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The Effect of a Modulation in Golgi Tendon Organ Afference on Joint Angle Reproduction

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Abstract-An experiment using an innovative device was designed to examine the effects of gravity though a change in body position on reproduction joint position sense (RJPS) at the ankle. While muscle spindles (MS) code information on changes in muscle length and adapt after prolonged stimulus, Golgi tendon organs (GTO) code information on muscle tension and are non-adapting. When our bodies are in a vertical position during sitting, stance and locomotion, gravity imparts constant tension on many muscles facilitating the indwelling GTO to function as a gravity receptor. Since GTOs likely contribute to proprioception, limb position may modulate feedback from GTOs and ultimately effect RJPS. It was hypothesized that a change in position from normal (vertical) to horizontal will produce differences in subjects' ability to perform an RJPS task making evident a contribution of the GTO to RJPS. A bench similar to that described by previous researchers was used to perform RJPS testing. Subjects underwent unilateral RJPS testing in plantar- and dorsi-flexion of the ankle. A total of 30 subjects were assessed on five on trials each for RJPS of the ankle in both a gravity dependent and a horizontal position. Performance was measured in degree variance from their target position (absolute error) as well as their tendency to overshoot or undershoot their target (constant error) across trials for RJPS.

It was observed that, as limb position changed, the absolute error of all subjects in their attempt to reproduce the target angle was not affected but their tendency to over/undershoot their target was. Constant error during the dorsi-flexion RJPS task was significantly reduced from vertical (M=1.46° ± 1.84°) to horizontal (M=0.46 ± 1.95°) p=0.02. Gender differences were not observed across tasks. In conclusion, the observed modulation of RJPS due to gravity changes is evidence in support of the hypothesis that the GTO acts as a gravitoreceptor. This study has demonstrated a potential role of the GTO to RJPS and sheds light on the need for further investigation in this area to strengthen our understanding of the percent contributions of the GTO and muscle spindle to proprioception.

Keywords- *Reproduction Joint Position Sense, Proprioception, Gravity, Golgi Tendon Organ, Mechanoreceptor, Target Angle*

I. INTRODUCTION

The human somatosensory system is responsible for detecting stimuli including touch, pain, pressure and joint displacement. The somatosensory system is critically involved in the maintenance of arousal, the sensory control of movement and receives and processes stimuli that affect both the body surface and deeper tissues [1,2,3]. Martin divides the somatosensory system into three categories: interoception, exteroception, and proprioception. Interoceptors provide information on internal body events such as blood pressure and blood glucose concentration. Exteroceptors code information from external stimuli such as sound, vision, skin sensation, and some chemical senses. Proprioceptors code information about the relative position of body segments to one another and about the position of the body in space. In addition to receptors within muscles, the eye and vestibular apparatus are also contributors to proprioception [2]. The function of this third somatosensory category of proprioceptors is the focus of the experiment presented here.

A person's ability to subjectively assess the position of a limb in space using proprioception is known as joint position sense (JPS), deriving input from both capsuloligamentous, muscular, and cutaneous receptors [4]. Of these sensory locations (that is, joint capsule, ligaments. muscles, and skin), it appears that JPS is derived primarily through input from receptors within muscle-tendon units [5,6]. The current view is that the contribution of receptors within capsuloligamentous structures is secondary to the role played by the muscle mechanoreceptors for JPS [4,7]. Furthermore, proprioceptive feedback provided by these muscle mechanoreceptors may be affected by change in gravity.

Muscle mechanoreceptors exist in two forms: the muscle spindle (MS) and the Golgi tendon organ (GTO). Muscle spindles code information on changes in muscle length and adapt after prolonged stimulus. Muscle spindles are located throughout the fleshy part of an extrafusal (skeletal) muscle belly. Traditional thought is that the MS provides the overwhelming majority of muscle mechanoreceptor feedback used for proprioception yet the percent contribution is unknown.

Human Golgi tendon organs code static and dynamic responses to motor unit tension related activation [8]. They are non-adapting and lie in series with roughly 15-20 extrafusal muscle fibers in large skeletal muscles such as the tibialis anterior, gastrocnemius and soleus. Stimulation of the GTO provides afferent feedback that mitigates the over stretching and/or derangement of a muscle. The serial arrangement of the Golgi tendon organs with the collagen fibers of a muscle gives these mechanoreceptors the ability to detect even minute changes in muscle tension and for this reason may be sensitive to changes in gravity. Due to the fact Golgi tendon organs are non-adapting and show significant response or impulse rate over a period of time in response to continued stimulation, they have been termed load receptors [9]. It has also been shown that muscle receptors including the Golgi tendon organs are sensitive to external forces acting on the limb, and that they are likely affected by changes in gravity [10]. It is hypothesized that body and or limb position may have a modulating effect on Golgi tendon feedback and ultimately on joint position sense due to the fact that the GTO central to gravity and verticality perception [11]. As a result, proprioception may be affected by change in gravity [12]. The theoretical issue underlying this study was tested by assessing the effect of a change in limb position (gravity) on a subject's ability to perform joint angle matching tasks.

