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Paradoxical Relationship in Sensorimotor System: Knee Joint Position Sense Absolute Error and Joint Stiffness Measures

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Abstract

Background—Relationships between joint position sense and the sensorimotor characteristics such as joint stiffness, time to detect motion, and time to peak torque during a perturbation test have rarely been investigated due to methodological challenges. The purpose of this study was to compare joint position sense and the sensorimotor characteristics in healthy individuals.

Methods—A total of 26 subjects were recruited and completed joint position sense and a perturbation test on isokinetic dynamometer. Joint position sense was assessed by comparison of the absolute angle difference between a reference and replicated position. During the perturbation test, the dynamometer moved the knee flexion angle from 70 to 30 degrees (0 degree represents a full knee extension) at the velocity of 500 degrees per second at random. Subjects were asked to react and pull back the leg as soon as they perceived the movement. Pearson or Spearman's correlation coefficients were used to assess these relationships ($P < 0.05$).

Findings—Larger joint position sense absolute error values were significantly correlated with higher short-range at 50 milliseconds ($r = 0.572$, $P = 0.002$), at 100 milliseconds ($\rho = 0.416$, $P = 0.035$), and reactive joint stiffness ($r = 0.395$, $P = 0.046$).

Interpretation—There was a paradoxical relationship between higher joint stiffness and worsened joint position sense. Potential reasons include sensory weighting within the sensorimotor system and thixotropic properties (after-effects of muscle eccentric contractions to increase stiffness and alter joint position sense).

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Keywords

Joint Position Sense; Stiffness; Sensorimotor System; Paradoxical Relationship

1. INTRODUCTION

Muscle tone or tension is defined as the resistance of a limb to passive movement where the resistance arises from passive and involuntary active forces (Gurfinkel et al., 2006). Regulation of muscle tone/tension involves the fusimotor system and the peripheral and central nervous system that act to alter muscle spindle sensitivity and the alpha motor neurons to produce muscle tone. Increased muscle tension is directly related to joint stiffness; and higher muscle tension (induced by an active muscle contraction of steady force) can result in higher joint stiffness at the time of joint perturbation (Needle et al., 2017). This increased muscle tone and higher joint stiffness likely play an important role in joint stability in humans as the first line of defense against aberrant forces applied to the joint. Because of muscle spindle involvement in muscle tension and joint stiffness regulation, sensory systems of the visual, vestibular, and proprioceptive systems are involved to influence muscle tone, joint stiffness, and ultimately whole-body motor control under the sensorimotor system (Johansson et al., 2000).

Previously, in order to assess an individual's sensorimotor characteristics, a high-velocity (500 degrees per second) perturbation test was developed (Nagai et al., 2018c). In this protocol, subjects were asked to react and flex their knee as soon as they perceived movement of their knee by a dynamometer. Several sensorimotor characteristics were measured: initial muscle tension/torque, short-range stiffness within 100 milliseconds from the initiation of the dynamometer movement, time to detect motion, time to react/reach the peak torque, and reactive stiffness from detection to peak torque. The results indicated that higher short-range stiffness was positively associated with time to peak torque and reactive stiffness, while no association was found between the initial muscle tension and short-range stiffness (Nagai et al., 2018b). Likely, this was due to residual slack in the actin-myosin sliding filaments. Despite the technical difficulty in designing and developing a high-velocity perturbation test device, the short-range stiffness values were sensitive enough to detect sex differences. Surprisingly, short-range stiffness was not correlated with time to detect motion (this sensation originates from sensory afferents of the muscle spindles). In other words, the contribution of the higher brain to stimulate both alpha and gamma motor neuron to regulate stiffness might govern and diminish the proprioceptive/sensory role of the muscle spindles (Nagai et al., 2018b).

From a clinical perspective, joint position sense (JPS) and threshold to detect motion are two common proprioception tests. Recent systematic reviews and meta-analyses have confirmed that individuals with musculoskeletal conditions such as anterior cruciate ligament (ACL) injury or osteoarthritis exhibit significant proprioceptive deficits (Kim et al., 2017; van Tunen et al., 2018). Development of comprehensive sensorimotor testing (encompassing both JPS and stiffness measurements during a high-velocity perturbation) and an understanding of each variable would play an important role in the future of musculoskeletal

medicine and personalized intervention strategies. Therefore, an objective of the current investigation was to examine the relationships between JPS and stiffness measurements. It was hypothesized that improved JPS (smaller values) would be significantly correlated with higher short-range stiffness values during a perturbation test.

