in which nonspatial cues may play only a small role.

The AD threshold was found to increase with increasing age, which might result from the need for high cognitive load in the tactile AD task. Thus, it may provide a monitoring mechanism in cognitive impairment diagnosis[9,10]. Although AD performance is affected by age-related decline, it can be significantly improved in young people by continuous training or similar tactile task training[23]. Furthermore, fMRI studies showed that a delayed match-to-sample tactile angle task activated certain cortical regions responsible for working memory, such as the posterior parietal cortex[17,24]. These findings suggest that tactile angle discrimination is a promising measure for tactile spatial acuity involving advanced cognition. Here, the tactile AD equipment and its use is described in detail. Other tactile researchers can reproduce the AD equipment and use it in their research.

The tactile AD equipment, or tactile semiautomatic passive-finger angle stimulator (TSPAS), uses an electronic slide to convey a pair of angle stimuli to slide passively across the skin (**Figure 1**). The subjects' arms lie comfortably, prostrate on a tabletop. The right hand sits on a hand plate in the table, and an index fingerpad is situated slightly below the opening of the plate. Computer software can control the slide, move it at a fixed speed, and move it forward and backward. As the slide moves forward, the angle stimuli slide passively across the skin at a fixed speed starting at the fingertip. When the slide moves backward to its starting position and changes to another pair of angle stimuli, the subject needs to lift the index finger up and wait for an order to lightly place it again at the opening. Thus, the equipment presents tactile angle stimuli at a controlled speed, stable contact duration, and constant interstimulus interval. The subject orally reports a sequence number, and the experimenter registers it as a response and proceeds to conduct the next trial.

[Place **Figure 1** here]

PROTOCOL:

Written informed consent was obtained from the subjects in compliance with the policies of the local medical ethics committee of Okayama University. The testing procedures gained review and consent from the local medical ethics committee of Okayama University.

1. Detailed composition and function of equipment

1.1. Tactile angle stimuli

1.1.1. The TSPAS uses two-dimensional (2D) raised angles to slide passively across the skin and form a tactile spatial representation of the angles (**Figure 2**). The tactile angles consist of plastic lines and square bases, which are both made from a transparent acrylic sheet. Because the lines composing the angles are equal and symmetrical, by symmetrically changing the spatial dimensions of the lines, all types of raised plane angles can be created.

1.1.2. Using a milling machine, cut the acrylic sheet into the polyline with two equal lines (8.0 mm long, 1.5 mm wide, and 1.0 mm high) symmetrically distributed along an imaginary bisector and the square base (40.0 mm long and wide, 3.0 mm high).

1.1.3. Glue the polyline to the center of the square base to create a 2D raised tactile angle stimulus.

1.1.4. Make pieces with angle sizes ranging from 50° to 70° in 2° increments. The end point distances (*d*, see **Figure 2**) of these angles are 6.8 mm, 7.0 mm, 7.3 mm, 7.5 mm, 7.8 mm, 8.0 mm (60° angle), 8.2 mm, 8.5 mm, 8.7 mm, 8.9 mm, and 9.2 mm. To reduce the impact of the end point distance on angle discrimination to the minimum, use a 60° angle as the reference angle, and other angles as comparison angles.

1.1.5. Make up 20 pairs of discriminated angles, including 20 identical reference angles and 10 pairs of identical comparison angles whose measured accuracies are ± 0.2°. Ensure that the reference angle is presented first 50% of the time when each pair is tested. The experiment can be easily and conveniently updated with tactile angle stimuli.

[Place **Figure 2** here]

1.2. Hand plate

1.2.1. To stabilize the subject's hand, craft a hand plate perpendicular to the electronic slide (**Figure 3**). First, using a milling machine, cut a 5.0 mm thick acrylic sheet into a 14.0 cm x 22.0 cm rectangle plate, and then fasten the rectangle plate to a base (14.0 cm wide, 14.0 cm long, and 8.5 high) with tape and glue. After that, using a milling machine, cut a rectangular opening (2.5 cm wide and 5.0 cm long) in the upper left corner of the plate. This allows only the index finger to contact the angle stimulus. Before the experiment, fix the subject's right hand wrist with nylon tape, and then instruct the subjects to lightly place their right index fingers at the opening of the plate.

