SMGroup

Conscious Proprioception Assessments in Sports Medicine: How Individuals Perform Each Submodality?

Takashi Nagai[1]*, Katelyn F Allison[1], Joseph L Schmitz[1], Timothy C Sell[2] and Scott M Lephart[3]

[1]Neuromuscular Research Laboratory, University of Pittsburgh, US

[2]Michael W Krzyzewski Human Performance Laboratory, Duke University, US

[3]Sports Medicine Research Institute, University of Kentucky, US

***Corresponding author:** Takashi Nagai, Neuromuscular Research Laboratory, University of Pittsburgh, Pittsburgh, PA, 3860 South Water Street, Pittsburgh, PA 15203; Tel: 412-246-0460; Fax: 412-246-0461; Email: tnagai@pitt.edu

Published Date: August 07, 2016

Copyright © Nagai T.This book chapter is open access distributed under the Creative Commons Attribution 4.0 International License, which allows users to download, copy and build upon published articles even for commercial purposes, as long as the author and publisher are properly credited.

ABSTRACT

Background: Proprioception plays a vital role in achieving functional joint stability of the knee. Numerous research studies have evaluated the effects of injury, surgery, rehabilitation, and training on proprioception in the sports medicine research. Joint position sense **(JPS)** and threshold to detect passive motion **(TTDPM)** have been commonly used while fewer studies have incorporated velocity sense **(VS)** and force sense **(FS)**. Due to the differences in the origin of information associated with each submodality, it is clinically important to understand how individuals perform each submodality and establish the relationship. Methods: Twenty physically active subjects (10 males and 10 females; age: 23.0 ± 3.4 years, height: 174.2 ± 12.1 cm, and mass: 70.3 ± 14.4 kg) participated in the study. Proprioception on their dominant leg was tested using an isokinetic dynamometer. For JPS, a subject extended his/her leg to a target position and replicated the position. During TTDPM, the subject was asked to detect slow-moving passive movement and the direction (flexion or extension). For FS, the subject exerted 30% of their peak isometric torque with and without visual feedback. For VS, the subject' knee was passively rotated by the dynamometry at 20°/sec, followed by actively reproducing the velocity. The average of five trials (absolute values between the target and replication trials) was used for analyses. Pearson Correlation or Spearman's Rho was used to establish the bi-variate relationship ($p < 0.05$). Results: There were no statistically significant correlations between each submodality. However, only significant correlations were found within TTDPM and VS (TTDPM flexion/extension, $r = 0.541$, $p = 0.014$; VS flexion/extension, $r = 0.934$, $p = 0.001$). Conclusion: The results reveal that individuals perform each submodality of proprioception differently. Based on the research questions, appropriate submodality should be used.

Keywords: Proprioception, joint position sense, threshold to detect passive motion, velocity sense, force sense, correlations

Copyright © Nagai T.This book chapter is open access distributed under the Creative Commons Attribution 4.0 International License, which allows users to download, copy and build upon published articles even for commercial purposes, as long as the author and publisher are properly credited.

INTRODUCTION

Proprioception is defined as afferent information arising from the internal peripheral areas of the body that contribute to postural control, joint stability, and several conscious sensations [1]. Proprioceptive information from afferent sensory organs (mechanoreceptors) reaches the central nervous system **(CNS)**, where it is processed and integrated with other somatosensory information to regulate neuromuscular control and properly maintain joint stability [2]. The role of proprioception (afferent signals) in directly influencing neuromuscular control and joint stability has been studied in sports medicine literature and injury prevention research [3,4]. Most proprioception assessment techniques in the field of sports medicine literature evaluate the integrity and function of conscious proprioception [5].

Conscious proprioception is divided into four submodalities: 1) joint position sense **(JPS)** – the ability to reproduce the target joint position actively or passively, 2) kinesthesia measured by threshold to detect passive motion **(TTDPM)** – the ability to detect the initiation of passive joint movement, 3) velocity sense **(VS)** – the ability to reproduce the target velocity, and 4) force sense **(FS)** – the ability to reproduce the target force [1]. In summary, JPS is likely influenced mainly by slow adapting mechanoreceptors [6,7]. TTDPM is influenced by muscle spindles, skin, and articular mechanoreceptors [8]. Primarily, the muscle spindle signals, with changes in length of the muscle fascicles, may be suggested to play a main role in TTDPM [9]. VS is mostly influenced by muscle spindles along with articular and cutaneous information similar to active JPS, but it is associated with a complex mixture of different cues such as timing, location, distance and velocity [10]. FS is thought to come from two sources: the sense of tension generated by afferent feedback from the musculotendinous mechanoreceptors and the sense of effort generated centrally [11].

