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Original research

Reliability and measurement precision of concentric-to-isometric and eccentric-to-isometric knee active joint position sense tests in uninjured physically active adults

Nicholas C. Clark [a, b, *], Jonathan S. Akins [c], Nicholas R. Heebner [a], Timothy C. Sell [a], John P. Abt [a], Mita Lovalekar [a], Scott M. Lephart [d]

[a] Neuromuscular Research Laboratory, School of Health and Rehabilitation Sciences, University of Pittsburgh, 3830 South Water Street, Pittsburgh, PA 15203, United States
[b] School of Sport, Health and Applied Science, St Mary's University, Waldegrave Road, Strawberry Hill, Twickenham, London, TW1 4SX, United Kingdom
[c] Department of Rehabilitation Science and Technology, School of Health and Rehabilitation Sciences, University of Pittsburgh, Suite 5044, Forbes Tower, Pittsburgh, PA 15260, United States
[d] College of Health Sciences, University of Kentucky, 900 South Limestone Street, Lexington, KY 40508, United States

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A B S T R A C T

Objectives: Proprioception is important because it is used by the central nervous system to mediate muscle control of joint stability, posture, and movement. Knee active joint position sense (AJPS) is one representation of knee proprioception. The purpose of this study was to establish the intra-tester, inter-session, test–retest reliability of concentric-to-isometric (seated knee extension; prone knee flexion) and eccentric-to-isometric (seated knee flexion; prone knee extension) knee AJPS tests in uninjured adults.
Design: Descriptive.
Setting: University laboratory.
Participants: Six males, six females (age 26.2 ± 5.7 years; height 171.1 ± 9.6 cm; mass 71.1 ± 16.6 kg).
Main Outcome Measures: Mean absolute error (AE; °); intraclass correlation coefficient (ICC) (2,1); standard error of measurement (SEM; °).
Results: Mean AE ranged from 3.18° to 5.97° across tests. The ICCs and SEMs were: seated knee extension 0.13, 1.3°; prone knee flexion 0.51, 1.2°; seated knee flexion 0.31, 1.7°; prone knee extension 0.87, 1.4°.
Conclusions: The prone knee flexion and prone knee extension tests demonstrated moderate to good reliability. Prone knee flexion and prone knee extension AJPS tests may be useful in cross-sectional studies estimating how proprioception contributes to knee functional joint stability or prospective studies estimating the role of proprioception in the onset of knee injury.

1. Introduction

Proprioception is defined as the sense of joint position (joint position sense (JPS)) and joint movement (kinesthesia) (Martin & Jessell, 1991; Riemann & Lephart, 2002), and results from mechanoreceptor stimulation in joint and muscle tissues (Kandel, 2013; Martin & Jessell, 1991). Proprioceptive input to the central nervous system (CNS) influences muscle activity at all three levels of sensorimotor control (spinal cord, brainstem, cerebral cortex), and is used by the CNS to mediate skeletal muscle control of joint stability, posture, and movement (Ghez, 1991; Lephart, Pincivero, Giraldo, & Fu, 1997). With regard to the knee, injury can result in destruction of mechanoreceptors (Bali, Dhillon, Vasistha, Kakkar, Chana, & Prabhakar, 2012). Loss of mechanoreceptors after knee injury is associated with impaired joint-muscle reflexes and abnormal movement patterns (Beard, Kyberd, O'Connor, Fergusson, & Dodd, 1994; Houck, De Haven, & Maloney, 2007; Wojtys & Huston, 1994). Consequently, authors have described how impaired proprioception is a potential contributing factor to first-time joint injury, repetitive joint injury, and the onset and progression of osteoarthrosis (OA) (Borsa, Sauers, & Lephart, 1999; Felson et al., 2009; Hurley, 1997; Roos, Herzog, Block, & Bennell, 2011; Segal

* Corresponding author. School of Sport, Health and Applied Science, St Mary's University, Waldegrave Road, Strawberry Hill, Twickenham, London, TW1 4SX, United Kingdom. Tel.: +44 (0) 20 8240 8246.
E-mail address: nicholas.clark@stmarys.ac.uk (N.C. Clark).

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et al., 2010). Therefore, because impaired proprioception is described as resulting in a potentially greater risk of joint trauma and subsequent OA, measurement of knee proprioception is clinically important.

