PROPRIOCEPTIVE ACUITY AS MEASURED BY TRADITIONAL MATCHING TASK VS. NOVEL PSYCHOPHYSICAL TASK

A THESIS
SUBMITTED TO THE FACULTY OF THE GRADUATE SCHOOL
OF THE UNIVERSITY OF MINNESOTA
BY

Naveen Elangovan

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
MASTER OF SCIENCE

Jürgen Konczak, PhD

December 2016

Acknowledgements

I would like to offer my sincerest gratitude to my academic advisor Dr. Jürgen Konczak, for consistently helping me with my thesis in all stages starting from its conception to defending it. Especially, his extraordinary insights provided me clarity of knowledge on the topic.

I would like to thank Dr. Michael Wade and Dr. David Nuckley for willing and offering to be part of my thesis committee.

I owe a special debt to my lab colleagues for helping me recruit subjects and also for helping me coordinate my thesis with other lab activities. I owe much to Amanda Herrmann for coordinating with me in the data collection process. I am indebted to Chiahao Lu and Joshua Aman for providing constructive feedback on various occasions throughout the project.

Thanks are due to all the subjects, who enthusiastically volunteered to expand the frontiers of science.

I would like to thank my friends who always extended their moral and social support in their own ways.

Thanking my parents and my brother must be a part, but not limited to this page. Their encouragement and best wishes made me come this far.

Dedication

This thesis is dedicated to

My parents

For boundless love and affection,

For always inspiring me to push the boundaries of my capabilities, and

For making sure that I always get the best in my life.

Abstract

Proprioceptive impairment causes movement inaccuracies and lack of inter-limb coordination in several movement disorders, which necessitates an accurate joint position sense evaluation as part of neurological evaluation. Currently, position sense acuity (i.e., the sharpness of the sense) is evaluated by means of joint position matching methods which involve matching a target position on one limb with the same limb or the other. These position sense evaluations can only identify severe impairments of position sense. They fail to isolate proprioception from other sensory inputs and are confounded by factors such as inter-hemispheric transfer and working memory. Alternatively, psychophysical evaluation methods are available. They are often used in research to evaluate joint position sense and are considered as 'gold standard' for assessing the sensitivity and acuity of the perceptual system. The purpose of this study was to compare and contrast the arm position sense acuity obtained by a contralateral matching task using a bimanual manipulandum with a psychophysical threshold measure using a passive motion apparatus. Results suggest that psychophysical testing provides a more precise measure of arm position sense acuity than measurements obtained in a contralateral matching task. Although, being two different evaluation methods for the common variable – arm position sense acuity, they show a poor correlation to each other. These findings suggest that psychophysical evaluation can help identify joint position sense impairment more accurately in patients with neurological disorders.

Table of Contents

List of Figures

INTRODUCTION

Proprioception

Proprioception is coined from the Latin word ‘*Proprius*’ which means one’s own self. Sherrington defined deep receptors for stimuli that “are traceable to actions of the organism itself, and …, since ..., the stimuli to the receptors are delivered by the organism itself, the deep receptors may be termed proprioceptors, and the deep field a field of proprioception” (Evarts, 1981). Proprioception is defined as the sense of body position and movement of one’s own limbs and body without using vision (Gardner, Martin, & Jessell, 2000). Gardner et al. (2000) describe that proprioception has two sub modalities which are sense of stationary position of the limbs (limb-position sense) and sense of limb movement (kinesthesia). Konczak and his colleagues (2009) describe kinesthesia as conscious awareness of limb position or motion in space. In contrast, proprioception refers to the unconscious processing of the proprioceptive signals used for reflexive and postural motor control while recognizing that proprioception also forms the basis of kinesthesia. This definition by Konczak (2009) will be followed in this article.

Proprioceptive contribution

Proprioception plays an integral role in motor control. Proprioceptive feedback is essential for the execution of goal-oriented movements ranging from gross movements such as kicking a soccer ball and playing a forehand in tennis to fine motor activities like typing letters in a keyboard. Higher centers of the brain receive and process the sensory impulses from proprioceptors of the body, along with those from eyes, skin (haptic impulses) and vestibular apparatus to produce goal-directed movements in a coordinated manner. Proprioceptive inputs to the somatosensory cortex provide information about the current position of the limbs. Using this information, primary motor cortex, in association with premotor area, is believed to estimate the desired target range of movement for the goal and create the necessary motor commands accordingly. (Grush, 2002; Wolpert & Miall, 1996). In complex motor behaviors such as locomotion, afferent proprioceptive input are responsible for rhythmic activation patterns of the leg muscles, compensation to gait perturbations, control of body's center of mass and adaptation to actual ground conditions (Dietz, 2002).

Lack of proprioception

Loss of proprioceptive feedback to the higher centers of the brain causes a number of movement abnormalities. Studies on deafferented patients showed that lack of proprioceptive feedback affected the spatial (Gordon, Ghilardi, & Ghez, 1995) and temporal aspects (Gentilucci, Toni, Chieffi, & Pavesi, 1994) of motor control. Gordon and his colleagues (1995) found that lack of proprioceptive feedback caused large spatial errors in terms of direction and amplitude in a simple reaching task. In a prehension task, Gentilucci and his coworkers (1994) found that deafferented patients took more time to reach an object, to reach the peak velocity and to reach the deceleration on comparison with normal subjects. These studies suggest that lack of proprioceptive feedback results in improper planning of the motor commands. Ghez and Sainburg (1995) suggest that proprioceptive impairment affects inter-limb coordination which is caused by issues in planning and learning of new movement patterns. Proprioceptive impairment (Fiorio et al., 2007; Ghez, Gordon, Ghilardi, Christakos, & Cooper, 1990; Mongeon, Blanchet, &

Messier, 2009; Rothwell et al., 1982) is believed to cause movement inaccuracies in various neurological conditions like Parkinson’s Disease, sensory neuropathies, etc.,

Evaluation of proprioception

Owing to the movement inaccuracies caused by the impairment of proprioception, evaluation of proprioception is crucial for any neurological evaluation. Position sense can be evaluated as both whole-body position sense and limb position sense. Whole body position sense involves the interaction of multiple sensory systems such as proprioceptors, touch, pressure, vision and vesibular apparatus, whereas testing of limb position sense can be restricted to proprioceptors, touch and pressure with well-designed evaluation methods.

Matching methods

In neurological clinics, limb position sense is usually tested by a joint-position matching task. In a matching task, the examiner passively moves the patient’s unaffected arm to a target position and then the patient actively moves the affected side to match the position of the unaffected limb. After the patient matches the target position, the examiner visually observes the position of both the arms and determines the impairment of proprioception. Depending upon the level of examiner’s clinical experience, the results may vary in a reevaluation of the proprioception in the same patient by the same or a different examiner.

In a research laboratory setting, the use of a bimanual manipulandum provides a more controlled method to test the position sense (Goble, 2010). This method simulates the clinical matching method, with patients actively matching the position of one arm to the other. The differences in their joint angular position can be measured precisely and will be used as a measure of their position sense acuity. These tests compare the position sensitivity of both the sides relative to each other rather than testing the position sense of each side individually. The position sensitivity from such tests is variable depending on the type of instruments used for testing.

In addition, these tasks involve active movements, which may be a confounding factor, if one is interested in solely measuring perceptual performance. The reason for confounding measures of perceptual acuity is that the active movement generates its own feedback signal that normally is integrated with the afferent feedback from the periphery. Volitional movements are a consequence of planned execution of the motor commands originating in the motor cortex. A copy of these motor commands reaches other centers such as cerebellum. This efference copy can then be used to predict the expected sensory feedback based on the planned motor commands (Blakemore, Frith, & Wolpert, 2001; Blakemore, Wolpert, & Frith, 1999).

