Enhancing Joint Position Sense through Concurrent Tactile Stimulation: Effects of Handedness

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Abstract

Joint position sense (JPS) is the awareness of limb position in the absence of vision, and is based on proprioceptive information from muscle, skin and joint receptors. There is initial evidence that JPS is enhanced by concurrent tactile stimulation such as applying an elastic brace to the joint (Herrington, Simmonds, & Hatcher, 2005). In addition, JPS acuity may be biased toward the non-preferred hand. In right handers and left handers the ability to match elbow angles has shown to be asymmetrical between the preferred and non-preferred arm, favoring the non-preferred arm (Goble & Brown, 2008). This study examined the effects of tactile stimulation on JPS with the use of an elastic brace on the elbow joint as a function of handedness. The rationale behind the study was to explore, if JPS at a proprioceptively less sensitive joint could be improved by added tactile stimulation. Specifically, by placing a brace on the preferred arm, I sought to decrease JPS error to the level of the non-preferred arm. JPS was measured through a bi-manual manipulandum, designed to measure angular displacement of the elbow joint in the horizontal plane. Thirty healthy adults, 20 right-handed and 10 left-handed, were recruited to participate in a contralateral concurrent elbow matching task, with and without tactile stimulation, at an amplitude of 40° in elbow extension. The results showed no statistically significant main effects for brace, handedness, or hand used. In addition, the respective 2- and 3-way interactions failed to reach significance. Thus, this experiment failed to confirm earlier reports showing beneficial effects of concurrent tactile stimulation on JPS. These findings indicate in healthy young adults training had little effect on the precision of the JPS as no changes occurred across trials within subjects. Further, earlier reports of the beneficial effects of knee joint bracing on JPS do not translate to the elbow joint. Overall this study is a significant contribution to the literature for gaining an understanding of how the elbow joint responds to bracing in healthy young adults, and suggests that the specialization of our non-preferred limb may only be in tasks where memory is included in the design.

Table of Contents

List of Figures

Introduction

Charles Sherrington introduced the term *proprioception* as the sense of oneself physically in the world (Kandel et al., 2013). Information from receptors in skeletal muscle, joint capsules, and the skin form the physiological basis for the conscious awareness of our joints in space. Individuals with proprioceptive deficits have difficulty with interjoint coordination and fail to control the interactions of joints during multijoint movements (Sainburg, Poizner, & Ghez, 1993), making it difficult to perform tasks of daily living. Patients suffering from Parkinson's disease (PD) have been shown to have reduced proprioceptive function, including poorly estimating limb position (Maschke et al., 2003; Zia, Cody, & O'Boyle, 2002) and passive joint motion (Konczak et al., 2007). With an emphasis on proprioceptive function and voluntary movement, I chose to study joint position sense (JPS) and how its acuity may be improved by tactile stimulation of superficial joint tissue. Normal healthy control study participants were asked to match concurrent elbow joint positions with and without wearing an elastic elbow brace, to test if concurrent tactile stimulation can assist in our proprioceptive function.

Tactile Stimulation

Placing an elastic brace on a joint was thought to give structural stability to the injured or weak joint, but various groups revealed that the brace is likely to assist in enhancing proprioceptive feedback. Compressive brace application has been shown to improve JPS through tactile stimulation of the mechanoreceptors at the shoulder joint (Ulkar et al., 2004), the knee joint (Birmingham et al., 2000), and the ankle (Miralles et al., 2010). However, other groups have found that bracing does not positively influence position sense awareness at the knee (Bottoni et al., 2013). Thus, the evidence of the beneficial effect of bracing on JPS precision is inconclusive.

The physiological basis of bracing is to manipulate the mechanoreceptors of the joint through concurrent pressure (tactile stimulation). Thijs et al. (2010) found in an fMRI study that the use of a neoprene sleeve incasing the knee increases both proprioceptive acuity and neural activity in the primary and secondary somatosensory cortex, specifically the left and right paracentral lobule and the left superior parietal lobule. This evidence suggests bracing may have more of a sensory than an orthopedic effect, and is associated with enhancing somatosensory neural networks associated with movement.

Handedness

Handedness, dexterity, laterality are all terms used to describe the extent of a person's preference towards one limb versus the other. While humans have gross anatomical symmetry in their limbs, this musculoskeletal similarity does not equal functional symmetry. We all observe our left and right arms perform at varying degrees of dexterity in certain tasks. Based on self-reported questionnaires, 90% of individuals are right-hand preferred when performing activities of daily living (Oldfield, 1971). One's handedness seems to play a substantial role in various associated performance asymmetries (Goble & Brown, 2008) some tasks favoring the preferred and some the non-preferred limb. These performance asymmetries are seen in numerous motor output studies.

Early studies by Woodworth (1899), who had studied under Charles Sherrington, saw numerous preferred right arm advantages in motor output including increases in the strength, speed and consistency of movement during a task where subjects were asked to draw lines of equal length with both hands (as cited in Elliott, Helsen, & Chua, 2001). These participants demonstrated an increased accuracy of the preferred limb in tasks with vision and at faster velocities. In addition, maximum grip forces are roughly 10 times larger when using one's preferred arm over the non-preferred arm (Armstrong & Oldham, 1999). Finally, several studies show strong support for a preferred arm advantage in the specification and control of an arm's trajectory movements (Sainburg & Wang, 2002; Sainburg & Kalakanis, 2000; Sainburg, 2002).

Conversely, there is empirical support for a non-preferred arm advantage in tasks that do not test speed, strength or accuracy, but rather examine proprioceptive or haptic acuity (Goble & Brown, 2008). For example, Squeri et al. (2012) tested if humans exploring the curvature of an object were more precise when they used the left, right or both hands. They found evidence for perceptual handedness with the non-preferred hand showing higher acuity. However, when information from both hands was available the information from our preferred hand was used.

Upper limb asymmetries have been demonstrated in visual and proprioceptive type tasks. Both vision and proprioception are thought to be the most important sensory modalities for voluntary movement. Vision provides a frame of reference for movement including information regarding object size and orientation in three dimensional space (Goodale, Westwood, & Milner, 2004). There is a greater relative reliance of the preferred arm on visual feedback for movement, whereas the non-preferred arm is likely to use proprioceptive information about the properties of the object, or the position of the limbs (Goble & Brown, 2008). Meaning our non-preferred limb may be more sensitive to proprioceptive changes than our preferred limb.

Recent studies have explored proprioceptive function by conducting sensory tests of limb JPS. JPS tests revealed non-preferred arm superiority in executing proprioceptive tasks in both right handers (RH) and left handers (LH) (Goble & Brown, 2007; Goble, Noble, & Brown, 2009). The enhanced proprioception of the non-preferred limb compared to the preferred may be task dependent. For example, the non-preferred arm showed better performance in an elbow matching task that required memory and interhemispheric transfer (Goble & Brown, 2007), meaning the differences in unimanual versus bimanual tasks also affect the relative JPS errors seen in the non-preferred limb. I sought to further these findings by enhancing our proprioceptive responses through tactile stimulation by use of an elastic brace.