Proprioception measurements can be performed under passive and active conditions, corresponding to where skeletal muscle is inactive and active, respectively. Passive conditions preferentially stimulate joint mechanoreceptors whereas active conditions assess both joint and muscle-tendon mechanoreceptors (Riemann, Myers, & Lephart, 2002). Researchers have employed different operational definitions as methods for studying the multi-component construct of knee proprioception. For example, knee JPS tests have included passive reproduction of passive positioning (PRPP) (Callaghan, Selfe, Bagley, & Oldham, 2002; Callaghan, Selfe, McHenry, & Oldham, 2008; Perlau, Frank, & Fick, 1995), active reproduction of passive positioning (ARPP) (Baker, Bennell, Stillman, Cowan, & Crossley, 2002; Bennell, Wee, Crossley, Stillman, & Hodges, 2005; Fridén, Roberts, Zätterström, Lindstrand, & Moritz, 1996), and active reproduction of active positioning (active JPS (AJPS)) (Callaghan et al., 2002; Callaghan et al., 2008; Drouin, Houglum, Perrin, & Gansneder, 2003). Knee kinesthesia tests have included threshold to detection of passive motion (TTDPM) (Barrack, Skinner, & Buckley, 1989; Borsa, Lephart, Irrgang, Safran, & Fu, 1997; Callaghan et al., 2002). Because tests such as PRPP and TTDPM are performed under conditions where muscle is relaxed, this may explain why passive tests are not strongly associated with measures of knee functional joint stability (e.g. hop tests) (Ageberg & Fridén, 2008; Borsa et al., 1997; Fridén, Roberts, Movin, & Wredmark, 1998) or the onset and progression of knee OA (Felson et al., 2009; Hurley, Scott, Rees, & Newham, 1997; Knoop et al., 2011). Passive tests may not be sufficiently functional because they do not stimulate the muscle spindle which is the most sensitive of all mechanoreceptors (Gordon & Ghez, 1991; Rothwell, 1994). Active tests for measuring proprioception may offer a better representation of the construct of knee proprioception under more functional conditions.

Active tests of knee proprioception can employ a variety of different muscle actions. Active tests such as ARPP and AJPS have been performed using concentric-to-isometric quadriceps muscle actions from a defined starting position (e.g. 90° knee flexion) to a predetermined target angle (e.g. 45° knee flexion) (Callaghan et al., 2002; Felson et al., 2009; Hurley et al., 1997), and concentric-to-isometric hamstrings muscle actions also from a defined starting position (e.g. 0° knee flexion) to a predetermined target angle (e.g. 45° knee flexion) (Ghiasi & Akbari, 2007). Concentric-to-isometric tests clearly do not employ eccentric muscle actions which generate the most powerful stimulus for the muscle spindle and are employed when decelerating joint motion and absorbing joint impact forces (Gordon & Ghez, 1991; LaStayo, Woolf, Lewek, Snyder-Mackler, Reich, & Lindstedt, 2003; Rothwell, 1994). Eccentric-to-isometric deceleration of high-velocity knee joint motions is important for limiting excessive joint displacements and preventing traumatic tissue injury (LaStayo et al., 2003). Eccentric-to-isometric absorption of repetitive knee joint impact forces (energy) during walking and running is important for protecting articular surfaces from cumulative shock that can contribute to the onset and progression of joint degeneration (OA) (Lewek, Rudolph, Axe, & Snyder-Mackler, 2002). Few authors have studied AJPS using eccentric-to-isometric quadriceps muscle actions (Drouin et al., 2003), and there appears to be no published reports using eccentric-to-isometric hamstrings muscle actions. Furthermore, recent reviews have concluded that existing tests of knee proprioception are inadequate and lacking in clinical relevance (Gokeler et al., 2011; Knoop et al., 2011). Cross-sectional studies report weak associations between existing tests of knee proprioception and knee functional joint stability defined by single-leg hop test performance (Gokeler et al., 2011). Prospective studies report no association between existing tests of knee proprioception and future onset of knee degeneration defined by x-ray evidence of OA (Knoop et al., 2011). Therefore, existing tests of knee proprioception appear to be failing with regards to usefully characterising proprioception relative to short-term measures of knee functional joint stability, as well as long-term imaging measures of tibiofemoral articular surface integrity which may be important relative to the onset of post-injury secondary OA. New tests of knee proprioception should, consequently, be developed for use in research and clinical practice.