Despite differences in the origin of information among each submodality, previous research on knee conscious proprioception commonly included JPS and/or TTDPM [12-18]. It is generally agreed that TTDPM and JPS are decreased in individuals with ACL injury, and these deficits may persist even after reconstruction surgery when compared to uninjured control group [12-16]. Among the individuals with ACL injury or reconstruction, enhanced proprioception also has been associated with high functional tests and patient satisfaction scores, supporting the notion that proprioception plays an important role in functional joint stability [14,19,20]. From a motor control and injury prevention perspective, better TTDPM was correlated with greater initial knee flexion angle during a landing task [21].

While JPS and TTDPM provide valuable proprioceptive information about the joint, other submodalities (VS and FS) may help researchers understand the more comprehensive view of one's proprioception ability and neuromuscular control. For example, several studies have evaluated VS in the upper extremity while few studies have utilized VS in the lower extremity [10,22-25]. When comparing VS and JPS in shoulder horizontal abduction/adduction movements, there was a lack of correlation, suggesting that those two submodalities should be evaluated separately

Copyright © Nagai T.This book chapter is open access distributed under the Creative Commons Attribution 4.0 International License, which allows users to download, copy and build upon published articles even for commercial purposes, as long as the author and publisher are properly credited.

[22]. Another interesting observation is that faster joint velocity has shown to result in larger VS replication errors [25] while slower joint velocity has made it more difficult for individuals to detect passive motion during TTDPM testing [26]. It is likely different mechanisms involved in how individuals replicate velocity and detect velocity. Another important submodality is FS. In the ankle literature, FS has demonstrated significant correlations with joint stiffness in subjects with chronic ankle instability while JPS was not correlated with stiffness [27]. The regulation of joint stiffness is one of the most important roles of proprioception. That is because the anticipatory control (feed forward) of joint stiffness can provide the first line of defense against sudden perturbation and potential injuries [28], indicating the importance of studying FS. While most studies incorporated one or two submodalities, in order to understand conscious proprioception, studies should include a comprehensive battery of tests that evaluate all submodalities of conscious proprioception.

Several questions regarding conscious proprioception of the knee warrant further investigation. Since there are very few studies on VS and FS on knee proprioception, it is largely unknown how VS and FS compare with more commonly tested modalities: JPS and TTDPM. A few studies have examined knee JPS, TTDPM, and FS in a single session and evaluated correlations among those submodalities [29,30]. The authors [29,30] did not find significant correlations, suggesting that each submodality should be treated as a separate entity in order to fully understand conscious proprioception. To complement previous studies on JPS, TTDPM, and FS, evaluating and understanding VS could provide additional information on how the VS is related to other submodalities. Although a few studies have compared TTDPM or JPS with VS or FS at the ankle [31] and shoulder [22] and reported no significant correlations among those submodalities, there has not been any studies incorporated all four submodalities at the knee in one single experimental session. Therefore, the purpose of this study was to explore how individuals perform each submodality at the knee. It was hypothesized that each submodality would not demonstrate significant correlations with other submodalities assessed. It is clinically important to understand how the proprioceptive information from each submodality may work together to provide afferent information necessary for motor control.

MATERIALS AND METHODS

Subjects

Twenty subjects (10 males and 10 females; age: 23.0 ± 3.4 years, height: 174.2 ± 12.1 cm, and mass: 70.3 ± 14.4 kg) were recruited from the university. Subjects provided written informed consent prior to participation in accordance with the University Institutional Review Board. All subjects were physically active, participating at least 20–30 minutes of exercise three times a week. Subjects reporting a history of serious knee injury or other lower extremity injury that require them to seek medical attention within the previous six months were excluded. Any subjects with mental disability or attention deficit were also excluded from the study, due to the nature of study requiring subjects' concentration and attention.

Copyright © Nagai T.This book chapter is open access distributed under the Creative Commons Attribution 4.0 International License, which allows users to download, copy and build upon published articles even for commercial purposes, as long as the author and publisher are properly credited.