Psychophysical methods

Psychophysics refers to the methods that are used to quantify perceptual system. Fechner (1966) coined the term “Psychophysics” to refer to the relation between the physical stimuli and the contents of consciousness such as sensations. Proprioception can be quantified as thresholds by psychophysical methods using a forced-choice paradigm. Forced-choice paradigm involves a method in which the subjects are forced to identify the odd stimulus from two of the stimuli presented to them. A threshold is defined as the smallest amount of stimulus energy necessary to produce as sensation (Gescheider, 1985). Detection threshold will be the smallest change in position that a person can consciously identify whereas discrimination threshold will be the critical difference between two positions that can be identified. For example, to measure the discrimination thresholds, the subject's arm will be passively moved to two different positions and the subject will be forced to make a judgment about which of these two positions were proximal to the body. Depending upon the correct or incorrect responses the distances between the two positions will be reduced or increased. A psychometric sensitivity function can be derived from these response data (Figure 3) and an area of uncertainty or the area where the subjects were not able to appreciate the differences in position can be found. Based on the sensitivity function, a maximum likelihood estimate of the just-noticeable difference (JND) thresholds can be found. These JND thresholds are a psychophysical measure of the proprioceptive acuity.

Proprioceptive acuity can also be measured by a traditional contralateral matching task used in clinical settings. In this task, the examiner *passively* moves the participant's arm to a desired position which serves as a *target* and the participant has to *actively match* the other arm to the target position. The absolute differences between the angular displacements of the two arms will provide the position error. The means of these position errors across trials will provide an approximate measure of the proprioception acuity.

The measures from the two evaluation methods just discussed are comparable. But there is no data available in the literature comparing these two measures. Psychophysical evaluation of proprioceptive acuity can theoretically be considered as more appropriate method for evaluating limb position sense for two reasons. First, it involves passive movements which eliminate the influence of efference copy information for sensing joint position sense. Active matching involves motor planning that introduces another confounding variable in the form of planning error which will influence the position sense perception and eventually position sense evaluation. Second, psychophysical testing is based on forced-choice paradigm. The participant has to perceive two positions and make a judgment about their similarity. Based on this theoretical perspective, psychophysical testing of proprioceptive acuity should provide a more precise and less variable measure when compared with the position error measured in a contralateral matching task.

PURPOSE STATEMENT

This study investigated the precision of arm position sense using two different methods – a contralateral matching method and a psychophysical method. The purpose of the study was to identify whether these two evaluation methods yield differences in position sense sensitivity and to study whether the measures from these two methods significantly correlate with each other. Given that psychophysical testing and contralateral matching are measuring position sense acuity, one would expect that the acuity measures derived from these methods should strongly correlate with each other. Also, psychophysical evaluation being a method that more efficiently controls for the confounding factors than the matching method, it should provide a smaller position sense acuity measure. If the psychophysical evaluation of proprioceptive acuity provides a more precise measure of acuity, then clinicians may consider this method as a new tool in their neurological evaluation of proprioception.

HYPOTHESIS

Based on these premises, two hypotheses were formulated:

First, mean of the JND thresholds for all the subjects obtained in the psychophysical task should be significantly different and less than mean of the position errors of all the subjects measured in the contralateral matching task.

Second, both these methods are just two different ways of assessing position sense acuity the measures yielded by them should strongly correlate to each other.

METHODS

Participants

Twenty-seven healthy young adults (mean ± SD = 25.7 ± 4.1 years; 26 right-handed, 1 left-handed person) participated in the study. All subjects were naïve to the device and the tasks. They had no injuries or pathologies involving the upper limb. Before the start of the procedure, the subjects were explained about the nature of the study and were allowed to voluntarily decide about the study participation. Each participant read and signed the consent forms approved by the Institutional Review Board of the University of Minnesota.

Instruments

A. Bimanual manipulandum

A bimanual manipulandum consisting of two horizontal levers (42 cm, each) which acted as bilateral moveable arm rest was used to test the position sensitivity in the contralateral matching method. The proximal ends of the arm rests were affixed to a near frictionless axle, which allowed the levers to move in a horizontal plane over the table surface. As shown in figure 1, the arm-rests had a hand grip whose distance from the axis can be adjusted to allow the participants with different forearm lengths to hold the grip comfortably. Participant aligned their arms in such a way that elbow joint axis was over the axis of the arm rest and forearms in mid-prone position as they hold the adjustable hand-grip. The angular position of the arm rests were monitored by the potentiometers attached to their respective axles. A change in the angular position of the arm rest caused voltage differences in the potentiometer. The analog signals from the potentiometer were

Figure 1. Bimanual manipulandum. A subject performing the contralateral matching task in a bimanual manipulandum with the examiner passively moving the non-dominant arm to the target position. All subjects were blindfolded with black opaque goggles during the contralateral matching task.

converted to digital signals using a digital Input-output board from National Instruments. The algorithm written in the BASIC language converted the voltage differences (in mV) to angular position (in degrees) and was stored in the computer hard disk for later analysis. The resolution of these potentiometers is 0.008°.

B. Passive motion apparatus

A passive motion apparatus was used to test the position sense acuity in the psychophysical evaluation method. The passive motion apparatus (figure 2A) can be used to test JND thresholds for limb position and limb motion sense. The apparatus has a moveable arm rest attached to an axle at the proximal end. The arm rest can be set to motion by a DC motor located at the distal end of the arm rest. The DC motor was controlled by a feed-forward controller circuit. The resolution of the motor in the passive motion apparatus is 0.00018°/step (5466 steps / 1°). The movement of the armrest changes the position of the forearm which will serve as the stimulus. The DC motor can move the arm rest in both clockwise and counter-clockwise directions at angular velocities between 0.06°/s and 2.85°/s. The arm rest can only move between two fixed points separated by an angle of 17°. The two points were set by limit switches in the arc of the arm-rest movement. When the arm rest comes in contact with the limit switches, it will be turned on which will stop the motor from moving any further. An adaptive algorithm based on the Quest algorithm (Watson & Pelli, 1983) and coded in Matlab ("Matlab: The Language of Technical Computing," 2010) determined the velocity and duration of the arm rest movement, thereby providing two different positions as a stimulus to the participant. The criteria used by the Quest algorithm to select the duration of the movement are discussed in the experimental procedure.