For a new test of knee proprioception to have clinical relevance, researchers and clinicians need to be confident the test yields a meaningful representation of the underlying physiological characteristic. Reliability is a foundation property for measurement procedures, and refers to the ability of a test to generate repeatable and consistent values (Portney & Watkins, 2009). Reliability is a critical prerequisite for measurement validity (Batterham & George, 2003; Portney & Watkins, 2009). Lack of reliability can undermine the validity of raw data and compromise the findings of subsequent statistical modelling. Therefore, before the clinical relevance of a knee proprioception test can be determined, the reliability of the test must first be established. This is the first step in any future research process intended to obtain a cross-sectional estimate regarding the role of proprioception in, for example, knee functional joint stability in uninjured athletes or to prospectively identify the role of knee proprioception in the onset of noncontact trauma or post-injury secondary OA.

The purpose of this study was to establish the intra-tester, inter-session, test–retest reliability of concentric-to-isometric and eccentric-to-isometric knee AJPS tests in uninjured physically active adults. Tests were designed to stimulate muscle proprioceptive apparatus over a range of muscle actions by deliberately exploiting alpha–gamma coactivation and excitation of muscle spindles, along with stimulation of Golgi tendon organs which are specifically sensitive to changes in active muscle tension (Gordon & Ghez, 1991; Rothwell, 1994). Eccentric muscle actions generate the most powerful stimulus for the muscle spindle and are critical for decelerating joint motion (Gordon & Ghez, 1991; LaStayo et al., 2003; Rothwell, 1994). Eccentric-to-isometric tests were specifically intended, therefore, to focus mechanical stimuli on the muscle spindle and simulate the natural sequence of muscle actions observed within neuromuscular strategies for limiting excessive joint displacements (eccentric-to-isometric). We hypothesised that tests would demonstrate good reliability using the intraclass correlation coefficient (ICC) as recommended by previous researchers (Atkinson & Nevill, 1998; Denegar & Ball, 1993). This study's findings have the potential to fill the first and most important gap in information regarding the reliability of new knee proprioception tests.

2. Methods

2.1. Sample size calculation

An *a priori* power analysis for ICC was performed using PASS 11 (NCSS Statistical Software, Utah). Twelve participants were required to achieve 82% power and detect an ICC of 0.90 with significance set at 0.05. To account for possible participant attrition or technical problems, two additional participants were recruited. A total of 14 participants were enrolled.

2.2. Ethical approval, informed consent, and participant recruitment

Ethical approval was obtained from the University's Institutional Review Board. Participants were recruited by flyers posted on the University campus. Informed consent was completed by all participants prior to the study procedures.

2.3. Participant characteristics

Inclusion criteria were: male or female; age 18–40 years; physically active (participation in exercise/sports, ≥3 sessions/week, ≥30 min/session). Benign joint hypermobility syndrome (BJHS) can result in decreased proprioceptive acuity (Sahin, Baskent, Cakmak, Salli, Ugurlu, & Berker, 2008). An exclusion criteria was, therefore, BJHS defined by a Beighton Scale score ≥4/9 (Remvig, Jensen, & Ward, 2007). Other exclusion criteria were: current lower quadrant pain; past knee ligament or meniscus time-loss injury; past lower quadrant fracture or surgery; current or past conditions that affect sensorimotor processing (e.g. diabetes, concussion); skin allergy to adhesive tape. Fourteen participants were recruited (seven males, seven females). However, data were lost for two participants (one male, one female) tested on the same day due to technical problems. Therefore, 12 participants remained as the study sample (male $n = 6$; female $n = 6$; age 26.2 ± 5.7 years; height 171.1 ± 9.6 cm; mass 71.1 ± 16.6 kg).

2.4. Instrumentation

Participants were positioned on a treatment table. An 'H-frame' was constructed (Figs. 1–4): the uprights were formed by PVC pipes inserted into separate wooden bases; the crossbar was formed by elastic tubing stretched between and looped around the uprights. The H-frame functioned as a range-of-motion (ROM) guide when cueing participants to target angles. A Universal Goniometer (Aircast, New Jersey) was used to set target angles. Knee AJPS data were collected using 14 mm diameter reflective markers and the Vicon motion capture system synchronized with eight MX13 infrared cameras (Vicon Motion Systems, Colorado). Cameras were positioned to ensure sagittal plane knee motion was captured. Calibration was performed according to manufacturer guidelines. The Vicon motion capture system has an accuracy of 117 μm (Windolf, Götzen, & Morlock, 2008). Data were sampled at 250 Hz.

