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Single leg squat ratings by clinicians are reliable and predict excessive hip internal rotation moment

Robert M. Barker-Davies[a,b,*], Andrew Roberts[a], Alexander N. Bennett[a,c], Daniel T.P. Fong[b], Patrick Wheeler[b], Mark P. Lewis[b]

[a] Academic Department of Military Rehabilitation, Defence Medical Rehabilitation Centre Headley Court, London, UK
[b] National Centre for Sport and Exercise Medicine, School of Sport Exercise and Health Sciences, Loughborough University, UK
[c] National Heart and Lung Institute, Faculty of Medicine, Imperial College, London, UK

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ABSTRACT

Background: Single leg squats are commonly used subjective assessments of general biomechanical function, injury risk, as a predictor for recovery and as an outcome measure of rehabilitation. While 3D motion capture is a useful tool for elite sports performance and research it is impractical for routine clinical use.

Research question: This cross-sectional study aims to: assess reliability and validity of clinicians' subjective ratings of single leg squats compared to 3D motion capture, and to identify whether performance predicts joint moments.

Methods: 22 healthy military volunteers were simultaneously recorded on video and 3D motion capture performing single leg squats. Videos were reviewed twice by 5 physiotherapists rating performance on a 0–5 scale assessing squat depth, hip adduction, pelvic obliquity, pelvic tilt and trunk flexion summated into a composite score.

Results: Hip adduction and trunk flexion exhibited moderate to substantial inter- and intra-rater reliability (range $\kappa = 0.408$–0.699) other individual criteria were mostly fair ($\kappa \le 0.4$). Composite scores for inter-rater reliability were $ICC_{(1,1)} = 0.419$ and $ICC_{(1,\kappa)} = 0.783$ and intra-rater reliability were $ICC_{(1,1)} = 0.672$ and $\kappa(w) = 0.526$. Validity against 3D kinematics was poor with only 6/75 individually rated criteria reaching $\kappa > 0.40$. Correlation was found between composite scores and hip internal rotation moment ($r_s = 0.571$, $p = 0.009$).

Significance: Repeated use of single leg squats by a single practitioner is supported. Comparisons between clinicians are unreliable but improved by average measures from multiple raters. Heterogeneous reliability across scoring components suggests a qualitative description of the criteria scored is less ambiguous than using composite scores in a clinical setting. Composite scores may be more useful for analysis at a population level. Poor validity against kinematic data suggests clinicians use additional information upon which they find agreement such as estimating kinetics. Correlation between hip internal rotation moment and subjective ratings may be such an example of clinicians trying to identify excessive abnormal loading.

1. Introduction

A commonly used clinical assessment of lower limb function is the single leg squat. This test is favoured by clinicians as it has relevance as a surrogate for higher functional activities such as running and jumping which are impractical to test either because of limitations of clinic space/facilities or due to the presence of pain in a patient population [1]. The single leg squat is used to give an idea of general biomechanical function and therefore as a potential risk factor for injury [2], a predictor for recovery and as an outcome measure of rehabilitation [3]. Whilst 3D motion capture is a useful tool for elite sports performance and research the time required for data capture and processing makes it difficult to provide immediate clinical information [4].

Abnormal kinematics that are potentially identifiable on single leg squat have been associated with injury. Lumbar stress injury has been associated with excessive knee valgus [2] and patellofemoral pain syndrome (PFPS) has been associated with excessive hip adduction, knee valgus, pelvic obliquity and ipsilateral trunk lean [5,6]. Kinematic single leg squat performance deficits have also been linked to other risk factors for injury. Females who have a greater risk of PFPS and anterior

* Corresponding author at: Academic Department of Military Rehabilitation, Defence Medical Rehabilitation Centre Headley Court, London, UK.
E-mail address: R.Barker-Davies@lboro.ac.uk (R.M. Barker-Davies).

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Table 1
Rating criteria for the Small Knee Bend (SKB) [22],Single Leg Squat (SLS) and Single Leg Decline Squat (SLDS) with kinematic interpretation for objective comparison. PFPS = patellofemoral pain syndrome.