2. METHODS

2.1 Participants

A total of 26 subjects were recruited for the study (15 males and 11 females). Means and standard deviations of demographic information were: age: 20.7 (5.7) years, height: 174.7 (8.9) cm, and weight: 73.4 (12.3) kg. A convenience sample was used to recruit healthy individuals (most subjects were referred by recreational or high-school/college athletes who were in the sports medicine clinic). All individuals were physically active and participated in exercise sessions or sports at least three times a week for a minimum of 60 minutes per session to be included in the study. There were no side-to-side limb differences; therefore, the average of both limbs was used for analyses. Individuals with a prior history of lower extremity injury/surgery in the past six months, neurological disorders, paralysis, neuromuscular disease, cardiovascular disease, exercise-induced injury, asthma, and/or pregnancy were excluded from the study. Prior to their participation, informed consents were obtained from each subject. The study was reviewed and approved by the Mayo Clinic Institutional Review Board.

2.2 Experimental Protocol

A high-velocity perturbation protocol and JPS protocol was previously described in detail (Nagai et al., 2018a, b; Nagai et al., 2018c). Briefly, an isokinetic dynamometer (HumacNORM, CSMi; Natick, MA, USA) was used for both tests. For the high-velocity perturbation, subjects sat on a chair with their knee secured and locked at 70 degrees of knee flexion. Subjects were asked to aggressively flex their shank in a posterior direction as quickly as possible as soon as they could sense any movement in their knee. As a safety mechanism, the dynamometer was set to stop at 30 degrees of knee flexion if the subject failed to react quickly enough. Raw data from the HumacNORM (both torque and position data) was collected at 1000 Hz with customized LabVIEW code (National Instruments; Austin, TX, USA) on a USB-1608G (Measurement Computing; Norton, MA, USA). The LabVIEW software was used to extract the initial torque ($TORQ_0$), short-range stiffness at 50 milliseconds and 100 milliseconds ($STIFF_{50}$ and $STIFF_{100}$), movement detection time ($TIME_{prop}$), time to peak torque ($TIME_{pk}$), and reactive stiffness ($STIFF_{reac}$). $TIME_{prop}$ was defined as the point at which acceleration of the dynamometer began to decrease and when torque deflected greater than 10% over a 5-millisecond interval. $STIFF_{reac}$ was defined as the stiffness between two time points: $TIME_{prop}$ and $TIME_{pk}$.

For JPS testing, each subject's leg was flexed, and then they were asked to actively move their leg to 45 degrees of knee flexion. This reference was chosen based on the previous results (Nagai et al., 2018a). Once the leg reached 45 degrees, the dynamometer locked the joint in place for 10 seconds while subjects were asked to remember the position and prepare to actively replicate the joint angle after return to the initial position. The difference between

the reference angle and replicated angle in absolute values was used as the JPS absolute error (JPS-AE). An average of three trials was used for analyses. Moderate intra-session reliability and precision measurements were previously established (intraclass correlation coefficient: ICC (3,k) = 0.588 (95% confidence interval: 0.251 – 0.797) and standard error of measurements: SEM = 1.107°).

2.3 Statistical Analysis

For statistical analyses, descriptive statistics (means and standard deviations) and Pearson correlation coefficients, r , were used to establish the relationships among the sensorimotor characteristics (TORQ₀, STIFF₅₀, STIFF₁₀₀, TIME_{prop}, TIME_{pk}, and STIFF_{reac}) and JPS-AE. Those variables, that were not normally distributed, Spearman's rank correlation coefficients, ρ , were used instead of Pearson coefficients. Significance was set at $\alpha < 0.05$.

3. RESULTS

Descriptive statistics (means and standard deviations) of the sensorimotor characteristics during a high-velocity perturbation test and JPS-AE are shown in Table 1. Correlation coefficients among the sensorimotor characteristics vs. JPS-AE and P -values are also shown in Table 1. There were significantly positive correlations between STIFF₅₀ and JPS-AE ($r = 0.572$, $P = 0.002$), between STIFF₁₀₀ and JPS-AE ($\rho = 0.416$, $P = 0.035$), and between STIFF_{reac} and JPS-AE ($r = 0.395$, $P = 0.046$). Those positive correlations meant that individuals with larger JPS error exhibited higher passive (STIFF₅₀ and STIFF₁₀₀) and reactive joint stiffness (STIFF_{reac}). A scatter plot of JPS-AE and STIFF_{50/100/reac} are shown in Figure 1. A linear regression line, equation, and goodness-of fit (R^2) value was calculated and added to each figure. R^2 values were 0.3269 (STIFF₅₀ and JPS-AE), 0.1452 (STIFF₁₀₀ and JPS-AE), and 0.1565 (STIFF_{reac} and JPS-AE).