[Place **Figure 3** here]

1.3. Motorized linear slide

1.3.1. The electronic slide with a maximum motion distance of 51.0 cm is moved in a straight direction using an easy linear motion motor with 5.0 cm high, 5.4 cm wide, and 71.0 cm long (see **Table of Materials**), which is a linear-motion system. Connect the motor to a personal computer and set and edit various data using dedicated data editing software (see **Table of Materials**). Ensure that these settings can make the electronic slide move a specified distance using a given speed with respect to the reference point. This is necessary when moving the angle stimuli directly from an arbitrary position to a specified position.

1.4. Computer control system

1.4.1. The TSPAS is a semiautomatic, computer-controlled system. The data editing software used to control the movement of the slide is PC-based software for editing the data necessary for the operation of motorized actuators. In the experiment, set the velocity of the slide at 20 mm/s and its moving distance at 80 mm for each trial. Each time a button is clicked, the slide moves as previously set.

2. Running an experiment

2.1. Before the experiment, first set the motion type as '**INC'**, motion distance as '**80 mm**', motion speed as '**20 mm/s**', motion function as '**single**', and axis as '**ID = 0**' in the data editing software (see the operating manual in the **Table of Materials** for instructions on how to set parameters) to ensure that the electronic slide can move a distance of 80 mm and a speed of 20 mm/s forward and backward, and at other distances and speeds.

2.2. Recruit subjects whose fingers are free of injuries and calluses. Try to recruit an equal number of male and female subjects within the age range from 18–35 years old. Note that there is a difference in tactile spatial acuity between female and male subjects, as well as old and young subjects[25,26].

2.3. Blindfold the subject and sit him or her at a table with the apparatus (**Figure 1**). Fix the right hand of the subject with nylon tape and subsequently instruct the subject to lightly place his or her right index finger at the opening of the hand plate (**Figure 3**).

2.4. Clamp a pair of angles, including the reference angle and the comparison angle, on the slide. After clicking the button, the pair of angles slide for a total distance of 80 mm. They passively go across the index fingerpad at a speed of 20 mm/s. Because there is a distance of 31.8 ± 0.8 mm between the reference angle and comparison angle, their interstimulus time interval is approximately 1.6 s.

2.5. After the subject perceives the sizes of the angles, he or she orally reports which of the two angles is larger. If the subject cannot identify which angle is larger, he or she can indicate that the angles are the same. Register the answer of the subject as the response data. After that, the next pair of angles will be continually replaced, presented, and perceived in the same way.

2.6. There are a total of 10 pairs of angles in the formal experiment. Present each pair 10x in a pseudorandom order in which the reference angle passes first 50% of the time. Thus, the experiment contains 100 trials. To avoid uncomfortable sensations on the index finger, after each series of 20 trials have the subject take a 3 min break. Before the experiment, each subject practices 10 trials with other angles to be familiar with the experimental procedure. The experiment should last ~40 min.

REPRESENTATIVE RESULTS:

In this study, the 3AFC (3-alternative forced-choice) technique and the logistic curve were used to estimate the tactile AD threshold. Participants were instructed to orally report the larger of the two angles perceived, or if they did not detect the difference. The equation of the logistic curve, which has been commonly applied to psychophysical experiments to measure thresholds[27–29] is:

$$y = \frac{1}{1+e^{\alpha+\beta x}} \quad (1)$$

In this equation, there are two key parameters, α and β. β is representative of the logistic curve growth, and $-\alpha/\beta$ represents the X value of the logistic curve midpoint.

To apply the logistic curve to describe the AD threshold, the 3AFC result must be expressed as a frequency distribution, shown as a black square in **Figure 4**. Therefore, when the reference angle was greater than the comparison angle, the subject responses were divided into two: one half was added to correct judgment and the other to incorrect, and the revised correct responses were then transferred to the rate. When the reference angle was greater than the comparison angle, the same steps were taken as previously indicated, and the revised rate was reduced by 1. Through these steps, a coordinate system was set, with the degree of the angle representing the horizontal axis and the vertical axis representing the proportion of responses in which the comparison angle was perceived to be greater than the reference angle (**Figure 4**). In this coordinate, a logistic curve could be fitted by the least square method. The AD threshold was defined as half of the difference between the angle at accuracy rates of 25% and 75%.