Clinical Rating Criteria	Kinematic Interpretation for objective comparison	Reasoning for kinematic threshold describing poor or excessive movement
SKB: "Does the knee move inward from the 2nd toe?" SLS/SLDS: "Is there excessive Hip adduction?"	Is the peak hip adduction greater than 10°?	Hip adduction easier to spot than interpreting knee valgus 6° v 2.3° mean difference with a higher likelihood of clinically meaningful difference 94% v 74% [20]. Excessive hip adduction defined as 10.6–11.4° when single leg squatting with data extracted at 45° [42].
SKS: "Does the pelvis drop (hitch) on the weight bearing side?" SLS/SLDS: "Is there excessive pelvic obliquity?"	Is peak pelvic obliquity greater than 10°?	11.8° mean difference between those rated good and poor by expert consensus [20].
SKB: "Does the knee fail to move 2 cm past the second toes?" SLS/SLDS: "Do they fail to squat to 60°?"	Is the peak knee flexion angle less than 40° (SKB)/60° (SLS/SLDS)?	SKB: 40° consensus opinion from our panel of experienced physiotherapists SLS/SLDS: 60° consensus [6,7,12,13].
SKB: "Does the trunk lean forward (flex)?" SLS/SLDS: "Is there excessive trunk flexion?"	Is the peak trunk flexion angle greater than 10°?	No compelling evidence from literature. Consensus opinion from our panel of experienced physiotherapists. Also simplicity across criteria.
SKB: "Does the pelvis tilt forwards (anteriorly)?" SLS/SLDS: "Is there excessive anterior pelvic tilt?"	Is the peak anterior pelvic tilt angle greater than 10°?	

cruciate ligament injury than males, exhibit excessive hip adduction, hip internal rotation and knee valgus [7–9]. Localised muscular fatigue has been associated with increased trunk flexion, pelvic obliquity, pelvic tilt, pelvic rotation and hip adduction [10].

There is limited research linking these kinematic abnormalities to the excessive loads they imply. A reduction in peak knee valgus (ES = 0.5 p = 0.051) has been associated with a larger reduction in valgus abduction moment (ES = 0.71, P = 0.03) after four weeks neuromuscular training [11]. Knee valgus alignment on single leg squats has also been associated with other trainable deficits such as reduced flexibility [12] and strength [13]. These modifiable risk factors are amenable to physical therapy that could result in improved outcomes. Correcting excessive knee valgus on the single leg squat in PFPS has associated decreases in pelvic obliquity, hip adduction and internal rotation and pain [14]. Improvements in single leg squat deficits effected by neuromuscular training have been maintained at 3 months follow up and associated with improved pain and function [15].

The reliability with which these biomechanical abnormalities can be identified from clinical examination of the single leg squat as opposed to more objective technologies such as 3D motion capture is uncertain [16]. Analysis of processed 2D video images has shown good intra-rater reliability (Intra-class correlation coefficients (ICC) > 0.59) [17], inter-rater reliability (ICC > 0.96) and validity (r = 0.81) when assessing knee valgus and hip adduction angles [4]. Annotation of still video pictures whilst more practical than 3D motion capture is still removed from immediate dynamic assessment in vivo. Using a 3-point qualitative scale (good, fair or poor technique) on viewing 2D full speed video 3 clinicians demonstrated good intra and inter-rater reliability (*Kappas* > 0.6*)* [18]. Such subjective measures however cannot be directly validated against 3D kinematics though increased hip adduction and decreased knee flexion have been associated with 'poor' ratings [19]. Frontal plane video ratings from 66 physiotherapists assessing binary questions for the presence of knee valgus and pelvic obliquity showed good inter/intra-rater reliability and validity against 3D kinematics [20]. This study aims to build upon this by adding knee flexion, pelvic tilt and trunk flexion to form a 5-point scale as well as including video analysis in the sagittal plane. The hypotheses to be tested are that 5 components of clinical single leg squat ratings, hip adduction, knee flexion, pelvic tilt, pelvic obliquity and trunk flexion are reliable and valid compared to 3D motion capture. It is also hypothesised that kinematic performance will predict lower limb joint moments associated with injury.

2. Methods

Based on a power of 80% (β-level = 0.8) and an α-level of 0.05 anticipating substantial reliability ($P_0 > 0.6$–$P_1 = 0.8$), the calculations of Walter [21] estimate the requirement for at least 5 raters (n) of 20 subjects (k).

A total of 25 healthy military volunteers were screened. The inclusion criteria were males aged 18–55 and exclusion criteria musculoskeletal injury in the preceding 6 months or associated occupational restrictions concerning physical activity. Participants in a range of military roles (Table 2) were invited to take part by the chief investigator (RBD). The Ministry of Defence Research Ethics Committee approved the study (684/MODREC/15) and all participants gave written informed consent. Each participant was invited to the biomechanics laboratory at the Defence Medical Rehabilitation Centre at a convenient time between September 2016 and February 2017. Participants undertook the following movements described below.