2.5. Procedures

Participants attended testing on two days (D1, D2) separated by a minimum of 24 h. Testing was performed in a quiet laboratory

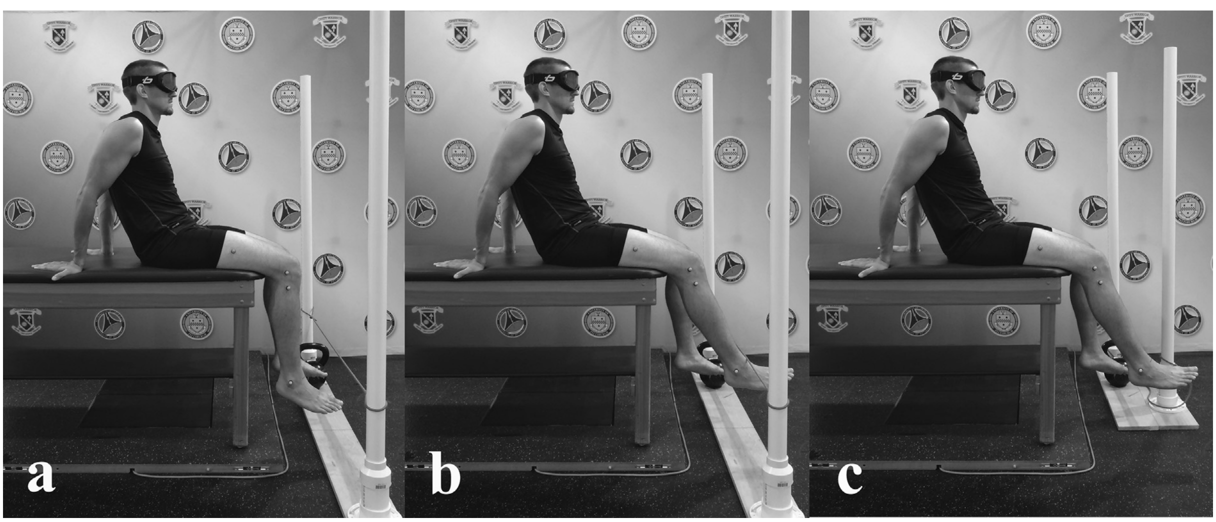

Fig. 1. Seated Knee Extension Test (a. start angle/position; b. target angle trial; c. reproduced angle trial with H-frame upright removed).

Fig. 2. Seated Knee Flexion Test (a. start angle/position; b. target angle trial; c. reproduced angle trial with H-frame upright removed).

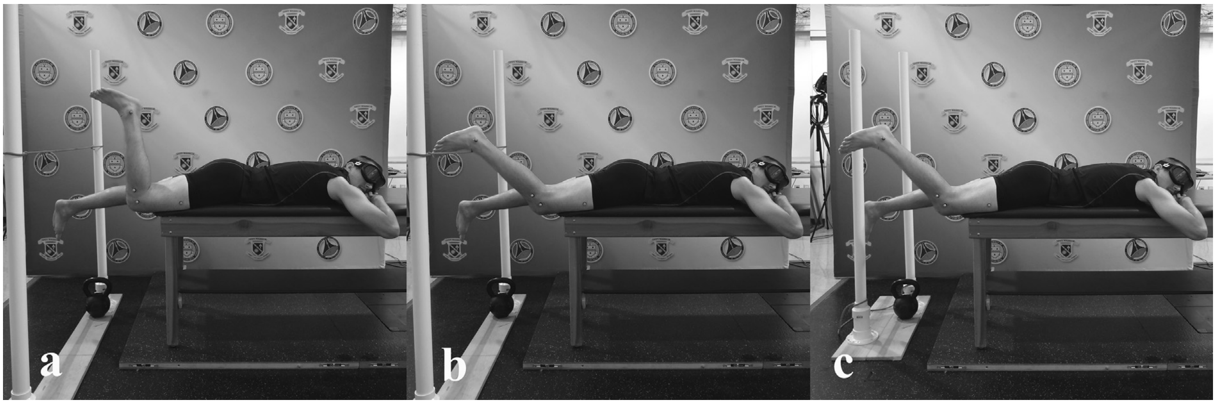

Fig. 3. Prone Knee Extension Test (a. start angle/position; b. target angle trial; c. reproduced angle trial with H-frame upright removed).

