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A SYSTEM FOR THE OBJECTIVE ASSESSMENT OF HAND PROPRIOCEPTIVE FUNCTION IN PEDIATRIC AND ADULT POPULATIONS

Jinseok Oh[1], Arash Mahnan, Jiapeng Xu, Jessica Holst-Wolf
Human Sensorimotor Control Laboratory, School of Kinesiology, University of Minnesota
Minneapolis, MN, USA

Hannah Block
School of Public Health, Indiana University
Bloomington, IN, USA

Jürgen Konczak
Human Sensorimotor Control Laboratory, School of Kinesiology, University of Minnesota
Minneapolis, MN, USA

ABSTRACT

Proprioceptive signals from mechanoreceptors embedded in ligaments, tendons, and muscles are essential for the control of muscle tone and voluntary movement. Numerous neurological and orthopedic disorders are associated with proprioceptive dysfunction that impairs the control of balance and/or fine motor function. However, obtaining objective measures of proprioceptive function is difficult in most clinical settings, because available assessment methods rely on specialized equipment, expertise, or are too time-consuming. This paper presents a new tablet-based system that objectively measures finger position sense by implementing a psychophysical threshold search method. We here provide initial data that demonstrate the ease-of-use and efficacy of the system.

Keywords: Acuity, Finger position sense, Proprioception, Perception

INTRODUCTION

Proprioception is defined as perception of joint and body position and movement in space. Proprioceptive signals are imperative for the neural control of muscle tone, and for motor control and learning. Several pediatric disorders such as developmental coordination disorder or cerebral palsy, and adult neurological disorders such as cortical stroke, Parkinson's disease or dystonia are associated with proprioceptive deficits [1-4]. Current clinical practice to assess these deficits relies mainly on subjective clinical impression [5]. For instance, current clinical approach for determining the severity of proprioceptive deficit in people with stroke relies on clinicians moving a patients' limb segment to two different positions (e.g. flexion and extension) and then ask the patient to discriminate between the two positions [6].

Within the last decade, there has been an attempt to quantify the degree of proprioceptive dysfunction using applications that rely on complex robotic technology [7-11]. These devices are typically not mobile and not easily integrated in clinical settings, imposing severe time constraints. Using robotic devices requires extra training by clinical personnel and is time consuming. This paper introduces a new assessment method of proprioceptive function that is simple, quick, user friendly, mobile, and has a low technical threshold. This implies that it is easily adoptable in many clinical settings. The system provides objective, psychophysical measures of finger position sense. Using this system, the entire testing and data analysis will take less than 10 minutes for one individual.

METHODS

2.1 Hardware system

The system hardware consists of a hardware stand and a tablet (Android/iOS) (**Fig. 1**). The hardware was designed using SolidWorks software and 3D-printed using an Ultimaker Original+ 3D printer with PLA filaments. The stand contains a base, tablet support, two legs, and a hand position checking mechanism. Each leg is height-adjustable and can elevate the base up to 25°. The stand can hold any size tablet ranging from 7 to 10.1 inches (17.78 to 25.65 cm). The support of the tablet is also adjustable. Two white intersecting lines on the base are used for calibrating the position of tablet.

The four cuboids fixed on the base are 10 cm in height. The hollow rectangular frame that is installed on the cuboids can move up and down, accommodating hands of different size and thickness. The two separate sliding bars move horizontally along

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[1] ohxxx414@umn.edu. 1900 University Avenue SE, Minneapolis, MN, USA

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the frame and the four sliding blocks, two on each bar, move vertically along the bar. The sliding parts will accommodate different tablet sizes (**Fig. 1**).

