DIRECTIONAL ACUITY OF WHOLE-BODY PERTURBATIONS DURING STANDING BALANCE

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DIRECTIONAL ACUITY OF WHOLE-BODY PERTURBATIONS

DURING STANDING BALANCE

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LIST OF ABBREVIATIONS

PD	Parkinson's disease
PEST	Parameter estimation sequential testing
2AFC	2 alternative forced choice task
2D1U	2 down 1 up

SUMMARY

Little is known about whether deficits in motion perception contribute to balance impairment among individuals with sensorimotor deficits such as Parkinson's disease (PD) and stroke. Our first objective was to measure sensory thresholds of directional acuity, in a young adult population, as a method to quantify kinaesthetic perception of the body's motion and direction in space during perturbations to standing balance. Our second objective was to validate a faster method for quantifying directional acuity thresholds in response to perturbations during standing by comparing two methods, parameter estimation by sequential testing (PEST) and the psychometric method. We found that the directional acuity threshold of whole-body perturbations for a young adult population was 9.1 $\pm$ 2.2° using the psychometric method. Sensory thresholds identified using PEST, an adaptive algorithm, required fewer trials (24 ± 4.8 trials vs. 99 trials) than those estimated from full psychometric curves but converged to thresholds within 1-5 confidence intervals of the psychometric threshold. The directional acuity thresholds, measured in this study, are the first known quantification of whole-body directional perception during standing. Future work is aimed at determining thresholds in clinical populations, such as PD and stroke, and in reducing the variability of the PEST method in order to generate a reliable estimate of sensory thresholds.

CHAPTER 1

INTRODUCTION

Motion perception is the conscious awareness of the body's position within space [1]. It is known to be based on sensory information from multiple inputs such as muscle-spindle receptors, Golgi tendon organs, joint capsules, ligaments, and cutaneous receptors [2]. All of these inputs contribute to the ability to maintain balance in a changing environment. Little is known about whether deficits in motion perception contribute to balance impairment among individuals with sensorimotor deficits such as Parkinson's disease (PD). Individuals with PD have movement abnormalities that are thought to arise from the loss of dopamine producing neurons that affect the basal ganglia circuitry. However, recent studies show that deficits in proprioception are closely linked to motor deficits that are commonly seen in PD [3], [4]. Parkinsonian patients have been shown to depend more on visual and proprioceptive input for sensory feedback and have depressed proprioception related potentials [5]. In addition, proprioceptive deficits can affect postural stability by impairing the ability to adapt to changing support conditions, postural sway while standing, and the accuracy of compensatory stepping [1]. Impairments in proprioception are known to correlate with the severity and duration of PD. Evidence for the link between proprioception and PD lies in studies that show that the basal ganglia are important for sensorimotor integration [1].

Motion perception can be studied using measurements of directional acuity of whole-body translations, which have mainly been conducted in seated subjects [6]. However, it is important to study motion perception in a standing position because proprioception, in addition to vestibular and cutaneous input, contribute to our ability to sense direction and magnitude of an impending fall and to appropriately activate muscles to restore balance while standing [7]. Previous work that has investigated motion perception in a standing position quantified thresholds of acceleration, but thresholds of directional acuity have not been quantified before [8]. In the study, acceleration was used as a measurement for sensitivity to motion while in this study we are using direction as a measurement of proprioception. The threshold of directional acuity, defined as a just noticeable difference in the angle between two perturbation directions, was identified using a 2-alternative forced choice task (2AFC). Two methods of psychophysics were used in determining the thresholds: the psychometric method and the parameter estimation by sequential testing (PEST) method.

The psychometric method determines a subject's performance on a task by repeatedly testing the behavioral response at pre-set stimulus values. [9]. In this study, the psychometric method required 99 trials that consisted of 9 repetitions of 11 different stimuli. In each trial, the subject must choose between two possible responses, either the perturbations were the same or they were different. If the subject was guessing, the accuracy would be approximately 50%. The subject's performance for each stimulus, between 50-100% accurate, was then plotted as a function of stimulus intensity and was fit with a psychometric curve. . Given that a 2AFC task was used and that chance was set at 50%, the threshold is determined at the 75%. Using the curve fit, the 75% threshold can be determined quantitatively. Although the psychometric method is commonly used in psychophysics, many experiments run into problems using this method due to the large number of trials that it requires.