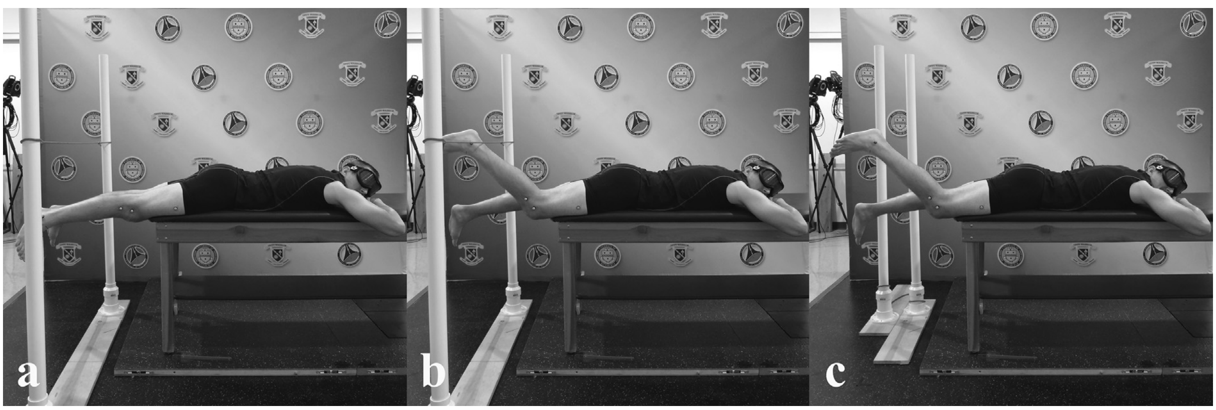

Fig. 4. Prone Knee Flexion Test (a. start angle/position; b. target angle trial; c. reproduced angle trial with H-frame upright removed).

space. Familiarisation trials were performed within both sessions to neutralise acute learning effects and stabilise acute hysteresis and thixotropy that could affect proprioceptive acuity over repeated movements (Birmingham et al., 1998; Proske, Morgan, & Gregory, 1993). All testing was led by the same researcher masked from data to negate researcher bias (Portney & Watkins, 2009). Because there are no consistent differences between sides for proprioception measures only the right knee was tested as performed in past work (Callaghan et al., 2002; Jerosch & Prymka, 1996). Test order was randomised for D1 to negate potential order effects (Portney & Watkins, 2009). Test order was duplicated for D2.

Participants wore spandex shorts and were barefoot and blindfolded for all tests. Marker placement was modified from previous work (Andersen, Terwilliger, & Denegar, 1995; Stillman & McMeeken, 2001): markers were placed over the lateral malleolus, head of fibula, femoral lateral epicondyle, and mid-point between the femoral lateral epicondyle and greater trochanter, and secured using double-sided adhesive tape. Markers remained on all anatomical sites for all tests. Participants were guided to carefully move between test positions to avoid knocking markers off the skin.

2.6. Knee active joint position sense tests

Four knee AJPS tests were performed (Table 1, Figs. 1–4). For seated tests, participants were in reclined sitting on the edge of the treatment table to relax the hamstrings, the popliteal fossa approximately 5 cm off the edge of the table to minimise cutaneous cues (Borsa et al., 1997), the hands placed behind the body for support (Figs. 1 and 2). For prone tests, participants lay prone on the treatment table with the proximal edge of the patella approximately 5 cm off the edge of the table to minimise cutaneous cues (Safran, Allen, Lephart, Borsa, Fu, & Harner, 1999), a hand under the head, the head turned sideways resting on the hand (Figs. 3 and 4). For all tests, participants were positioned so that the lateral aspect of the thigh was aligned with the lateral edge of the treatment table. Prior to test trials, the target angle (TA) was set using the goniometer: the axis aligned with the femoral lateral epicondyle; the stationary arm aligned with the femoral greater trochanter; the moving arm aligned with the lateral malleolus. Goniometer measurement of knee ROM is reliable (ICC (2,1) = 0.96) (Clark, Gumbrell, Rana, & Traole, 1999). A 45° knee flexion TA was used

Table 1
Knee active joint position sense tests.