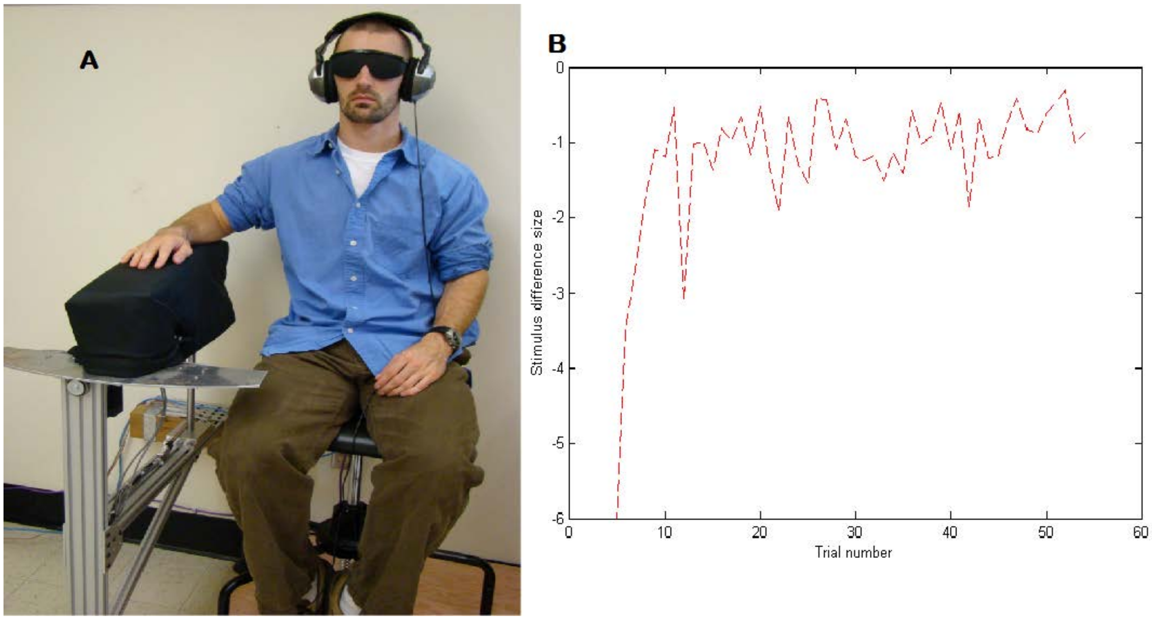


Figure 2. Passive motion apparatus. A) Subject performing the psychophysical task using the passive motion apparatus. Vision was blocked with black opaque goggles and sound was masked by pink noise emanating from headphones. B) Differences between the two position stimuli (in degrees) across trials for one of the subjects participated in the study. Stimulus difference size started with 6° and converged to around 1°.

Procedure

To avoid the order effects, participants were randomly assigned to perform the two tasks in one of the two possible orders. The order of the tasks was counter-balanced across the complete sample. Before the start of the procedure, handedness of all subjects was assessed using the *Edinburgh Handedness Inventory* (Oldfield, 1971). This is a simple inventory that provides a quantitative measure of handedness. It determines the handedness based on a cumulative score for hand preferences for a set of ten activities which are writing, drawing, throwing, using scissors, toothbrush, knife (without fork), spoon, broom, striking a match and opening a lid. To control for the effects of hand dominance/hemispheric lateralization on proprioceptive acuity, dominant arm was tested for all subjects. The tasks involved in the study are described as follows.

A. Contralateral matching method

In the contralateral matching evaluation, subjects rested both of their forearms on the moveable splints of a bimanual manipulandum while being seated in an upright position. Starting position was the position in which the shoulder is slightly flexed and abducted and elbow at approximately 90° of flexion. Subjects were instructed to hold the hand grip in a relaxed manner for two reasons. First, to eliminate any muscular contractions as this would restrict the examiners ability to move the arm rest. Second, to avoid processing of active motor commands as this would provide an efferent copy of motor command aiding in the perception of position sense. The arm rest had a stopper that checked the movement beyond the starting position ensuring the same starting position for all the trials. The task involved 20 trials. In each trial, the examiner moved the splint on the subject’s non-dominant side to a range of 10 degrees from the starting position. This position on the non-dominant arm served as the *target position*. Then the subject had to actively match the target position with their dominant arm. The angular displacements on both sides were recorded on the subject’s call of reaching the target position. The procedure was repeated for the rest of the trials. The participants were allowed a few practice trials before the start of the task to understand the procedure. During the whole task, all the subjects wore a pair of opaque spectacles that blocked the vision of the arm position.

B. Psychophysical method

During the psychophysical evaluation, the subjects were seated in an upright position with their dominant arm resting on the arm rest of the passive motion apparatus. The arm rest consisted of foam padding to nullify the vibration effects of the DC motor. During the task, subjects wore headphones that played *pink noise* to mask possible auditory cues due to motor noise. A pair of opaque spectacles eliminated any visual cues of splint/arm movement. The starting position of the armrest for the psychophysical method was similar to that of the contralateral matching method. Each trial involved two passive movements of the forearm – a standard and a comparison. The standard was always an angular displacement of 10° from the starting position. The comparison was an angular displacement which is less than 10° from the starting position. Each of these movements began at the same starting position with the armrest moving in a direction towards the body in all the trials. When the armrest reaches the desired position of the first passive movement, it will pause and will move back to the starting position. This is followed by the second passive movement for the trial. After each trial subjects were asked, “Which of these two movements went further?” or “Which of these movements came closer to the body?” The subjects responded by saying “1” or “2” indicating their perception about which movement came closer to the body, where “1” represents the first movement and “2” represents the second movement. Based on these responses, an adaptive QUEST algorithm selected the angular displacement for comparison stimulus for the subsequent trial. The quest algorithm is based on the assumption that the subjects' threshold do not vary from trial to trial. The algorithm assumes an initial probability distribution function for the threshold (King-Smith, Grigsby, Vingrys, Benes, & Supowit, 1994). If the subjects' perception matched with the stimulus difference presented, the algorithm considers the threshold is probably below the stimulus difference and reduces the stimulus difference between the standard and the comparison stimuli for the next trial. If the subjects' perception did not match, the algorithm considers the threshold is above the stimulus difference and increases the stimulus difference for the next trial. In simple terms, if the subjects' response was correct, the succeeding trial was made "tougher" and if wrong, the trial was made "easier". The adaptive algorithm ensured that the difference between the standard and the comparison stimuli converged to the JND threshold (Figure 2B).

Each trial began with the examiner pressing the button. The order of the standard and comparison movements was randomly switched between trials. The arm rest moved at a constant angular velocity of 2°/s for both the standard and comparison movements of all the trials for all subjects. The task involved a variable number of trials usually between 40 and 60 trials as determined by the adaptive algorithm. The participants were given rest periods of 1-2 minutes for every 12-15 trials to avoid mental fatigue and to ensure more active focus on the task. They were also allowed to take voluntary rest periods, if they needed. At the beginning of the testing, subjects were allowed a few practice trials for familiarization with the task.

Measurements

A. Contralateral Matching Method

For the contralateral matching method, the potentiometer deflections for both the arm-rests were recorded in degrees for all the trials for every subject and were saved as individual data files for each subject. The deflection in the non-dominant side served as the target value while that in the dominant side served as the match value. The *absolute difference* between these two values served as the position error. Figure 4 shows the position error across all trials (n of trials = 20) for one of the subjects participated in the study. The position error values of all the twenty trials for all the subjects were found using a customized software program in Matlab. The mean position error values of all subjects were copied to another data file.

B. Psychophysical method

Figure 2.B shows the difference between the two stimuli presented to one of the subjects for every trial during the psychophysical task. The stimulus difference size converged to the position sense acuity of the subject as the trials progressed. Based on the subjects' responses for every trial, the percentage of correct responses was computed and fitted with a cumulative Gaussian function using a custom-written algorithm based on MATLAB Technical Programming Language. Gaussian function is a curve-fitting procedure (Figure 3) which was used to fit the percentage of correct responses for each subject to derive the psychometric variable – JND threshold. This function transforms the stimulus differences in logarithmic scale and represents it as a discrete array of numbers,

typically with about 50 equally spaced elements. These span a finite stimulus range that is thought almost surely to contain the threshold value. When the new stimulus is presented, it is recorded as correct or incorrect. Then the logarithmic array is updated by adding the correct/incorrect responses in two different arrays. The maximum likelihood estimate of the threshold is obtained by updating these arrays after each trial and by scanning the logarithmic array for its maximal element. 75% correct response rate served as the psychophysical or JND threshold for all the subjects.