The PEST method, also known as the staircase method, was developed in order to get around the problem of too many trials in the psychometric method. The PEST method starts at an intensity above or below the expected threshold and adaptively decreases or increases the stimulus intensity based on the subject performance until the threshold is reached [10]. In this study, we use the 2-down-1-up (2D1U) method, which identifies the 70.7% threshold for a 2AFC task. There is no PEST method that can mathematically target the 75% threshold and thus previous studies have used the 2D1U [8].

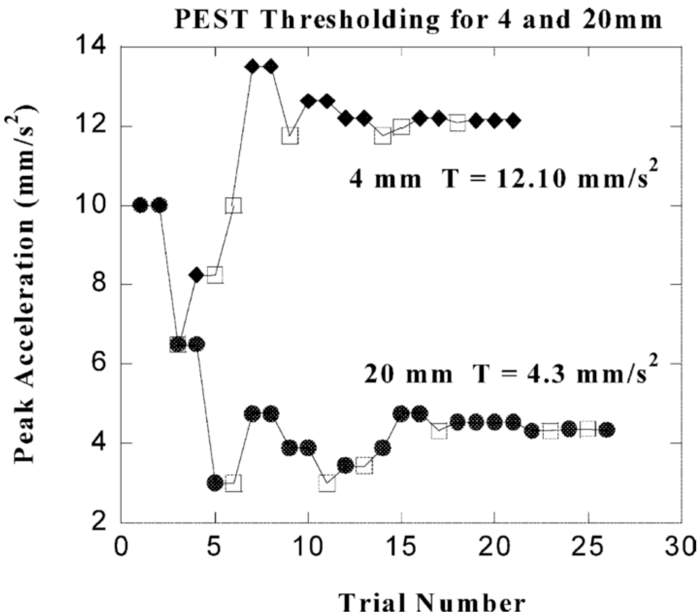

Figure 1.1 An example 2D1U PEST algorithm used in the Richerdson study [8].

Our first goal was to quantify motion perception in a young adult population by measuring sensory thresholds of directional acuity in response to full body perturbations while standing. Our second goal was to validate a faster method to determine thresholds of directional acuity by comparing the parameter estimation sequential testing (PEST) to the psychometric method [10]. Directional acuity is a good measurement of proprioception across different populations especially in individuals with Parkinson's disease. Individuals with PD rely more on cognitive means for balance and thus may depend more on proprioception in comparison to young adults [11]. Thus, directional acuity thresholds allows for the study of proprioception and its effects on balance.

CHAPTER 2

METHODS

Participants

All experimental protocols were approved by the Institutional Review Boards of Georgia Tech and Emory University. Written informed consent and a HIPAA form was obtained from all participants before they were enrolled into the experiment. A total of thirteen healthy young adults (mean age 21.7 ± 3.0 years), consisting of 5 females and 8 males, were recruited to participate in the experiment. All participants were required to be older than 18 years of age and have had no history of musculoskeletal or neurologic disorders as assessed by a self-report. In addition, all participants must be native English speakers in order to limit the confounding effect of language learning on spatial perception [12].

Experimental Protocol

A full body perception task was carried out in order to determine a directional acuity threshold for each subject. For each trial, the participant stood on a translating platform while blindfolded and wearing headphones playing white noise in order to remove any possible visual and auditory cues. The blindfold and headphones eliminated auditory and visual information, limiting the subject to proprioceptive and vestibular cues alone. Stance width was standardized for each participant by having the middle of their heels positioned at a distance that matched their inter-ASIS (anterior superior iliac spine) distance. The participant's stance width was marked in order to maintain consistency throughout the experiment. Each trial in the experiment consisted of two perturbations in which the participant was tasked to determine whether or not the two perturbations were in the same or different direction. After the pair of perturbations, the platform would return straight forward to not give the subject any feedback on the direction of the previous movements. The layout of angle directions on the platform consisted of 0° representing the direction to the right, 90° representing the direction forward, 180° representing the direction the left, and 270° representing the direction backward. The participant's directional acuity was measured relative to one cardinal direction and thus the first perturbation was always in the 270° direction while the second perturbation ranged from 255-285° (+/- 15° from the cardinal direction) in the horizontal plane (Figure 2.1).