Instrumentation

All proprioception testing was done on the Biodex System 3 Multi-Joint Testing and Rehabilitation System (Biodex Medical Inc., Shirley, NY). The reliability and validity of the dynamometer hardware has been shown to be excellent (Intraclass Correlation Coefficient **(ICC)**=0.99–1.00) [32].Torque values during FS testing were automatically adjusted for gravity by the Biodex Advantage Software v.3.0 (Biodex Medical Inc., Shirley, NY). TTDPM data was collected with the Biodex Research Toolkit software (Biodex Medical Inc., Shirley, NY). For VS, analogdata containing angular position information was recorded through the Peak Motus 3D Motion Analysis System Software Version 8.2 (ViconPeak, Centennial, CO) at 100 Hz.

Procedures

For the sagittal plane JPS, TTDPM, and VS tests, a subject was seated upright with a blindfold and headphones to eliminate visual and auditory cues. Only the dominant leg was tested, and limb dominance was defined by the leg used to kick a ball [33]. For TTDPM tests, the subject wore an air compression sleeve (PresSsion Gradient Sequential Compression Units, Chattanooga Group, Hixon, TN) to minimize tactile sensation [34]. For other sagittal plane tests, the subject's limb was firmly strapped to the Biodex leg attachment. Testing orders were counter-balanced. A five-minute rest between each submodality was used to ensure no mental and/or physical fatigue from the previous testing.

Joint position sense

The active JPS test was started at 90 degrees of knee flexion, and the subject was asked to extend the knee. When the joint reached the predetermined target position (15 degrees of knee flexion), the Biodex stopped automatically and held the position for 10 seconds. The subject was asked to remember this angle, and the joint was moved passively into the starting position. The subject was then asked to reproduce the angle and press the stop button when he or she felt their knee joint reached the target position. The amount of discrepancy between the target position and replicated position was recorded as a JPS error. Five repetitions were performed. Since JPS could have both positive (overshooting) and negative (undershooting) values that could potentially cancel each other, the absolute values (only the magnitude of errors) were used in the analyses. Reliability and precision was established previously in our laboratory (ICC = 0.87; Standard Error of Measurement **(SEM)** = 0.69 degrees).

Threshold to detect passive motion

The TTDPM testing was started with the knee in the starting position (15 degrees of flexion). At an unannounced time (0-20 seconds), the knee was passively moved into either flexion or extension at a rate of 0.25 degrees/second. The subject was instructed to press a stop-button as soon as he or she felt motion and could identify the direction (either flexion or extension direction). Because the movement can be perceived prior to the direction of the movement, the subject had

Copyright © Nagai T.This book chapter is open access distributed under the Creative Commons Attribution 4.0 International License, which allows users to download, copy and build upon published articles even for commercial purposes, as long as the author and publisher are properly credited.

to perceive both movement and direction correctly [35]. During each trial, the subject had to state which direction it moved. If the subject pushed a stop-button and identified the wrong direction, the trial was not counted. The arc traveled between the initiation of motion and the final position was recorded in degrees. In total, five repetitions for flexion and extension direction each were randomly performed. Reliability and precision was established previously in our laboratory (ICC = 0.88–0.92; SEM = 0.19–0.22 degrees).

Force sense

First, the subject was asked to perform three repetitions of maximum voluntary isometric contraction **(MVIC)** for knee flexion and extension for five seconds with a ten-second rest between repetitions. The knee was set at a starting position of 45 degrees of flexion. The maximum torques for three trials were averaged and recorded as the mean MVIC. The target extension force during FS was set at 30% of the mean MVIC. The subject performed the isometric knee extension, maintaining the target torque while watching the computer monitor (the subject could see his/her torque output on the monitor, and the target torque was clearly marked). After five seconds rest, the subject was asked to reproduce the target torque once again without visual feedback. A total of five repetitions were performed. FS data were exported into Excel spreadsheet (Microsoft, Seattle, WA), where the last three seconds out of five seconds was averaged for both visual and non-visual trials. The flexion FS was done in the exact same way. Similar to JPS, potential cancelling of a FS error due to over/undershooting, the absolute value was used. The average of five trials was used for analyses. Reliability and precision was established previously in our laboratory (ICC = 0.79–0.83; SEM = 1.0–1.8 Nm).