Purpose

This research is intended to fill the knowledge gap about how tactile stimulation affects proprioceptive acuity at an upper limb joint and whether handedness differentially affects such acuity. By applying a brace on the elbow joint, I sought to increase sensory input through touch and pressure, which may influence the precision of JPS. I investigated whether the non-preferred limb was more sensitive than the preferred, and whether placing a brace on the preferred elbow could improve the acuity to the level of the non-preferred. The following general research questions were tested:

1) Does wearing a brace improve JPS? Enhancing the tactile stimulation on the elbow joint by introducing an elastic arm brace to the matching limb may increase elbow JPS acuity.

2) Is joint position matching performance between preferred and non-preferred hands different when wearing the brace? From other findings which show the non-preferred limb may have enhanced proprioceptive function, I tested if the interaction with the brace will decrease the JPS error of the preferred arm to the level of the non-preferred arm.

I also wanted to test RH and LH with this design because of the similarities and differences in handedness with regards to proprioception that have been cited in the literature.

Several issues to consider when designing a limb matching study include amplitude differences, active verse passive motion, ipsilateral and contralateral movements. I chose to explore the contralateral matching condition with an understanding that there is an interhemispheric transfer of sensory information through the corpus callosum. The testing amplitude was 40 degrees of elbow extension.

Specific Aims

1. **To determine if wearing an elastic elbow brace enhances proprioceptive acuity in an arm position matching task.** A statistically significant main effect between the braced and non-braced JPS error will verify the hypothesis that bracing can improve JPS.
2. **To determine if there is a differential effect on position sense precision between wearing an elastic arm brace on the preferred or non-preferred arm, in both right and left handed populations.** A statistically significant interaction between bracing and handedness will verify the hypothesis that bracing the preferred arm reduced the JPS error to the level of our non-preferred limb.

Methods

Study Participants

Thirty healthy adults, 14 males and 16 females, age ranging from 18-30 years (mean ± SD: 23.36 ± 2.91), without a known history of neurological, musculoskeletal, or peripheral nerve disease were recruited. All participants were tested for hand dominance utilizing the Edinburgh Handedness Inventory (Oldfield, 1971). The inventory consists of ten levels of assessment: writing, drawing, throwing, using scissors, a toothbrush, a knife without a fork, a spoon, a broom (upper hand), opening a box, and striking a match. A level of complete right handedness is represented by a score of 100 while a level of complete left handedness is scored as -100. Right-handed participants scored a mean ± SD: 77.25 ± 20.36, range: +100 to +35, while left-handed participants scored a mean ± SD: -76.50 ± 19.16, range: -100 to -45. Informed written consent was obtained from all participants prior to participation. The study was approved by the University of Minnesota institutional review board.

Experimental Setup

Elbow position sense was measured using a custom-built bi-manual manipulandum, which measures angular displacement of the elbow joint in the horizontal plane. The bi-manual manipulandum was constructed in the Human Sensorimotor Control lab at the University of Minnesota. It consists of an adjustable high-density polyethylene base, two aluminum encoder housings, two US Digital H6 optical encoders, two quadrature cables (differential), two differential quadrature-to-USB adapters (QSB-Ds) and a laptop to run the US Digital encoder calibration and data logging software. The digital encoder output was recorded by software US Digital Device Explorer and was then converted to degrees using MATLAB Technical Programming Language (Matlab 7.0, The MathWorks, Inc., Natick, Massachusetts). The encoders recorded lever position with an accuracy of 0.0366° at a sampling rate of 100Hz.

Study participants were seated on a height-adjustable chair in front of the bi-manual manipulandum with both arms resting at 30° from the horizontal plane (Figure 1A). The manipulandum is equipped with length adjustable wooden arm supports and foam pads to ensure the participants comfort and fit to the device.

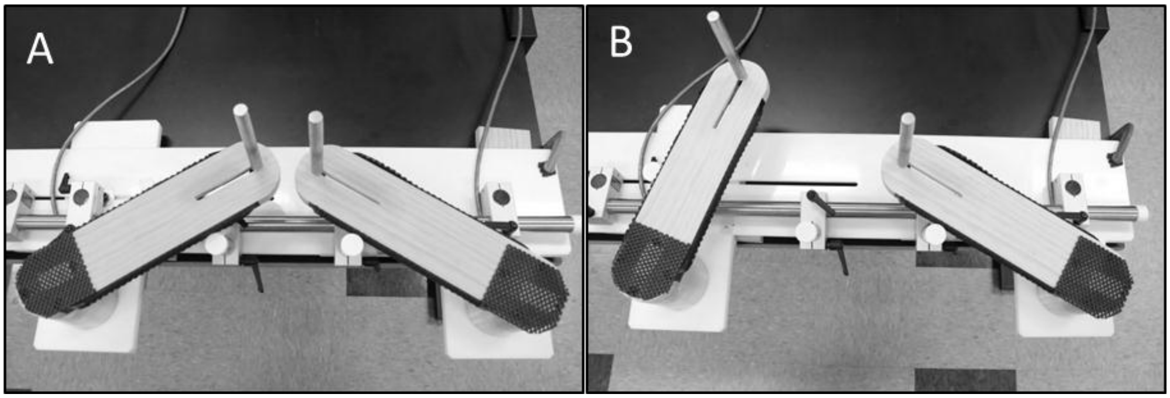

Figure 1: Bi-manual manipulandum set-up. **A)** Start position of the bi-manual manipulandum arms at 30° from the horizontal. **B)** Position of the left arm at Reference angle of 40° elbow extension, from start position, in the horizontal plane.

Procedure

Prior to data collection, study participants were given practice trials of elbow extension/flexion to familiarize themselves with the setup and task.Goggles occluded a participant’s vision during data collection.

The experiment consisted of study conditions without bracing and with bracing, and matching with the right arm and left arm, for a total of four study conditions. Matching consists of moving one arm to a position and using the other arm to mimic that same angle on the opposite limb. Figure 2 represents two of the four study conditions, without brace (Figure 2A&B), and with bracing (Figure 2 C&D). The study task is termed a contralateral concurrent matching task where the participants’ reference limb (RL) is passively moved by an experimenter to the 40° target position, as depicted in Figure 2, then the participant actively moves the matching limb (ML) to a position that they feel best represents the angle of the RL. One experimenter positioned every RL for all participants to ensure intra-rater reliability. In the first condition there is no brace on the elbow and the participant’s preferred arm is the ML and non-preferred arm is RL. During the second condition, the limb task is switched: the participant’s preferred arm is the RL, and the non-preferred arm is the ML. The third condition consists of placing an elastic brace on the preferred arm, the ML, while the non-preferred is the RL and does not have a brace. The fourth condition the limb task is switched with the brace now on the non-preferred ML. Each condition starts with 2 practice trials that are not recorded, then 10 recorded trials in each condition, totaling 40 recorded trials per participant.