One of the most well accepted methods of measuring joint position sense previously described is reproduction of passive positioning otherwise known as reproduction joint position sense (RJPS) [7]. This protocol requires the joint to be placed in an initial starting position. Then, the distal limb segment is moved such that the joint achieves a target angle. This angle is held for a few seconds and then passively returned to the original starting position. The subject is then asked to actively move to reproduce the target angle. The trials are repeated several times while position data is recorded [13, 14]. Performance is measured by degree variance from the target angle in terms of absolute error as well as constant error.

The purpose of this study was1 to assess the effect of gravity, by modifying limb position, on RJPS at the ankle. Results of this study shed light on the relative contribution of Golgi tendon organs versus muscle spindles to joint position sense. It was hypothesized that a change in position from normal (vertical) to horizontal will produce differences in the absolute error (H1) and constant error (H2) as measured by a subjects' ability to perform an RJPS task making evident a contribution of the GTO to RJPS. Lastly, it was hypothesized that there would be no observable differences (H3) between men and women regarding the effect of gravity on their RJPS abilities.

II. METHODS

Thirty subjects were recruited and interviewed for this study. Each received a pre-participation orthopedic lower leg exam by an Athletic Trainer, Certified (ATC) to rule out any abnormalities (i.e. abnormal ligament laxity, congenital deformities, neurological deficits, etc.) that may have affected experimental data. The 30 healthy (15 women, 15 men) subjects were screened using a questionnaire, which asked for details on age, gender, and medical history. Individuals with a history of any previous serious lower leg injury or surgery, and/or those who currently had ankle pathology, were excluded from this study. The orthopedic evaluation included an assessment for presence of pain, stress tests to determine ligamentous stability, circulatory tests, assessment of cutaneous sensation, and tests of active, passive, and resisted ranges of motions.

Reproduction joint position sense (RJPS) was measured in accordance with the subject's ability to actively return to a randomly selected target position in the plantar- and dorsi-flexion ranges of motion (ROM). An active RJPS paradigm was selected in order to utilize a well-accepted repositioning technique for RJPS at the knee [7,15]. Due to the fact that muscle mechanoreceptors are stimulated during both passive and active movements and gravitational pull is altered in various positions, it was assumed that the chosen paradigm would successfully test for a treatment effect of a change in body position.

Ankle position data was measured using an instrumented platform (Figure 1) previously developed with a moveable footplate capable of providing electrogoniometric data [16]. The footplate was stabilized throughout testing with the use of a counterbalance system, which created an unresisted range of motion at the talocrural joint. Attached to the platform was a precision potentiometer (Spectrol, Type 157, Ontario, CA, USA), which allowed a measure of specific angular position digitally, displaying the position to the nearest tenth of a degree on a digital liquid crystal display and computer data collection system. Joint repositioning trials were collected at a rate of 100 Hz. Laboratory tests of this apparatus have demonstrated a repeatable range of motion error of less that $\pm$ 0.05°. The potentiometer was aligned with lateral aspect of the ankle to assure that the numbers supplied were accurate readings for the talocrural joint in the sagittal plane. This information was then recorded on a computer through a 16-bit analog to a digital board using Bioware® V.3.22 (Kistler Instrument Corporation, Amherst, NY, USA) data collection software. A range of motion block was used to set the talocrural neutral position (0º), achieved when the foot is at a right angle to the tibia. Upon completion of data collection with each subject the RJPS apparatus was recalibrated to assure accuracy throughout data collection.

To ensure RJPS was affected only by movement and mechanoreceptors within the lower leg, subjects were blindfolded and asked to wear headphones playing white noise to ensure both visual and auditory cues did not affect the results. To limit undesired cutaneous feedback, no straps were used to hold the subject's foot to the platform. RJPS was then assessed through the plantar- and dorsi-flexion ROMs under the conditions of vertical (while sitting) and horizontal (while back- lying with hips and knees at 90°) with the experimental leg's foot resting on the footplate of the apparatus. RJPS measures were taken by passively placing the dominant ankle to a random target angle and asking the subject to actively reposition their ankle to the target angle from a neutral starting position. Five trails were conducted at each range of motion while recording absolute and constant errors.

Figure 1. RJPS electrogoniometer apparatus.

They were then passively placed to a random target position. The subjects were held in that position for five seconds, asked to remember the target angle, and then passively returned to their neutral starting position. Subjects were then asked to actively reposition their foot as closely to the target angle as possible. Through headphone communication, audio mixed over the white noise, subjects were instructed to press a momentary switch indicator placed in their hand, signaling their achievement of the target-reposition task (Figure 2).

