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SENSITIVITY AND REPEATABILITY OF THE KNEE TORQUE AND ANGLE ACTIVE TRACKING TASKS

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ABSTRACT

The aim of our study was to test sensitivity and repeatability of torque and angle active tracking tasks at the knee joint and to compare the results of these two tests with one another. Twenty-four healthy young volunteers participated in the study (age 23.2 ± 2.16 years). Each subject performed two active tracking tasks: knee torque tracking task (KTT) and knee angle tracking task (KAT) – three 60-second repetitions each task. The reference signal which the subject tried to follow via visual feedback was a cyclically repeating sinusoidal curve (0.25 Hz cycle frequency) with the normalized amplitude (10-90 % active range of motion for KAT and 30-60 % maximal voluntary torque for KTT). For both, KAT and KTT, low repeatability was observed for a single repetition test design, while the repeatability increases to reasonably good when using the three repetitions average as a measure (intra-class correlation coefficient 0.822 and 0.806 for KAT and KTT, respectively). The presence of statistically significant differences (t-test, $p < 0.001$) and the low correlation determination ($R^2 = 0.137$) between KAT and KTT suggests that these two tests measure two separate sensory-motor skills and rely on different underlying sensory sub-systems. We strongly believe that the active tracking methods can become a useful tool for sensory-motor function assessment in clinical and research work. However, in order to gain the best possible metric characteristics of these methods and to diminish the learning effect, additional research efforts are needed.

Keywords: motor control, diagnostics, sensory-motor integration, testing, feedback

OBČUTLJIVOST IN PONOVLJIVOST METOD AKTIVNEGA SLEDENJA KOTA IN NAVORA V KOLENSKEM SKLEPU

IZVLEČEK

Namen naše raziskave je bil preveriti občutljivost in ponovljivost metod aktivnega sledenja kota in navora v kolenskem sklepu ter primerjati rezultata obeh merilnih metod. V raziskavi je sodelovalo štiriindvajset mladih zdravih oseb (starost 23,2 ± 2,16 let). Vsak merjenec je izvedel dve nalogi aktivnega sledenja: slednje kota v kolenu (KAT) in sledenje navora v kolenu (KTT) – po tri 60-sekundne ponovitve vsake naloge. Referenčni signal, ki ga je moral slediti se je ciklično ponavljal in je imel sinusno obliko (frekvenca cikla 0,25 Hz) in normalizirano amplitudo (10-90 % aktivnega obsega giba za KAT in 30-60 % največjega zavestnega navora za KTT). Za oba testa so rezultati pokazali nizko stopnjo ponovljivosti pri uporabi enkratne ponovitve, medtem ko se je leta povzpela na zadovoljivo raven z uporabo povprečja treh zaporednih ponovitev (koeficient intra-klasne korelacije 0,822 in 0,806 za KAT oziroma KTT). Statistično značilne razlike (t-test, $p < 0,001$) in nizka korelacija ($R^2 = 0,137$) med KAT in KTT kažejo, da z izbranima dvema testoma merimo različni gibalni veščini, ki temeljita na različnih senzoričnih podsistemih. Verjamemo, da metode aktivnega sledenja lahko postanejo koristne za vrednotenje senzorično-motoričnih funkcij v kliničnem in raziskovalnem delu. Da bi dosegli čim boljše merske značilnosti teh metod in zmanjšali učinek učenja, pa bodo potrebni dodatni raziskovalni napori.

Ključne besede: motorična kontrola, diagnostika, senzorično-motorična integracija, testiranje, povratna zanka

INTRODUCTION

Awareness of body movement and position can be subdivided into four basic senses: (i) kinesthesia, (ii) sense of muscle tension, (iii) sense of effort with which muscle work is performed, and (iv) sense of body balance (Proske, 2006). Afferent sensory information derived from receptors throughout the body (Lephart, Reimann, & Fu, 2000) travel to the central nervous system where perception takes place. According to the sensory signaling, appropriate motor responses are prepared at different levels of the central nervous system. Body movement and position senses are directly linked with the function of the sensory-motor system.