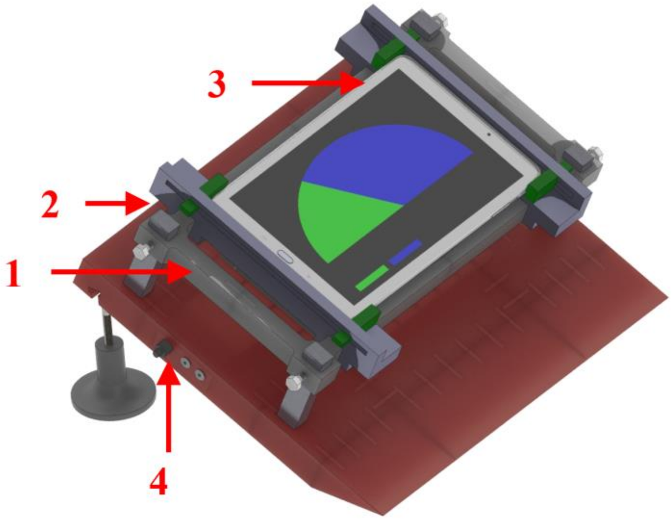

FIGURE 1: THE COMPLETE SYSTEM: **1.** THE HOLLOW RECTANGULAR FRAME MOVING VERTICALLY ALONG THE CUBIODS, **2.** TWO HORIZONTAL SLIDING BARS TO CORRECTLY POSITION ANY SIZE TABLET, **3.** FOUR HORIZONTAL SLIDING BLOCKS TO POSITION THE TABLET, **4.** THE ON/OFF SWITCH AND TWO LEDS.

In order to ensure the stationary position of the user's finger during testing, the base contains a finger position checking mechanism. The mechanism consists of three grooves at the center of the base with three pin-holder blocks inserted (**Fig. 2 A**). In addition, the mechanism has an embedded circuitry that comprises pin holders, a set of springs, two LEDs, one on/off switch, and a set of two 1.5V batteries (**Fig. 2B**). Turning on the switch on the lateral side of the stand (**4** in **Fig. 1**) closes the circuitry and turns on LED 1.

There are inserts for four pins in holders. Depending on which hand is tested, two of the inserts will be used (**Fig. 3**). For instance, for testing the right hand, the pins are placed in the upper left and lower right inserts (**Fig. 3**). The pins work as a guide for the correct finger's placement relative to the tablet and its display. User will place the hand on the base, locating the metacarpophalangeal joint of the index finger next to the bottom pin. This finger's contact creates a slight displacement of the pins and its holder (less than 2mm). The pin holders have thin metal plates attached to them. Displacing the pins, closes the second circuit and turns on the LED 2 (**Fig. 2B)**. If the user fails to maintain the appropriate hand position, LED 2 will turn off, requesting the readjustment of the hand position.

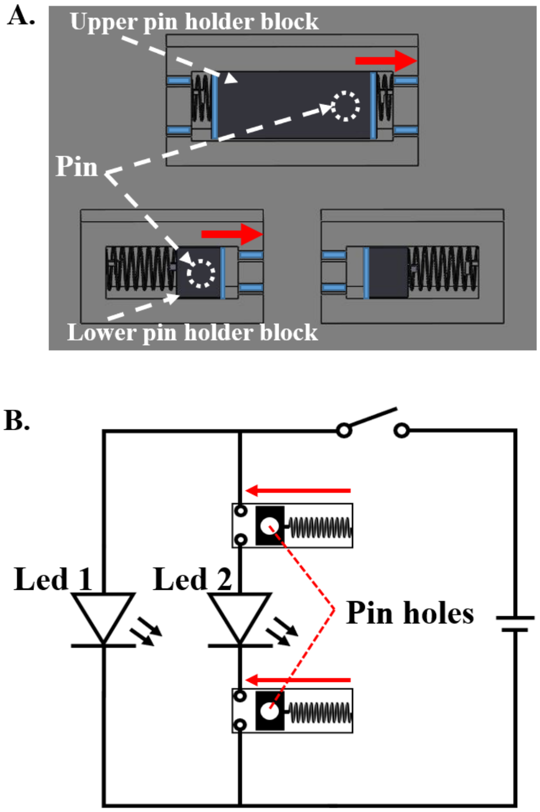

FIGURE 2: ILLUSTRATION OF THE FINGER POSTION CHECKING MECHANISM. **A.** THE THREE GROOVES AND THE PIN HOLDER BLOCKS FOR TESTING THE RIGHT HAND. THE BLUE COLOR INDICATES METAL PIECES. **B.** DIAGRAM OF THE CIRCUITRY OF THE FINGER POSITION CHECKING MECHANISM. IN BOTH **A** AND **B**, THE RED ARROW INDICATES THE DIRECTION THE PINS ARE TOUCHED TO ACTIVATE THE SECOND CIRCUITRY THAT TURNS ON LED 2.