Data was recorded in the Bioware system after passive target positioning (by the researcher), and following the subject's signal of completion of the target-repositioning task.

This project employed a cross-over design regarding the order of the gravity varying conditions. Specifically, the vertical gravity condition was conducted over a 10-trail assessment of RJPS in plantar- and dorsi- flexion for 15 (50%) of the participants. The other 15 participants performed the RJPS tasks under horizontal gravity condition, followed by the vertical condition. The participants were randomly assigned with regard to the order of the two gravity related conditions as well as which ROM was assesses first (plantar- vs, dorsi-flexion) under each condition. There was a 5 minute waiting period between each gravity condition and the RJPS assessment.

This study used a pretest-posttest design. The independent variable was the gravity related condition while the dependent variable was reproduction of joint position sense task. Results were evaluated for statistical significance ($p < 0.05$) using a paired, two-tail t-test computed for both constant and absolute error values among all subjects and independent t-tests to evaluate across genders.

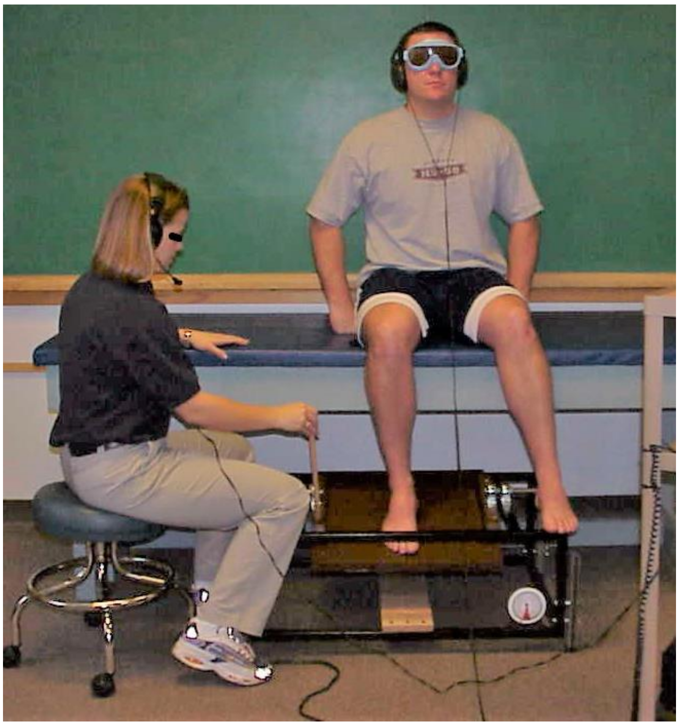

Figure 2. Subject position during data collection.

III. RESULTS

Upon completion of data analysis, no significant differences in absolute error between the vertical condition (M=2.19° ± 1.20°) and the horizontal condition (M=2.42° ± 0.83°) were found during plantar flexion, nor were any significant differences observed between the vertical condition (M=2.17° ± 1.15°) and the horizontal condition (M=1.90° ± 1.06°) during dorsi-flexion (Figure 3). These results refute our first hypotheses, which stated a change in position would have an effect on the absolute error of RJPS scores.

Further analysis demonstrated that no significant difference in constant error between the vertical condition (M=0.19° ± 1.96°) and the horizontal condition (M=0.45° ± 1.73°) was found among subjects during plantar flexion.

A significant difference was observed in constant error between the vertical condition (M=1.46° ± 1.84°) and the horizontal condition (M=0.46° ± 1.95°, $P = 0.02$) during dorsi-flexion (Figure 4). These results are in support of our second hypotheses, which stated a change in position would have an effect on the constant error of RJPS scores.

The data was also analyzed according to gender. No significant ($p > 0.05$) differences were detected in changes of absolute nor constant error in plantar-flexion or dorsi-flexion (Table 1) between genders. The third research hypothesis was supported.

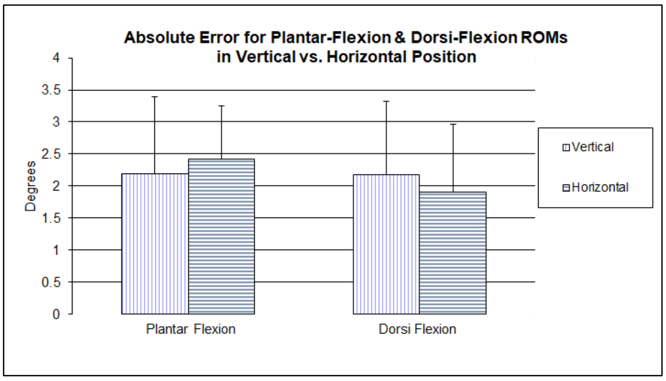

Figure 3. Group absolute error (AE) differences between vertical and horizontal conditions.