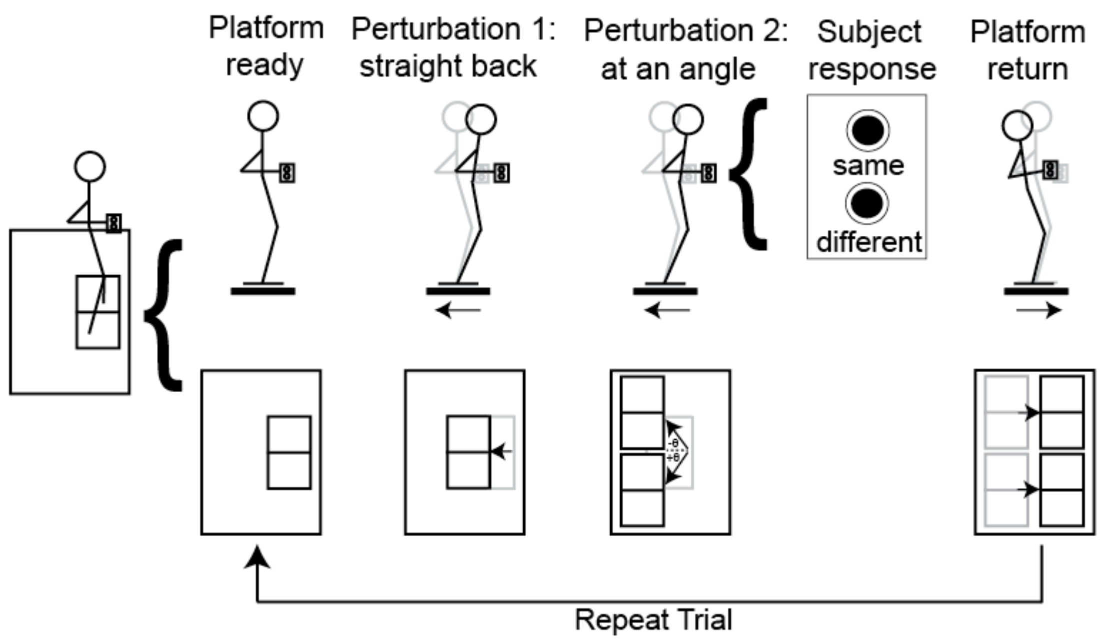

Figure 2.1 Participants stood on a translating platform where the first perturbation was straight back, 270°, and the second perturbation ranged from 255 - 285°. The participants responded with 'same' or 'different' based on direction after the second perturbation in each trial. After the pair of perturbations, the platform returned straight forward to not give the subject any feedback on the previous perturbations. The session ended when a threshold was reached, which depended on whether the PEST or psychometric method was used.

The ΔΘ represents the difference in angle direction between the first two perturbations. The subject was not told that the first perturbation was always in the same direction, nor when the perturbations would occur. After the second perturbation, the subject would respond on whether or not the direction of the first two perturbations was the same or different using a response box. The response box had 2 buttons, “same” or “different”, and was held throughout each trial. The third perturbation returned the platform in order to prepare for the next trial and was always in the 90° direction, straight forward, to prevent the subject from receiving any feedback on the lateral movement of the two previous perturbations. Each perturbation had a displacement of 7.5 cm, a velocity of 15 m/s, and a peak acceleration of 0.1 m/s^2. The direction of the second perturbation, or ΔΘ, for each trial was determined based on whether the psychometric method or the parameter estimation by sequential testing method was used. Trials continued until a directional acuity threshold was reached.