Subject position	Joint motion	Start angle (°)	Target angle (°)	Muscle group	Muscle action sequence	H-frame crossbar alignment	Figure
Seated	Knee extension	90	45	Quadriceps	Concentric-to-isometric	Anterior ankle joint line	1
	Knee flexion	0	45	Quadriceps	Eccentric-to-isometric	Posterior ankle joint line	2
Prone	Knee extension	90	45	Hamstrings	Eccentric-to isometric	Anterior joint line	3
	Knee flexion	0	45	Hamstrings	Concentric-to-isometric	Posterior ankle joint line	4

because it is a point that: is within sports-specific movement patterns (Sigward & Powers, 2006), lies within the ROM in which noncontact knee injuries occur (Krosshaug et al., 2007), generates relatively low tibiofemoral capsuloligamentous tissue tensile loads (Escamilla, Fleisig, Zheng, Barrentine, Wilk, & Andrews, 1998), theoretically results in low capsuloligamentous mechanoreceptor discharge, preferentially stimulates musculotendinous mechanoreceptors, and relaxes antagonist muscles by avoiding end-ROM stretch and limiting antagonist mechanoreceptor discharge.

After the TA was set, participants briefly held the TA while the H-frame was positioned to ensure the same TA was assumed for each trial. The H-frame was positioned so that the crossbar just touched the skin overlying the anterior or posterior ankle joint line (Table 1, Figs. 1–4) which was carefully palpated and marked with a surgical pen; the level of the crossbar was secured for each trial by taping the tubing to the uprights with athletic tape; the position of the H-frame uprights was set for each test by marking the outline of the wooden bases on the floor with athletic tape. Because the tubing was a non-rigid structure participants were unable to rest the leg on the crossbar and relax the muscles. Whenever participants were asked to reproduce the TA (designated the ‘reproduced angle’ (RA)), one of the uprights and its separate base was moved aside so that participants could no longer touch the tubing or gain cutaneous feedback (Figs. 1–4). Prior to testing, participants actively extended and flexed the knee 10 times through a 0–90° ROM to stabilise acute hysteresis and thixotropy (Proske et al., 1993). For all tests, participants performed a sequence modified from the literature (Birmingham et al., 1998; Callaghan et al., 2002): 1. participants were cued to “slowly and smoothly” move from the start angle (SA) to the TA (Table 1), press the Vicon trigger at the TA to mark that point in the data, and hold the TA for 5 s. When holding the TA verbal cues included: “Keep holding your leg there … concentrate on feeling where your leg is in space … keep holding your leg there”; 2. participants were cued to return to the SA for 5 s; 3. one of the H-frame uprights was moved aside; 4. participants were cued to reproduce the TA and press the trigger again when they felt they had done so; 5. the RA was recorded; 6. participants were cued to return to the SA; 7. the H-frame upright was replaced for the next trial. The sequence was repeated for five trials. For each RA trial, participants were not permitted to ‘find’ the TA by oscillating the knee (repeatedly extending and flexing back-and-forth) since this would negate the concentric or eccentric focus of each test. Reproduction of the TA was performed in a smooth movement to ensure only the desired muscle action was performed. If the knee was oscillated the trial was discarded and repeated.

2.7. Data reduction

Data were collected using a custom template in the Vicon Nexus software. The template consisted of a two-segment model: the proximal segment represented the thigh; the distal segment represented the shank; the markers placed on each segment were used to create vectors that defined each segment; the angle in space between the thigh and the shank was measured by calculating the dot product of the vectors (James, Sizer, Starch, Lockhart, & Slauterbeck, 2004). Marker trajectories were smoothed within the Vicon software using a Woltring filter (Woltring, 1994). Data were exported from the Vicon software in text file format and then processed with a custom script in Matlab R2012a (Mathworks, Massachusetts). The absolute difference between the TA and RA was calculated and designated the absolute error (AE; °) (Callaghan et al., 2002; Stillman & McMeeken, 2001). Previous researchers have stated the AE variable is most appropriate for expressing knee JPS (Olsson, Lund, Henriksen, Rogind, Bliddal, & Danneskiold-Samsoe, 2004). The premise underlying the AE variable was that the smaller the AE the better the proprioceptive acuity. The mean AE from five trials for each test was used for statistical analysis.

2.8. Statistical analysis

Analyses were performed using SPSS 21 (SPSS Inc., Chicago). Normality of data was assessed with the Shapiro–Wilk test and then significance tests were used to screen for between-session (D1 to D2) systematic bias (Atkinson & Nevill, 1998). Reliability was assessed using ICC (2,1) and 95% confidence intervals, and then measurement precision was calculated using standard error of measurement (SEM) (Atkinson & Nevill, 1998; Denegar & Ball, 1993). Significance levels were set *a priori* ($\alpha = 0.05$).

