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A NEW SYSTEM TO OBJECTIVELY MEASURE ANKLE PROPRIOCEPTION

Arash Mahnan[1], Jessica Holst-Wolf, Jürgen Konczak
Human Sensorimotor Control Laboratory, School of Kinesiology, University of Minnesota
Minneapolis, Minnesota, United States of America

ABSTRACT

Proprioceptive afferents from the ankle joint are essential feedback for maintaining balance. However, there is no widely accepted test or measurement system available for determining the proprioceptive accuracy of the human ankle joint. Here, we present a system with a novel hardware design that applies an established psychometric testing protocol that generates a Just-Noticeable-Difference (JND) threshold as a measure of ankle proprioceptive acuity at the end of testing. To establish the system validity, twelve healthy adult participants completed the assessment. Testing required 25 trials and took approximately 10 minutes to complete. We show exemplar data of the ankle JND threshold and the summary results for all twelve participants. This assessment has the potential to become a tool for clinicians to identify proprioceptive impairment at the ankle and to assess the efficacy of sensorimotor interventions for improving balance in clinical populations.
Keywords: Ankle joint, proprioception, JND

NOMENCLATURE

CoR	Center of Rotation
JND	Just noticeable difference

INTRODUCTION

Proprioception is defined as the ability to sense the position and movement of the limbs and body [1]. Proprioception is necessary for control of voluntary movement and of muscle tone. Numerous adult neurological disorders such as Parkinson's disease, stroke and dystonia, as well as pediatric conditions like developmental coordination disorder (DCD) or cerebral palsy are associated with deficits in proprioception, which profoundly degrade motor performance and motor development [1-5].

In addition, proprioceptive input from the lower limbs plays a crucial role in upright stance and postural control when integrated with tactile, vestibular, and visual inputs [6]. However, there is no sophisticated system to objectively measure proprioceptive acuity at the ankle joint, an essential joint for balance control. As such, the extent of ankle somatosensory impairment in neurological conditions is largely unknown and the impact of ankle somatosensory dysfunction on sensorimotor control is poorly understood.

The goal of this paper is to introduce a novel device and method for quantitative and objective assessment of ankle proprioceptive acuity. Such objective measure of ankle proprioceptive acuity can be used to identify and characterize ankle somatosensory dysfunction in clinical populations.

METHODS

2.1 Hardware system

The device is designed to determine a JND threshold in the primary ankle medial-lateral joint axis, dorsiflexion-plantarflexion. The hardware elements of the system are depicted in Figure 1.

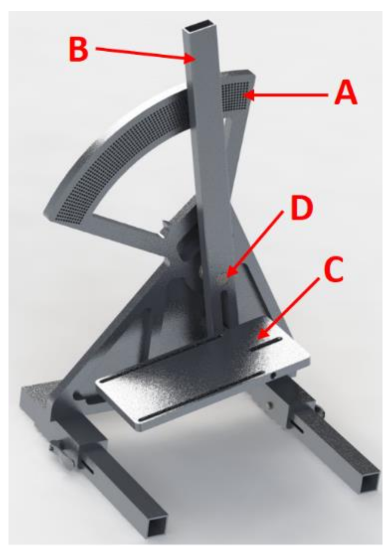

Figure 1. Hardware of assessment device. A) Pegboard, B) hand lever, C) footrest, D) Center of Rotation (CoR).

[1] Contact author: amahnan@umn.edu.

The pegboard has a range of 70 degrees with resolution of 0.1 degrees and is designed for setting the ankle position during the experiment (Figure 2). An encoder (US Digital H6 Ball Bearing Optical Shaft Encoder; resolution 0.009°, 10,000 cycles per revolution) is positioned on the center of rotation (CoR) of the system. The encoder measures the ankle joint angular position and velocity during testing. The footrest, heel rest, and leg rest are adjustable to account for differences in the anthropometrics of participants and to assure that the ankle joint's CoR is aligned with the encoder CoR.

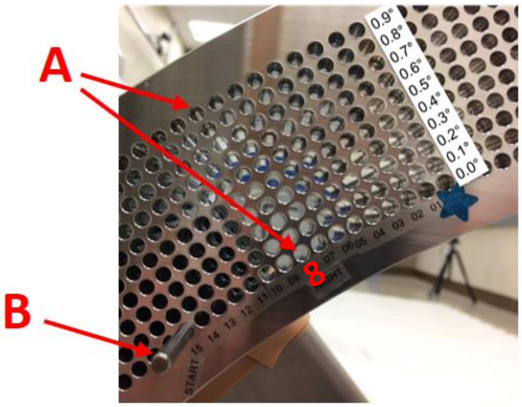

Figure 2. A subset of holes in the pegboard. Each hole in vertical direction indicates a 0.1-degree difference in angle, and in horizontal direction illustrates a 1-degree difference. A) The lower point indicates the angle value of 8 degrees, while the top arrow indicates 8.9 degrees. B) Shows the stopper which will be inserted into a specific hole during the experiment procedure to stop the handle and presents a specific ankle position to the participant.