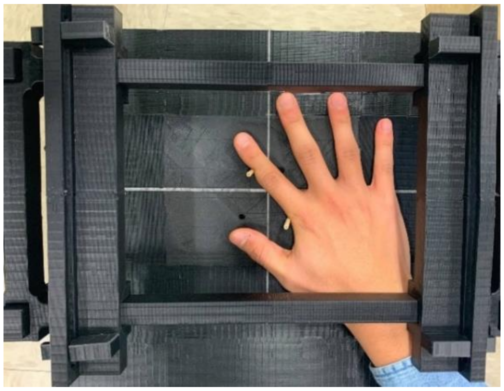

FIGURE 3: THE PLACEMENT OF THE PINS ON THE BASE FOR A USER TESTING THE RIGHT HAND. THE TWO WHITE ORTHOGONAL LINES ON THE BASE ARE FOR TABLET POSITIONING CALIBRATION.

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2.2 Assessment Software

The software is based on code written in Python (version 3.6) and Kivy (version 1.10.0) programming language. The software contains an interactive assessment, in which the tablet display is dissected into two colored areas that are divided by a diagonal line (**Fig. 4**). The stimulus is defined as the angular difference between the line dissecting the colored areas on the screen and the actual angle of the index finger (50°) (**Fig. 4**). The software uses three anthropometric measures of the index finger: 1) length of the finger, 2) center of the metacarpophalangeal joint relative to the edge of the hand, and 3) the width of the finger at the proximal interphalangeal joint. These measures are used to adjust the assessment screen dimensions to the individual hand anthropometrics of the user. The origin of the dissecting line is the center of metacarpophalangeal joint, and the height of the colored display is determined by the user's finger length.

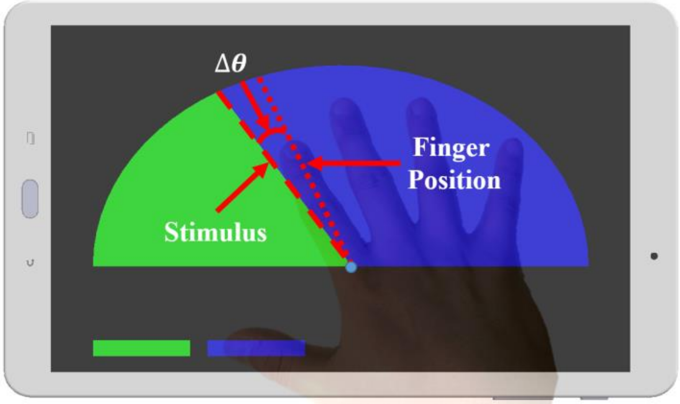

FIGURE 4: EXAMPLE OF A DISPLAY VIEWED BY THE USER. THE DISPLAY SHOWS A SEMICIRCLE DISECTED INTO TWO AREAS. THE USER DETERMINES UNDER WHICH AREA HIS/HER FINGER IS POSITIONED AND THEN PRESSES THE APPROPRIATE COLOR BAR AT THE BOTTOM OF THE DISPLAY. $\Delta\theta$: ANGULAR DIFFERENCE.

The assessment is a two-forced-choice judgment that requires the user to select which colored area the finger is located behind or directly under ("left" or "right"). The judgement will be completed by pressing the button of the same color and relative position in the lower left of the display [12].

2.2.1 Psi-marginal algorithm

The Psi-marginal method [13, 14] is a Bayesian inference algorithm. The system uses a Gumbel (1) probability function with two parameters α and β [15]. Parameter α is a threshold parameter and β is a slope parameter for the function.

$$F_G = 1 - \exp\left(10^{\beta(x-\alpha)}\right) \tag{1}$$

As F is not directly observable, F is inferred by the trend of responses. For stimulus x, the probability of observing x is given by probability function ψ

$$\psi(x;\alpha,\beta,\gamma,\lambda) = \gamma + (1-\gamma-\lambda)F_G(x;\alpha,\beta) \tag{2}$$

, where γ is the guess rate, the reciprocal of the number of possible choices. Given that there are two possible choices γ = 0.5. λ is the lapse rate, which is the probability of making an unintended erroneous choice. On each trial, with the given stimulus intensity and the response, Psi-marginal algorithm derives the posterior distribution of parameters α and β, marginalizing on λ. The posterior probability for each α and β (α = a, β = b) is noted as (3).

$$p_{\alpha\beta}(\alpha = a, \beta = b) = \sum_{l} p(\alpha = a, \beta = b, \lambda = l) \tag{3}$$

The entropy for the derived posterior distribution is calculated in (4).

$$H = -\sum_{a}\sum_{b} p_{\alpha\beta}(a,b)\log_2 p_{\alpha\beta}(a,b) \tag{4}$$

Based on the user's response and the updated posterior distribution of α and β, the algorithm estimates the entropy values for all possible stimuli. The next stimulus intensity will be the one with the lowest entropy.