3. Results

Summary statistics are presented in Table 2. Mean values for all tests were lower on D2.

The mean D1-D2 difference was consistently less than one degree. Data were normally distributed, and paired t-tests showed no significant differences between D1 and D2 mean values for any test. Knee AJPS test ICCs, 95% confidence intervals, and SEMs are reported in Table 3. The prone knee extension and prone knee flexion tests demonstrated higher ICCs than the seated knee extension and seated knee flexion tests. An ICC above 0.75 can be considered good reliability and an ICC below 0.75 moderate reliability (Portney & Watkins, 2009). The SEM was similar across all tests.

4. Discussion

The purpose of this study was to establish the intra-tester, inter-session, test–retest reliability of concentric-to-isometric and eccentric-to-isometric knee AJPS tests in uninjured physically active adults. We hypothesised that tests would demonstrate good reliability using the ICC. The results of this study partially support our hypothesis since the prone knee extension test demonstrated

Table 2
Knee active joint position sense test summary statistics (n = 12).

Subject position	Joint motion	D1 Absolute error mean ± SD (°)	D2 Absolute error mean ± SD (°)	D1 − D2 Absolute error differences mean ± SD (°)
Seated	Knee extension	3.19 ± 1.47	3.18 ± 1.50	0.01 ± 2.09
	Knee flexion	4.37 ± 2.52	3.89 ± 1.49	0.49 ± 2.45
Prone	Knee extension	5.97 ± 3.59	5.09 ± 3.53	0.89 ± 1.63
	Knee flexion	4.70 ± 1.71	3.70 ± 2.13	1.01 ± 1.80

D1 = Day 1.
D2 = Day 2.
SD = standard deviation.

Table 3
Knee active joint position sense test reliability statistics (n = 12).

Subject position	Joint motion	ICC (2,1)	ICC (2,1) 95% confidence interval	SEM (°)
Seated	Knee extension	0.13	−0.62, 0.58	1.3
	Knee flexion	0.31	−0.31, 0.74	1.7
Prone	Knee extension	0.87	0.61, 0.96	1.4
	Knee flexion	0.51	0.01, 0.83	1.2

ICC = intraclass correlation coefficient.
SEM = standard error of measurement.

good reliability (Table 3) defined as an ICC ≥ 0.75 (Portney & Watkins, 2009). The prone knee flexion test demonstrated moderate reliability (Table 3) (Portney & Watkins, 2009). The seated knee extension and seated knee flexion tests were not reliable (Table 3).

It is not possible to directly compare the ICC values for the prone knee extension or prone knee flexion tests with ICCs reported by other authors. This is because there appears to be no other report using the prone knee extension test as a measure of hamstrings-focused eccentric-to-isometric AJPS, because studies used different instrumentation and procedures, and because different ICC models yield different ICC values (Denegar & Ball, 1993). The alternative, therefore, is to indirectly compare the present findings to research that has used other types of knee AJPS test or ICC model. The ICC values in this study are higher than those reported by authors using a prone knee flexion test (ICC (2,1) = 0.40) (Olsson et al., 2004) and a seated knee flexion test (ICC (2,k) = 0.57) (Drouin et al., 2003), and are consistent with those reported for other seated knee flexion tests (ICC (3,1) = 0.86) (Piriyaprasarth, Morris, Winter, & Bialocerkowski, 2008). The SEM values in this study are lower than those reported using a seated knee extension test (2.4°) (Kramer, Handfield, Kiefer, Forwell, & Birmingham, 1997), and consistent with those using a seated knee flexion test (1.2–1.3°) (Drouin et al., 2003; Piriyaprasarth et al., 2008). The SEM value is important alongside the ICC value because a low ICC may not be of major concern if the SEM is within an acceptably small range (Denegar & Ball, 1993). The ICC and SEM values from this study are favourable when compared to those reported by other authors. This suggests the prone knee extension test and prone knee flexion test may be useful in future laboratory and clinical research studies of knee AJPS.