Psychometric Method

For the 2-alternative forced choice (2-AFC) psychometric method, a 75% probability threshold was determined by testing a randomized sequence of ΔΘs that spanned a range of ±15°, ±12°, ±9°, ±6°, ±3° and 0 [10]. Eleven ΔΘs were pre-selected and each ΔΘ was presented nine times. The set of ΔΘ was then randomized and presented to each subject. If the subject took a step during the trial, the trial was omitted and was presented again at a later time during the session. The session ended when ninety-nine good trials were recorded.

Parameter estimation by sequential testing method

The second method, PEST, uses an adaptive algorithm to approach a directional acuity threshold [10]. An initial ΔΘ of +1° or -1°, an initial step size of 4°, and a stopping step size criterion of 0.5° were chosen for each PEST that was run [8]. The PEST algorithm that is traditionally used to target a 75% threshold is the 2D1U (2-down-1-up) method [8]. As opposed to the psychometric method, which uses preselected ΔΘ values, the PEST method employs a standard 2D1U algorithm that chooses ΔΘs for each trial based on the subject's response to the previous trials. The session ended when the iterative step size fell to 0.5° or lower. In order to test whether subjects improved throughout the experiment, a second PEST was run on 9 of the 13 subjects.

Data Analysis

For the psychometric method, the data was analyzed using the Wichmann toolbox MATLAB code in order to determine the 75% probability threshold and the confidence interval [9]. The threshold for the PEST method was determined to be the ΔΘ that was tested when the step size fell to 0.5° [8]. The left and right psychometric thresholds were compared to determine if any significant difference was present. The thresholds from the two methods, psychometric and PEST, were also compared in order to determine where the PEST threshold was in relation to the psychometric threshold and the confidence intervals. The accuracy and precision of the floor motion was analyzed in order to determine the actual movement compared to the desired direction of movement.

Computational Modeling

A computation model was used in order to determine the variability in PEST and its ability to narrow down to a threshold over multiple sessions. A simulated subject was created based on a psychometric curve taken from an experimentally tested subject. A ground truth experiment was carried out computationally where the subject's experimental psychometric curve was assumed to be the true perceptual capability. The simulated subject's response to each trial was generated as a random number from a standard set. The random generated number was compared to the probability of responses from the known psychometric curve in order to determine whether the simulated subject responded with a "same" or "different" for that trial. The simulation was carried out using both the psychometric and PEST methods. The same experimental parameters were used for the model. 750 simulations were completed for each method.

RESULTS

Experimental Paradigm

The experimental paradigm used to measure directional acuity thresholds consisted of two perturbations with the subject determining whether the direction of the two perturbations were the same or different (Figure 2.1). In addition, the actual platform movement was analyzed which showed that the precision of the platform decreases as the ΔΘ gets closer to 0° and the accuracy decreases as the ΔΘ gets farther from 0° (Figure 3.1).