The first stimulus will have a 30° angular difference from the index finger. For a right hand user, the first stimulus will be 30° to the left. In order to prevent any directional bias in the user's response, two algorithms are implemented separately for the two opposite directions. The stimuli direction changes after the first seven trials, then alternates for every five trials. Each direction has twenty-five trials.

2.3 Test Protocol

2.3.1 System calibration

At system start up, the calibration screen is displayed (**Fig. 5**). As part of the system calibration, the tablet will be positioned by aligning the two orthogonal lines drawn on the base of the stand (**Fig. 3**) with the two orthogonal lines appearing on the tablet's screen. When the alignment is complete, the examiner will touch the tablet screen, and a pop-up window asking if calibration is done will be shown. The examiner can click on the pop-up window to finish calibration.

2.3.2 Assessment with the psi-marginal method

Assessment using Psi-marginal method requires approximately less than 10 minutes total to complete. The assessment procedure is as followed:

- After calibration, the examiner will measure the anthropometric dimension of index finger.
- Based on the user's handedness, the pins are inserted to the appropriate inserts. Users close their eyes while the examiner positions the hand on the base.
- Once the tablet is placed in its right position, the examiner will verify the hand position using the LED indicator lights and then instruct the user to maintain this hand position for the duration of the assessment.

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- With eyes open, the user will see the assessment screen and complete a short 4-trial familiarization protocol to verify that the instructions were understood.
- The user then begins the assessment.

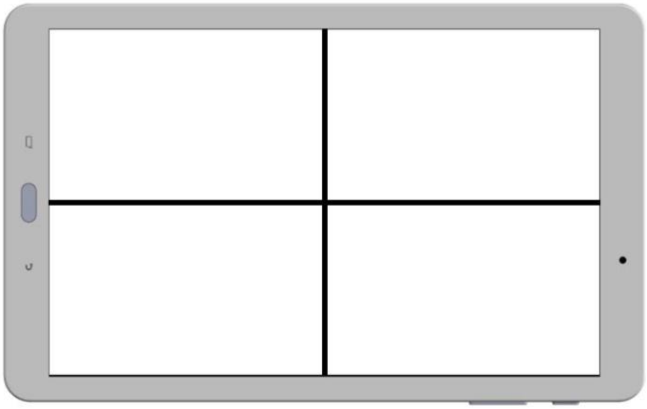

FIGURE 5: CALIBRATION SCREEN. THE EXAMINER CENTERS THE TABLET IN THE STAND THAT THE TWO BLACK LINES ALIGN WITH THE WHITE LINES ON THE BASE.

2.4 Data Analysis

The assessment software automatically stores the data in JavaScript Object Notation (JSON) format once the test is complete. The user's response on each trial is categorized into either 1 (right) or 0 (left). The entire responses are divided into bins, and an assumed psychometric function is fitted on the binned data.

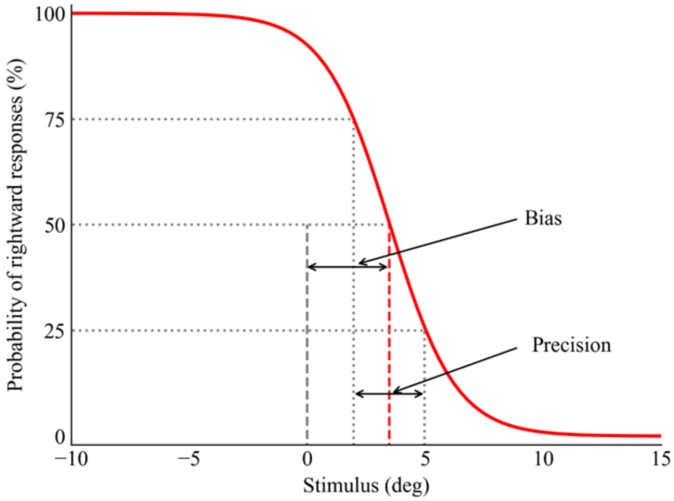

FIGURE 6: AN EXEMPLAR PSYCHOMETRIC FUNCTION OF THE FINGER POSITION THRESHOLD

The accuracy of visual-proprioceptive mapping can be explained with respect to bias and precision calculated from the psychometric function. *Bias* is the difference between the true physical position of the finger (0°) and the perceived finger position. It is defined as the stimulus intensity with the 50 percent chance of judging the finger to be to the right of the stimulus line (**Fig. 6**). *Precision* is the measure of response variability of the perceived finger position. *Precision* is expressed as the difference between the two stimulus intensities associated with the 25th and the 75th percent chance of judging the finger to be to the right of the line (**Fig. 6**).