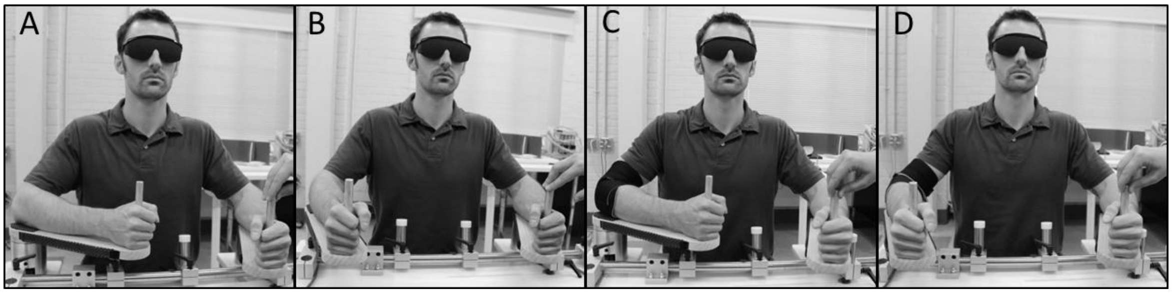

Figure 2: Experimental procedure. **A)** 1st condition with the experimenter moving RL to the 40° testing amplitude. **B)** Participant matching the angle with opposite limb. **C)** 3rd condition with the experimenter moving RL to the 40° testing amplitude. **D)** Participant matching angle with braced ML.

The instructions given to the study participant included maintaining a relaxed arm while the experimenter moves the RL to the 40° target position. The participant was instructed not to focus on the duration of the RL to the stop position, rather to focus solely on the final elbow position once the limb had stopped moving. Once the experimenter reached the position for the RL, the participant is given the command "match", and actively moved the ML to where he/she felt best represents the angle of the opposite limb. A command of "okay" by the participant indicated a final matched position and a recording of the bi-manual manipulandum angular displacement occurred over 1 second. After the recording, the experimenter instructed the participant to return both arms to start position before the next trial began. Study duration was 45 minutes in length with 5 minutes breaks between conditions. To keep concentration levels high, a break for 2 minutes occurred after the first 5 trials.

Design and Analysis

The study consisted of four conditions of contralateral concurrent matching tasks with 10 trials of each condition. The order of the conditions was randomized between participants using a Latin Square design. A software program based on MATLAB Technical Programming Language (Matlab 7.0, The MathWorks, Inc., Natick, Massachusetts) was used to calculate the joint position sense error (JPS) for each trial (*JPS error= ML –RL [deg]).* The JPS error angle is signed, that is, it can indicate an over- or undershoot of the movement. Based on all 1200 trials that were entered into the analysis, mean JPS error for the complete sample was 0.75° (SD: 3.79°). Considering the mean JPS *error* of each subject showed that 11 subject tended undershoot on average (mean: -3.27°; SD: 2.30°) and 19 subjects had a tendency to overshoot (mean: 3.09°; SD: 2.14°). Thus, there was no particular bias in the population to systematically over- or undershoot. Therefore, it was decided to collapse the data and use *absolute JPS error* for further analysis, the duration of the paper will term this as *JPS error.*

All subsequent statistical analysis was performed using the software program IBM SPSS Statistics for Windows, Version 21.0. The data was analyzed after removing thirteen trials that are considered outliers (see Outlier Analysis for details). A generalized linear model (GLM) was created to test for the main effects of *brace*, *handedness*, and *hand used*, and the respective 2- and 3-way interactions. The GLM accounts for the factors to be related to one another, for example each participant matched with their non-preferred limb with a brace on. The GLM was used to see if one could predict a reduction in JPS error by use of the brace and handedness. The GLM takes into account each factor and how it they interact with each other. The alpha level of significance was set to 0.05.

Results

Outlier Analysis

The outlier analysis was computed on the JPS error values prior to computing absolute JPS error. Suggested by Tukey (1977), any trial that fell outside +/- 3 standard deviations from the mean was considered an outlier (as cited in Hoaglin, Mosteller, & Tukey, 1983). The total number of trials excluded from the analysis was thirteen out of 1200 trials.

Effect of Bracing

To obtain an understanding of the effect on JPS error when an elastic brace is placed on the elbow, exemplar data of two individuals are presented in Figure 3. Figure 3A represents a participant who showed a reduction in JPS error between the non-braced and the braced conditions, conversely Figure 3B represents a participant who shows an increase in JPS error when the brace was placed on the elbow.

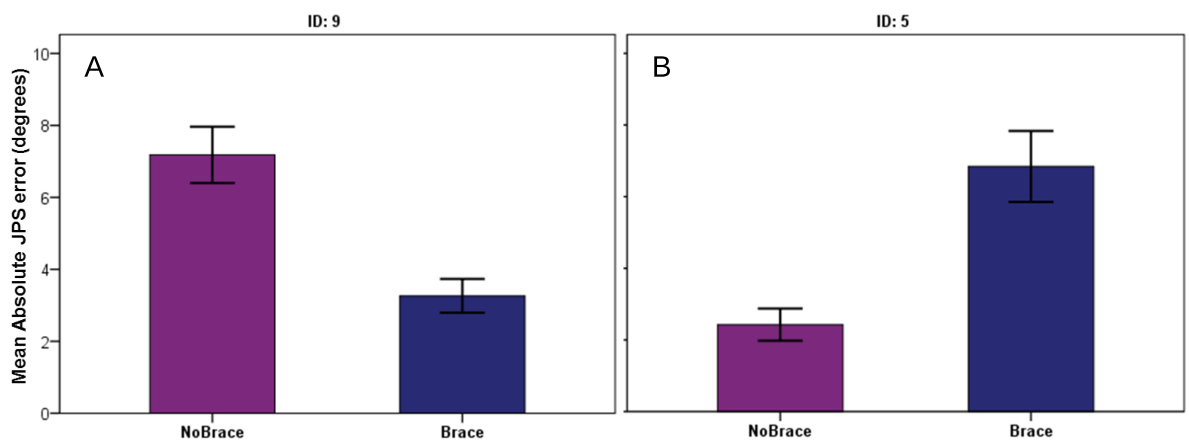

Figure 3: Exemplar brace effect. **A)** Represents a participant who did show hypothesized bracing effect. **B)** Represents an increase in error during braced conditions. Error bars are ± 1 SE.

To understand the magnitude of JPS error from non-braced to braced conditions in the complete sample, Figure 4 shows each participant's mean error scores for bracing and no-bracing plotted against one another. In sixteen out of 30 participants, ten RH and six LH, JPS error increased in the braced condition when compared to the no-braced condition (see data points above the diagonal line of equality in Fig. 4). Thirteen participants, nine RH and four LH, showed a decrease in JPS error from non-braced to braced, meaning their performance improved, represented below the diagonal line (see data points below the diagonal line of equality in Fig. 4). One right hander's performance was roughly the same under both conditions. Linear regression showed that their JPS errors without the brace did not significantly predict their JPS errors with the elbow brace β=0.322, $t(28)$=1.70, p =0.10. Likewise, JPS errors did not explain a significant portion of variance in JPS error with the brace on, R^2= 0.306, $F(1, 28)$ =2.89, p = 0.10.