Especially in medicine and rehabilitation, different methods have been used to assess sensory-motor function and specific senses respectively. Among others (Guskiewic, 2003; Patten, Kothari, Whitney, Lexell, & Lum, 2003; Wikstrom, Tilman, Chmielewski, & Borsa, 2006), force and angle active tracking methods (ATM) have been widely used in the rehabilitation of neurological diseases and screening of the level of motor control and learning impairment (Chung, Cho, & Lee, 2006; Kurillo, Zupan, & Bajd, 2004; Kriz, Hermsdorfer, Marquardt, & Mai, 1995). Most often, ATM were applied to hand grip strength measuring devices (Kurillo et al., 2004). To a lesser extent other applications are described, such as tracking more functional activities like squatting, stair stepping etc. (Maffiuletti, Bizzini, Schatt, & Munzinger, 2005; Patten et al., 2003).

To our knowledge, no ATM studies have applied this assessment tool to the screening and diagnostics of the locomotor system in rehabilitation and injury prevention protocols. However, soft tissue trauma usually accompanies damage to the proprioceptive sensory system (Johansson, Sjolander, & Sojka, 1991; Myers, Wassinger, & Lephart, 2006). Sensory reweighing takes place, replacing the loss with the available non-damaged sensors, in order to compensate for the loss (Johansson et al., 1991; Schwegart & Mergner, 2008). Sometimes injury adaptations persist which can cause permanent insufficiencies, possibly resulting in inappropriate movement reorganization (Podraza & White, 2010). From this perspective, the use of ATM in sport science and practice has a potential in diagnostics and evaluation, especially in the context of the prevention and rehabilitation protocols.

Using ATM in circumstances where the activity of specific sensory systems is stressed, the function of the above mentioned senses can be assessed in more detail. By measuring the capability to accurately sense and control movement with relatively low force involvement, the sensory-motor integration, which is based on joint and skin receptors, can be pronounced. On the other hand, the function of muscle force and effort sensors can be assessed by ATM which requires force modulation in the absence of the movement.

If we would like to use the ATM in the science and practice of kinesiology and sports medicine, it is important to thoroughly understand the metric characteristics of these methods. Because of its rich sensory structure, high injury incidence, and crucial role in the diversity of movements, the knee joint should be of special interest in this context. The aim of our study was therefore to test the sensitivity and repeatability of torque and angle active tracking tasks at the knee joint. Additionally, within-task comparison was done.

MATERIALS AND METHODS

Subjects

Twenty-four healthy young volunteers participated in the study (18 males and 6 females; age 23.2 ± 2.16 years; body height 176.2 ± 8.6cm; body weight 73.9 ± 12.3

kg). A history of injuries to the neuro-muscular and/or skeleto-articular systems that could affect measurement results were used as exclusion criteria. The procedure, which was approved by the National Medical Ethics Committee, was explained to all subjects prior to the test and they also signed their written consent.

Motor tasks and study design

Each subject performed two active tracking tasks: knee torque tracking task (KTT) and knee angle tracking task (KAT). Two different mechanical braces were used for KTT and KAT respectively. Seated in an isometric measurement chair (Wise Technologies, Ljubljana, Slovenia), a subject was tracking torque by statically extending their lower leg against a handle (Figure 1A). The torso was supported and hips fixed at 90˚. The axis of the knee joint was aligned with the axis of the handle with the sustained 50° knee flexion (0° representing full extension). The examined leg was fixed to the handle at the distal part of the lower leg. During measurements, a subject was asked to hold the side of the seat with their hands and to sustain contact with the torso support by leaning backward. On-line feedback on knee extensor torque was provided over the computer screen positioned in front of the subject.