[Place **Figure 4** here]

To test whether this curve was accurate, the goodness-of-fit for the logistic curve was evaluated using a chi-squared test, which was used to determine whether there was a significant difference between the observed rates and the expected rates (i.e., the values in the fitted logistic curves). Here, the null hypothesis states that there is no significant difference between the observed and expected values. The value of the chi-squared test was determined using the following formula:

$$\chi^2 = \sum_{i=1}^{n} \frac{(O_i - E_i)^2}{E_i} \quad (2)$$

In this equation, O = observed value, and E = expected value.

To test whether the null hypothesis could be rejected, a significance level of 15% was chosen as the cutoff criterion[28] and the critical value was calculated ($\chi^2_{(8)}0.15 = 12.03$). Because there were

10 categories and the mean and standard deviation were used to fit the data to a logistic curve, there were 8 degrees of freedom (10–2). Thus, if the value from the chi-squared test of the logistic curve was larger than this critical value, the null hypothesis was rejected. The value (2.14) from the chi-squared test was smaller than this critical value (12.03), which indicates that the logistic curve fitting was suitable.

FIGURE LEGENDS:

Figure 1: Overview of the TSPAS. The equipment consists of four parts: 1) tactile angle stimuli (i.e., the reference angle and ten comparison angles); 2) the hand plate that fixes the hand of the subject in place and keeps only the index finger in contact with the stimuli; 3) the electronic slider that carries the tactile stimuli; and 4) the personal computer (PC) control system that controls the speed and the movement distance of the electronic slide.

Figure 2: Example of tactile angle stimuli. (**A**) An example of the reference angle (60°) and two (50° and 70°) of the ten comparison angles used in the experiment. In particular, detailed parameters of the reference angle were drawn. *d* represents the end point distance, *R* represents the radius of curvature in the local apex, and *r* represents the radius of curvature in the end point. (**B**) Example of a raised angle seen in 3D. The height of the raised line is 1.0 mm from the 3D view.

Figure 3: Hand position of the subject and tactile angle stimuli movement direction. The right hand of the subject was secured with nylon tape, and the subject was instructed to place his or her right index finger into the opening in the plate. The angle stimuli were clamped on the apparatus and were horizontally moved by the electronic slide to passively slide across the fingerpad.

Figure 4: Logistic curve fit. The accuracy data of one subject in the AD task were used to fit the logistic curve using the least square method. The black squares represent the revised rates of one subject who completed the tactile AD task. The solid line is representative of the logistic curve acquired through the least square method when the residual was the smallest. Dashed lines indicate two points (A_1, 0.25) and (A_2, 0.75), and the AD threshold is (A_2-A_1)/2. After fitting the logistic curve, the specific parameters were obtained (α = 21.40, β = -0.35) and the AD threshold was calculated (3.51°).

DISCUSSION:

A new measure for tactile spatial acuity, tactile AD, is presented. In this system a pair of angles passively slides across the immobilized index fingerpad of a subject. AD combines the advantages of GO and TPD, reducing the impact of intensive cues and the neural peak impulse rate of a single point. This study shows that there is a gradual change in perceptual discrimination as the angle difference changes between the reference angle and the comparison angle[4]. In addition to the age effect, training effect, and cognitive impairment diagnosis monitoring of AD[9,10,23], tactile AD is a valuable measure for tactile spatial acuity. Its variability needs to be verified in further studies, however. For example, tactile AD should correlate with other validated measures of tactile spatial acuity such as pattern or braille letter discrimination[7,8].

Like other methods measuring tactile spatial perception, AD applies the threshold to measure angle discriminability. Unexpectedly, the smaller the angle discrimination threshold, the stronger the angle discriminability. In previous studies, an interpolation method was used to pinpoint the threshold value[9,10]. Although the method does not need to assume that the subject's behavior is captured using a psychometric function, it only fits data of a half-size range of the comparison angles. In the current experiment, to cover the entire range of comparison angles, the logistic curve was used to calculate the threshold[27,29]. Because half of the comparison angles are smaller than the reference angle and the other half are larger than the reference angle, the current method can fit all data points once and calculate the angle discrimination threshold. The goodness-of-fit for the logistic curve was evaluated using a chi-squared test and the logistic curve fitting was found suitable[28].