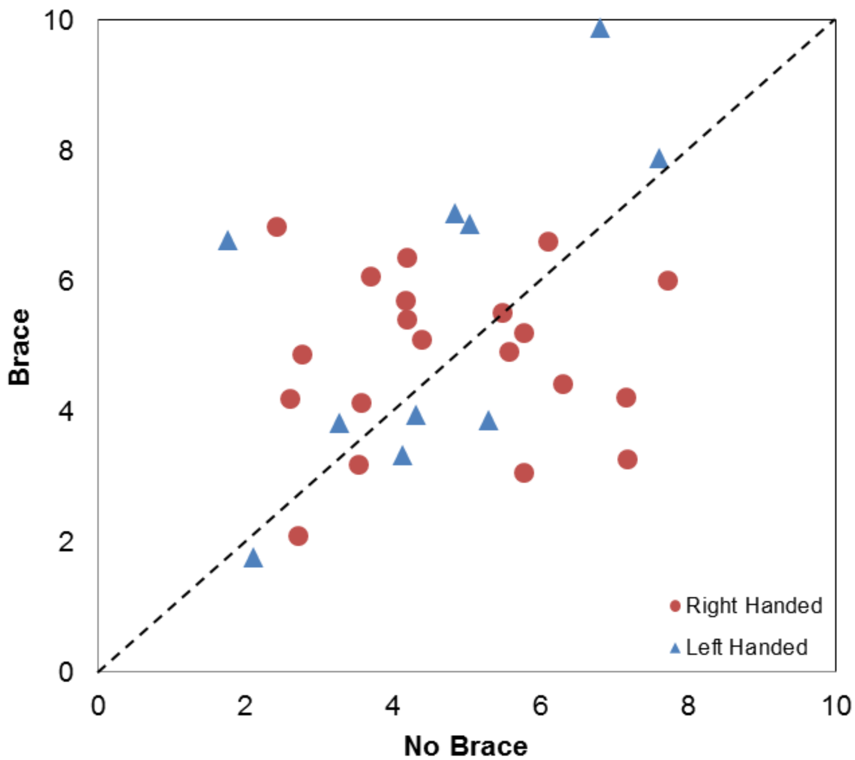

Figure 4: Scatterplot of each participant's mean bracing JPS error scores. The vertical axis defined by the Brace conditions and the horizontal axis defined by the No Brace conditions. Data below the diagonal line of equality indicates that JPS error decreased as an effect of bracing, while above shows the JPS error increased as an effect of bracing.

Figure 5 shows the relative improvements for all thirty study participants, a positive percentage indicates the hypothesized bracing effect, while a negative percent is a decrement in JPS error with the brace. Notice the large positive and negative variability once the brace was applied. There was an 8%-55% improvement in JPS error in 13/30 participants (43%) and seventeen participants (57% of sample) showed a decrement in JPS error ranging from1%-275%.

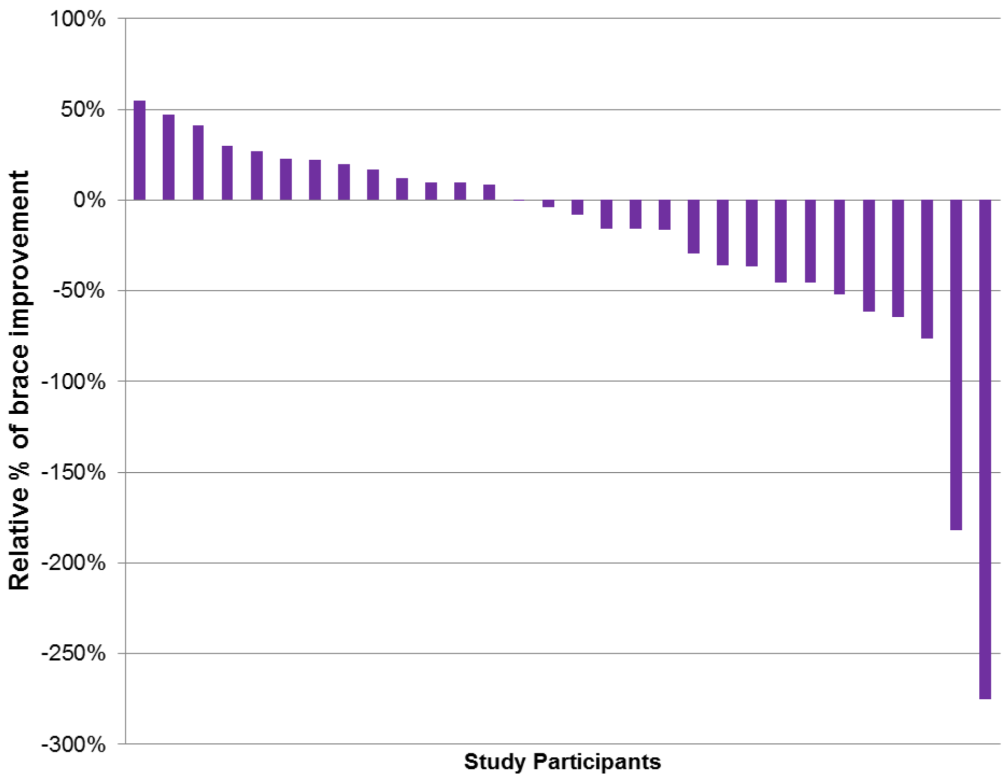

Figure 5: Relative effect of bracing on JPS with respect to no bracing. Each bar represents the relative improvement/decrement of a single participant. Data are sorted in descending order.

To test the hypothesis in specific aim 1, that bracing may reduce JPS error in all study participants, results from the GLM indicated no statistically significant main effect of bracing (mean ± SE: NoBrace 4.68 ± 0.321; Brace: 5.11 ± 0.345; X^2= 0.224; *df*= 1; *p*=0.636) (Figure 6).