When performing KAT a subject was lying sideways, with upper leg positioned horizontally into the brace (Wise Technologies, Ljubljana, Slovenia) in order to minimize the gravitational effect (Figure 1B). To ensure a comfortable position, the torso was supported enabling a good view of the feedback screen. The axes of the knee and that of the lever arm were aligned. The thigh and shin were additionally fixed with foam to prevent any discrepancies in axes positioning during movement and to additionally limit cutaneus sensory stimulation. The other leg was comfortably positioned in front

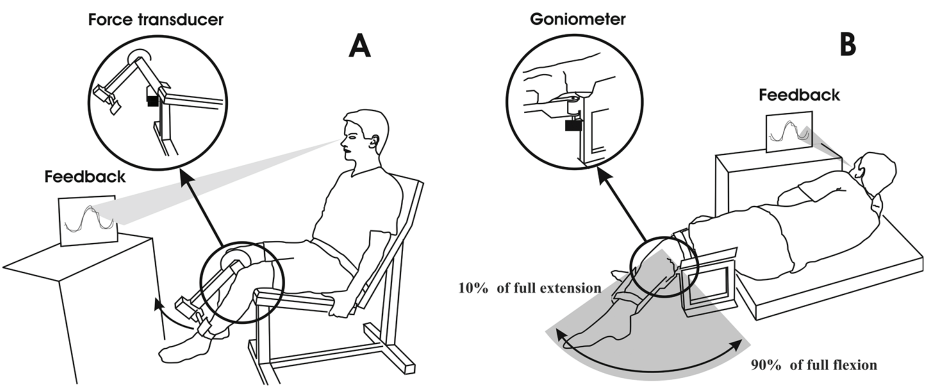

Figure 1: Force tracking was measured in specially designed measurement chair (A), and angle tracking with leg positioned into the brace by lying sideways (B).

of the brace. An electronic goniometer was embadded in the axis of the brace in order to measure the knee angle in real time.

Both tracking tasks were carried out unilaterally using the dominant leg. Before the start of the main measurements, maximal voluntary contractions of knee extensors and maximal active range of motion at the knee were acquired for normalization reasons. This was followed by three 20-second trials of each task to become familiar with the measurement method. On a computer screen, two signals were displayed: the preprogrammed "reference signal" (RS) and the "actual signal" (AS) acquired from the torque and angle sensor, respectively. The goal was to follow the RS with the AS as accurately as possible. The movement of the AS was possible by isometricaly contracting or relaxing knee extensors (KTT) or by actively flexing and extending the knee (KAT). The RS signal had a fixed frequency of 0.25 Hz, sinusoidal shape, and normalized amplitude. The latter was set at 30 % to 60 % of the maximal torque and at 10 % to 90 % of the maximal active range of motion for KTT and KAT, respectively.

For the main measurements, each subject performed each task (KTT and KAT) three times for 60 seconds. In order to avoid the development of fatigue, a subject performed all the repetitions of the KAT first and then moved to KTT as the second task. Four-minute breaks were used between trials to additionally minimize fatigue effects.

Data processing and statistical analysis

Signals from the electronic torque and angle sensors, respectively, were acquired with 1000 Hz sampling rate and stored on the computer for later analysis. Custom designed software (LabVIEW, Natinal Instruments, USA) was used to process the acquired signal. Root mean square (RMS) was computed for the difference between RS and AS. By expressing RMS relative to RS's amplitude and time, normalized amplitude (NA) was computed enabling comparison between different subjects (Equation 1). Only 50 seconds of the signal were processed excluding first 8 and last 2 seconds.

Equation 1: Equation used to calculate NA. RMS was computed by summing all differences between RS (F1) and AS (F2) values. RMS was then divided by RS amplitude (aF1) and duration of acquired signal (t).

$$NA = \left[\sqrt{\sum (F1 - F2)^2} \,/\, aF1 \right] / \, t$$

The calculated parameters were analysed with statistical software (SPSS 17.0, IBM, New York, USA). Descriptive statistics were calculated for single trials and averages. For intra-visit repeatability, we used two complementary approaches; intra-class correlation coefficient (ICC) and additionally mean error (ME) and typical error (TE) of the measurement. ICC was separately analysed for single (ICC(1,1)) and averages of two (ICC(1,2)) and three repetitions (ICC(1,3)) of the same task. According to Shrout and Fleiss (1979) ICC can be defined as high (> 0.90), medium (0.80 – 0.90) or low (< 0.80). To analyse the differences and inter-connections between the KTT and KAT a paired t-test and Pearson correlation determination coefficient (R^2) were used. These two analyses were done on averaged NAs of the three repetitions of the same task. To check for potential fatigue development in the case of KTT, the first and last 25 seconds were also separately analysed and the average of the three repetitions used for paired t-test analysis of statistical significance. The level of statistical significance for all tests was set at $p \leq 0.05$.