RESULTS

In total, five healthy, young adult participants were tested. The protocol was approved by the University of Minnesota Institutional Review Board.

A user's performance over the entire assessment shows that by the end of the trials, the stimulus value decreased and eventually converged to the actual finger positon, indicated as the stimulus of 0° (**Fig. 7**). This shows that the user was able to estimate the correct position of the index finger.

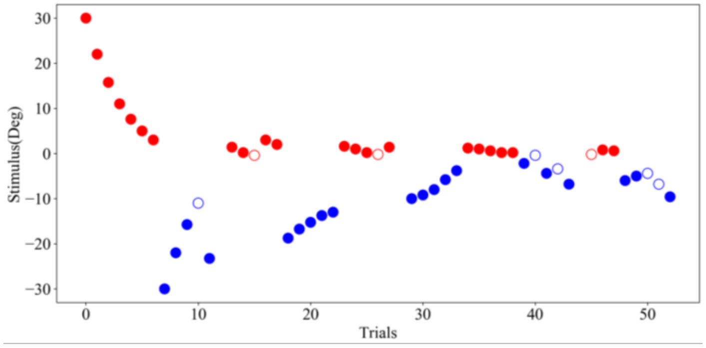

FIGURE 7: A RIGHT-HANDED USER'S PERFORMANCE IN THE FINGER POSITION SENSE ASSESSMENT. RED CIRCLES INDICATE LEFT TO RIGHT ALGORITHM DIRECTION. BLUE CIRCLES SHOW THE OPOSITE. FILLED CIRCLES CORRESPOND TO THE CORRECT RESPONSES.

Bias and precision data of the five participants have been observed simultaneously to understand each individual's accuracy of visual proprioceptive mapping (**Fig. 8**). The mean bias was 1.6° (± 2.2°) and the mean precision was 1.2° (±1.1°). One participant had a negative bias (-1.1°) showing that the participant's finger position sense was biased toward the left. However, given that the participant's precision was 2.1°, it is probable that the participant was close to correctly judging one's index finger position. Among the four remaining participants, two were both precise (0.3° for both) and marginally biased (0.4° and 0.1°, respectively), and the other two were biased toward the right (3.5° and 5.0°).

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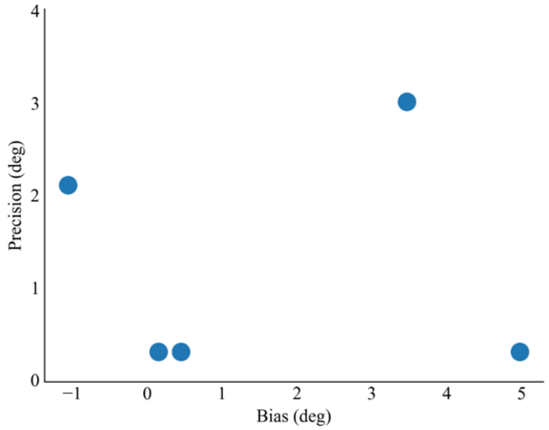

FIGURE 8: BIAS AND PRECISION DATA OF THE FIVE PARTICIPANTS.

DISCUSSION

This assessment relies on neural processes of multimodal sensory integration. Users need to map a visual position to a perceived finger position that solely relies on proprioceptive signals. Thus, while this method provides an objective measure of position sense, one need to recognize that this is not a test of unimodal proprioceptive perception, but a test that relies on proprioception to make a judgement about the position of a visual stimulus. There are established methods that rely on procedures in which a limb or limb segment is passively displaced, but such methods require the use of a passive motion apparatus or robotic device to displace the limb to a desired position [7-11]. However, the simplicity of the method is intriguing and makes this system so versatile. For example, the interactive nature of the test and the intuitive display makes the system suitable to be used in young children or people with impaired movement (e.g. due to cortical stroke) or reduced cognitive ability. Young children find it difficult to concentrate for a long time during a prolonged assessment that is typically associated with psychophysical testing procedures. However, within 5 minutes of testing, this system can generate an objective estimate of finger position sense acuity. Thus, the system has the potential to be used as a quick diagnostic tool for young children and adults with proprioceptive deficits.

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