For the small knee bend (SKB) verbal instruction was given as follows:

> *"Stand on one leg with your foot pointing forward. Place the unsupported foot behind you by bending your knee 90°. While keeping your body upright, keeping your pelvis and heel in position, bend your knee so that your knee is in line with your 2nd toe and moves past it until you can no longer see the tape line."* [22].

5 repetitions were tested [12] allowing 2–3 practice repetitions immediately prior to testing [5,7]. There was one minute of rest between trials [6,7]. Individual SKB scoring items [22] were interpreted as per Table 1.

Squat movements were standardised and 2 further tests the single leg squat (SLS) and with the addition of a 25° decline board [23] the

Table 2
Demographics of participants.

N = 20	Mean (Range) ± SD
Age (years)	34.3 (23–52) ± 6.7
Height (m)	1.79 (1.69–1.89) ± 0.05
Weight (kg)	85.6 (73.3–99.7) ± 9.1
BMI	26.7 (20.5–30.6) ± 2.8
Leg Dominance	Right n = 18 Left n = 2
Role	Administrative Officers n = 5, Aircraft Technicians n = 4, Doctors n = 2, Nurses n = 6, Physical Training Instructors n = 3

single leg decline squat (SLDS) were developed. Participants were instructed for SLS and SLDS to squat to 60° knee flexion using metronome pacing over a 4 s cycle [7,13]. The non-stance leg was flexed at the knee to 90° [7]. Again 5 repetitions were captured following 2–3 practice squats with a minute's rest between trials.

The testing sequence was SKB followed by SLS then SLDS. Tests were conducted bilaterally with the first leg to be tested decided by coin toss. Leg dominance according to which leg a participant would kick a ball with was recorded. Pain caused by the squats after each trial was monitored with a 100 mm visual analogue scale.

Video data was recorded at 120 Hz using fixed mounted cameras at a height of 0.77 m; 4.8 m and 3.6 m from the participant in the frontal and sagittal planes respectively. For each participant, repetitions 2, 3 and 4 were replayed twice in both planes at full speed on a large screen television to 5 physiotherapist raters (educated to MSc level or higher and a minimum of 9 years' clinical experience). Immediately prior to rating each rater was briefed on the assessment criteria as per Table 1. Raters were asked to make ratings based on performance up to the depth of squat required for the test and ignore abnormal movements beyond so that overachieving participants were not rated poorly and to aid comparison with motion capture data. Raters recorded their assessments independently and repeated the procedure for intra-rater reliability after a minimum of 2 weeks.

For kinematic and kinetic data acquisition and processing 8 body segments (feet, shank, thigh, pelvis and trunk) were defined using retro-reflective markers placed on the following anatomical landmarks by the same operator (RBD): Acromio-clavicular joints, anterior and posterior shoulders aligned through the centre of the humeral head, a side marker on the right overlying teres major, sternum, xiphisternum, cervical vertebra 7, thoracic vertebra 10, anterior and posterior superior iliac spines, a pelvic cluster of 3 markers, thigh and leg clusters of 4 markers, lateral and medial femoral condyles, lateral and medial malleoli, posterior calcanei, 1st and 5th metatarsal phalangeal joints. The segments were defined as follows; pelvis and thigh according to Wu [24], shank according to Peters [25], foot according to Pratt [26], and trunk according to Gutierrez [27]. The shank and pelvis were tracked using clusters recommended by Manal [28] and Borhani [29] respectively. For the calculation of joint moments an additional foot segment was created based on a modified Helen Hayes set [30] which is better aligned with the dissection positions of Dempster [31] for the purpose of inverse dynamics calculation. Joint moments were normalised to participant mass.

A VICON (Oxford, UK) 10 camera motion capture system and one AMTI (Boston, USA) force plate captured data at 120 Hz and 1200 Hz respectively. Following static and range of motion calibration trials participants performed the squats as described above.

All squat trials were trimmed to the corresponding 2nd, 3rd and 4th repetitions (as replayed to raters). Data was labelled in Vicon Nexus (version 2.1) and processed in Visual 3D (C-motion version 6.0, Rochelle, USA). Kinematic data was filtered using a 6 Hz low pass bi-directional Butterworth filter [32] and gaps were interpolated using a 3rd order least squares fit (maximum 10 frames) [33]. Kinetic data was filtered separately at 50 Hz [34].