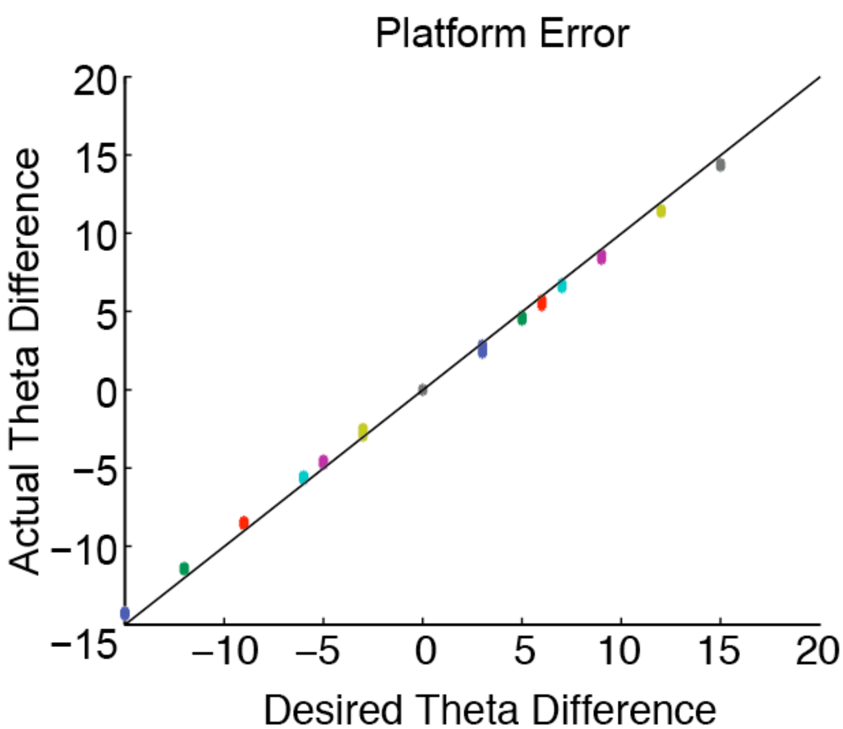

Figure 3.1 The actual theta difference is always smaller than the desired theta difference. The mean error for each ΔΘ decreases as the ΔΘ gets closer to 0.

Psychometric Thresholds

Psychometric curves to determine directional acuity thresholds were measured for each subject with a sample subject having a threshold of 9.2° (Figure 3.2A). Ninety-nine trials were used to determine two thresholds, the left and right, for each subject. There was no statistically significant difference between the left and right directional acuity thresholds ($p < 0.05$) (Figure 3.2B). The average directional acuity threshold for the 13 subjects was 9.1° ± 2.2° (Figure 3.2C).

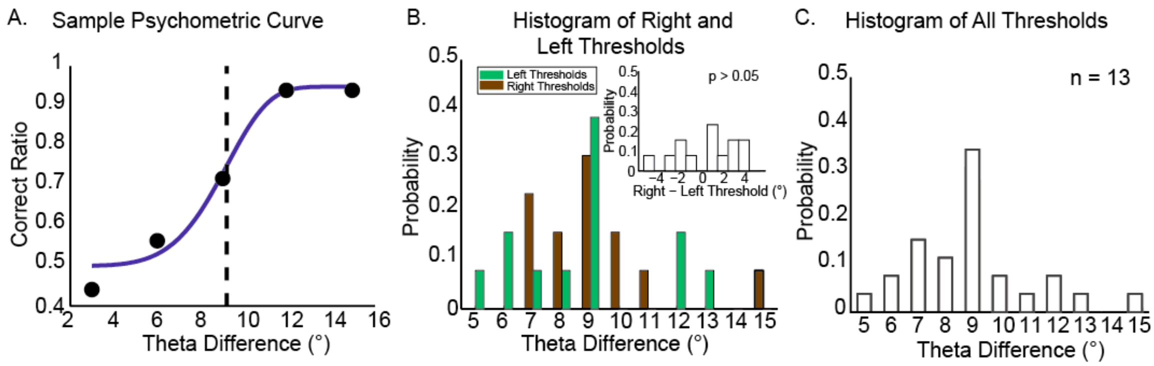

Figure 3.2 A) An example of one subject's psychometric curve with a directional acuity threshold of 9.2°. B) Ninety-nine trials were used to reach two psychometric thresholds, left and right, for each of the 13 subjects ($p<0.05$). C) The average directional acuity threshold was 9.1° ± 2.2°.

PEST Thresholds Compared to Psychometric Thresholds

The PEST method was carried out two times for 9 subjects and one time for 4 subjects in order to measure directional acuity thresholds. An example from the same subject shows the PEST threshold at -7.5° for the first session and -9.5° for the second session (Figure 3.3A). The number of trials PEST required in order to reach two thresholds, left and right, was an average of 24.0 ± 4.9 trials (Figure 3.3B). 63% of the PEST thresholds fell within one 90% psychometric confidence interval while 91% of the PEST thresholds lie within 1-3 psychometric confidence intervals (Figure 3.3C, 3.3D).