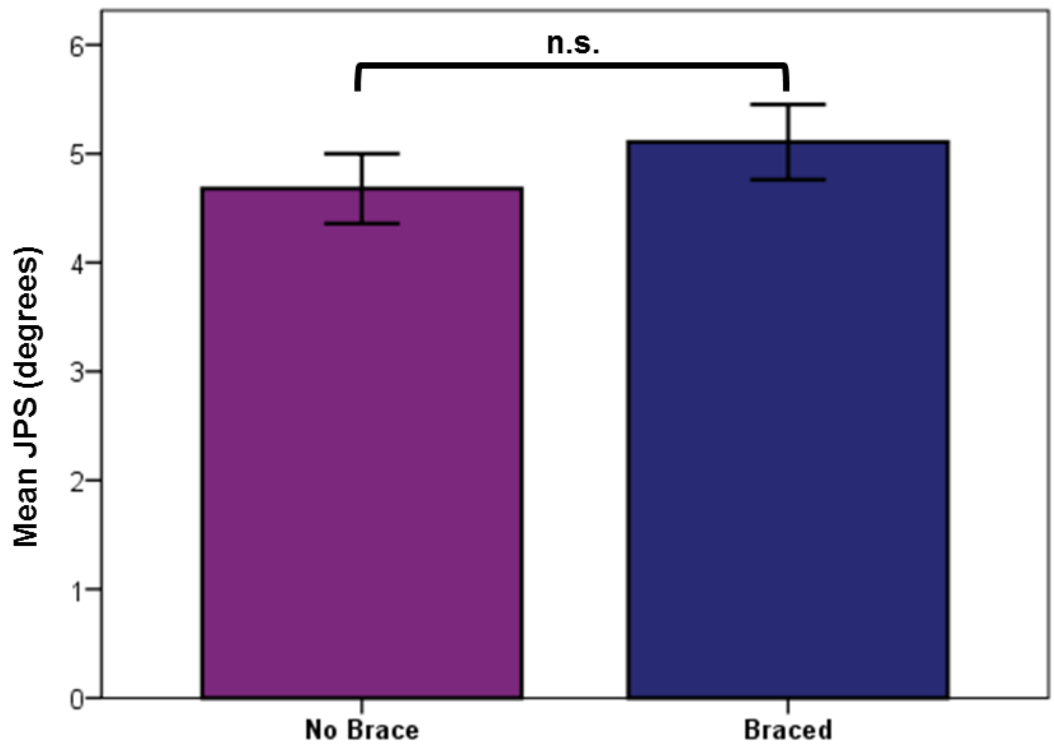

Figure 6: Main effect of bracing. Mean ± SE: <u>NoBrace</u> 4.68 ± 0.321; <u>Brace</u>: 5.11 ± 0.345. Error bars are ± 1 SE.

Variable error (VE) was obtained by calculating the standard deviation around each participant's mean JPS error scores. A one-way ANOVA was conducted to compare the VE of the braced and no braced conditions. No significant effect of brace was found for VE (mean ± SE: NoBraceVE 2.53 ± 0.145; BraceVE: 2.65 ± 0.152; $F(1, 118) = 0.308$; $df = 1$; $p = 0.58$), indicating that the two bracing conditions did not show systematic differences in variability. In other words, the variability of JPS error was not reduced from non-braced to the braced condition.

Effect of Handedness

To understand the effect of handedness, or hand preference, exemplar data of mean JPS errors for two study participants is shown in Figure 7. Figure 7A represents a participant who did show a reduction in JPS error between the non-preferred conditions and the preferred conditions. Conversely, Figure 7B represents a participant who shows no change between using the preferred or non-preferred limb. Note that participant ID 9 was an example of the improvement from bracing (Figure 3A), however they did not show a handedness effect (Figure 7B).

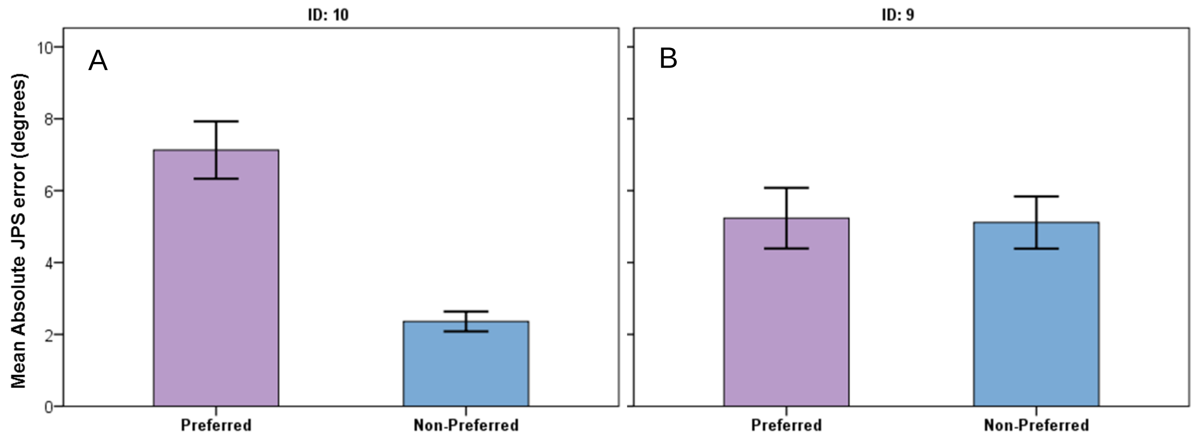

Figure 7: Exemplar handedness effect. **A)** Represents a participant who did show a non-preferred arm effect. **B)** Represents a participant who showed no change between preferred and non-preferred limb. Error bars are ± 1 SE.

To understand the magnitude of JPS error from preferred arm to non-preferred arm conditions in the complete sample, Figure 8 shows a plot of each participant's mean error scores for handedness. In nineteen out of 30 participants, fourteen RH and five LH, JPS error decreased from the preferred condition to the non-preferred condition represented below the diagonal line, indicating an improvement in performance under the non-preferred arm condition. Eleven participants, six RH and five LH, revealed a higher JPS error in the non-preferred conditions, meaning their performance decreased from preferred to non-preferred. A subsequent linear regression showed that their JPS errors in the preferred arm conditions did not significantly predict their JPS errors in the non-preferred arm conditions β=-0.162, $t(28)$=-0.79, p = 0.436. Likewise, JPS errors did not explain a significant portion of variance in JPS error in the non-preferred condition, R^2= 0.148, $F(1, 28)$ = 0.624, p = 0.436.