Inter- and intra-rater reliability of criteria was calculated using *Fleiss* and *Cohen's Kappa* respectively. Inter- and intra-rater reliability of composite scores was calculated using one way random single $_{(1,1)}$ and average $_{(1,\kappa)}$ measures ICC. *Weighted Kappa* was also used for intra-rater reliability of composite scores.

Kinematics for each variable occurring at the time of peak knee flexion upon each of the three analysed squats were averaged. Mean angle for each variable was then dichotomised according to thresholds in Table 1. Individual *Cohen's Kappas* for raters were then calculated against the objective scores for agreement. The summated composite scores were assessed using *weighted Kappa*.

Mean composite physiotherapist rating scores were explored for bivariate correlations with total objective scores derived from the kinematic data, and kinetic data including area under the curve (AUC) for valgus knee moment, knee internal and external rotation moments, extensor knee moment and hip adductor and internal rotation moments. All calculations were undertaken using SPSS software (version 23, IBM, Armonk, NY, USA).

There has been no involvement of the funding organisation (Higher Education Funding Council for England) in the data collection, analysis, interpretation or approval pertaining to this manuscript.

3. Results

Two participants did not meet the exclusion criteria one having had a hamstring strain in the week preceding testing and one participant had a restriction in ankle dorsiflexion from a previous injury and were not enrolled. One further participant's data was excluded due to incomplete saving of concurrent video data meaning that 22 participants completed the study. Two participants had outlying data due to an excessive squat depth as set by the protocol that resulted in almost a third of variables being classified as deviating from normal distribution. These participants were removed from the analysis (Appendix A in Supplementary material) resulting in a final analysis of 20 participants.

All squats were tested bilaterally. Theoretical kinematic differences between sides were excluded to account for possible effects of laboratory set-up, leg dominance or acquired skill. Paired *t*-tests or Wilcoxon matched pairs were used according to normality of distribution (Appendix B in Supplementary material). The only significant differences in kinematics related to testing order, which was randomised. Further reliability of subjective physiotherapist score rating and subsequent validity testing was carried out on the left hand sided data only. None of the participants experienced pain on testing so use of pain scale data for covariate analysis was not required. No adverse events occurred.

Inter- and intra-rater reliability on scoring criteria is represented in Fig. 1(a–c). Hip adduction and trunk flexion criteria across all squat variations are most reliable with 15/18 results exhibiting at least moderate reliability ($K > 0.4$) and 5/9 results for trunk flexion exhibiting substantial reliability ($K > 0.6$). Reliability of knee flexion, pelvic obliquity and tilt was consistently fair ($K = 0.2–0.4$) or worse.

Inter- and intra-rater reliability on composite scores is represented in Fig. 1(d). The SLS was found to be the most reliable measure, with at least moderate reliability for inter- and intra-rater reliability. Intra-rater reliability is better than inter-rater reliability across all squat variations ($ICC_{(1,1)} = 0.672$ compared to $ICC_{(1,1)} = 0.419$ respectively for SLS). Inter-rater average measures are more reliable than single measures across all squat variations ($ICC_{(1,1)} = 0.614–0.783$ compared to $ICC_{(1,\kappa)} = 0.242–0.419$ respectively). Generally agreement with 3D kinematics was poor to fair, with only 6/75 individually rated criteria $\kappa > 0.40$ and one $\kappa > 0.60$ (Appendix C in Supplementary material).

Mean composite scores were not normally distributed ($W_{(20)} \leq 0.904$, $p \leq 0.049$) therefore Spearman's correlations were used. Significant correlation was found between SKB scores and both the AUC hip internal rotation moment ($r_s = 0.571$, $p = 0.009$), and the AUC extensor knee moment ($r_s = -0.451$, $p = 0.046$). There were no further significant correlations between SLS or SLDS scores with the moments described above.

Significant correlation was found between objective total SLS ratings derived from peak kinematics and AUC valgus knee moment on SLS ($r_s = 0.643$, $p = 0.002$).