RESULTS

Results of basic statistics are presented in Table 1. Absolute values of NA for KAT and KTT are about the same, while KTT-NA shows slightly stronger measures of central tendency (average range 2.26 vs. 1.97 and average normalized standard deviation 21.5 % vs. 17.6 %).

Table 1: Descreptive statistics for KAT-NA and KTT-NA including mean values ($\bar{X}$), standard deviations (S.D.), minimum (MIN), and maximum (MAX) values. For both the tests single repetition values (R_1, R_2, and R_3) as well as average of the first two repetitions (AVG_{R12}) and all three repetitions (AVG_{R13}) respectively, are presented.

	KAT-NA					KTT-NA				
	R_1	R_2	R_3	AVG_{R12}	AVG_{R13}	R_1	R_2	R_3	AVG_{R12}	AVG_{R13}
	2.65	2.33	2.15	2.49	2.38	2.89	2.94	2.95	2.92	2.94
S.D.	0.66	0.52	0.51	0.55	0.51	0.59	0.47	0.68	0.48	0.52
MIN	1.61	1.25	1.21	1.43	1.42	1.96	2.05	1.86	2.01	1.96
MAX	4.22	3.36	3.62	3.71	3.68	3.82	3.70	4.65	3.73	3.92

The results of the repeatability analyses are shown in Table 2. ICC, ME, and TE were in the same range for both used ATM. Low repeatability was observed for a single repetition test design, while it increases with the average of two repetitions, and it gains values considered reasonably good when the average of three 60-second repetitions are used (ICC(1,3) is 0.822 and 0.806 for KAT-NA and KTT-NA, respectively). ME and TE values additionally support the acceptable level of repeatability for both motor tasks when using the average of three repetitions.

Table 2: Repeatability measures for KAT-NA and KTT-NA including ICC for single (ICC(1,1)), average of two (ICC(1,2)) and average of three (ICC(1,3)) repetitions, mean error (ME), and typical error (TE), respectively.

	ICC(1,1)	ICC(1,2)	ICC(1,3)	ME	TE
KAT-NA	0.607	0.765	0.822	0.232	0.141
KTT-NA	0.592	0.726	0.806	0.209	0.163

Statistically significant differences were observed when comparing NA values for KAT and KTT (t-test, $p < 0.001$). This data is additionally supported by a very low and not statistically significant correlation coefficient (Figure 2).

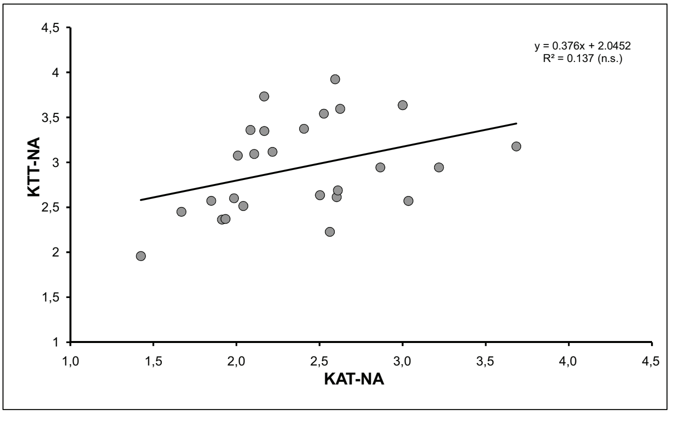

Figure 2: Correlation between KTT and KAT results. Each dot represent one subject. The equation for the fitted linear function and the Pearson correlation determination coefficient (R^2) are presented in the top right corner.