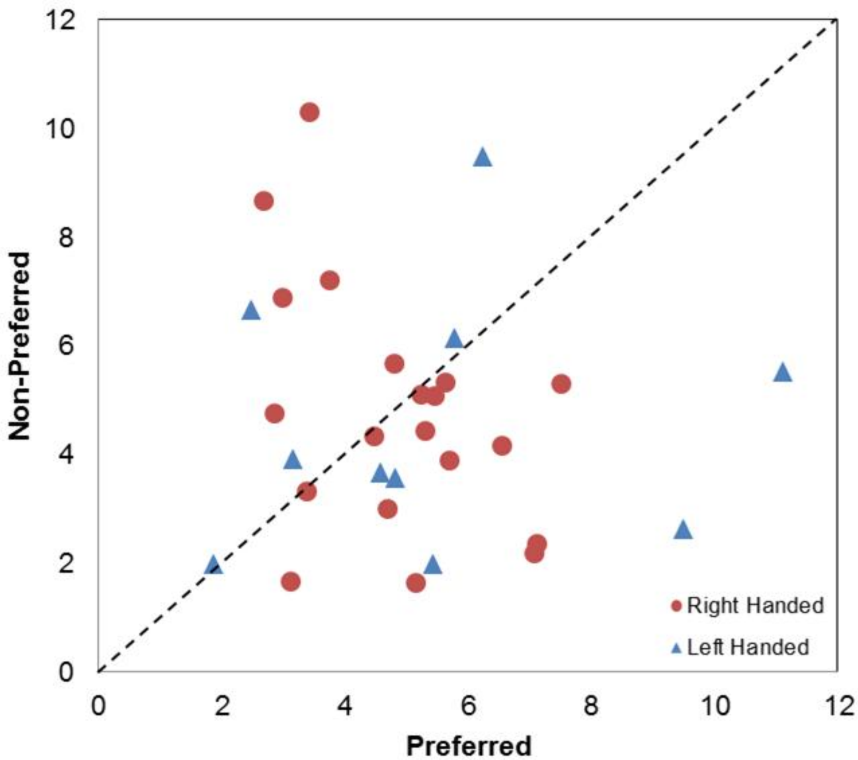

Figure 8: Scatterplot of each participant's mean handedness JPS error scores. The vertical axis defined by the Non-Preferred conditions and the horizontal axis defined by the Preferred condition. If the participant's data point is below the diagonal line, that indicates the participant improved by in the Non-Preferred conditions.

Figure 9 shows the relative improvements for all thirty participants, a positive percentage indicates the hypothesized non-preferred arm advantage, while a negative percent is a decrement in JPS error between non-preferred to preferred arm. Notice the large positive and negative variability within subjects. Nineteen participants (63%) had more accuracy in the non-preferred conditions ranging from 2%-72% improvements. Eleven participants (37%) had decrements in improvement ranging from 6%-223%. This represents that nineteen participants show a non-preferred arm improvement in acuity ranging from 2%-72% relative JPS error.

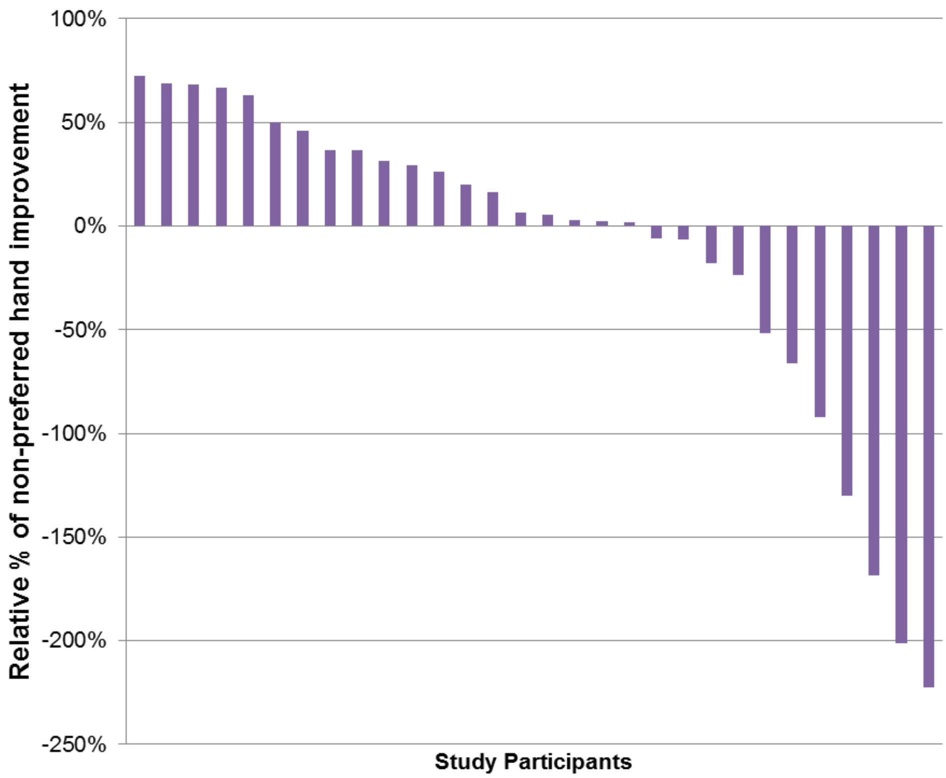

Figure 9: Relative effect of non-preferred hand on JPS with respect to preferred hand. Each bar represents the relative improvement/decrement of a single participant. Data are sorted in descending order.

To test the hypothesis that the non-preferred limb is more accurate in tests of proprioceptive acuity, results from a GLM procedure indicated a non-statistically significant main effect of handedness (mean ±SE: Non-Preferred 4.70 ± 0.345; Preferred: 5.08 ± 0.316; X^2=1.241; *df*= 1; *p*= 0.265) (Figure 10).

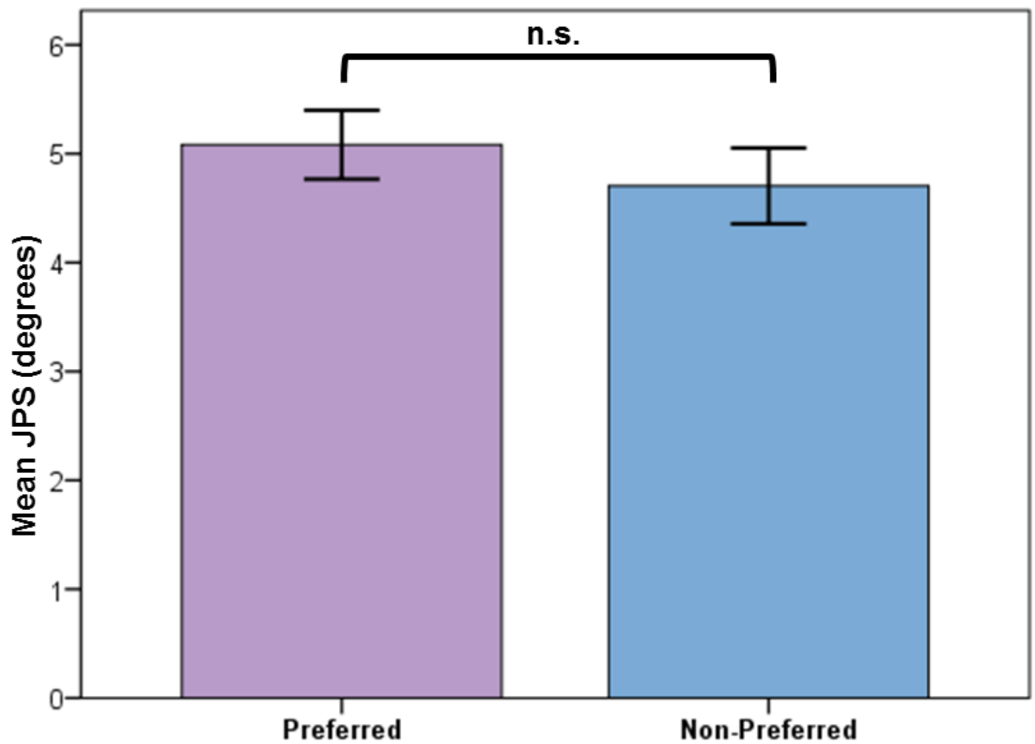

Figure 10: Main effect of handedness. Mean ±SE: Non-Preferred 4.70 ± 0.345; Preferred: 5.08 ± 0.316. Error bars are ± 1 SE.