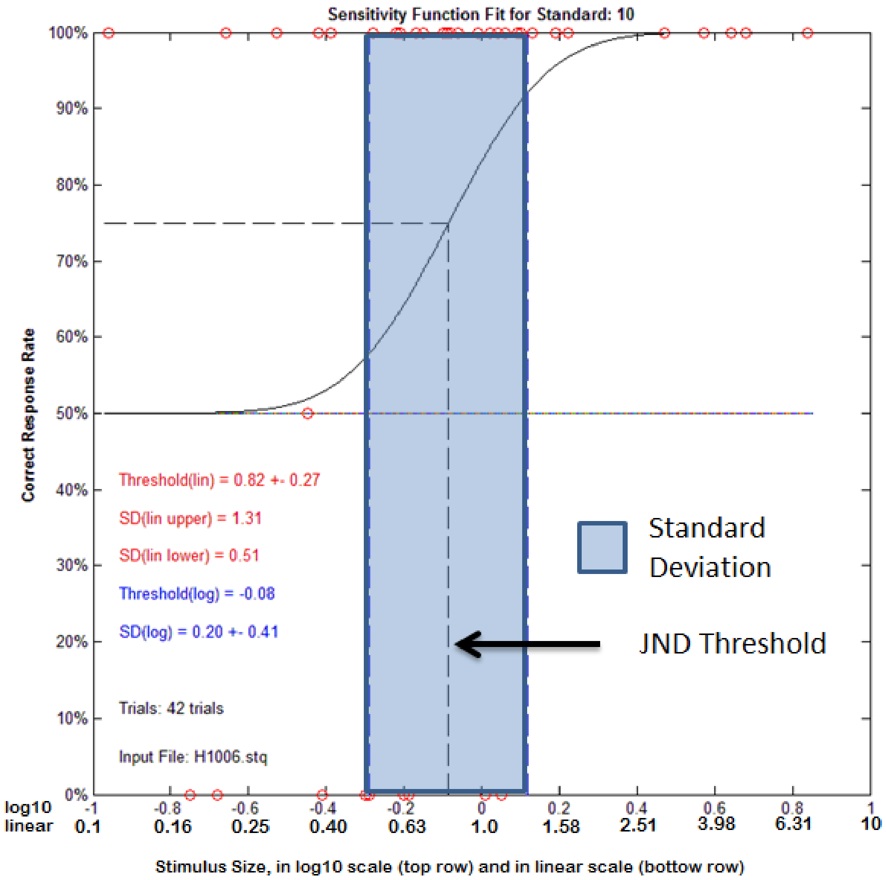


Figure 3. A sensitivity function fit showing the discrimination thresholds for one subject. Dotted line shows the JND threshold for the subject (0.82°). Shaded area shows the standard deviation of the JND threshold.

The JND threshold values of all subjects were copied to the data file that had mean position error values of the contralateral matching task. This data file that contained both the psychophysical thresholds and mean position error values was further analyzed using a statistical programming software *R – A language and environment for statistical computing* (R Development Core Team, 2011) .

ANALYSIS

The mean position error values and the JND thresholds were two different measures of position sense as evaluated by the contralateral matching method and the psychophysical method respectively. These two different measures of position sensitivity were analyzed using a custom-written algorithm based on R statistical programming language (R Development Core Team, 2011). The mean, median and standard deviation of these measures were found. The density distribution of these measures was studied (Figure 6). Box plots and residual plots were plotted to identify the potential outliers in the dataset. A paired t-test of the two different measures of position sensitivity was performed to determine the significance of mean differences between these measures. Correlation analysis followed regression analysis was performed to determine whether these variables strongly correlate to each other.

RESULTS

Outlier Analysis

In an analysis of the quartile ranges, two subjects' data (15 & 24) were outside 1.5 times the interquartile range. Further analysis of the data showed that the subjects 15 & 24 are above two standard deviations of the mean values. Based on these findings, the subjects 15 & 24 were classified as outliers and were excluded from further analysis (Frigge, Hoaglin, & Iglewicz, 1989).

Contrasting position error versus JND threshold

Position sense acuity as measured by the two evaluation methods – contralateral matching method and psychophysical method were contrasted against each other to understand the differences between the measures. Figure 5 shows the position sense acuity measured by the two evaluation methods for each subject. Psychophysical method produced a JND threshold that was more often smaller than the position error produced by the contralateral matching method. The density distribution of the JND threshold and position error are shown in figure 6.

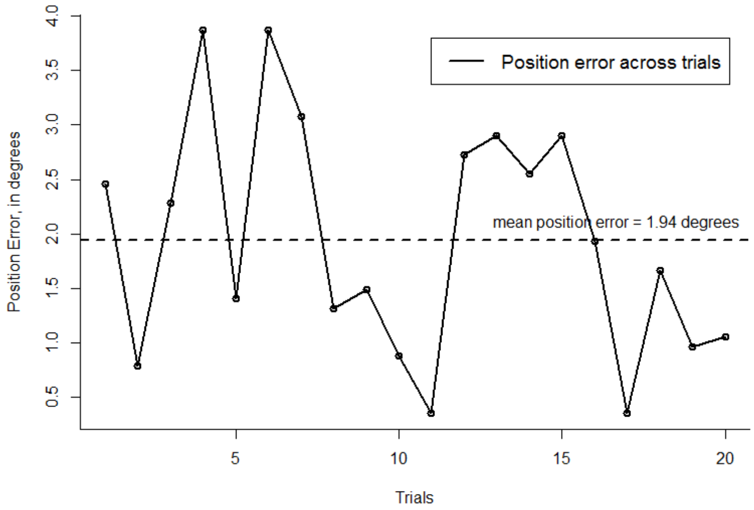


Figure 4. Absolute position error values in the contralateral matching task across all the trials for one of the subjects who participated in the study.

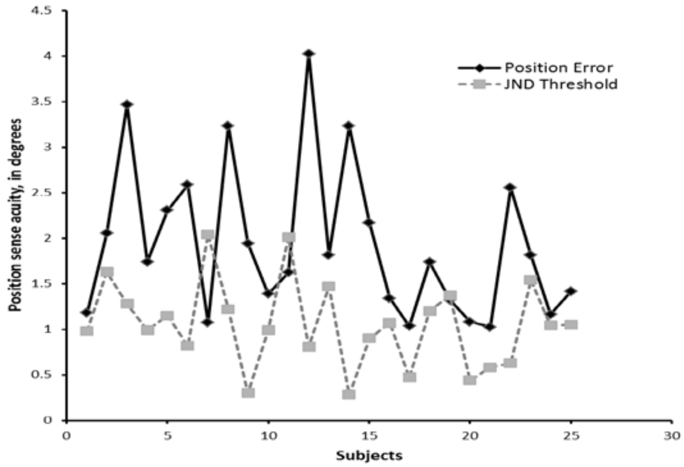


Figure 5. Position sense acuity as measured by the two evaluation methods. Black diamonds shows the position sense acuity as measured by the contralateral matching method for each subject and are connected by a black solid line. Gray squares shows the position sense acuity as measured by psychophysical testing for each subject and are connected by a gray dashed line.

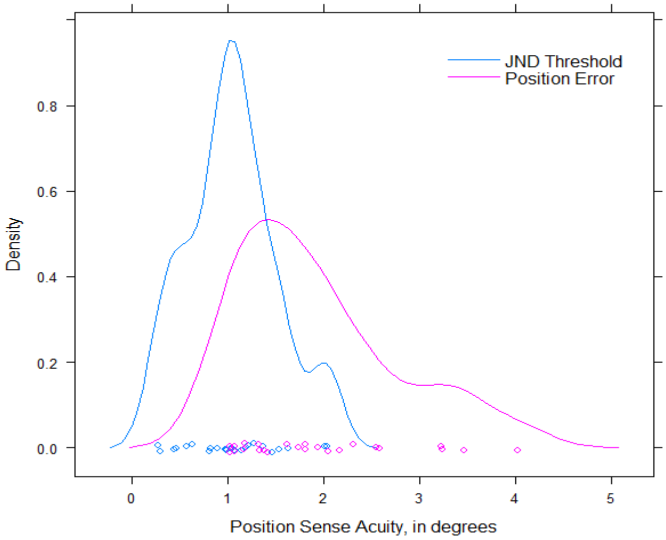


Figure 6. Density distribution of the mean position error and JND threshold of all subjects.