Velocity sense

First, while the subject sat on the dynamometer chair with a blindfold, the dynamometer arm of the Biodex passively moved the subject's knee in flexion/extension continuously for five repetitions at 20 degrees/second. During those passive movements (the arc of motion from 0 to 90 degrees of knee flexion), the subject was asked to pay attention to their joint movement velocity. Next, the subject was asked to replicate the movements by actively extending and flexing at the same velocity as closely as they could. A total of 10 repetitions (five repetitions in each direction) were used to assess the velocity sense. Once raw data containing angular position information was captured at 100 Hz, the data were filtered using a low pass Butterworth 2nd order, zero lag digital filter with cutoff frequency of 1 Hz. Due to the velocity stoppage at the end-range (from extension to flexion and from flexion to extension), the middle range of motion (the arc of motion from 15 to 75 degrees of knee flexion) was used to capture a velocity value. The absolute differences between the Biodex velocity (reference velocity = 20 degrees/second) and the subject's reproduction velocity were recorded as a velocity sense error (in degrees/second). The average of five trials was used for analyses. Reliability and precision was established previously in our laboratory (ICC = 0.68–0.81; SEM = 1.08–0.80 degrees/second).

Copyright © Nagai T.This book chapter is open access distributed under the Creative Commons Attribution 4.0 International License, which allows users to download, copy and build upon published articles even for commercial purposes, as long as the author and publisher are properly credited.

Statistical Analysis

All variables were analyzed with SPSS 20.0 (SPSS, Inc., Chicago, IL). First, normality tests were done using Shapiro-Wilk tests. Based on the normality, either Pearson Correlation (parametric test) or Spearman's Rho was used to establish the bi-variate relationship. Significance was set at $p<0.05$ *a priori* for all correlation analyses.

RESULTS

Means and standard deviations are presented in Table 1. The correlation results are presented in Table 2. Based on the Shapiro-Wilk normality tests, TTDPM flexion/extension and VS flexion were not normally distributed. Therefore, comparison of those variables was done using Spearman's Rho. Out of 21 pairs/comparisons, two pairs were significantly correlated ($p < 0.05$). Specifically, TTDPM extension was significantly correlated with TTDPM flexion ($r = 0.541$, $p = 0.014$), and VS extension was significantly correlated with VS flexion ($r = 0.934$, $p = 0.001$).

Table 1: Descriptive Statistics.

Variables	Mean	SD
JPS (degrees)	3.29	1.58
TTDPM Flexion (degrees)	1.14	0.52
TTDPM Extension (degrees)	0.83	0.60
FS Flexion (Newton-Meters)	2.29	0.97
FS Extension (Newton-Meters)	3.49	1.87
VS Flexion (degrees/second)	4.24	2.58
VS Extension (degrees/second)	3.50	2.11

Table 2: Correlation Result.

	TTDPM Flex	TTDPM Ext	FS Flex	FS Ext	VS Flex	VS Ext
JPS	0.169 0.477	0.278 0.236	-0.175 0.462	0.100 0.674	0.119 0.618	-0.007 0.976
TTDPM Flex	-	0.541 0.014*	-0.175 0.462	0.100 0.674	0.098 0.680	0.179 0.449
TTDPM Ext		-	-0.235 0.319	0.031 0.897	-0.106 0.656	-0.031 0.897
FS Flex			-	0.327 0.159	-0.206 0.383	-0.143 0.548
FS Ext				-	0.231 0.327	0.406 0.076
VS Flex					-	0.934 0.001*

The first value represents correlation coefficient, and the second value represents p-value.

* represents significant correlation ($p<0.05$).

Copyright © Nagai T.This book chapter is open access distributed under the Creative Commons Attribution 4.0 International License, which allows users to download, copy and build upon published articles even for commercial purposes, as long as the author and publisher are properly credited.

DISCUSSION

The purpose of this study was to explore the relationship between four different submodalities of proprioception at the knee within the same study population during a single study session. This study revealed no relationship between each submodality. Therefore, the hypothesis was supported. The current findings are in accordance with previous studies that did not find significant relationship between each submodality. The differences between knee JPS and TTDPM were reported as early as 1985 in sports medicine literature [36]. More recent studies have indicated similar findings as the authors compared correlations among knee JPS, TTDPM, and FS and found no significant correlations [29]. The differences between submodalities were found in other joints as well. As stated previously, in an ankle study, a significant correlation between FS and stiffness was reported while no significant relationship was found between JPS and stiffness, suggesting that JPS and FS are two separate entities [27]. In a shoulder study, no significant correlations were demonstrated between JPS and VS in shoulder horizontal abduction/adduction movements [22]. The sources of proprioceptive signals and areas of conscious perception could help in explaining the current and previous findings of no relationship between submodalities [5].