Interaction Effects

To test the hypothesis in specific aim two that placing a brace on the preferred arm will improve JPS to the level of the non-preferred arm, Figure 11 shows the interaction between brace and handedness. The appropriate statistical test from the GLM failed to reject the null hypothesis, X^2=0.216; *df*= 1; *p*=0.642. I also tested if regardless of handedness, perhaps the left hand used or the right hand used would influence how participant responds to the brace, which it did not. Figure 12 shows the interaction between bracing and hand used, X^2=0.024; *df*= 1; *p*=0.877. The three way interaction between *bracing*, *handedness* and *hand used* also shows a non-significance of X^2=0.979; *df*= 1; *p*=0.322.

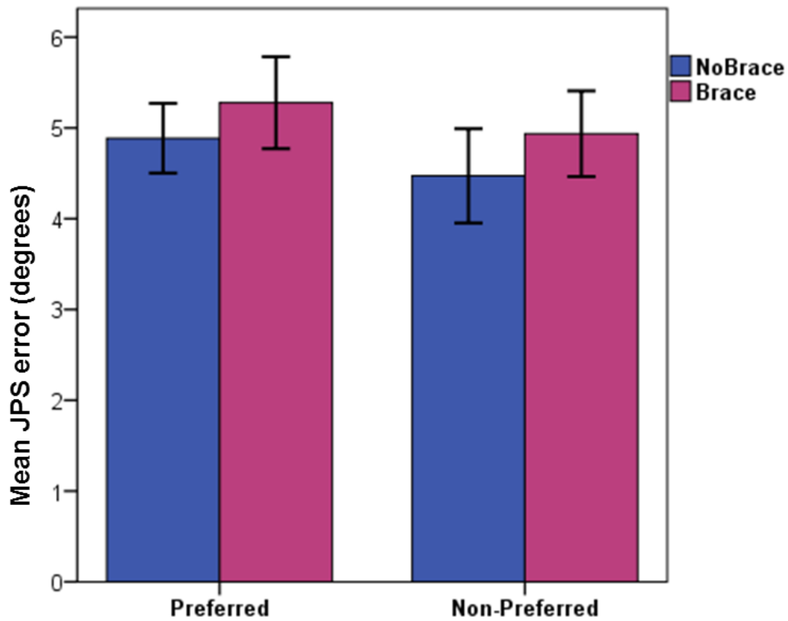

Figure 11: Interaction between handedness and bracing.

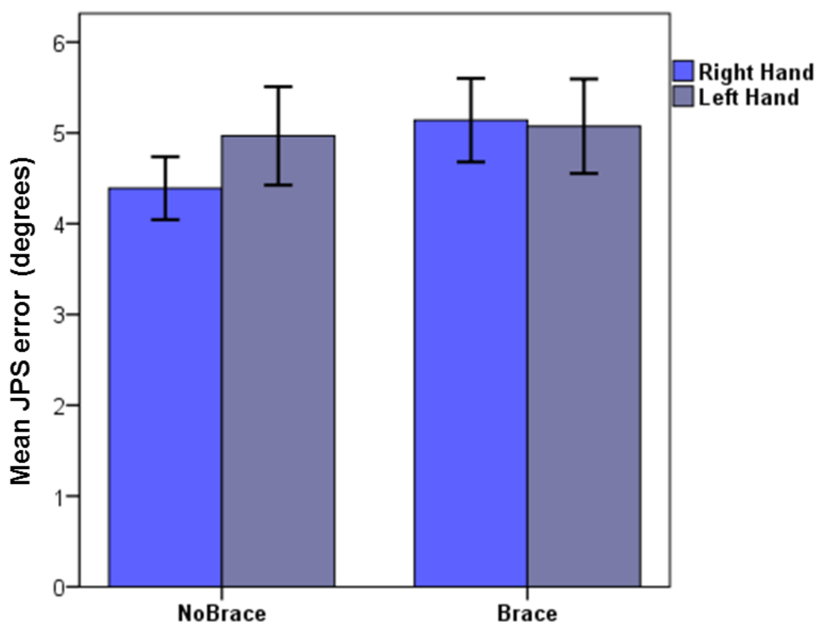

Figure 12: Interaction between bracing and hand used.

Power Analysis

Using the bracing effect size of 0.11 and the handedness effect size of 0.097 calculated from the X^2 test, an *a posteriori* power analysis using the G*Power 3 computer software (Faul et al., 2007) was performed to obtain information of the needed sample size for finding a significant effect of bracing and effect of handedness. The results indicated that a total sample of 648 and 830 participants respectively would be needed to reach a level of significance alpha .05 with 80% power.

Discussion

The overall goal of this study was to assess if joint position sense could be enhanced through concurrent tactile stimulation and if handedness affected JPS and interacted with the applied tactile stimulation. The first aim of the study was to test the hypothesis that placing an elastic brace on the elbow during a concurrent contralateral matching task would yield a smaller JPS error than without wearing the brace. The second aim of the study was to test if the intervention of the brace on the preferred arm decreases the JPS error to the error level of the non-preferred arm. Based on the results of the study, I failed to support either hypothesis. In this discussion I will lay out possible explanations for these null findings. First, I will discuss if small sample size and lack of experimental precision can account for the findings. Second, I will discuss the study population and the implications of JPS and normal healthy adults. Third, I review the literature with groups who have shown a bracing effect on specific joints and implications about the present study. Finally, I discuss the null findings of handedness effect through the differences in this online contralateral concurrent matching task and of others who show a non-preferred arm improvement in proprioceptive tasks.

Were the results biased by sample size and lack of experimental precision?

Previous studies that found effects of bracing on JPS, haptic acuity, and proprioceptive function each had sample sizes ranging between 13 (Thijs et al., 2010), 26 (Ulkar et al., 2004), to 40 participants (Miralles et al., 2010). The current study had a sample size of 30 subjects. Thus, based on these previous studies the sample size of this study falls in the upper third of previous samples and should have yielded sufficient power to show possible statistical differences. Applying an *a posteriori* power analysis to the data revealed that a sample size of 648 for bracing would be needed to reach a level of statistical significance. This suggests that a) the real differences are indeed very small and b) that a null finding is likely true for this population.

To address critiques of these 30 participants being of a biased sample, all participants met the inclusion criteria of no neurological conditions, no peripheral limb issues, and no upper limb strength or health asymmetries. Also, prior to data collection, which took place during workday hours, the participants were given notice of the necessary level of concentration that must be met for tests of proprioceptive sense in the absence of vision, and all met the cognitive demands of the task. The design of the experiment places each participant to be his or her own control, thus no bias between conditions. All participants were naive to the study hypotheses. All the evidence I provide, suggest an unbiased sample that could explain my null finding.