4. DISCUSSION

The current results indicate that individuals with larger JPS errors had significantly higher short-range stiffness and reactive stiffness. While these comparisons were significant, they were opposite of the hypothesis. The actual values of each dependent variable (TORQ₀, STIFF₅₀, STIFF₁₀₀, TIME_{prop}, TIME_{pk}, STIFF_{reac}, and JPSAE) in the current investigation/protocols were in line with the values from the previous investigations (Nagai et al., 2018a, b), which indicate that the data were collected according to the defined protocols.

The major finding of the current study was a paradoxical relationship of joint stiffness and JPS (Figure 1). Interestingly, this paradoxical relationship in JPS was observed previously when JPS was compared to another proprioception modality: threshold to detect passive motion (TTDPM) in elite ballet dancers (Barrack et al., 1984). Dancers had significantly worse JPS but better TTDPM than their matched controls (Barrack et al., 1984). The authors theorized that overshooting JPS errors (replicated joint positions were more extended than reference positions) and better TTDPM were due to general joint laxity and superior muscle development with muscle spindles sensitive to passive movement, respectively. Similarly, in the current investigation, individuals with higher stiffness had tendency to overshoot the target and ended up with a more extended knee joint position. In the current investigation,

there were more male participants. Males generally exhibit higher muscular strength/stiffness and less flexibility of the hamstrings than females (Blackburn et al., 2004). Therefore, increased JPS error and higher stiffness values in the current participants (not elite dancers) were unlikely to be caused by general joint laxity. Two potential reasons for the paradoxical relationship are discussed below: sensory weighting within the sensorimotor system (Mugge et al., 2009) and thixotropic property of muscle fibers (Hagbarth et al., 1985).

First, from a physiological perspective, muscle spindles' primary endings (Ia afferent fibers) and secondary endings (II afferent fibers) are largely responsible for kinesthetic sensation of muscle length and changes in length (Proske and Gandevia, 2012). In addition, Golgi tendon organs' Ib afferent fibers (responsible for muscle force information) are active even when muscles are weakly active or relaxed due to residual resting muscle tone (Fallon and Macefield, 2007). This co-activation of two primary mechanoreceptors can cause either increased or decreased kinesthetic accuracy likely due to sensory weighting. Sensory weighting is task-dependent (for example, we weight more on vision, vestibular, and somatosensory during balance) and highly adaptable based on previous experience and plays an important role in motor control and learning (Ostry and Gribble, 2016). Mugge et al. investigated the role of arm push/pull positioning and force feedback on variable spring stiffness of a hydraulic cylinder/piston and demonstrated that force feedback (Golgi tendon organs' involvement) was weighted heavier than position feedback (muscle spindles' involvement) when subjects were moving their arm with higher piston stiffness (Mugge et al., 2009). In addition, when two senses (joint position and muscle force) compete in the same task, stiffness increases as the primary mechanism to increase the stability in the sensorimotor system (Mugge et al., 2009). Although their testing protocol (arm pull-push task) is not directly comparable to the current investigation (knee JPS and high-velocity perturbation), their results and the current results suggest that those individuals who produced higher stiffness values likely weighted force sensory feedback more than position sensory feedback. A paradoxical relationship might partially be explained by sensory weighting (higher stiffness with higher force feedback and less position sense).

Another potential reason includes the thixotropic property of muscle fibers and its influence on proprioceptive sense (Hagbarth et al., 1985; Proske et al., 2014). Thixotropy refers to materials which change their physical properties as a result of being moved or "after-effects" (Hagbarth et al., 1985; Proske et al., 2014). Both intrinsic fibers of muscle spindles and extrinsic muscle fibers exhibit thixotropic property (Proske et al., 2014). Based on this property, repeated eccentric contractions can result in greater residual actin-myosin attachments and higher muscle tension, while faulty proprioceptive senses are being perceived by the brain (Torres et al., 2010). In the current experiment, subjects performed several eccentric contractions of the hamstrings muscles during a high velocity perturbation test (practices and real trials). In turn, both muscle fibers and muscles spindles in the knee flexor muscles were likely elongated during JPS testing; therefore, almost all subjects were consistently overshooting the target position, resulting more extended knee JPS. To support this contention, elbow flexion JPS overshooting was observed after repeated contractions of the antagonist muscles (Winter et al., 2005).