From an anatomical and physiological point of view, the senses of movement and position are thought to be two separate senses [37]. The sense of movement (as in TTDPM) is primarily associated with the discharge rate of muscles spindles based on fascicular length changes with skin and articular receptors adding anatomical frame (mid- and end-range of motion at specific joint)[37]. The sense of position (as in JPS) is thought to involve the thixotropic changes (history dependent changes in resting tone) in muscle spindles as well as other slow-adapting mechanoreceptors [37]. In our study, we observed no significant correlation between JPS and TTDPM ($r = 0.169 – 0.278$, $p = 0.236 – 0.477$), supporting the physiological explanation. Another consideration for using JPS and TTDPM in sports medicine research is their reliability and validity. When reliability values of various JPS tests and TTDPM in the same subjects are compared, TTDPM was found to be the most reliable [38]. Our laboratory found the similar results [39]. When evaluating the proprioception in individuals with ACL-deficiency (due to injury) and ACL-intact controls, the ACL-deficiency group scored significantly higher TTDPM (slower in detecting motion), but did not exhibit impairment in JPS relative to controls [18,40]. Researchers should be aware of those findings when deciding which submodality should be used in their study.

The sense of force is thought to be derived from a sense of effort and a sense of muscle tension, while the tendon organs are thought to be the main source of information regarding muscle tension [37]. The tendon organs have high stretch threshold and are mostly activated with active muscle contraction [41], making FS testing uniquely different from passive JPS (joint position replication task is performed while the joint is being moved passively by a dynamometer) and TTDPM, but, similar to active JPS (subjects replicate their joint actively – the current JPS testing) and VS. Based on the physiological differences, the current finding (no correlation between TTDPM and FS) makes sense. Additionally, there was a trend for significant correlation between VS Extension

Copyright © Nagai T.This book chapter is open access distributed under the Creative Commons Attribution 4.0 International License, which allows users to download, copy and build upon published articles even for commercial purposes, as long as the author and publisher are properly credited.

and FS Extension (r = 0.406, p = 0.076). It is speculated that this trend is due to the fact that the same knee extensor muscles are active and responsible for reproducing a target torque for FS as well as a target speed for VS (by contracting the knee extensors steadily). On the other hand, less muscle force is required during VS flexion because the flexion direction is the same direction as the gravity. In the sports medicine literature, relatively few studies have incorporated FS at the knee joint. Repeated eccentric contractions for the knee extensors have shown to disrupt FS for up to two days after testing [42]. Contrarily, a fatigue protocol using repeated concentric contractions did not seem to disrupt FS [43]. An ankle FS study has revealed that individuals with chronic ankle instability have greater FS errors when compared to individuals without instability [44]. Another study found that higher FS error was correlated with increased stiffness, suggesting that FS plays an important role in the neuromuscular control and the regulation (or a lack of regulation) of muscle stiffness [27].

In general, there have been fewer VS studies compared to other proprioception submodalities in the sports medicine literature. Regarding VS testing, some studies have used velocity discrimination methods [22,31,45] while others [23-25], including the present study, have used velocity replication methods. Both methods are shown to be reliable. The sense of velocity is thought to be originated primarily from muscles spindles from many muscles along with cutaneous and articular mechanoreceptors movement cues such as timing, location, distance, and velocity information [10]. Many subjects expressed that it was the hardest submodality out of the four to perform. Despite the few VS studies available, studies have demonstrated that older adults (mean age = 76 years) had significantly higher (worse performance) TTDPM and VS errors than young adults (mean age = 26 years) [45]. Additionally, VS (especially at higher velocity) has shown to be negatively affected after localized muscular fatiguing exercise [46]. Future studies should incorporate clinical populations.

In the current investigation, the only significant correlations were demonstrated within submodality (between TTDPM flexion and TTDPM extension; between VS flexion and VS extension) while no significant correlation was demonstrated between FS flexion and FS extension. During the TTDPM testing, the dynamometer arm moves toward either flexion or extension direction at the same speed (0.25 degrees/second). In other words, the task itself is identical for both flexion and extension (subjects press the bottom and identify the direction). Similarly, during the VS testing, subjects were constantly moving their knee flexion/extension at the constant speed as close as they could from the reference speed generated by the dynamometer (20 degrees/second) throughout the trial. On the other hand, during the FS testing, the target force was based on the individuals' maximal voluntary isometric contraction values. As the knee extension strength is much stronger than knee flexor strength, the target values for FS extension and flexion differed significantly. That might explain a lack of correlation between two measures within the FS testing. Another submodality, JPS, had only direction (from 90 degrees to 15 degrees); therefore, we were unable to compare within JPS testing.