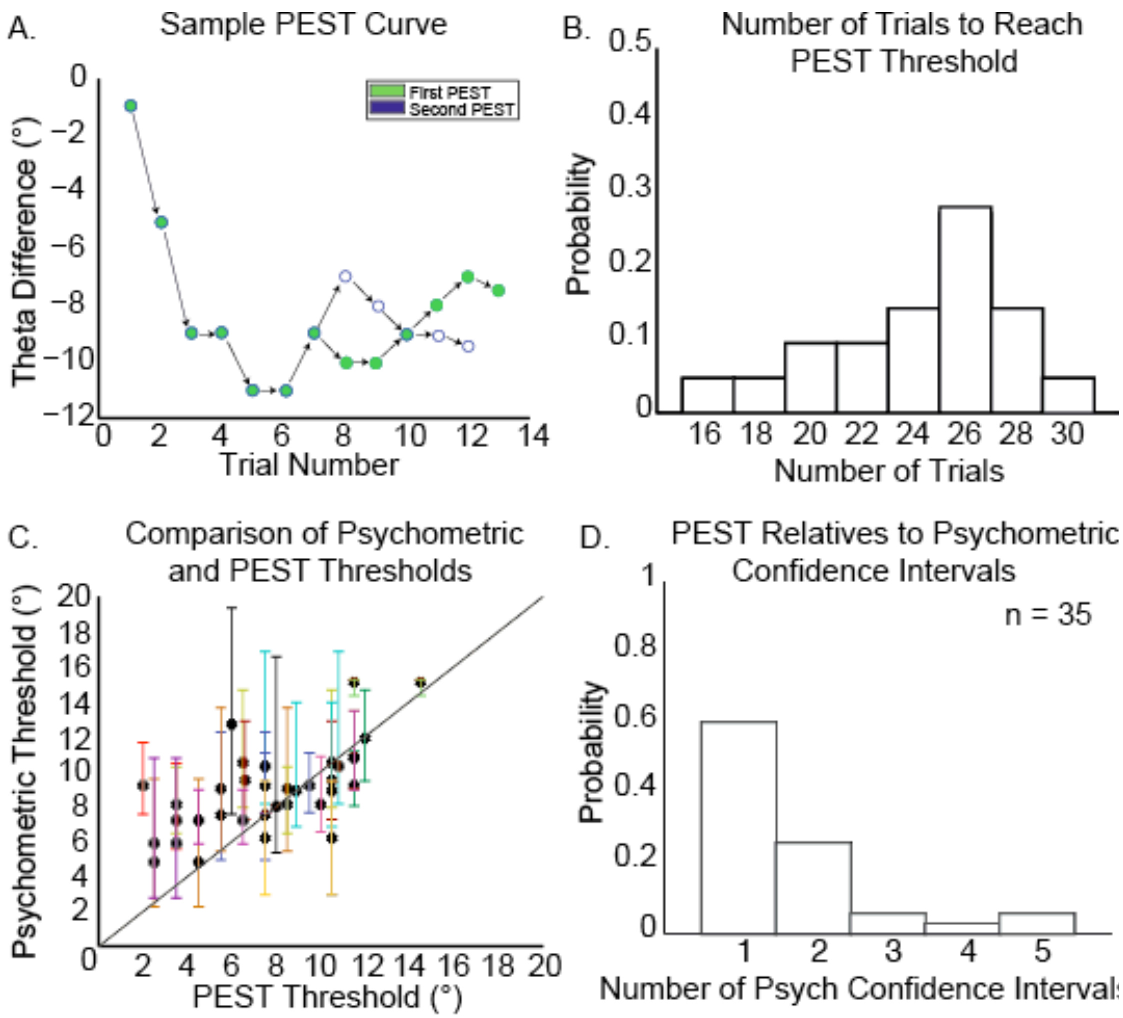

Figure 3.3 A) An example of one subject's PEST trials with the threshold being -7.5° in the first PEST and -9.5° in the second PEST. B) The average number of trials needed to reach each pair of thresholds in PEST, left and right, was 24.0 ± 4.9. C) The PEST and psychometric threshold for each subject was plotted with 63% of PEST thresholds falling in the 90% confidence interval for the psychometric curve. D) 91% of PEST thresholds lie within 1-3 psychometric confidence intervals.