The distribution of the JND threshold was tall and narrow, while the distribution of the position error was short and wide suggesting that the standard deviation of the JND threshold was smaller than the position error.

A descriptive statistical analysis of the absolute position error values for all the subjects in the contralateral matching task showed a mean of 1.93°, a median of 1.74° and a standard deviation of 0.84°. The descriptive analysis of the JND thresholds of all the subjects showed a mean of 1.05°, a median of 1.04° and a standard deviation of 0.47°. A paired t-test (figure 7) showed that the mean absolute error values of the contralateral matching task is significantly larger than the psychophysical thresholds with t(24) = 4.36 and p = 0.0002. These results show that JND thresholds are more precise and less variable in comparison with position error measured by the contralateral matching method.

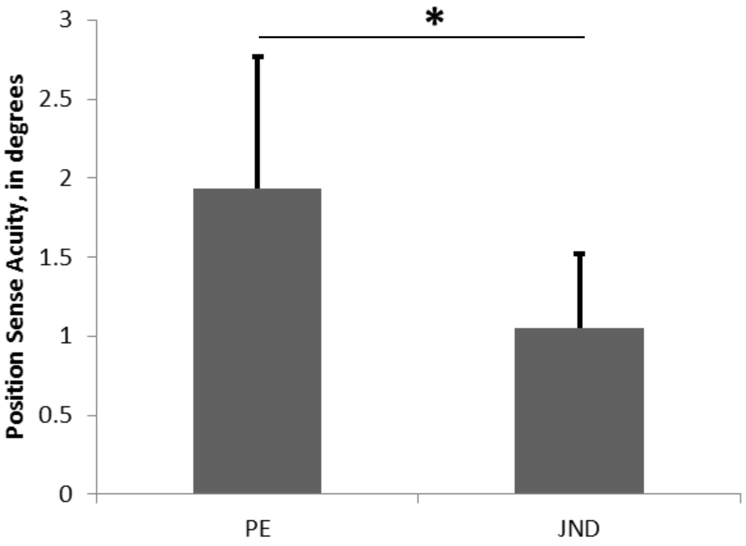


Figure 7. Mean position Sense acuity as measured by the two evaluation methods – the contralateral matching method and the psychophysical method. Columns shows the

means and the error bars show the standard deviations of the two measurements for all the subjects. *Note:* * - p <0.001

Relationships between position error and JND threshold

Relationships between the JND threshold and position error were analyzed. In figure 8, JND threshold obtained for each subject during the psychophysical method were arranged from smallest to largest and were plotted against the corresponding position error for each subject. This graph suggests that there is no linear relationship between the two measures of the position sense acuity. In order to study the relationships between the JND threshold and position error, correlation and regression analyses were done.

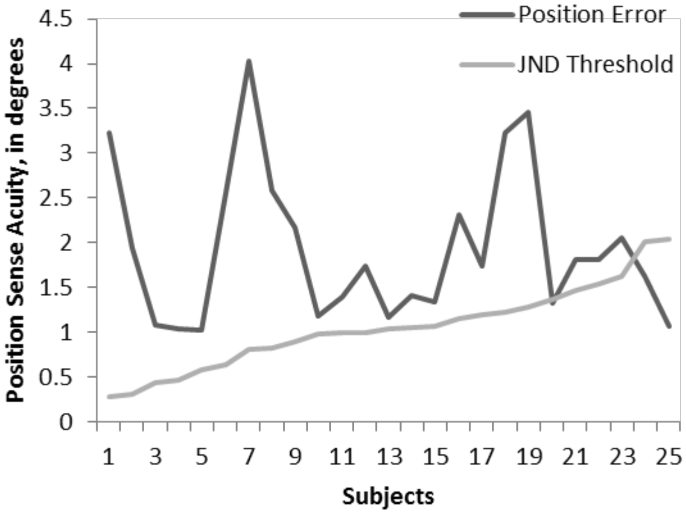


Figure 8. Position sense acuity of all subjects. Subjects are rearranged from smallest to largest JND threshold values. JND threshold values of all the subjects and their corresponding position error values were plotted.

Correlation analysis between the JND threshold values and mean displacement error values of all the subjects showed a poor negative correlation (r = -0.13). In a linear regression analysis, mean position error values poorly predicted the JND threshold values, b = 2.1701, t(23) = -0.2267, p = 0.55. Mean position error also poorly explained the variance in JND threshold values, $R^2 = 0.0161$, F(1,23) = 0.38, p = 0.55. Figure 9 shows the JND threshold plotted against the mean position error for all the subjects. Note that the points are scattered and also, the regression line is almost parallel to the X- axis. These results provide evidence that the position error measured by the contralateral matching method is poorly correlated with the JND threshold measured by the psychophysical evaluation method.

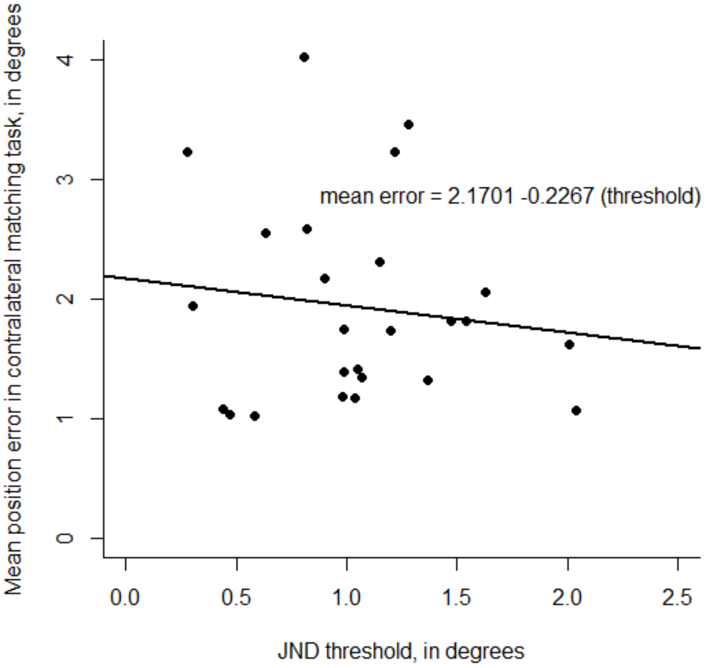


Figure 9. Graph showing the JND thresholds plotted against the mean position error values of all subjects (n=25). Each point corresponds to each subject's position error in the y-axis and the JND threshold in the x-axis. The solid black line represents the least squares regression line. This line shows that there is a poor negative correlation between the variables.

DISCUSSION

The goal of the study was to identify the more appropriate and accurate position sense acuity measure among two different measures evaluated by a traditional contralateral matching task and a psychophysical task. Specifically, I tried to achieve the following aims. 1) To find whether JND threshold is a more precise measure of the position sense acuity than the absolute position error. 2) To analyze whether these different measures of position sense acuity correlate with each other.

Main findings of the study were as follows: The differences between the JND threshold and the position error were highly significant. JND threshold was smaller in magnitude in comparison with the position error. Also, the JND thresholds poorly explained the variances in the absolute position error. In other words, JND thresholds obtained by the psychophysical testing do not relate to absolute position error values measured by the contralateral matching method.