To conduct the AD experiments using the TSPAS system, the following points should be noted: First, because TSPAS is a semiautomatic system using PC software, it is necessary to verify again that the slide can move at the speed and distance set before the experiment. Second, it is necessary to determine whether or not the subject is awake during the experiment. Because the subject wears an eye mask during the experiment, he or she can easily become sleepy. In this case, the subject may miss some information and make an incorrect decision. Third, the enforced breaks are also necessary. If the fingerpad of the subject continues to be stimulated for a long time, the fingerpad may adapt to the raised angle stimulus and it may be hard for the subject to distinguish the difference between angles. Or the long period of stimulation may cause uncomfortable sensations in the fingerpad. Therefore, the number of trials and breaks should be strictly controlled.

The current characteristics of TSPAS and the range of tactile angles could limit the range of people tested. Therefore, TSPAS needs to use different ranges of tactile angles for different groups of people to measure their tactile spatial acuity. For example, because older people have a far bigger AD threshold than younger people[9,10], the current range of tactile angles used in TSPAS cannot measure their AD threshold. Additionally, for those individuals whose fingerpads cannot completely feel the tactile angles, TSPAS is not valid at all, because they cannot envision the tactile angle by the passive sliding across their fingerpads. The difference in tactile spatial acuity between female and male subjects[25] must be kept in mind as well. Future projects may need a lot of modification to determine the range of tactile angles to use for different groups of people in clinical use.

Although TSPAS can control the moving speed and distance of angle stimuli well, the manual delivery of angle stimuli is time-consuming and requires considerable attention and concentration on the part of the experimenter[6]. To eliminate these shortcomings with manual operations, a fully automatic tactile AD system was designed. The purpose of developing automatic equipment is to establish uncomplicated, efficient, and affordable equipment for controlled tactile angle applications. However, a remaining challenge is how the equipment can precisely and quickly adjust various angle sizes in a very short time. Hopefully the AD system described will be used and verified by others and promote the movement towards automatic tactile testing.

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DISCLOSURES:

The authors declare that they have no competing conflicts of interest, financial or otherwise.