Timewise, a comparison of the first and the second half of the KTT showed no statistically significant differences (t-test, $p = 0.479$), suggesting no presence of fatigue effect.

DISCUSSION

The purpose of this study was to test repeatability of two ATMs at the knee joint, the first being joint position tracking and the second joint extension torque tracking. Furthermore, we tested the hypothesis that KAT and KTT measure two different entities related to the sensory-motor control. Results of our study confirmed the hypothesis since statistically significant differences were present between KAT-NA and KTT-NA (p <

0.001) and the correlation determination between the two was very low ($R^2 = 0.137$). The results of repeatability analyses pointed out that both ATMs gain higher repeatability (ICC = 0.822 and 0.806 for KAT-NA and KTT-NA, respectively) if the amplitude and time-normalized values, calculated as three repetitions average, were observed.

The knee joint is one of the most complex joints in the human body, regarding its structure, the related sensory-motor function as well as traumatic and overuse injuries. In daily activities, it primarily operates in closed kinetic chain movements (support phase of gait, squats, jumps, etc.). However, in sports specific movements the open kinetic chain movement patterns are also represented, especially through dynamic kicks. The multiple function of the knee makes this body region one of the most prone to injuries (Atanda, Reddy, Rice, & Terry, 2009; Brophy, Silvers, & Mandelbaum, 2010; Prodromos, Han, Rogowski, Jayce, & Shi, 2007). Injuries at the knee joint result in structural malformations which are addressed either surgically or conservatively and are almost always accompanied by changed/deprived sensory-motor control of movement (Ingersoll, Gridstaff, Pietrosimone, & Hart, 2008; Palmieri-Smith, & Thomas, 2009). Today's rehabilitation protocols therefore address this issue with special attention integrating the proprioceptive exercises as a part of the kinesioterapeutic routine (Grodski, & Marks, 2008; Myer, Paterno, Ford, & Hewett, 2008). However, a good, reliable, sensitive and repeatable tool for well quantified differential evaluation of the knee sensory-motor control is missing in clinical practice. On the other hand, strength, power, and complex balance testing (Chiari, Rocchi, & Cappello, 2002; Pua, Bryant, Steele, Newton, & Wrigley, 2008; Rocchi, Chiari, & Cappello, 2004) have already become a part of that routine. We believe that ATM represent a promising way to cover this missing gap in the physiatrics, ortophaedics, and physioteraphy clinical practice.

Sensory-motor function of the knee joint is very reach and when interpreting the results of ATM one should consider the multi-source nature of the sensory inflow. The sense of body position and movement known as kinaesthesia primarily depends on information from peripheral proprioceptors and vision (Proske, 2005). Peripheral proprioceptors are located in muscles, tendons, ligaments, joint capsules, menisci and skin (Johansson, Pedersen, Bergenheim, & Djupsjobacka, 2000; Solomonow, 2006). These receptors are sensitive to specific mechanical stimuli. Skin receptors contribute information on compression and stretching of the skin (Johansson et al., 1991; Rudomin, 2002). Joint receptors contribute information such as onset of movement, acceleration, tension and compression (Solomonow, 2006). The musculo-tendinous system hosts two other important proprioceptors. Muscle spindle is located besides individual muscle fibers, and provides information on muscle length and velocity of muscle stretching/shortening (Proske & Gandevia, 2009). The Golgi tendon organ on the other hand, senses tension in ligaments resulting from muscle contraction or extrinsic forces. Sense of effort and tension on the other hand depends on previously described muscle and tendon sensors as well as on a centrally produced sense of effort (Sanes & Shadmehr, 1995). From the explained sensory populations involved in the active tracking tasks we can easily hypothesise that KAT should primarily involve position sensors (joint-, capsule-, skin-, and muscle length sensors), while KTT should involve force sensors (Golgi tendon organ, sense of effort) to a greater extent.