A direct comparison between the AE data for this study and previous literature is also limited because there appears to be no other report using a hamstrings-focused eccentric-to-isometric AJPS test. The alternative, therefore, is to also indirectly compare the present AE data to data reported by authors who have used different instrumentation and procedures. Some form of data comparison is useful to consider whether the AE data collected during this study is acceptable as a representation of the construct of AJPS and underlying muscle-tendon mechanoreceptor stimulation. Mean AE values for the prone knee extension and prone knee flexion tests (Table 2) are similar to values reported for a selection of hamstrings- and quadriceps-focused knee AJPS tests (3.60–6.06°) (Callaghan et al., 2002; Drouin et al., 2003; Ghiasi & Akbari, 2007; Olsson et al., 2004). Although we cannot directly compare the data from this study to the data from other studies for the reasons previously cited, the present mean AE values are similar to values reported by other authors. The present mean AE values can, therefore, be accepted and corroborated as a physiological representation of the construct of AJPS and underlying muscle-tendon mechanoreceptor stimulation.

It is not clear why the hamstrings-focused tests demonstrated reliability but the quadriceps-focused tests did not (Table 3). From a neuroanatomical perspective, mammalian hamstring and vasti muscles demonstrate a similar relative abundance of muscle spindles (Banks, 2006). From a biomechanical perspective, changes in muscle spindle length are related to fibre pennation angle, extrafusal fibre length, and muscle moment arm length (Banks, 2006). Pennation angles of muscles comprising the hamstring and quadriceps muscle groups change during knee flexion and extension (Chleboun, France, Crill, Braddock, & Howell, 2001; Fukunaga, Ichinose, Ito, Kawakami, & Fukashiro, 1997). Extrafusal fibre (fascicle) length changes by a greater proportion in vasti muscles than in hamstrings muscles with knee joint motion (Refshauge, Chan, Taylor, & McCloskey, 1995). Moment arm length changes considerably in muscles comprising the quadriceps but not in muscles comprising the hamstrings during knee joint motion (Visser, Hoogkamer, Bobbert, & Huijing, 1990). In addition, the hamstrings are biarticular muscles crossing both the hip and the knee whereas the vasti muscles are monoarticular muscles crossing only the knee, with biarticular muscles demonstrating different CNS activation characteristics compared to monoarticular muscles (Doorenbosch, Welter, & van Ingen, 1997). Therefore, alpha–gamma coactivation characteristics (Gordon & Ghez, 1991; Rothwell, 1994) combined with pennation angle, fibre length, and moment arm length changes present a complex multivariate system that could profoundly and differentially affect hamstrings and quadriceps muscle spindle length changes. Overall, an incomplete model of joint sensorimotor control exists with unclear sensory roles for different types of muscles (Banks, 2006), and future research is needed to further explore the neuroanatomical, neurophysiological, and biomechanical factors influencing knee proprioception.

Potential technical limitations included movement artefacts due to movement of skin overlying a bony landmark (Reinschmidt, van den Bogert, Nigg, Lundberg, & Murphy, 1997). This study employed sagittal plane knee motion which has been reported to yield the least skin-marker movement artefacts compared to other planes of motion (Reinschmidt et al., 1997), and skin-marker movement artefacts were addressed across all trials, tests, and test sessions with the same robust filtering process (Woltring, 1994). Potential tester limitations included between-session inconsistency of marker placement due to inaccurate palpation. Palpation of major bony landmarks and anatomical structures is most reliable in experienced practitioners (Downey, Taylor, & Niere, 1999; Simmonds & Kumar, 1993), and all test procedures were performed by the same researcher with more than 11 years of advanced manual therapy clinical practice.

In cross-sectional studies, tests of knee AJPS could be used to estimate the role of proprioception in knee functional joint stability (Fitzgerald, Lephart, Hwang, & Wainner, 2001). In prospective studies, tests of knee AJPS could be used to estimate the role of proprioception as a predictor of first-time joint injury, second joint injury, and the onset of OA (Knoop et al., 2011; Sell et al., 2010). The prone knee extension test demonstrated good reliability and the prone knee flexion test demonstrated moderate reliability; these tests may, therefore, have clinical utility in future cross-sectional and prospective studies that wish to include measures of knee AJPS. The seated knee extension and seated knee flexion tests were not reliable. Future research should design new tests of quadriceps-focused knee AJPS and determine their reliability. Quadriceps-focused tests could then also be used in various study designs investigating aspects of knee proprioception and knee functional joint stability.

5. Conclusion

The prone knee extension and prone knee flexion tests demonstrated good and moderate reliability, respectively. The prone knee extension test may be particularly useful as a hamstrings-focused eccentric-to-isometric AJPS test in future research studies.

Conflict of interest

None declared.

Ethical approval

Ethical approval was obtained from the Institutional Review Board, University of Pittsburgh.

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