Possibility of errors

Figure 8**,** apart from showing the absence of a linear relationship between the two variables, it also shows that the position sense acuity measured by the psychophysical method appears to be more precise than that measured by the traditional matching method. Most often the subjects recorded lesser magnitude of JND threshold than the position error, which means psychophysical method provides a more precise position sensitivity measure. This mean difference did not fall within the measurement error. The resolution of the encoders of the manipulandum was 0.008°, while the spatial resolution of the passive motion apparatus was 0.00018°. Thus, it is highly unlikely that the reported mean differences are not valid, because they fall within the measurement error of the instrument systems.

Factors influencing the relationship between different position sense acuity measures

Despite being two different measures of position sense acuity, JND threshold and position error do not correlate with each other. Grob and his colleagues (2002) also found a lack of correlation with different measurements of proprioception in the knee joint. This lack of relationship between different position sense acuity measures can be explained by neural contributions as well as the methodological distinctions that vary between these two evaluations. First, the contralateral task involves both the arms, which necessitates transfer of the proprioceptive impulses from one side of the body to the other. This transfer depends on the inter-colossal connections between the two cerebral hemispheres which may not be involved in the psychophysical task which is unilateral in nature. Second, the psychophysical task presents two different stimulus positions at different points in time. This temporal variation in presentation of the stimulus needs the use of memory in the psychophysical task, which may not be involved in the contralateral matching task (figure 11). Since the study involved young healthy adults, it is highly unlikely that they have inter-colossal degeneration and/or lack of memory to explain the differences between the two measures. Third, the target position in the contra-lateral matching task was set by the passive movement of the arm. This passively set target position controls for the efferent copy of the motor commands and thereby the predicted sensory feedback (figure 10). But the active movement during matching brings in some new variability in the form of motor planning and motor execution. Motor planning in the active movement is prone to be associated with some intrinsic planning error, which

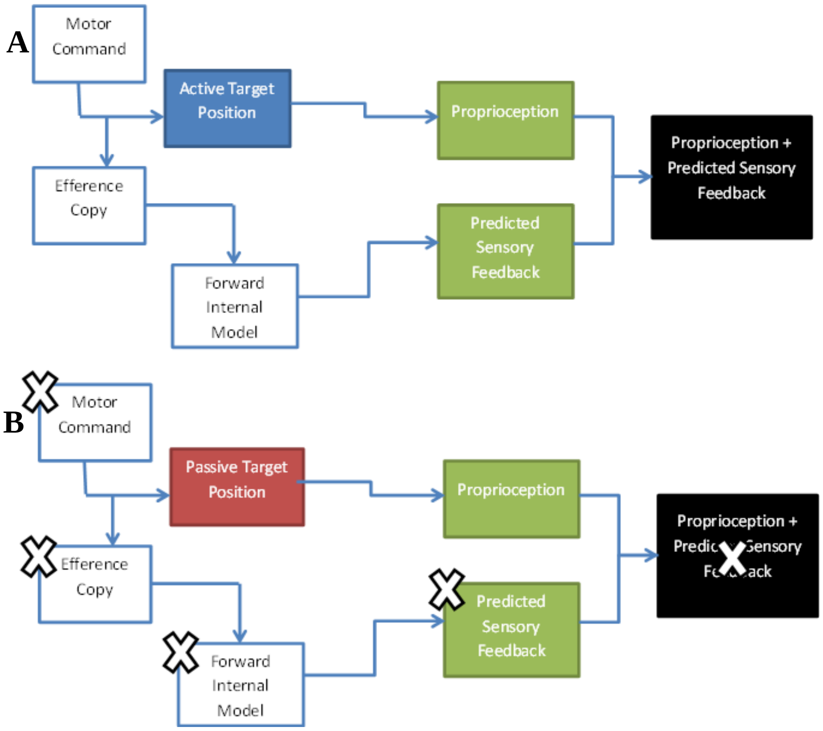


Figure 10. Schema showing confounding variables for A) Active target position in matching task and B) Passive target position in matching task. Passive target position controls for the confounding variable – predicted sensory feedback in the contralateral matching method.

cannot be rectified, as the subjects do not get any feedback about the matching accuracy and there could be no learning effect in a span of 20 trials. (A pilot study performed prior to the study, that involved contralateral matching of 60 trials at three different angular positions demonstrated no effects of learning). Since the psychophysical task is entirely passive movements, it remains unaffected by the variability due to motor planning and movement execution. Fourth, psychophysical task involved a forced-choice paradigm, which softly forced the subjects to pay more attention to the task, so that they can verbally produce a response. These could be the reasons for the two different position sense acuity measures for not correlating/poorly correlating with each other.

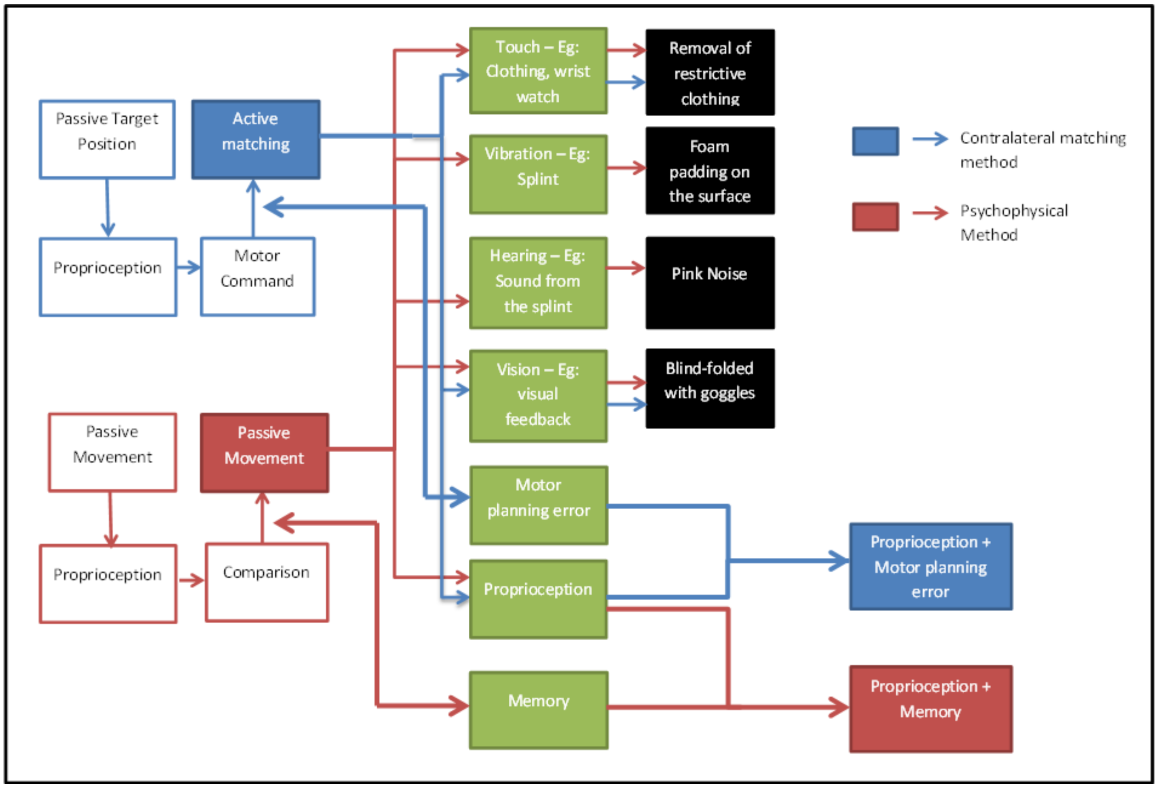


Figure 11. Schematic diagram depicting the various factors influencing the position sense acuity evaluation in the contralateral matching method and psychophysical method.