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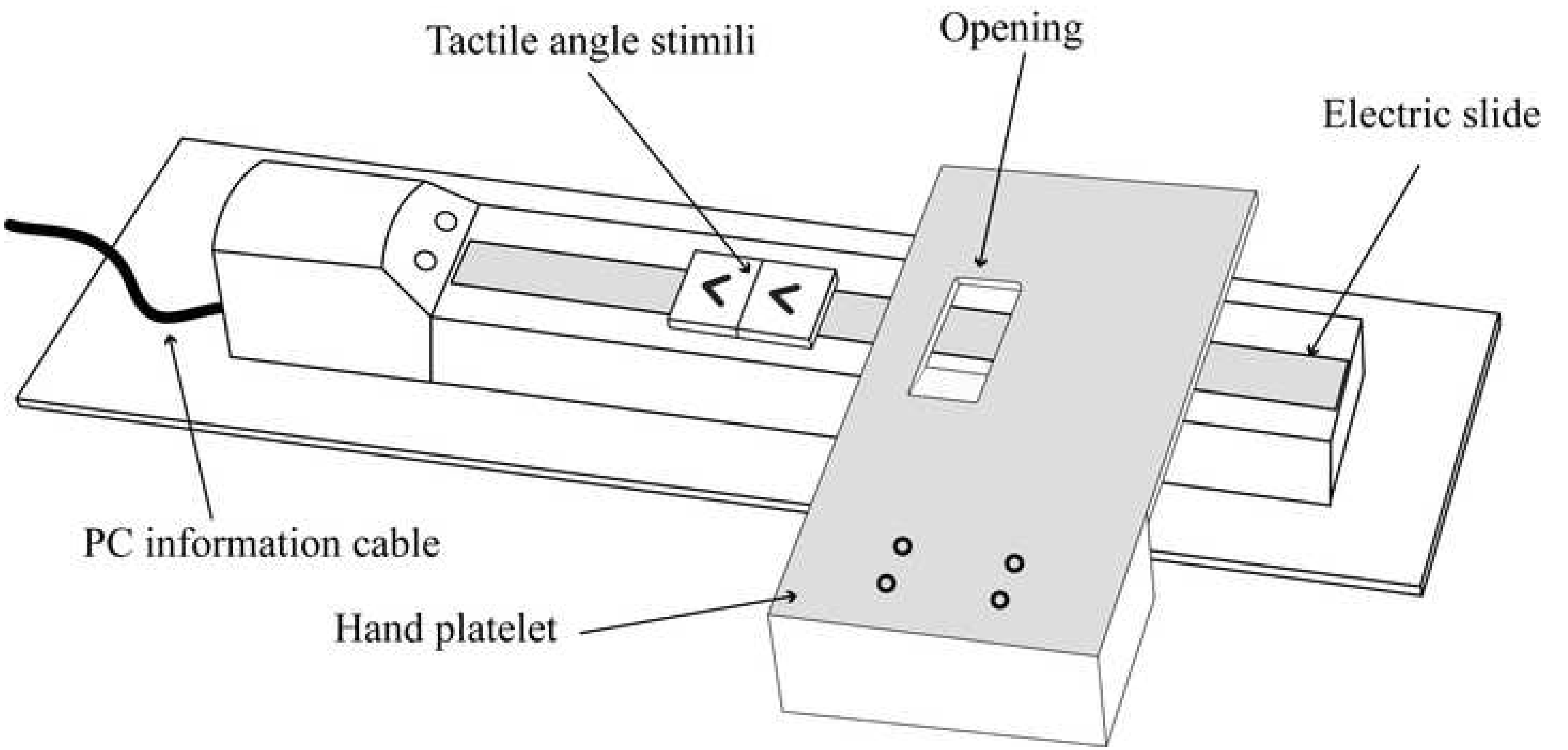
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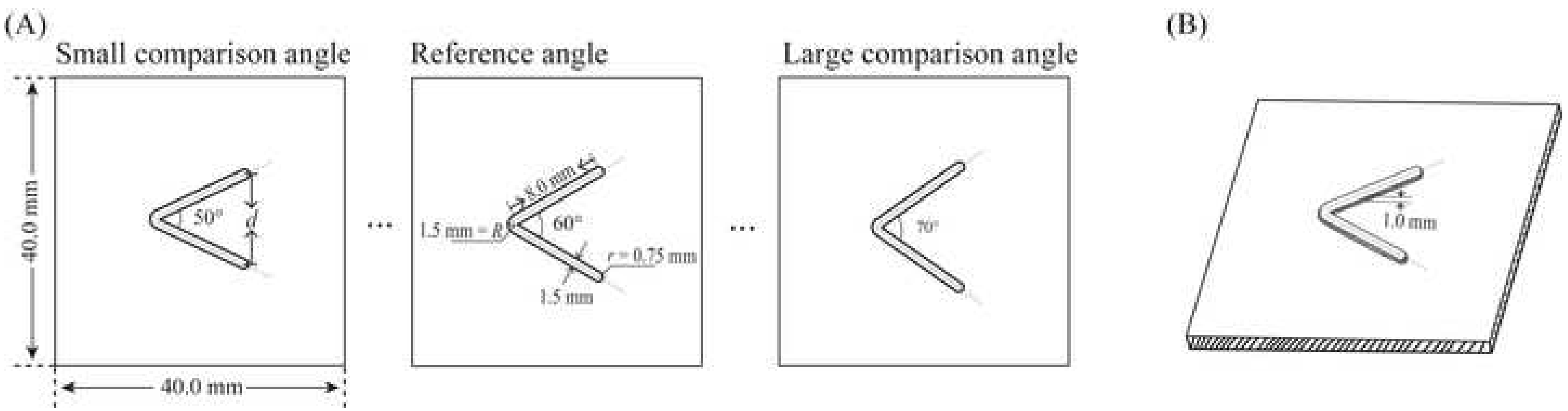
(A)