Copyright © Nagai T.This book chapter is open access distributed under the Creative Commons Attribution 4.0 International License, which allows users to download, copy and build upon published articles even for commercial purposes, as long as the author and publisher are properly credited.

In conclusion, a few submodalities have been used to describe subject's conscious proprioception. The present investigation, as well as others, has revealed that each submodality, based on its anatomical and physiological difference, should be tested and interpreted as a separate entity. A question may arise as to which submodality would be preferred or appropriate. That would likely depend on the research question. Even within each submodality, testing methodologies and procedures are quite different among studies; therefore, it is important to establish reliability and precision. Conscious proprioception testing could be a powerful tool to assess the integrity of underlying anatomical and physiological system as well as overall joint stability and motor control in sports medicine and injury prevention research.

ACKNOWLEDGEMENTS

This research received no specific grant. The authors have no financial relationship to disclose. The authors would like to thank the subjects for their participation.

Figure 1: Threshold to Detect Passive Motion.

Copyright © Nagai T.This book chapter is open access distributed under the Creative Commons Attribution 4.0 International License, which allows users to download, copy and build upon published articles even for commercial purposes, as long as the author and publisher are properly credited.

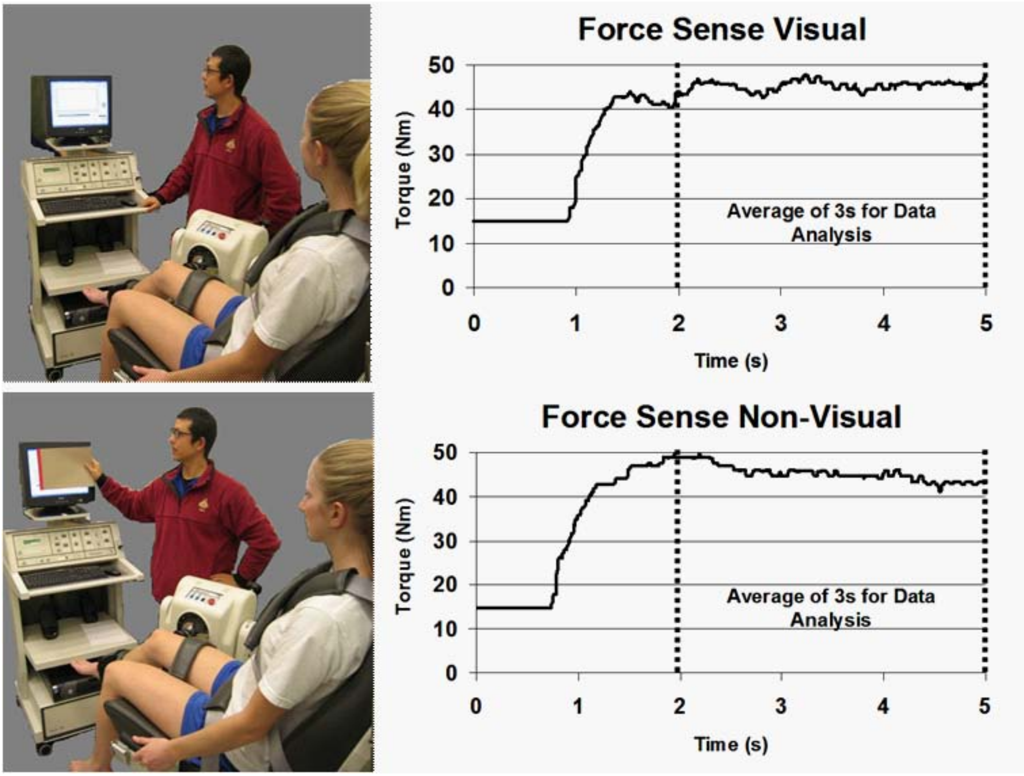

Figure 2: Force Sense and Data.

References

1. Riemann BL, Lephart SM. The sensorimotor system, part I: the physiologic basis of functional joint stability. J Athl Train. 2002; 37: 71-79.

2. Lephart SM, Riemann BL, Fu FH. Introduction to the sensorimotor system. In: Lephart SM, Fu FH, editors. Proprioception and Neuromuscular Control in Joint Stability. Champaign, IL: Human Kinetics. 2000.