4. Discussion

Moderate to substantial reliability has been demonstrated for 2 SLS rating components, hip adduction and trunk flexion as well as the overall composite score. Knee flexion, pelvic tilt and pelvic obliquity were less reliable. Validity against kinematics alone was poor though significant correlation with kinetics highlighted the complexity of

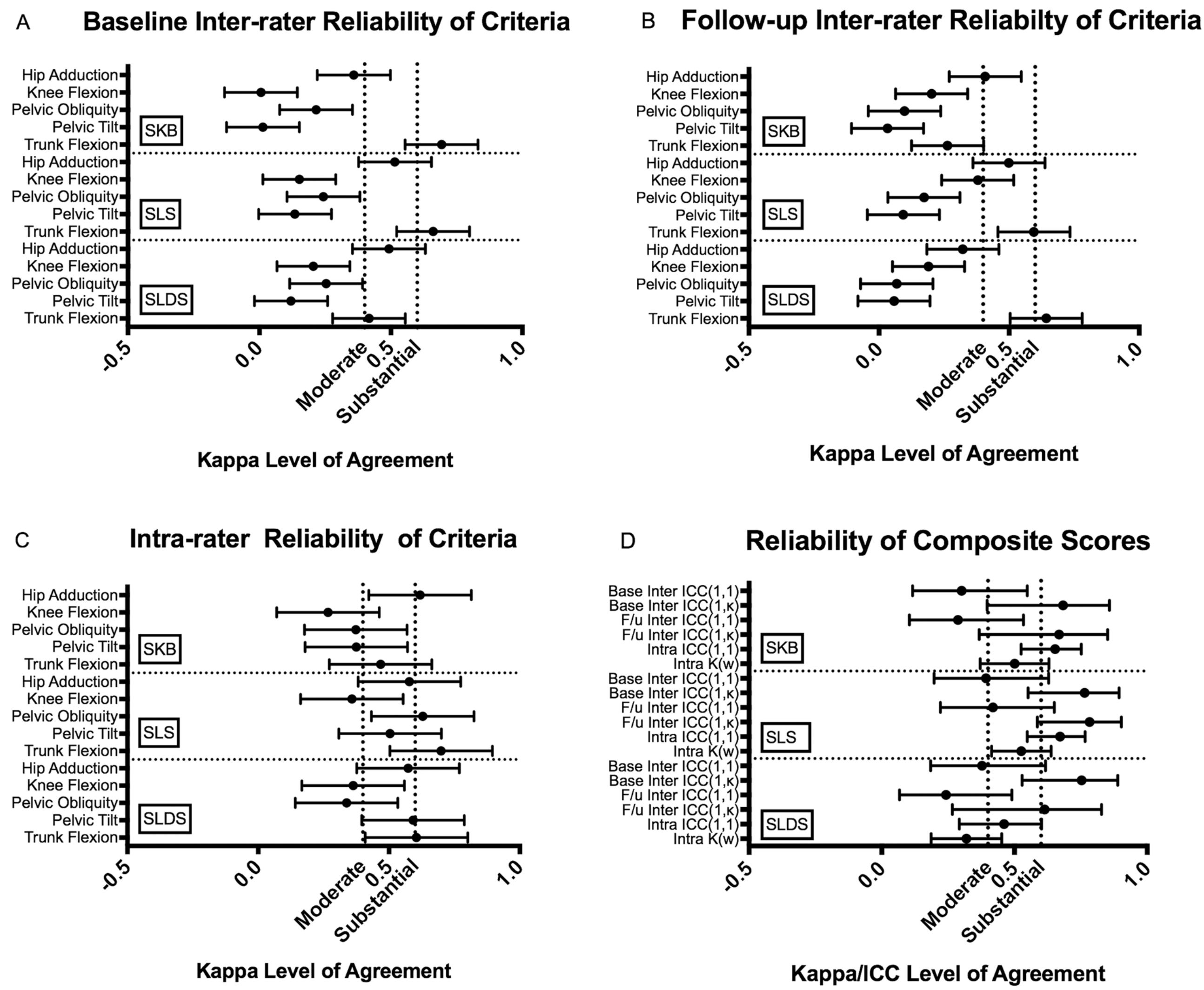

Fig. 1. (a) Inter-rater reliability at baseline, (b) follow-up and (c) intra-rater reliability of individual scoring criteria and (d) Inter-rater reliability at baseline, on follow-up and intra-rater reliability on composite scores. SKB = Small Knee Bend, SLS = Single Leg Squat, SLDS = Single Leg Decline Squat, ICC(1,1) and ICC (1,κ) = One way random single and average measure Intraclass Correlation Coefficients Respectively, K(W) = *Weighted Kappa*.

validating clinical opinion with continuous data.

Whilst low composite scores for functional movement screening are associated with increased overuse injury risk they do not have high positive predictive value in young active populations. This is despite using ROC curve analysis to identify optimal cut-off points [35]. This demands a more forensic assessment of the criteria that make up those scores. In order to do this a rating scale with scoring criteria directly comparable with objective measures (Table 1) was used. Although this study was conducted in a healthy population performance of such tasks has been shown to differ across occupational roles [36] and therefore a heterogenous population was sought.