Small comparison angle
Reference angle
Large comparison angle
(B)
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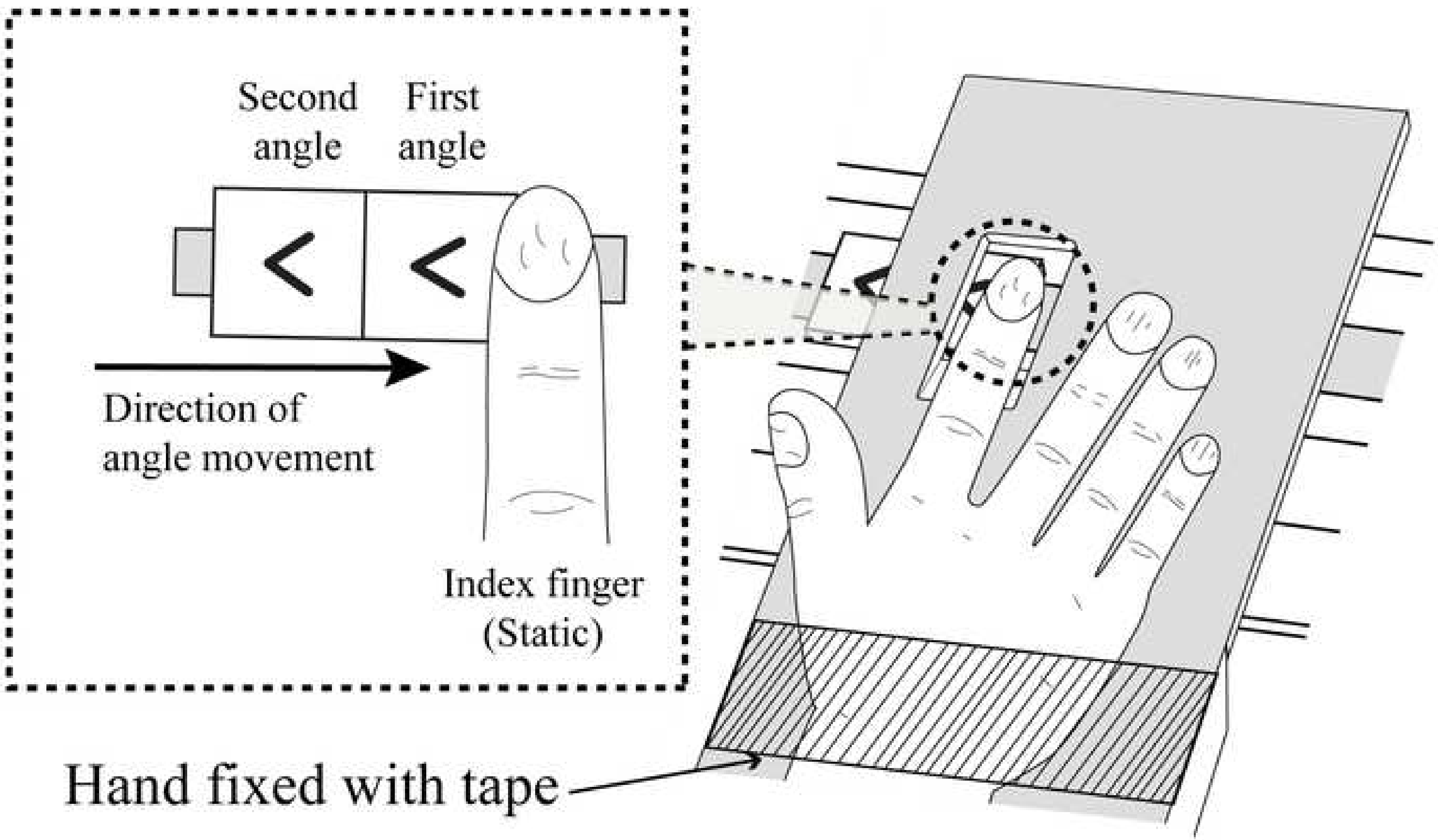
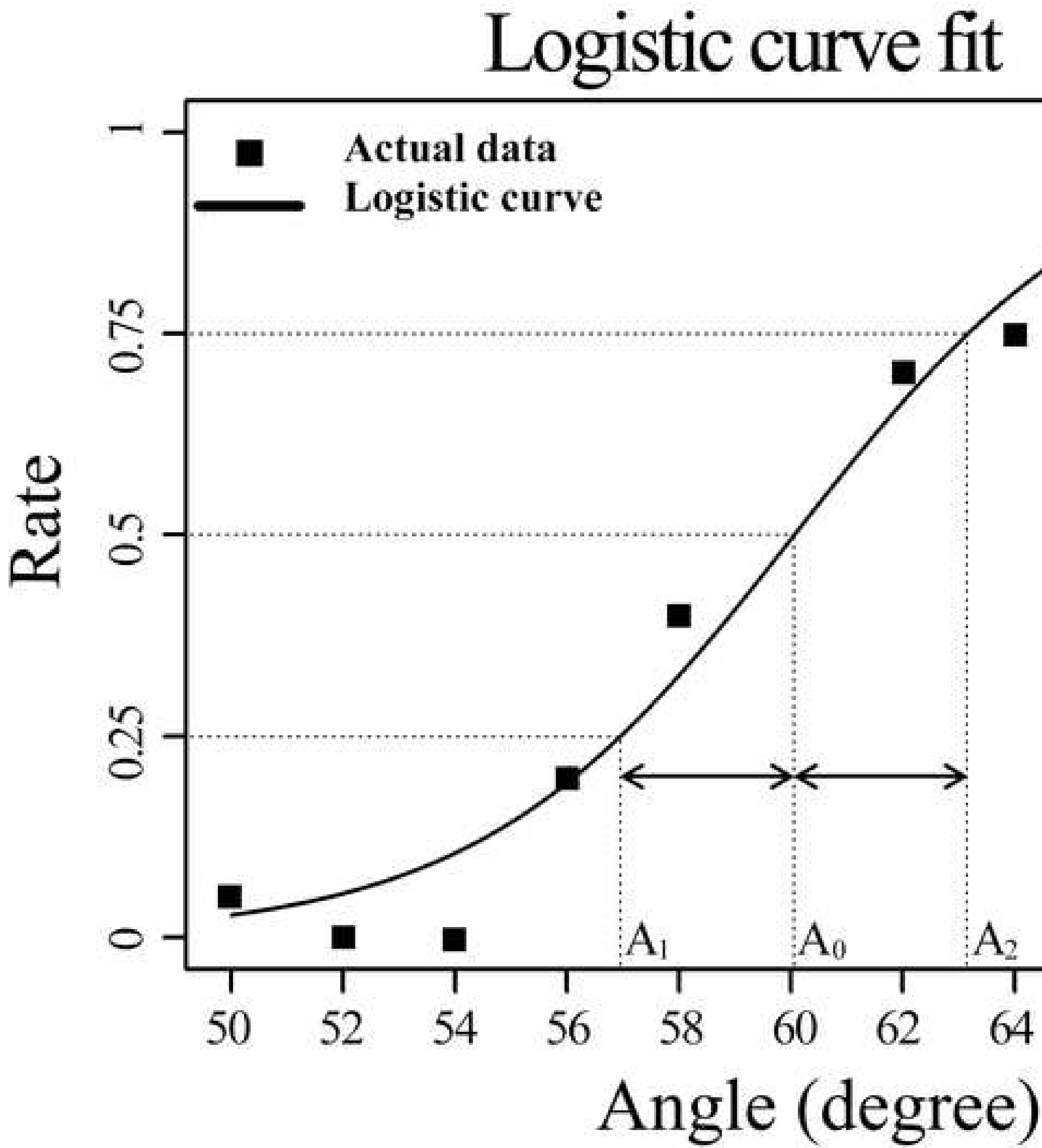