Clinical tool

Based on the findings of this study, the psychophysical evaluation of the joint position sense acuity appears to be an ideal tool for diagnosing milder forms of proprioceptive impairment. A study by Deshpande and his colleagues (2003) has shown that the psychophysical evaluation of position sense is reliable. Although the precision and reliability of the psychophysical evaluation are established, there are few limitations that need to be addressed before the tool can be used in clinics. Despite most subjects participated in the study recording lower JND thresholds, two of the subjects recorded a lesser magnitude in position error than the JND threshold. In one of these two subjects, who produced a mean position error of 1.07 degrees, sensitivity fitting function did not produce the best fit even after 60 trials. As the evaluation of the position sense acuity depends on the subjects' responses to the forced-choice, it is possible that fitting function did not have enough incorrect responses to produce the best fit even after 60 trials. The necessity for more number of trials makes the psychophysical evaluation a lengthy process. On an average, the psychophysical evaluation took about 25-35 min for evaluating the position sense acuity for each subject, while a contralateral matching method takes about 3-5 minutes. This evaluation time can be reduced by optimizing the algorithm so that the stimulus difference converges more efficiently to reach psychophysical thresholds at a lesser number of trials. One other limitation for the application of psychophysical evaluation in clinics could be the lack of availability of the age-specific normative data to identify the milder forms of impairments. If further research establishes the normative data, this evaluation method will be a gold standard tool for the evaluation of joint position sense acuity.

CONCLUSION

Current position sense evaluation methods in clinics are efficient in identifying severe position sense impairment. But they cannot identify mild-moderate impairment of proprioception. Also, the reliability of these matching methods is infrequently considered. Psychophysical thresholds, while being reliable, provide a more precise estimation of the position sense acuity. This psychophysical evaluation might potentially identify milder forms of proprioceptive impairment. With a little extra investment of time, the amount of precision that this evaluation method can achieve in assessing joint position sense acuity, can make it a potential tool in neurological clinics.

Bibliography

Blakemore, S., Frith, C., & Wolpert, D. (2001). The cerebellum is involved in predicting the sensory consequences of action. *Neuroreport, 12*, 1879-1963.

Blakemore, S., Wolpert, D., & Frith, C. (1999). The cerebellum contributes to somatosensory cortical activity during self-produced tactile stimulation. *NeuroImage, 10*, 448-507. doi: 10.1006/nimg.1999.0478

Deshpande, N., Connelly, D., Culham, E., & Costigan, P. (2003). Reliability and validity of ankle proprioceptive measures. *Archives of physical medicine and rehabilitation, 84*, 883-892.

Dietz, V. (2002). Proprioception and locomotor disorders. *Nature reviews. Neuroscience, 3*, 781-871. doi: 10.1038/nrn939

Evarts, E. V. (1981). Sherrington's concept of proprioception. *Trends in Neurosciences, 4*, 44-90.

Fechner, G. T., Boring, E. G., Howes, D. H., & Adler, H. E. (1966). Elements of Psychophysics. Translated by Helmut E. Adler. Edited by Davis H. Howes And Edwin G. Boring, With an Introd. by Edwin G. Boring.

Fiorio, M., Stanzani, C., Rothwell, J., Bhatia, K., Moretto, G., Fiaschi, A., & Tinazzi, M. (2007). Defective temporal discrimination of passive movements in Parkinson's disease. *Neuroscience letters, 417*, 312-317. doi: 10.1016/j.neulet.2007.02.050

Frigge, M., Hoaglin, D., & Iglewicz, B. (1989). Some implementations of the boxplot. *American Statistician, 43*(1), 50-54.

Gardner, E. P., Martin, J. H., & Jessell, T. M. (2000). The bodily senses. In E. R. Kandel, J. H. Schwartz & T. M. Jessell (Eds.), *Principles of neural science* (Fourth ed., Vol. 4, pp. 430-450): McGraw-Hill.

Gentilucci, M., Toni, I., Chieffi, S., & Pavesi, G. (1994). The role of proprioception in the control of prehension movements: a kinematic study in a peripherally deafferented patient and in normal subjects. [Clinical Trial]. *Exp Brain Res, 99*(3), 483-500.

Gescheider, G. A. (1985). *Psychophysics: method, theory, and application* (Second ed.): Lawrence Erlbaum Associates, Inc. Publishers.

Ghez, C., Gordon, J., Ghilardi, M. F., Christakos, C. N., & Cooper, S. E. (1990). Roles of proprioceptive input in the programming of arm trajectories. [Research Support, U.S. Gov't, P.H.S.]. *Cold Spring Harb Symp Quant Biol, 55*, 837-847.

Ghez, C., & Sainburg, R. (1995). Proprioceptive control of interjoint coordination. *Canadian journal of physiology and pharmacology, 73*, 273-357.

Goble, D. (2010). Proprioceptive acuity assessment via joint position matching: from basic science to general practice. *Physical therapy, 90*, 1176-1260. doi: 10.2522/ptj.20090399

Gordon, J., Ghilardi, M., & Ghez, C. (1995). Impairments of reaching movements in patients without proprioception. I. Spatial errors. *Journal of neurophysiology, 73*, 347-407.

Grob, K., Kuster, M., Higgins, S., Lloyd, D., & Yata, H. (2002). Lack of correlation between different measurements of proprioception in the knee. *The Journal of bone and joint surgery. British volume, 84*, 614-622.

Grush, R. (2002). An introduction to the main principles of emulation: motor control, imagery, and perception. (Behavioral and Brain Sciences (2004) 27, 377–442).

King-Smith, P., Grigsby, S., Vingrys, A., Benes, S., & Supowit, A. (1994). Efficient and unbiased modifications of the QUEST threshold method: theory, simulations, experimental evaluation and practical implementation. *Vision research, 34*, 885-1797.

Konczak, J., Corcos, D., Horak, F., Poizner, H., Shapiro, M., Tuite, P., . . . Maschke, M. (2009). Proprioception and motor control in Parkinson's disease. *Journal of motor behavior, 41*, 543-595. doi: 10.3200/35-09-002

. Matlab: The Language of Technical Computing (Version 7.11.0.584). (2010): The Mathworks Inc.

Mongeon, D., Blanchet, P., & Messier, J. (2009). Impact of Parkinson's disease and dopaminergic medication on proprioceptive processing. *Neuroscience, 158*, 426-466. doi: 10.1016/j.neuroscience.2008.10.013

Oldfield, R. (1971). The assessment and analysis of handedness: the Edinburgh inventory. *Neuropsychologia, 9*, 97-210.

Rothwell, J., Traub, M., Day, B., Obeso, J., Thomas, P., & Marsden, C. (1982). Manual motor performance in a deafferented man. *Brain : a journal of neurology, 105 (Pt 3)*, 515-557.

Team, R. D. C. (2011). R: A language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing. Retrieved from http://www.R-project.org/

Watson, A., & Pelli, D. (1983). QUEST: a Bayesian adaptive psychometric method. *Perception & psychophysics, 33*, 113-133.

Wolpert, D., & Miall, R. (1996). Forward Models for Physiological Motor Control. *Neural networks : the official journal of the International Neural Network Society, 9*, 1265-2544.

APPENDIX - I

University of Minnesota

Human Sensorimotor
Control Laboratory

ADULT CONSENT FORM
The Development of Limb Position Sense Across the Lifespan

Principal Investigator:	**Jürgen Konczak**	**(612) 624-4370**
Co-Investigator:	**Amanda Herrmann**	**(612) 625-3313**
Co-Investigator:	**Naveen Elangovan**	**(612) 625-3313**

Purpose and Background

The Human Sensorimotor Control Laboratory at the University of Minnesota examines the ability of human adults to sense joint position, to determine the differences between active and passive movement on position sense sensitivity, and to investigate if this ability can be trained.