These results indicate hip adduction and trunk flexion may be easier for clinicians to identify than knee flexion, pelvic tilt or obliquity as illustrated by the inter-rater reliabilities (Fig. 1a and b). As anticipated intra-rater reliability is stronger than comparisons between raters and the pattern of agreement is repeated in that hip adduction and trunk flexion almost meet substantial agreement throughout (Fig. 1c). Hip adduction as illustrated in Table 1 relates to knee valgus [20] which is likely to represent the most well understood risk factor for injury by clinicians [2,6,8]. This may explain its superior reliability to other criteria.

The use of ICC (Fig. 1d) on composite scores distinguishes between the strength of reliability for single and average raters making clear that when comparing scores between raters average measures offer much improved reliability. As a screening tool or for clinical use these scores must be interpreted with caution unless an average is taken, in this case using 5 experienced physiotherapists. This is likely to be difficult to achieve in a clinical setting.

These scores may be of more use clinically if the rater remains constant for follow-up interpretation as demonstrated by substantial intra-rater reliability (Fig. 1d). Repeated testing is desirable in a screening and clinical setting. Moran et al's systematic review discusses the propensity of studies examining the predictive value for injury of composite functional movement scores to use just one assessment. As time between baseline assessment and injury occurrence increases the likelihood of confounders explaining an increase in injury risk increases. They suggest investigators consider the use of repeat assessments to improve construct validity [37].

As demonstrated by the low agreement between individual raters and kinematic data validity was consistently poor to fair. A possible explanation for this could be that the cut off points selected in Table 1 were rather arbitrary and our raters' perception of excessive movement did not match those from which mean kinematic differences were derived [20]. However in the SLS and SLDS for one criteria, peak knee flexion, a reference angle was demonstrated using a goniometer immediately prior to each rating session. 3-D motion capture derived objective peak knee flexion did not agree with clinicians' ratings despite this. It also seems unfeasible that even experienced clinicians would be able to interpret 5 separate reference angles simultaneously.

It may be possible that clinicians use additional information upon which they find agreement. For example estimating the kinetics that in common pathologies such as PFPS and patellar tendinopathy represent the underlying risk factor they wish to consider [18]. As the agreement between raters and binary outcomes was poor in light of good average measures inter-rater reliability further exploration was undertaken to try and explain this. The correlation found between hip internal rotation moment and SKB ratings may be representative of the valgus collapse type loading clinicians seek to modify [3,38–40]. Negative correlation between extensor knee moment and SKB ratings likely represents a lack of ability to load normally through the patella tendon [41]. The correlation between the objective SLS ratings and knee valgus moment provides some evidence that screening tests based on kinematic descriptors can inform clinicians of exposure to abnormal loading.

This research was conducted with a view to a future study using these tests in patients with patellar tendinopathy. This influenced our decision to squat to 60° at which point patella tendon force increases almost as a function of knee flexion without excessive patella-femoral force [41]. To increase patella tendon force further we repeated the same test with the addition of a 25° decline board [41].

As raters viewed video playback rather than watch the assessments live due to varying levels of availability and the need to standardise exposure this could be considered a limitation. Rating a live assessment will enable the raters' depth perception which is lost watching 2D video. These results may therefore underestimate reliability and validity as a result.

5. Conclusion

These results support the repeated use of single leg squats by a single practitioner. As an isolated test for comparison between individual patients assessment by different practitioners is likely to be unreliable. This may be improved by average measures from multiple raters. It is important to emphasise the improved reliability of hip adduction and trunk flexion over knee flexion, pelvic obliquity and tilt when interpreting composite scores. This heterogeneous reliability across scoring components suggests a qualitative description of the criteria scored is less ambiguous than using composite scores in a clinical setting. Composite scores may be more useful for analysis at a population level with appropriately adjusted weighting.

Poor validity against kinematic data suggests clinicians use additional information upon which they find agreement such as estimating kinetics. Correlation between hip internal rotation moment and SKB ratings may be such an example of clinicians trying to identify excessive abnormal loading.

Conflict of interest statement

All authors declare no conflicts of interest.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.gaitpost.2018.02.016.