Our preliminary studies showed that a sine-shaped RS with the speed of one cycle per four seconds (0.25 Hz) has better repeatability characteristics than other shapes (triangular, rectangular, trapezoid) and faster speeds (1 Hz or 0.5 Hz) of the RS. We used these data in order to optimize KAT and KTT metric characteristics, needed to make comparisons between these two feedback regulated tasks. However, it is difficult to exclude the involvement of feed-forward control (Nielsen, 2004), while the cyclic nature of the RS implicates also the anticipation of the required ongoing movement. The latter is especially true for RS signals with cycle durations of only 1 to 2 seconds and therefore we were not able to use them in the evaluation of the sensory-motor function (Schmidt & Lee, 1999). Using the "randomized" RS shape and dynamics could be a promising way to minimize anticipation and learning effect while gaining the sensitivity of the method.

The repeatability of KAT and KTT in the knee joint was medium high in our testing. The majority of studies (Carrey, Anderson, Kimberly, Lewis, Auerbach, & Uguribil, 2004; Carey, Patterson, & Hollenstein, 1988; Maffiuletti et al., 2005; Patten et al., 2003) only tested the repeatability with the use of ICC, which has shown the method to have high repeatability. Contrary to ours, the majority of other studies also measured tracking accuracy on distal parts of upper extremities, which are known for high levels of cortical innervation which results in high motion accuracy. Despite medium-high repeatability, our study proved that tracking test results improved during repeats at later visits.

In our preliminary study (Rosker, Kalc, & Šarabon, in press) we have shown that among cyclic-patterned RSs (ramp, triangular, and sinusoidal) sinusoidal shape has the highest repeatability, however, there is no difference in their sensitivity. This was also the reason why the sinusoidal RS was used in the current study, meaning that lower inter- and intra-visit ICC values would be expected if we would do the same study with the other shapes of the RS. Furthermore, a random-shaped RS is another possibility which could help further improve the ATMs, since the preliminary results (Rosker & Sarabon, 2010) suggest comparable repeatability, but higher sensitivity and diminished learning effect.

Understanding the biomechanics of the knee joint is of crucial importance for designing injury prevention and rehabilitation protocols (Englund, 2010). In this context, its function is strongly dependent on the function of the neighbouring joints (Reiman, Bolgla, & Lorenz, 2009) and therefore represents an important linking part of the lower extremity, positioned between the hip and ankle. We should bear in mind these functional characteristics in the future development of the ATM for the lower extremity assessment. We believe that a combination of single joint and multi joint active tracking tasks in force and angle tracking domain could be a promising approach with high practical relevance.

Until recently, the tracking method was only used for monitoring and evaluating motion control in healthy people and people with neurological defects. However, it has become increasingly more popular as a therapeutic aid, especially in the treatment of neurological cases (Carrey, Kimberley, Lewis, Auerbach, Dorsey, Rundquist, & Uguribil, 2002; Cho, Shin, Kwon, Lee, Lee, Lee et al., 2007; Chung et al., 2006). It was discovered that practice involving tracking methods also improves the kinaesthetic feeling in individual joints (Kriz et al., 1995). Based on the above, we can conclude that ATM will be further developed and used, both in research (studies of motor control, motor learning, etc.) and in practical activities in sports and rehabilitation (evaluating effects of training and other interventions, kinesthetics and coordination practice, joint control re-education in post-traumatic and post-surgery states, etc.).

CONCLUSION

From the results of this study we can draw a conclusion that KAT and KTT tests are sensitive to detecting inter-individual differences. It is important to point out that the repeatability of both methods were sufficient only when averaging three consecutive repetitions, while the single repetition ICC values were low. From the significant differences between the KAT-NA and KTT-NA and the low correlation between the two we can hypothesise that these two tasks involve different sensory sub-systems as a predominant somatosensory feedback. We strongly believe that the active tracking methods can become a useful tool for sensory-motor function assessment in clinical and research work. However, in order to improve the metric characteristics of these methods and to diminish the learning effect, additional studies are needed.

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REFERENCES

Atanda, A., Reddy, D., Rice, J. A., & Terry, M. A. (2009). Injuries and chronic conditions of the knee in young athletes. Pediatrics in Review/American Academy of Pediatrics, 30(11), 419–28.