Second angle
First angle
Direction of angle movement
Index finger (Static)
Hand fixed with tape


Logistic curve fit
Actual data
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0.25
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A1
A0
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50
52
54
56
58
60
62
64
66
68
70
Angle (degree)

Table of Materials

Click here to access/download;Table of Materials;JoVE_Table_of_Materials.xlsx

Name of Material/Equipment	Company	Catalog Number	Comments/Description
Acrylic sheet (3 mm)	MonotaRO Co.,Ltd.	33159874	Good Material
Acrylic sheet (1 mm)	MonotaRO Co.,Ltd.	45547101	Good Material
EZ limo (easy linear motion motor)	ORIENTAL MOTOR CO., LTD. Made in Japan	EZS3	Good Motorized Linear Slides
Data Editing Software	ORIENTAL MOTOR CO., LTD. Made in Japan	EZED2	easy to use
Operating Manual (Orientalmotor)	ORIENTAL MOTOR CO., LTD. Made in Japan	HL-17151-2	Good Guidebook

Mar. 8, 2020

Dear Dr. Phillip Steindel

Thank you for allowing us to again submit a revised version of our manuscript entitled "**A Tactile Semiautomatic Passive-Finger Angle Stimulator (TSPAS)**" with the manuscript number JoVE61218R2.