3. Proske U. What is the role of muscle receptors in proprioception? Muscle Nerve. 2005; 31: 780-787.

4. Prochazka A, Gillard D, Bennett DJ. Positive force feedback control of muscles. J Neurophysiol. 1997; 77: 3226-3236.

5. Riemann BL, Myers JB, Lephart SM. Sensorimotor system measurement techniques. J Athl Train. 2002; 37: 85-98.

6. Clark FJ, Burgess PR. Slowly adapting receptors in cat knee joint: can they signal joint angle? J Neurophysiol. 1975; 38: 1448-1463.

7. Ferrell WR. The response of slowly adapting mechanoreceptors in the cat knee joint to tetanic contraction of hind limb muscles. Q J Exp Physiol. 1985; 70: 337-345.

8. Proske U. Kinesthesia: the role of muscle receptors. Muscle Nerve. 2006; 34: 545-558.

9. Hall LA, McCloskey DI. Detections of movements imposed on finger, elbow and shoulder joints. J Physiol. 1983; 335: 519-533.

10. Kerr GK, Worringham CJ. Velocity perception and proprioception. Adv Exp Med Biol. 2002; 508: 79-86.

11. Proske U, Gregory JE, Morgan DL, Percival P, Weerakkody NS. Force matching errors following eccentric exercise. Hum Mov Sci. 2004; 23: 365-378.

12. Barrack RL, Skinner HB, Buckley SL. Proprioception in the anterior cruciate deficient knee. Am J Sports Med. 1989; 17: 1-6.

13. Barrett DS1. Proprioception and function after anterior cruciate reconstruction. J Bone Joint Surg Br. 1991; 73: 833-837.

Copyright © Nagai T.This book chapter is open access distributed under the Creative Commons Attribution 4.0 International License, which allows users to download, copy and build upon published articles even for commercial purposes, as long as the author and publisher are properly credited.

14. Borsa PA, Lephart SM, Irrgang JJ, Safran MR, Fu FH. The effects of joint position and direction of joint motion on proprioceptive sensibility in anterior cruciate ligament-deficient athletes. Am J Sports Med. 1997; 25: 336-340.

15. Corrigan JP, Cashman WF, Brady MP. Proprioception in the cruciate deficient knee. J Bone Joint Surg Br. 1992; 74: 247-250.

16. Iwasa J, Ochi M, Adachi N, Tobita M, Katsube K. Proprioceptive improvement in knees with anterior cruciate ligament reconstruction. Clin Orthop Relat Res. 2000; 168-176.

17. Bonfim TR, Jansen Paccola CA, Barela JA. Proprioceptive and behavior impairments in individuals with anterior cruciate ligament reconstructed knees. Arch Phys Med Rehabil. 2003; 84: 1217-1223.

18. Reider B, Arcand MA, Diehl LH, Mroczek K, Abulencia A. Proprioception of the knee before and after anterior cruciate ligament reconstruction. Arthroscopy. 2003; 19: 2-12.

19. Fremerey RW, Lobenhoffer P, Zeichen J, Skutek M, Bosch U. Proprioception after rehabilitation and reconstruction in knees with deficiency of the anterior cruciate ligament: a prospective, longitudinal study. J Bone Joint Surg Br. 2000; 82: 801-806.

20. Katayama M, Higuchi H, Kimura M, Kobayashi A, Hatayama K. Proprioception and performance after anterior cruciate ligament rupture. Int Orthop. 2004; 28: 278-281.

21. Nagai T, Sell TC, House AJ, Abt JP, Lephart SM. Knee proprioception and strength and landing kinematics during a single-leg stop-jump task. J Athl Train. 2013; 48: 31-38.

22. Djupsjobacka M, Domkin D. Correlation analysis of proprioceptive acuity in ipsilateral position-matching and velocity-discrimination. Somatosens Mot Res. 2005; 22:85-93.

23. Lönn J, Djupsjöbacka M, Johansson H. Replication and discrimination of limb movement velocity. Somatosens Mot Res. 2001; 18: 76-82.

24. Jerosch J, Brinkmann T, Schneppenheim M. The angle velocity reproduction test (AVRT) as sensorimotor function of the glenohumeral complex. Arch Orthop Trauma Surg. 2003; 123: 151-157.

25. Drouin JM, Arnold BL, Gansneder BM. Active knee joint velocity replication measures are stable and accurate in healthy individuals. Somatosens Mot Res. 2003; 20: 281-287.

26. Refshauge KM, Chan R, Taylor JL, McCloskey DI. Detection of movements imposed on human hip, knee, ankle and toe joints. J Physiol. 1995; 488: 231-241.