2.2 Procedure

At the beginning of the test protocol, the examiner takes anthropometric measures of the lateral malleolus (height and distance from the heel) and adjusts the system to align the participant's ankle joint with the system CoR (Figure 3). While sitting on a chair, participants place their foot on a footrest of the device, which rotates in the sagittal plane allowing for foot dorsiflexion/plantarflexion. The weight of the lower leg is supported by the adjustable leg rest, which holds the lower leg at a 45° angle relative to the floor to assure that the ankle is at a neutral (90°) joint position.

The participants wear vision occluding goggles to block vision of foot/ankle position. For our feasibility testing, participants wore headphones playing low-volume pink noise as a concentration aid during discrimination testing.

The examiner starts the testing procedure using stoppers inserted in the pegboard holes and the system handle to rotate the footrest from the initial neutral (90 degree) position to the reference position. After presenting the reference position for 2 seconds, the examiner returns the footrest to neutral and then rotates to a comparison position for 2 seconds before returning to neutral. The reference and comparison positions are pseudo-randomized during testing (see Figure 4).

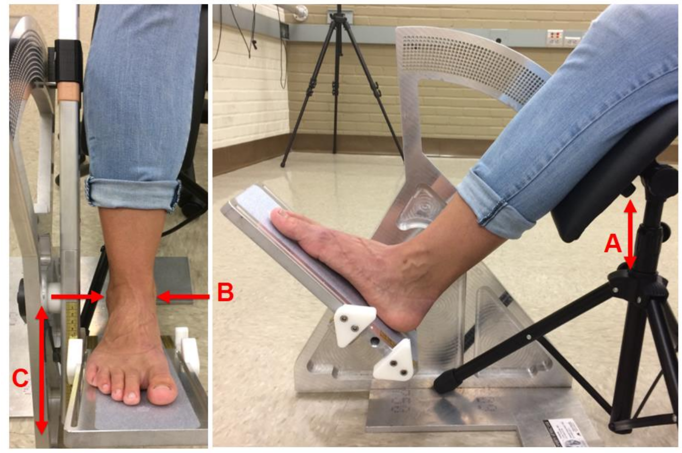

Figure 3. Experimental setup. The examiner adjusts the leg rest (A), heel rest (not depicted here), and footrest, to align the ankle with the system CoR (B + C) before starting the testing procedure.

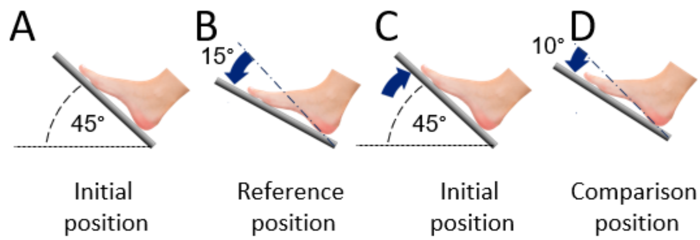

Figure 4. An example trial, the trial order is from A to D. A) The footrest is at the neutral (initial) position, which is 45° from the ground with the ankle at 9o°. Next, the examiner rotates the foot to B) the reference position, 15° plantar flexion from the neutral position, next the footrest rotates back to C) the neutral position, and finally rotates to D) the comparison position, 10° plantar flexion relative to the neutral position.

After each trial, the participant makes a verbal judgment to the question "In which position were your toes closer to the floor, the first or second position?" The responses are binary indicating correct or incorrect judgments. The psi-marginal method is a Bayesian inference based adaptive algorithm [7] which uses the prior stimulus (the angular difference between the reference and the comparison position) and the participants' responses to select the next stimulus value. Testing requires 25 trials and takes approximately 10 minutes to complete.

After completing all trials, the algorithm fits a Gumbel probability function [8] to the recorded data:

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

, where x is stimulus value, α and β are threshold and slope of the function, respectively. The algorithm finally calculated the just-noticeable-difference (JND) threshold as a measure of ankle proprioceptive acuity. JND threshold is defined as the angle for which the participant will have a 75% correct response rate [8] (see Figure 5).