Brophy, R. H., Silvers, H. J., & Mandelbaum, B. R. (2010). Anterior cruciate ligament injuries: etiology and prevention. Sports Medicine and Arthroscopy Review, 18(1), 2–11.

Carrey, J. R., Anderson, K. M., Kimberly, T. J., Lewis, S. M., Auerbach, E. J., & Ugurbil, K. (2004). fMRI analysis of ankle movement tracking training in subjects with stroke. Experimental Brain Research, 154(3), 281–290.

Carrey, J. R., Kimberley, T. J., Lewis, S. M., Auerbach, E. J., Dorsey, L., Rundquist, P., et al. (2002). Analysis of fMRI and finger tracking training in subjects with chronic stroke. Brain: A Journal of Neurology. 125(4), 773–788.

Carrey, J. R., Patterson, R., & Hollenstein, P. J. (1988). Sensitivity and reliability of force tracking and joint-movement tracking scores in healthy subjects. Physical Therapy, 68(7), 1087–1091.

Chiari, L., Rocchi, L., & Cappello, A. (2002). Stabilometric parameters are affected by anthropometry and foot placement. Clinical Biomechanics, 17, 666–677.

Cho, S., Shin, H., Kwon, Y., Lee, M. Y., Lee, Y., Lee, C., et al. (2007). Cortical activation changes induced by visual biofeedback tracking training in chronic stroke patients. Neuro Rehabilitation, 22(2), 77–84.

Chung, Y., Cho, S. H., & Lee, Y. H. (2006). Effect of the knee joint tracking training in closed kinetic chain condition for stroke patients. Restorative Neurology and Neuroscience, 24(3), 173–180.

Englund, M. (2010). The role of biomechanics in the initiation and progression of OA of the knee. Best Practice & Research Clinical Rheumatology, 24(1), 39–46.

Grodski, M., & Marks, R. (2008). Exercises following anterior cruciate ligament reconstructive surgery: biomechanical considerations and efficacy of current approaches. Research in Sports Medicine, 16(2), 75–96.

Guskiewicz, K. M. (2003). Assessment of postural stability following sport-related concussion. Current Sports Medicine Reports, 2(1), 24–30.

Ingersoll, C. D., Grindstaff, T. L., Pietrosimone, B. G., & Hart, J. M. (2008). Neuromuscular consequences of anterior cruciate ligament injury. Clinical Sports Medicine, 27(3), 383–404.

Johansson, H., Pedersen, J., Bergenheim, M., & Djupsjobacka, M. (2000). Peripheral afferents of the knee: Their effects on central mechanisms regulating muscle stiffness, joint stability, and proprioception and coordination. In S.M. Lephart, & F.H., Fu. (editors), Proprioception and neuromuscular control in joint stability (5–23). Champaign, Human Kinetics.

Johansson, H., Sjölander, P., & Sojka, P. (1991). Receptors in the knee joint ligaments and their role in the biomechanics of the joint. Critical Reviews in Biomedical Engineering, 18(5), 341–368.

Kriz, G., Hermsdörfer, J., Marquardt, C., & Mai, N. (1995). Feedback-based training of grip force control in patients with brain damage. Archives of Physical Medicine and Rehabilitation, 76(7), 653–9.

Kurillo, G., Zupan, A., & Bajd, T. (2004). Force tracking system for the assessment of grip force control in patients with neuromuscular diseases. Clinical Biomechanics, 19(10), 1014–1021.

Lephart, S. M., Reiman, B. L.. & Fu, F. H. (2000). Introduction to the sensorimotor system. In S.M. Lephart, & F. H., Fu. (editors), Proprioception and neuromuscular control in joint stability (XVII-XXIV). Champaigh: Human Kinetics.

Maffiulettii, N., Bizzini, M., Schatt, S., & Munzinger, U. (2005). A multi-joint lower-limb tracking trajectory test for the assessment of motor coordination. Neuroscience Letters, 384, 106–111.

Myer, G. D., Paterno, M. V., Ford, K. R., & Hewett, T. E. (2008). Neuromuscular training techniques to target deficits before return to sport after anterior cruciate ligament reconstruction. The Journal of Strength & Conditioning Research, 22(3), 987–1014.