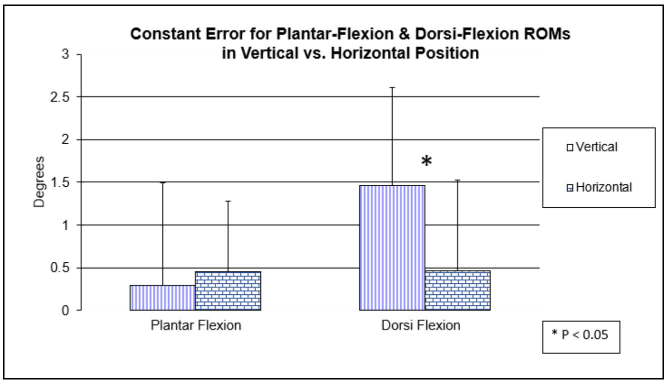

Figure 4. Group constant error (CE) differences between vertical and horizontal conditions.

TABLE I. MEAN (SD) VALUES FOR ERROR MEASURE DIFFERENCES (DEGREES,°) ACROSS GRAVITY CONDITIONS AMONG GENDERS.

	Plantar Flexion		Dorsi-Flexion	
	Men	Women	Men	Women
AE	-0.19 (1.49)	0.31 (1.71)	-0.19 (1.62)	-0.34 (1.32)
CE	0.12 (2.14)	0.20 (1.77)	-1.20 (2.60)	-0.79 (2.01)

Abbreviations: AE= Absolute error, CE= Constant error. No significant difference between men and women error values

In summary, while no effect was observed on absolute error in any condition, a significant effect of body position on a subject's tendency to overshoot their target was noted during active RJPS dorsi-flexion supporting H2. Upon a gender analysis, no differences were detected in changes of absolute nor constant error in plantar-flexion or dorsi-flexion between man and women.

IV. DISCUSSION

The experiment described here was conducted to facilitate a better understanding of the sensory contributions to motor performance. It has been that shown that there is a proprioceptive dependence on muscle mechanoreceptors and that the GTO is sensitive to even minute changes in muscle tension. Furthermore, different positions of the body can modulate muscle tension as gravity's line of pull on the muscle tendon units changes with position. The question was posed: if GTO feedback can be affected by the slightest changes in muscle tension, is proprioception also affected a change in gravity? To answer this, an experiment was design to measure proprioceptive abilities in varying body positions. As a result, it was observed that the subjects' abilities to recreate target joint angles, regardless of the direction of their inaccuracy (absolute error), was not affected. However, when moving in one a specific ROM (dorsi-flexion) while in an altered gravity environment (horizontal) subjects' ability in this regard (constant error) was improved. Specifically, their ability to overshoot the desired target angle was reduced.

One possible explanation is that a sensory component critical to the control of the homing-in on the final target location after the initial impulse burst, becomes enhanced with an alteration in gravity. According to the theory that distance and location programming operate conjointly, as a subject attempts to reproduce a desired joint angle, they make an initial impulse toward the target using distance programming and then home in on the target using location programming [17]. Absolute error may not be affected by a change in gravity due to the fact that the pattern of motor efference included in the compiling of the motor program used to move the perceived distance to the target position is no more variable in any given gravity position, whereas CE is affected in certain ROMs. Data collected during the RJPS testing suggests that the location of a target angle is predetermined by sensory information collected during blind passive positioning and the homing-in on the target is completed based on the previously stored position data. That is, in the horizontal gravity position, afferent triceps surae GTO data is more valuable to be used during joint angle repositioning than when passively being moved to the target position under more gravity load in the vertical position. Alternatively, while in altered gravity, judgment of the initial distance to a target could be enhanced by a constant amount resulting in a significantly decreased CE and a tendency for subjects to more accurately under- or over-shoot their target angle. Either of these mechanisms or both could be at play with the improvement in CE observed during dorsi-flexion in this study.

V. CONCLUSIONS

While a change in body position does not appear to have a dramatic effect on all aspects of proprioception, it does appear to enhance one's tendency not to overshoot their joint angle target in at least one particular ROM. As a result, it appears that we can rely on our own position sense during volitional movements as our body travels in space and that, in certain positions, we may even have enhanced abilities. We can infer that, the use of the feedback from the muscle mechanoreceptors is used by the CNS in a different way depending on the body's position. Is there a sensory re-weighting toward triceps surea GTO feedback for use when generating a desired joint stiffness when gravity is altered? In order to fully understand the role and contribution of the GTO on our sense of body position, further research needs to be conducted on other joints and on other altered environments investigating RJPS as well as kinesthesia. It is hoped that further research will provide more information about how and to what extent the central nervous system uses information from our somatosensory system and, in particular, from the GTO.

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