References

[1] C. Whatman, P. Hume, W. Hing, Kinematics during lower extremity functional screening tests in young athletes – are they reliable and valid? Phys. Ther. Sport 14 (2) (2013) 87–93.
[2] H. Bayne, B. Elliott, A. Campbell, et al., Lumbar load in adolescent fast bowlers: a prospective injury study, J. Sci. Med. Sport 19 (2) (2016) 117–122.
[3] M. Baldon Rde, F.V. Serrao, R. Scattone Silva, et al., Effects of functional stabilization training on pain, function, and lower extremity biomechanics in women with patellofemoral pain: a randomized clinical trial, J. Orthop. Sports Phys. Ther. 44 (4) (2014) 240-A8.
[4] L. Herrington, F. Alenezi, M. Alzhrani, et al., The reliability and criterion validity of 2D video assessment of single leg squat and hop landing, J. Electromyogr. Kinesiol. 34 (2017) 80–85.
[5] C.Y. Song, H.Y. Huang, S.C. Chen, et al., Effects of femoral rotational taping on pain, lower extremity kinematics, and muscle activation in female patients with patellofemoral pain, J. Sci. Med. Sport 18 (4) (2015) 388–393.
[6] T.H. Nakagawa, C.D. Maciel, F.V. Serrao, Trunk biomechanics and its association with hip and knee kinematics in patients with and without patellofemoral pain, Man. Ther. 20 (1) (2015) 189–193.
[7] R. Scattone Silva, F.V. Serrao, Sex differences in trunk, pelvis, hip and knee kinematics and eccentric hip torque in adolescents, Clin. Biomech. 29 (9) (2014) 1063–1069.
[8] J. Yamazaki, T. Muneta, Y.J. Ju, et al., Differences in kinematics of single leg squatting between anterior cruciate ligament-injured patients and healthy controls, Knee Surg. Sports Traumatol. Arthrosc. 18 (1) (2010) 56–63.
[9] M.K. Dwyer, S.N. Boudreau, C.G. Mattacola, et al., Comparison of lower extremity kinematics and hip muscle activation during rehabilitation tasks between sexes, J. Athl. Train. 45 (2) (2010) 181–190.
[10] B.K. Weeks, C.P. Carty, S.A. Horan, Effect of sex and fatigue on single leg squat kinematics in healthy young adults, BMC Musculoskelet. Disord. 16 (2015) 271.
[11] I. Wouters, T. Almonroeder, B. Dejarlais, et al., Effects of a movement training program on hip and knee joint frontal plane running mechanics, Int. J. Sports Phys. Ther. 7 (6) (2012) 637–646.
[12] N. Wyndow, A. De Jong, K. Rial, et al., The relationship of foot and ankle mobility to the frontal plane projection angle in asymptomatic adults, J. Foot Ankle Res. 9 (2016) 3.
[13] L. Stickler, M. Finley, H. Gulgin, Relationship between hip and core strength and frontal plane alignment during a single leg squat, Phys. Ther. Sport 16 (1) (2015) 66–71.
[14] V. Graci, G.B. Salsich, Trunk and lower extremity segment kinematics and their relationship to pain following movement instruction during a single-leg squat in females with dynamic knee valgus and patellofemoral pain, J. Sci. Med. Sport 18 (3) (2015) 343–347.
[15] R.W. Willy, J.P. Scholz, I.S. Davis, Mirror gait retraining for the treatment of patellofemoral pain in female runners, Clin. Biomech. 27 (10) (2012) 1045–1051.
[16] B.R. Kivlan, R.L. Martin, Functional performance testing of the hip in athletes: a systematic review for reliability and validity, Int. J. Sports Phys. Ther. 7 (4) (2012) 402–412.
[17] A. Munro, L. Herrington, M. Carolan, Reliability of 2-dimensional video assessment of frontal-plane dynamic knee valgus during common athletic screening tasks, J. Sport Rehabil. 21 (1) (2012) 7–11.
[18] K.M. Crossley, W.J. Zhang, A.G. Schache, et al., Performance on the single-leg squat task indicates hip abductor muscle function, Am. J. Sports Med. 39 (4) (2011) 866–873.
[19] S.A. Horan, S.L. Watson, C.P. Carty, et al., Lower-limb kinematics of single-leg squat performance in young adults, Physiother. Can. 66 (3) (2014) 228–233.
[20] C. Whatman, P. Hume, W. Hing, The reliability and validity of physiotherapist visual rating of dynamic pelvis and knee alignment in young athletes, Phys. Ther. Sport 14 (3) (2013) 168–174.
[21] S.D. Walter, M. Eliasziw, A. Donner, Sample size and optimal designs for reliability studies, Stat. Med. 17 (1) (1998) 101–110.
[22] M.W. Nadine Botha, Mo Gimpel, Sarah Mottram, et al., Movement patterns during a small knee bend test in academy footballers with femoroacetabular impingement (FAI), Working Papers in the Health Sciences, University of Southampton, 2014, p. 10.
[23] J. Zwerver, S.W. Bredeweg, A.L. Hof, Biomechanical analysis of the single-leg decline squat, Br. J. Sports Med. 41 (4) (2007) 264–268.
[24] G. Wu, P.R. Cavanagh, ISB recommendations for standardization in the reporting of kinematic data, J. Biomech. 28 (10) (1995) 1257–1261.
[25] A. Peters, M. Sangeux, M.E. Morris, et al., Determination of the optimal locations of surface-mounted markers on the tibial segment, Gait Posture 29 (1) (2009) 42–48.
[26] E.J. Pratt, M.L. Reeves, J.M. van der Meulen, et al., The development, preliminary validation and clinical utility of a shoe model to quantify foot and footwear kinematics in 3-D, Gait Posture 36 (3) (2012) 434–438.
[27] E.M. Gutierrez, A. Bartonek, Y. Haglund-Akerlind, et al., Centre of mass motion during gait in persons with myelomeningocele, Gait Posture 18 (2) (2003) 37–46.
[28] K. Manal, I. McClay, S. Stanhope, et al., Comparison of surface mounted markers and attachment methods in estimating tibial rotations during walking: an in vivo study, Gait Posture 11 (1) (2000) 38–45.
[29] M. Borhani, A.H. McGregor, A.M. Bull, An alternative technical marker set for the pelvis is more repeatable than the standard pelvic marker set, Gait Posture 38 (4) (2013) 1032–1037.
[30] M.P. Kadaba, H.K. Ramakrishnan, M.E. Wootten, Measurement of lower extremity kinematics during level walking, J. Orthop. Res. 8 (3) (1990) 383–392.