We also appreciate the encouraging, critical and constructive comments on this manuscript by the editors. The comments have been very thorough and useful in improving the manuscript. We strongly believe that the comments and suggestions have increased the scientific value of the revised manuscript by many folds. We are pleased to say that we have addressed all the concerns raised, and the manuscript has been modified according to the editors' suggestions.

Point-by-point responses to the editors' comments (written in light blue) are outlined in the response letter.

Thank you for your consideration, and we look forward to hearing from you.
Yours sincerely,

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Editorial comments:

<u>Authors' Response</u>: *First, we thank the editors for the careful reading and very helpful suggestions. The manuscript has been modified, taking into account all the editors' comments and suggestions. All changes in the text are in light blue.*

Question 1. 1: Please include more exact specifications for the various components of the device (e.g, .stl files).

<u>Authors' Response</u>: *We thank the editors for the suggestion. We have added the more exact specifications for the hand plate and linear slide in the revised manuscript (page 4-5, line 168-171; page 5, line 181-182).*

Question 2. 1.1.2: How exactly is the polyline 'placed'? is it, e.g., glued on?

<u>Authors' Response</u>: *We thank the editors for the questions. We stuck the polyline to the center of the square base with glue. We have revised the sentence to "using the glue, stick the polyline to the center of the square base to create a 2-D raised tactile angle stimulus." in the revised manuscript (page 4, line 148).*

Question 3. 1.2: How exactly do you 'craft' the platelet. Also, 'platelet' may not be the correct term (it usually refers to the blood component).

<u>Authors' Response</u>: *We thank the editors for the question and suggestion. We used a milling machine to cut a 3mm high acrylic sheet and make a hand plate. And we have added the method in the revised manuscript (page 4-5, line 168-171). Additionally, as the editors suggested, we used "plate" to replace "platelet".*

The added content in the revised manuscript on page 4-5, line 168-171 is :

> *······. First, using a milling machine, cut a 5.0 mm thick acrylic sheet into a 14.0 * 22.0 cm rectangle plate, and then fasten the rectangle plate to a cub base (14.0 cm wide, 14.0 cm long, and 8.5 high) with the tape and glue. After that, using a milling machine, ······*

Question 4. 'Set all kinds of parameters' is extremely vague, especially if this section is to be filmed. Please provide more details about setting these, including exact values of all parameters to be set.

<u>Authors' Response</u>: *We thank the editors for point out the deficiency. We have provided more details and modified the sentence to "set motion type as 'INC', motion distance as '80 mm', motion speed as '20 mm/s', motion function as 'single', and axis as 'ID = 0'" in the revised manuscript (page 5, line 197-198).*

Question 5. Figure 1: 'Electronic slider' is a better term.

<u>Authors' Response</u>: *As the editors suggested, we have modified "Electric slide" to "Electronic slider" in the revised manuscript (page 11, line 425-426).*

Question 6. Figure 4: There are multiple black squares here, although the legend seems to indicate there is only one. Please clarify.

Authors' Response: *We thank the editors for reminding us of that. We have modified the sentence to "The black squares represent the revised rates of one subject who completed the tactile AD task" in the revised manuscript (page 11, line 443).*

Question 7. Please remove the embedded figures from the manuscript and move the figure legends to a separate section after the Results. You may indicate a specific location for a figure in the final manuscript by using, e.g., '[Place Figure 1 here]'.
Authors' Response: *As the editors suggested, we have removed the embedded figures from the manuscript and moved the figure legends to a separate section after the references. And we have indicated a specific location for a figure in the revised manuscript.*

Again, we thank the reviewer for the careful reading of the manuscript and especially for the insightful suggestions. We have addressed these points in the revised manuscript, which significantly improved the quality of our study, and we are willing to make further changes, if necessary.