27. Docherty CL, Arnold BL, Zinder SM, Granata K, Gansneder BM. Relationship between two proprioceptive measures and stiffness at the ankle. J Electromyogr Kinesiol. 2004; 14: 317-324.

28. Morgan DL. Separation of active and passive components of short-range stiffness of muscle. Am J Physiol. 1977; 232: 45-49.

29. Li L, Ji ZQ, Li YX, Liu WT1. Correlation study of knee joint proprioception test results using common test methods. J Phys Ther Sci. 2016; 28: 478-482.

30. Grob KR, Kuster MS, Higgins SA, Lloyd DG, Yata H. Lack of correlation between different measurements of proprioception in the knee. J Bone Joint Surg Br. 2002; 84: 614-618.

31. de Jong A, Kilbreath SL, Refshauge KM, Adams R. Performance in different proprioceptive tests does not correlate in ankles with recurrent sprain. Arch Phys Med Rehabil. 2005; 86: 2101-2105.

32. Drouin JM, Valovich-mcLeod TC, Shultz SJ, Gansneder BM, Perrin DH. Reliability and validity of the Biodex system 3 pro isokinetic dynamometer velocity, torque and position measurements. Eur J Appl Physiol. 2004; 91: 22-29.

33. Wojtys EM, Huston LJ, Taylor PD, Bastian SD. Neuromuscular adaptations in isokinetic, isotonic, and agility training programs. Am J Sports Med. 1996; 24: 187-192.

34. Horch KW, Clark FJ, Burgess PR. Awareness of knee joint angle under static conditions. J Neurophysiol. 1975; 38: 1436-1447.

35. McCloskey DI. Kinesthetic sensibility. Physiol Rev. 1978; 58: 763-820.

36. Barrack RL, Skinner HB, Cook SD. Proprioception of the knee joint. Paradoxical effect of training. Am J Phys Med. 1984; 63: 175-181.

37. Proske U, Gandevia SC. The proprioceptive senses: their roles in signaling body shape, body position and movement, and muscle force. Physiol Rev. 2012; 92: 1651-1697.

38. Beynnon BD, Renstrom P, Konradsen L, Elmqvist LG, Gottlieb D, Dirks M. Validation of techniques to measure knee proprioception. In: Lephart SM, Fu FH, editors. Proprioception and neuromuscular control in joint stability. Champaign, IL: Human Kinetics. 2000; 127-138.

39. Nagai T, Sell TC, Nakagawa T, Myers JB, Fu FH, Lephart SM. Feasibility of knee flexion/extension proprioception assessments in a clinical setting. National Athletic Trainers Association Annual Meeting and Clinical Symposia, Anaheim, CA. 2007; 26-30.

Copyright © Nagai T.This book chapter is open access distributed under the Creative Commons Attribution 4.0 International License, which allows users to download, copy and build upon published articles even for commercial purposes, as long as the author and publisher are properly credited.

40. Ozenci AM, Inanmaz E, Ozcanli H, Soyuncu Y, Samanci N, Dagseven T, et al. Proprioceptive comparison of allograft and autograft anterior cruciate ligament reconstructions. Knee Surg Sports Traumatol Arthrosc. 2007; 15: 1432-1437.

41. Jami L. Golgi tendon organs in mammalian skeletal muscle: functional properties and central actions. Physiol Rev. 1992; 72: 623-666.

42. Torres R, Vasques J, Duarte JA, Cabri JM. Knee proprioception after exercise-induced muscle damage. Int J Sports Med. 2010; 31: 410-415.

43. Allison KF, Sell TC, Benjaminse A, Lephart SM. Force Sense of the Knee Not Affected by Fatiguing the Knee Extensors and Flexors. J Sport Rehabil. 2016; 25: 155-163.

44. Docherty CL, Arnold BL. Force sense deficits in functionally unstable ankles. J Orthop Res. 2008; 26: 1489-1493.

45. Westlake KP, Wu Y, Culham EG. Velocity discrimination: reliability and construct validity in older adults. Hum Mov Sci. 2007; 26: 443-456.

46. Pedersen J, Lönn J, Hellström F, Djupsjöbacka M, Johansson H. Localized muscle fatigue decreases the acuity of the movement sense in the human shoulder. Med Sci Sports Exerc. 1999; 31: 1047-1052.

Copyright © Nagai T.This book chapter is open access distributed under the Creative Commons Attribution 4.0 International License, which allows users to download, copy and build upon published articles even for commercial purposes, as long as the author and publisher are properly credited.