Procedures

If you agree to be in this study, you will be asked to come to the laboratory to complete a sensory and a motor task. Prior to testing, a short assessment of handedness will be completed to determine the dominant hand. The sensory task will require you to sit in a chair with your arm placed on a moving arm rest, while wearing goggles and headphones. The arm rest will support the arm while a motor is used to passively move the forearm. You will then be asked to make a judgment about the movement velocity or movement distance. In a subsequent motor task, you will place your arm on the arm rest of a manipulandum. You will be asked to actively move your forearm as accurately as possible to a specific target position.

Risk and Discomfort

We believe that our study imposes no risks other than fatigue. We work closely with the individuals to find a convenient time for testing. If you do not want to participate in the testing activities, we will stop the assessment, accommodate retesting you on a better day, if desired, or completely stop the investigation.

Benefits
There is no direct benefit to you for participation in this study.

Compensation:
No compensation will be given to subjects.

Research Related Injury:
In the event that this research activity results in an injury, treatment will be available, including first aid, emergency treatment, and follow-up care as needed. Care for such injuries will be billed in the ordinary manner, to you or your insurance company. If you have suffered a research related injury let the study investigators know right away.

Confidentiality:
Regarding confidentiality, you will receive an ID number from the investigators and all data will be analyzed using that number. No individual will be able to be identified. All our data are retained in a locked file cabinet and a password is used with our computerized data files. In any sort of report we might publish, we will not include any information that will make it possible to identify a subject.

Voluntary Nature of the Study:
Participation in this study is entirely voluntary. You may terminate the experiment at any time without penalty. Your decision whether or not to participate will not affect your current or future relations with the University of Minnesota or with the researchers. If you decide to participate, you are free to withdraw at any time without affecting those relationships.

Contacts and Questions:
The researchers conducting this study are Amanda Herrmann, Naveen Elangovan and Dr. Jürgen Konczak. You may ask questions now. If you have questions later, you may contact Amanda Herrmann or Naveen Elangovan at (612) 625-3313.

If you have any questions or concerns regarding the study and would like to talk to someone other than the research(s), contact the Fairview Research Helpline at telephone number 612-672-7692 or toll free at 866-508-6961. You may also contact this office in writing or in person at Fairview University Medical Center - Riverside Campus, #815 Professional Building, 2200 Riverside Avenue, Minneapolis, MN 55454.**You will be given a copy of this form to keep for your records.**

Initials_____/_____

Statement of Consent:
I have read the above information. I have asked questions and have received answers. I consent to participate in the study.

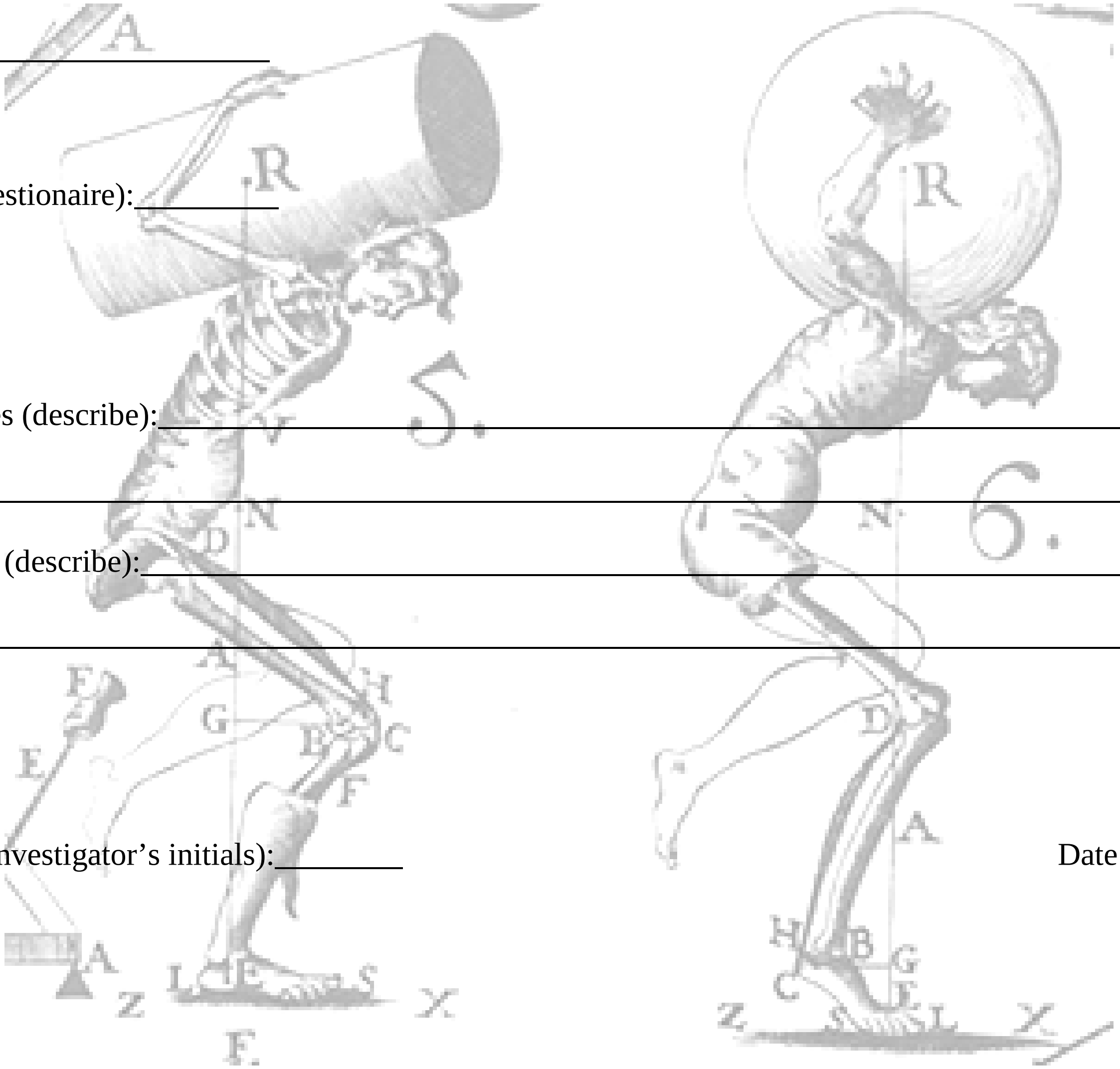
Name: ____ Date: ______________________
(PLEASE PRINT)

Signature____ Date: ______________________

Signature of Investigator: ____ Date: ______________________

APPENDIX - II

Subject Information Form



Subject Number:______________________

Date:___________

Handedness Score (attach questionaire):_______

Age:_________

Birthdate:__________

Right Upper Limb Pathologies (describe):____

____

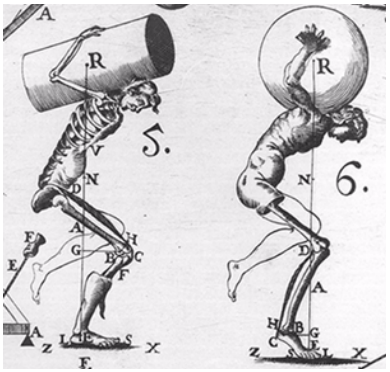
Left Upper Limb Pathologies (describe):____

____

Subject Accepted for study (investigator's initials):______ Date:________

APPENDIX - III

Handedness questionnaire



Study name ____________________

Subject number ____________________

Date ____________________

	Which hand do you prefer?			**Do you ever use the other hand?**	
	right	**left**	**no preference**	**yes**	**no**
Writing					
Drawing					
Throwing					
Using scissors					
Using a toothbrush					
Using a knife without a fork					
Using a spoon					
Using a broom (upper hand)					
Opening a box					

Total score: ______________________________