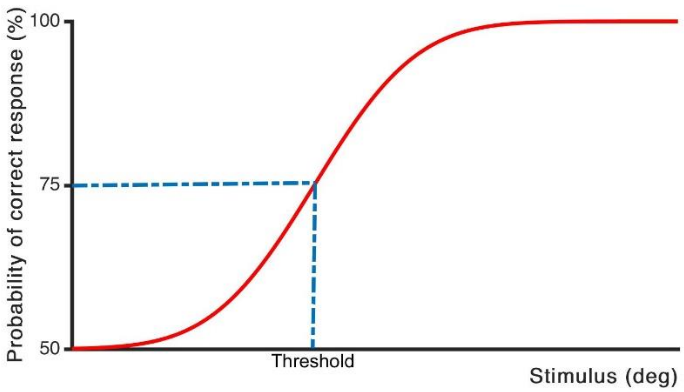

Figure 5. Cumulative Gaussian function fitted to the responses for the discrimination task. The 75% correct response point is defined as the JND threshold (halfway between guessing, 50% correct, and easily identifiable stimulus, 100% correct).

2.3 Participants

Twelve adults (5 M, 7 F, ages 19 – 23 years, mean 21.1 years) with no history of central or peripheral nervous system disorder and no current lower limb injury were recruited. The experiment protocol was approved by Institutional Research Board of the University of Minnesota. All participants consented prior to participation.

RESULTS

After completion of the experiment, the stimulus values for each trial and the corresponding response were recorded for further analysis. Figure 6 shows an exemplar dataset for one participant. The stimulus value changed over 25 trials, the stimulus value, or the angular difference between the reference and comparison positions, decreased after correct judgments and increased after incorrect responses.

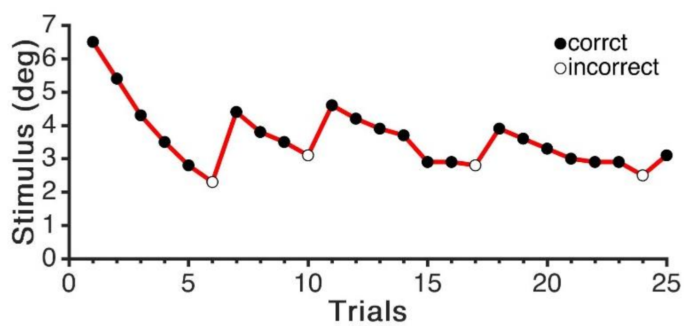

Figure 6. Exemplary results from one participant. The adaptive method decreases the stimulus value after a correct judgment. The stimulus value increases if the participant was incorrect. Eventually, the stimulus values converge to a value with higher certainty.

All participants completed the experiment for both dominant and non-dominant ankles (Figure 7). The JND threshold for dominant ankle joint ranged from 1.2° - 3.6° and for the non-dominant ankle from 1° - 5.1°. The average JND threshold for the dominant ankle joint was 2.4° and for non-dominant ankle was 2.6°. That is, we found no evidence that footedness affects ankle joint proprioceptive acuity.

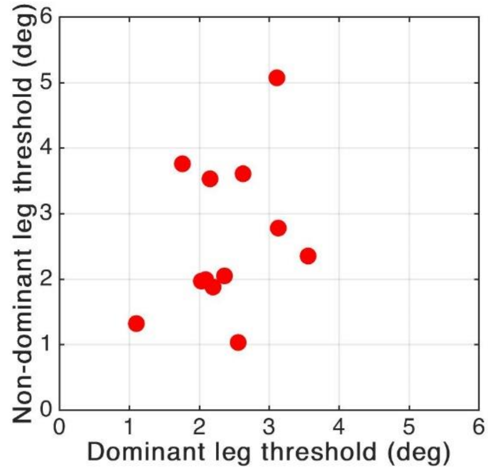

Figure 7. JND threshold for both dominant and non-dominant ankle for all 12 participants.

DISCUSSION

This novel ankle system combines a lightweight novel hardware design with a computer-based psychophysical test algorithm to generate a Just-Noticeable-Difference threshold as an objective measure of ankle proprioceptive acuity. Given its 0.1-degree resolution of the pegboard, the device provides a highly precise quantitative assessment of ankle proprioception that is sensitive to detect small changes in acuity. Thus, the proposed system has the potential to become a useful tool for neurologists, oncologists, pediatricians and physical therapists to characterize and monitor somatosensory dysfunction at the ankle, which is known to impair balance ability during standing and locomotion. Moreover, the system can be used to monitor therapeutic success longitudinally.

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