Computational Model of PEST and Psychometric Methods

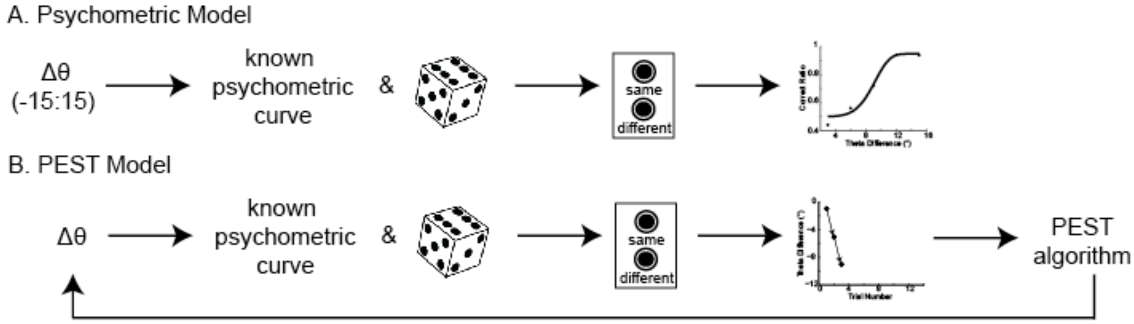

Figure 3.4 A) The psychometric model was built based on an assumed known psychometric curve from one subject with the same experimental parameters. 750 thresholds were simulated. B) The PEST model was built based on the same assumed psychometric curve used in (A) and 750 thresholds were simulated.

The computational model, which consisted of 750 thresholds measured using each method, showed that the average number of trials required to reach a one sided threshold for PEST was 12.9 ± 3.8 trials (Figure 3.4A, 3.4B, and 3.5A). The computational model also showed that the PEST method converged to a threshold with greater variability compared to the psychometric method with PEST thresholds ranging from 1.5° to 12.5° and psychometric thresholds ranging from 6.1° to 13.0° (Figure 3.5B). The computational models also showed that as the number of trials increases, the average error of the PEST threshold increases in comparison to the assumed psychometric threshold.