The current investigation has clinical implications. For example, decreased hamstring strength is a risk factor for future ACL injury in female athletes (Myer et al., 2009). Females have less muscular strength and muscular stiffness than males even after normalized to their body mass (Blackburn et al., 2004). In addition, individuals with decreased hamstrings stiffness have been shown to land with biomechanical risk factors characteristics of ACL injury such as increased valgus moments, anterior tibial shear force, and decreased knee flexion angle at initial contact (Blackburn 2013). Poor trunk JPS and knee JPS was also identified as a prospective risk factor of ACL injury and lower extremity injuries, respectively (Mohammadi et al., 2013; Zazulak et al., 2007). In an interesting aspect of the study by Mohammadi et al., individuals with a greater increase in JPS error values after two hours of military physical training were at higher risk of future lower extremity injury, compared to those with higher baseline JPS error values (Mohammadi et al., 2013). Therefore, an individual's ability to adapt and adjust well in the environment to maintain joint stability might reflect their true proprioceptive sense. Based on the current findings and discussion on sensory weighting and thixotropic properties, proprioceptive deficits at baseline alone might not be sufficient to describe an individual's sensorimotor system and identify their ACL injury risk. A recent review paper recommends proprioception testing in addition to anthropometrics, strength, movement biomechanics, and psychological testing to screen risk of future musculoskeletal injuries, especially in healthy athletic population (Hewett et al., 2019). Furthermore, it is critical for physicians and therapists to understand relationships among various sensorimotor characteristics to fully appreciate an individual's risk. Future investigations should include those tests and analyses and improve preventive medicine and clinical guidelines.

The current study has limitations. First, some subjects found it difficult to detect and stop the dynamometer during a perturbation test due to the high velocity of rotation applied by the dynamometer arm. In addition, the resistance torque limit was set at 60 N which was easily achievable for these subjects. Therefore, the current method became a quick reaction test. Further refinements (an increase in torque limit and slower perturbation speed) would likely improve the reactive torque output. However, even with a higher reactive torque and $STIFF_{\text{reac}}$, similar short-range stiffness values would likely be observed: $STIFF_{50}$ and $STIFF_{100}$. Another limitation is that the JPS and high-velocity perturbation tests were conducted within the same day over a two-hour period. As mentioned earlier, sensory weighting and thixotropic effects in stiffness and JPS may remain from perturbation test practices to JPS test. Although we are confident that randomization in testing order took care of this limitation, it should be acknowledged. Subjects in the study were young and physically active; therefore, it has limited generalizability to older individuals and individuals with pathological conditions. Lastly, another potential source of error/variability in JPS is a role of warmup (Subasi et al., 2008). A few practice tests were performed prior to each JPS and perturbation test, but no formal warm-up was conducted to optimize the proprioceptive feedback.

5. Conclusion

The current investigation found a paradoxical relationship between JPS absolute error values and all stiffness measurements ($STIFF_{50}$, $STIFF_{100}$, and $STIFF_{\text{reac}}$) during a perturbation

test. Individuals with higher position sense error values could likely compensate with increased stiffness. This relationship was in part explained by sensory weighting and thixotropic properties. The current findings do not minimize the importance of proprioception testing as there is clear evidence of proprioceptive deficits in clinical patients such as individuals with ACL injury or osteoarthritis (Kim et al., 2017; van Tunen et al., 2018). Instead, it demonstrated that the sensorimotor system was highly adaptable and history-dependent. Clinical tests should incorporate both sensory acuity and neuromuscular control, particularly stiffness regulation, to fully understand an individual's sensorimotor system.

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Highlights

- Joint position sense is a common proprioception test.
- Regulation of joint stiffness is critically important for joint stability.
- The relationships between sensory / motor functions have rarely examined together.
- Higher position sense error values exhibit higher joint stiffness measurements.
- A paradoxical relationship of joint position sense and stiffness is explained.

Figure 1.

Scatter plot of knee joint position sense (JPS) absolute error values (°) and stiffness measures (Nm/°) during a high-velocity perturbation test. The horizontal and vertical axes represent JPS and knee joint stiffness of all subjects, respectively. The top, middle, and bottom plots reflect JPS and short-range stiffness in 50 and 100 milliseconds (STIFF₅₀ / STIFF₁₀₀) and reactive stiffness (STIFF_{reac}), respectively. A linear regression line and relationship (R^2 value) are provided.

Table 1.

Descriptive Statistics and Correlation Analyses with Joint Position Sense Absolute Error

Variables of Interest	Means (SD)	Correlation Coefficients	P-Value
Resting Muscle Tension: TORQ ₀ (Nm)	3.7 (2.4)	0.089	0.666
Stiffness from 0ms to 50ms: STIFF ₅₀ (Nm/°)	26.8 (9.0)	0.572	0.002
Stiffness from 0ms to 100ms: STIFF ₁₀₀ (Nm/°)	5.4 (1.3)	0.416	0.035
Threshold to Detect Movement: TIME _{prop} (ms)	142.2 (13.6)	0.179	0.382
Time to Peak Torque: TIME _{pk} (ms)	322.0 (26.8)	- 0.054	0.792
Reactive Muscle Stiffness: STIFF _{reac} (Nm/°)	2.5 (0.7)	0.395	0.046
Joint Position Sense Absolute Error: JPS-AE (°)	4.5 (1.2)	-	-