[31] Dempster, Space requirements of the seated operator, WADC Technical Report, University of Michigan, Wright-Patterson Airforce Base, Ohio, 1955.
[32] D.A. Winter, H.G. Sidwall, D.A. Hobson, Measurement and reduction of noise in kinematics of locomotion, J. Biomech. 7 (2) (1974) 157–159.
[33] S.J. Howarth, J.P. Callaghan, Quantitative assessment of the accuracy for three interpolation techniques in kinematic analysis of human movement, Comput. Methods Biomech. Biomed. Eng. 13 (6) (2010) 847–855.
[34] B.D. Roewer, K.R. Ford, G.D. Myer, et al., The 'impact' of force filtering cut-off frequency on the peak knee abduction moment during landing: artefact or 'artifiction'? Br. J. Sports Med. 48 (6) (2014) 464–468.
[35] T.T. Bushman, T.L. Grier, M. Canham-Chervak, et al., The functional movement screen and injury risk: association and predictive value in active men, Am. J. Sports Med. 44 (2) (2016) 297–304.
[36] D.S. Teyhen, S.W. Shaffer, R.J. Butler, et al., Application of athletic movement tests that predict injury risk in a military population: development of normative data, Mil. Med. 181 (10) (2016) 1324–1334.
[37] R.W. Moran, A.G. Schneiders, J. Mason, et al., Do functional movement screen (FMS) composite scores predict subsequent injury? A systematic review with meta-analysis, Br. J. Sports Med. 51 (23) (2017) 1661–1669.
[38] G.B. Salsich, V. Graci, D.E. Maxam, The effects of movement pattern modification on lower extremity kinematics and pain in women with patellofemoral pain, J. Orthop. Sports Phys. Ther. 42 (12) (2012) 1017–1024.
[39] A. Hickey, D. Hopper, T. Hall, et al., The effect of the mulligan knee taping technique on patellofemoral pain and lower limb biomechanics, Am. J. Sports Med. 44 (5) (2016) 1179–1185.
[40] J.H. Hollman, C.M. Galardi, I.H. Lin, et al., Frontal and transverse plane hip kinematics and gluteus maximus recruitment correlate with frontal plane knee kinematics during single-leg squat tests in women, Clin. Biomech. 29 (4) (2014) 468–474.
[41] J. Zwerver, S.W. Bredeweg, A.L. Hof, Biomechanical analysis of the single-leg decline squat, Br. J. Sports Med. 41 (4) (2007) 264–268.
[42] R. Willy, S. Davis, The effect of a hip strengthening program on mechanics during runnning and during a single leg squat, J. Orthop. Sports Phys. Ther. 41 (9) (2011) 625–632.