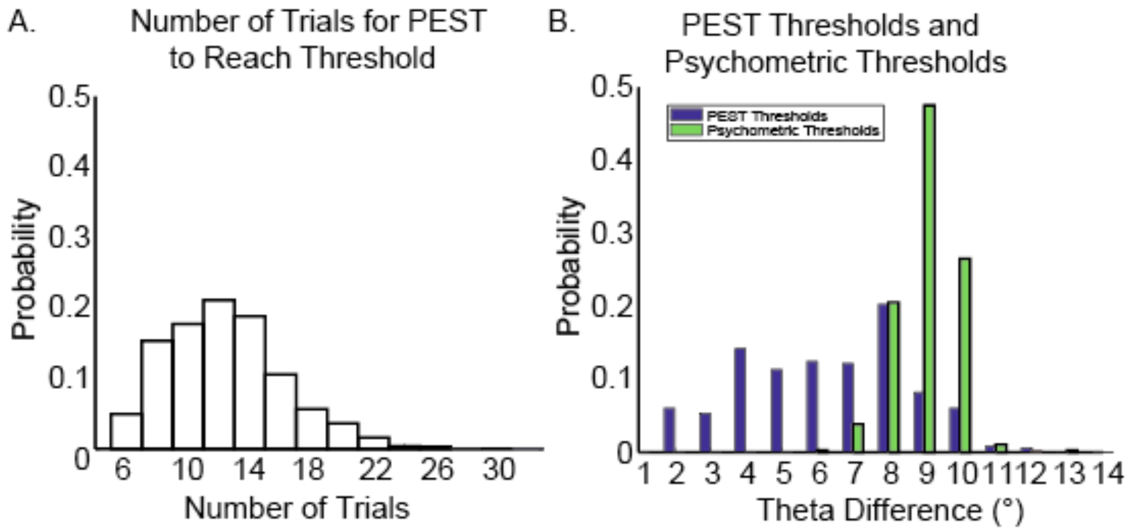

Figure 3.5 A) The average number of trials required to reach a one sided threshold for PEST was 12.9 ± 3.8. B) The computational PEST and psychometric thresholds were plotted with the PEST thresholds ranging from 1.5° to 12.5° and the psychometric thresholds ranging from 6.1° to 13.0°.

DISCUSSION

Discrimination thresholds, measured in this study, are the first known quantification of whole-body directional perception during standing. The directional acuity thresholds of 9.1° ± 2.2° were found to be higher than those of individual joints, such as hip flexions (2.3° threshold) and knee movements (3.8° threshold), and higher than discrimination thresholds for seated subjects of heading direction (6.0° threshold) [13]–[15]. As more sensorimotor integration is required for whole-body perception, there is possibly a larger effect from the spontaneous fluctuations or noise in the brain [16]. In addition, the thresholds from the joint angles could possibly sum up to be the threshold of the whole-body. On the other hand, previous literature work has also shown that combined sensory information can lead to lower thresholds in whole-body experiments [17].

The requirement of many trials limits the number of experimental parameters that can be tested in a given session due to subject exhaustion. The psychometric method provides information about both the directional acuity threshold and the psychometric curve, but requires a large number of trials (99 trials). The high trial count also limits the study to healthy populations where subjects can withstand large number of trials. To over come this limitation, we implemented the PEST method, which only provides information about the directional acuity threshold, but uses fewer trials to reach a threshold (average of 24.0 ± 4.8 trials). Other adaptive methods have been used, such as QUEST, but they do not significantly lower the number of trials, with approximately 100 trials required in one study to reach a threshold [18], [19]. However, the PEST method is shown to converge to thresholds with greater variability than the psychometric method in the computational model. Experimentally, 91% of the PEST thresholds lie within 1-3 confidence intervals of the psychometric threshold.

Given the current results, it cannot be concluded that PEST is reliable enough to use in replacement of the psychometric method to determine thresholds of directional acuity. In order to be able to study proprioceptive deficits in an older adults or clinical populations, the number of trials must be reduced. Since individuals with PD have been shown to have proprioceptive deficits, it is expected that their thresholds of directional acuity will be larger than a young adult population [20]. If the difference in thresholds between the two populations is larger than the variability of PEST, it is possible that PEST could be used to characterize thresholds in a clinical population. Literature studies suggest that perceptual threshold for individuals with PD can be up to 92-166% larger than normal subjects [21].

Future steps could include testing other adaptive algorithms such as Bayesian and maximum likelihood procedures. Examples of these adaptive algorithms are the ML-PEST and the Kontsevich and Tyler method [22], [23]. Another possible future step would be to quantify how different the directional acuity threshold for another population must be in order for it to be detected by the PEST given its current variability. In addition, there is a lot of current data that can be analyzed including response time for each trial. It would be expected that as the $\Delta\Theta$ gets closer to the threshold, the response time would increase. Other analysis includes testing a subject over a week to determine if learning or adaptation occurs in the experiment. Another possible step would be to test other cardinal directions in a young adult population to determine if thresholds change in different directions and if so by what magnitude. Other cardinal directions could be of different magnitudes given that different muscles and biomechanics are being used to maintain balance.

CONCLUSION

Motion perception was quantified in a young adult population using whole body translations. Thresholds of directional acuity were measured to be 9.1° ± 2.2° for a young adult population. PEST was validated as a faster method; however, the PEST method converged with greater variability than the psychometric method. In addition, PEST did not always converge on the same threshold as the psychometric threshold. Future work in validating whether PEST can be used to measure directional acuity thresholds must be completed before PEST is used over the psychometric method.

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