The bi-manual manipulandum testing device did not account for the null findings. It is specifically designed to assess elbow JPS and was sensitive enough to detect changes in angular displacement. The encoders have a 0.0366° resolution, which is less than a tenth the size of the overall participant's mean JPS error value (4.85°). Therefore, the bi-manual manipulandum was sensitive enough to detect changes in JPS errors.

In addition, the overall error means are similar to JPS errors seen in other concurrent elbow matching studies (Goble & Brown, 2007; Goble et al., 2009). That is, the present study JPS errors are within the expected range associated with 40° amplitude in elbow extension. Based on the arguments above, I have little evidence that the experimental design skewed or was responsible for the results.

Can young adult JPS acuity be improved at all?

The lack of a significant main effect for bracing illustrates that the use of an elastic brace does not aid in elbow joint position sense awareness in a young healthy adult population. One interpretation of these findings is that a ceiling effect was observed. That is, in healthy young adults JPS acuity is already so precise that any additional stimulation through another somatosensory sense has no appreciative effect on overall JPS precision. Consider that the mean of no-brace JPS errors is 4.68°, which falls within 12% of the 40° movement amplitude tested. This may underline the fact that healthy young adults were already very "good" at matching opposite limb positions, so bracing was not able enhance JPS accuracy.

Perhaps applying an elastic brace to the elbow joint in an aging population and in a population with proprioceptive deficits, such as PD, bracing may enhance JPS acuity. In future studies of JPS awareness in elderly and PD patients, who have shown large JPS errors compared to aging adults (Konczak et al., 2012), a bracing effect may be found due to a larger area for improvement in the populations, which in turn could aid in tasks of daily living.

Outlook for future studies could look at the difference in tactile stimulation (via elastic elbow brace) verse cutaneous vibrotactile stimulation (via vibratory motors placed on skin). Perhaps a higher stimulation at the cutaneous level could illicit the proprioceptive inputs that an elastic brace could not.

Is bracing the upper limb different than bracing the lower limb?

Most bracing effect studies have been based on the assessment of proprioceptive function of the knee. The research outlined below discusses a bracing effect in knee structures and how the null finding of bracing the elbow may be due to the differences in the tasks associated with upper limb verse the lower limb. Beynnon et al. (2002) completed a comprehensive review of the effect of bandaging, bracing, and neoprene sleeves (elastic bracing) following anterior cruciate ligament (ACL) injuries. They correlated findings from studies on ACL tears that JPS can be impaired over time and the use of an elastic bandage to ACL injured knees improved JPS within the first year of injury. Translating the findings from Beynnon et al. 2002 to the present study suggest that without an injury to the elbow, the bracing may not have an appreciative effect on proprioception.

Stillman and McMeeken (2001) found in a test of unilateral lower limb active matching in a weight bearing braced condition was more accurate than in a non-weight bearing braced supine test condition, implying that in a weight bearing condition you will find differences in joint position sense. In the present study, the participants' were positioned such that the elbow able to move freely in extension in a semi-horizontal plane so the task was mostly non-weight bearing in design, thus, they were associated with relatively low levels of muscle activation. Perhaps in future studies of elbow JPS a condition of weight bearing versus active muscle contraction (e.g. arm muscle contraction without weight bearing) may show differences in acuity levels. Suggestions for future studies could entail increasing the participant's muscular tone throughout the matching phase, via a reaction force or simply by having the participant contract throughout the matching phase. This excitation of the muscle may enhance proprioceptive feedback to the muscles thus increasing proprioceptive acuity.

The movement and amplitude associated with testing JPS errors could also explain the null result. Bottoni et al. 2013 tested the effect of bracing the knee and JPS in healthy young males at two amplitudes in both passive flexion and extension. They found no statistical significant effect of bracing but did see a lower proprioceptive threshold starting at a more flexed knee angle and moving in extension. Their results can be interpreted two ways, first that in healthy young adults JPS cannot be trained by the use of an elastic brace, and second the start and end position of the moving limb can influence seeing slight changes in JPS error in braced conditions. The practicality that bracing only improves JPS error if the joint is positioned in a certain way during a certain motion does not translate to daily life movements and should be interpreted as such.

Thus even in structures such as the knee which has widely been studied in tests of proprioceptive function, there are discrepancies in the findings. It is important to note that the proprioceptive systems in our lower limbs may be different than our upper limbs. Postural stability through maintaining balance with the knowledge of our weight bearing lower limbs in space is crucial in upright ambulation. The networks and connectivity are different between the elbow and the knee which may account for the difference in findings of proprioceptive acuity at the elbow.

Are the null findings of handedness based on the design of online sensory feedback?

At first, the null finding of handedness in this task seems to be an inconsistent finding with respect to other studies. However, the tasks performed in other studies had additional components which may account for non-preferred limb advantages. Goble and Brown (2007) saw non-preferred target elbow angles to be more accurate than the preferred arm, but only in the matching condition which required both interhemispheric transfer and memory. Squeri et al. (2012) examined how haptic information about an object's shape affects haptic precision, and if using one or both hands improves the ability to sense an object's level of curvature. The participants virtually explored the object curve in an outward motion and returned in an inward motion, requiring a memory of this first curve to compare before giving a haptic judgment. They found in the unimanual task, the non-preferred hand was superior at perceiving the differences in the contours. Han et al. (2013) study on a pinch task in which participants were asked to memorize and judge five different pinch positions both unimanually and bimanually. Their results also show a non-preferred/hemisphere superiority effect in both RH and LH.

All tasks which showed a statistically significant non-preferred arm advantage included a memory component. In contrast my study, with a design most similar to the work of Goble and Brown (2007), the concurrent nature of the task allowed the study participants to have an online frame of reference of their joint position. I wanted to isolate the interaction of bracing and handedness, so by not including a memory component any result would be a clear indication that bracing may improve JPS in our preferred limb. Thus this contralateral concurrent elbow matching task did not include a memory component so did not show upper limb asymmetries of proprioceptive acuity. Stelmach, Kelso, & Wallace (1975) found in studies of short-term motor memory, that proprioceptive cues can provide the necessary information for recalling a limb position, with an importance on pre-selection of limb position. Thus limb position matching trials should take into account the participant’s selection of desired positions. Further studies in assessing handedness effects should study both the use and non-used of memory to further gain our understanding how these two systems interact.

Conclusion

In summary, this thesis shows no effect of bracing and no interaction between handedness and bracing. Outlook from these results further our understanding of joint position sense acuity of the elbow in healthy young adults, and a bracing effect may be seen in populations who have areas to improve in JPS errors such as the elderly or patients with proprioceptive deficits such as Parkinson’s disease. The results from this study also indicate from past research that found a non-preferred advantage in tasks of proprioception, may only be found in tasks where memory is included in the study design. Overall this study is a significant contribution to the literature for gaining an understanding of how the elbow joint responds to bracing in healthy young adults, and suggests that the specialization of our non-preferred limb may only be in tasks where memory is included in the design.

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