Myers, J. B., Wassinger, C. A., & Lephart, S. M. (2006). Sensorimotor contribution to shoulder stability: effect of injury and rehabilitation. Manual Therapy, 11(3), 197–201.

Nielsen, J. B. (2004). Sensorimotor integration at spinal level as a basis for muscle coordination during voluntary movement in humans. Journal of Applied Physiology, 96(5), 1961–1967.

Palmieri-Smith, R. M., & Thomas, A. C. (2009). A neuromuscular mechanism of posttraumatic osteoarthritis associated with ACL injury. Exercise and Sports Sciences Reviews, 37(3), 147–153.

Patten, C., Kothari, D., Whitney, J., Lexell, J., & Lum, P. S. (2003). Reliability and responsiveness of elbow trajectory tracking in chronic poststroke hemiparesis. Journal of Rehabilitation Research and Development, 40(6), 487–500.

Podraza, J. T., & White, S. C. (2010). Effect of knee flexion angle on ground reaction forces, knee moments and muscle co-contraction during and impact like deceleration landing: implications for the non-contact mechanism of ACL njury. The Knee, 17(4), 291–295.

Proske, U. (2006). Kinesthesia: the role of muscle receptors. Muscle & Nerve, 34(5), 545–558.

Proske, U., & Gandevia, S. C. (2009). The kinaesthetic senses. The Journal of Physiology, 587, 4139–4146.

Prodromos, C. C., Han, Y., Rogowski, J., Joyce, B., & Shi, K. (2007). A meta-analysis of the incidence of anterior cruciate ligament tears as a function of gender, sport, and a knee injury-reduction regimen. Arthroscopy, 23(12), 1320–1325.

Pua, Y. H., Bryant, A. L., Steele, J. R., Newton, R. U., & Wrigley, T. V. (2008). Isokinetic dynamometry in anterior cruciate ligamentinjury and reconstruction. Annales of the Academy of Medicine, 37(4), 330–340.

Reiman, M. P., Bolgla, L. A., & Lorenz, D. (2009). Hip functions influence on knee dysfunction: a proximal link to a distal problem. Journal of Sports Rehabilitation, 18(1), 33–46.

Rocchi, L., Chiari, L., & Cappello, A. (2004). Feature selection of stabilometric parameters based on principal component analysis. Medical & Biological Engineering & Computing, 42, 71–79.

Rosker, J., Kalc, M., & Sarabon, N. (in press). An attempt to optimise the active knee angle tracking test while using a cyclic movement pattern. Kinesiologia Slovenica.

Rosker, J., & Sarabon, N. (2010). Introduction of the random curve to joint angle tracking tests. In: Sport science: where the cultures meet (p. 230–231). Köln: European College of Sport Science.

Rudomin, P. (2002). Selectivity of the central control of sensory information in the mammalian spinal cord. Advances in Experimental Medicine and Biology, 508, 157–170.

Sanes, J. N., & Shadmer, R. (1995). Sense of muscular effort and somasthetic afferent information in humans. Canadian Journal of Physiology and Pharmacology, 73(2), 223–233.

Schmidt, R. A., & Lee, T. D. (1999). Motor control and learning: a behavioral emphasis. Champaign (IL): Human Kinetics.

Schwegart, G., & Mergner, T. (2008). Human stance beyond steady state response and inverted pendulum simplification. Experimental Brain Research, 185, 635–653.

Shrout, P. E., & Fleiss, J. L. (1979). Intraclass Correlations: Uses in Assessing Rater Reliability. Psycological Bulletin, 86(2), 420–428.

Solomonow, M. (2006). Sensory motor control of ligaments and associated neuromuscular disorders. Journal of Electromyography & Kinesiology, 16(6), 549–567.

Wikstrom, E. A., Tillman, M. D., Chmielewski, T. L., & Borsa, P. A. (2006). Measurement and evaluation of dynamic joint stability of the knee and ankle after injury. Sports Medicine, 36(5), 393–410.