The reliability of a maximal isometric hip strength and simultaneous surface EMG screening protocol in elite, junior rugby league athletes

Charlton, Paula C., Mentiplay, Benjamin F., Grimaldi, Alison, Pua, Yong-Hao and Clark, Ross A.

Charlton, P. C., Mentiplay, B. F., Grimaldi, A., Pua, Y.-H. and Clark, R. A. (2017). The reliability of a maximal isometric hip strength and simultaneous surface EMG screening protocol in elite, junior rugby league athletes. *Journal of Science and Medicine in Sport*, 20(2), pp. 139-145. https://doi.org/10.1016/j.jsams.2016.06.008

Title: The reliability of a maximal isometric hip strength and simultaneous surface EMG screening protocol in elite, junior rugby league athletes

Author: Paula C. Charlton Benjamin F. Mentiplay Alison Grimaldi Yong-Hao Pua Ross A. Clark

PII: S1440-2440(16)30113-X
DOI: http://dx.doi.org/doi:10.1016/j.jsams.2016.06.008
Reference: JSAMS 1345

To appear in: *Journal of Science and Medicine in Sport*

Received date: 14-1-2016
Revised date: 19-5-2016
Accepted date: 16-6-2016

Please cite this article as: Charlton PC, Mentiplay BF, Grimaldi A, Pua Y-H, Clark RA, The reliability of a maximal isometric hip strength and simultaneous surface EMG screening protocol in elite, junior rugby league athletes., *Journal of Science and Medicine in Sport* (2016), http://dx.doi.org/10.1016/j.jsams.2016.06.008

The reliability of a maximal isometric hip strength and simultaneous surface EMG screening protocol in elite, junior rugby league athletes.

Paula C. Charlton[a], Benjamin F. Mentiplay[b], Alison Grimaldi[c], Yong-Hao Pua[d], and Ross A. Clark[b]

[a] Department of Physical Therapies, Australian Institute of Sport, Canberra, Australia

[b] School of Exercise Science, Faculty of Health Sciences, Australian Catholic University, Melbourne, Australia

[c] Division of Physiotherapy, School of Health and Rehabilitation Sciences, The University of Queensland, Australia

[d] Department of Physiotherapy, Singapore General Hospital, Singapore

Corresponding Author:

Dr Paula C. Charlton, Senior Sports Physiotherapist

Department of Physical Therapies

Australian Institute of Sport, Bruce, Canberra

Australia 2616

Email: paula.charlton@ausport.gov.au

Tel: +61 401360110

Word Count: 3061

Abstract Word Count: 235

Number of Tables: 2

Number of Figures: 1

The reliability of a maximal isometric hip strength and simultaneous surface EMG screening protocol in elite, junior rugby league athletes.

Abstract

Objectives: Firstly to describe the reliability of assessing maximal isometric strength of the hip abductor and adductor musculature using a hand held dynamometry (HHD) protocol with simultaneous wireless surface electromyographic (sEMG) evaluation of the gluteus medius (GM) and adductor longus (AL). Secondly, to describe the correlation between isometric strength recorded with the HHD protocol and a laboratory standard isokinetic device.

Design: Reliability and correlational study

Methods: A sample of 24 elite, male, junior, rugby league athletes, age 16-20 years participated in repeated HHD and isometric Kin-Com (KC) strength testing with simultaneous sEMG assessment, on average (range) six (five to seven) days apart by a single assessor. Strength tests included; unilateral hip abduction (ABD) and adduction (ADD) and bilateral ADD assessed with squeeze (SQ) tests in 0 and 45 degrees of hip flexion.

Results: HHD demonstrated good to excellent inter-session reliability for all outcome measures ($ICC_{(2,1)}$ = 0.76 - 0.91) and good to excellent association with the laboratory reference KC ($ICC_{(2,1)}$ = 0.80 - 0.88). Whilst intra-session, inter-trial reliability of EMG activation and co-activation outcome measures ranged from moderate to excellent ($ICC_{(2,1)}$ = 0.70 – 0.94), inter-session reliability was poor (all $ICC_{(2,1)} < 0.50$).

Conclusions: Isometric strength testing of the hip ABD and ADD musculature using HHD may be measured reliably in elite, junior rugby league athletes. Due to the poor inter-session reliability of sEMG measures, it is not recommended for athlete screening purposes if using the techniques implemented in this study.

Key Words: athletes; muscle strength; thigh; sports; hip; gluteal muscle; hip muscle

Introduction

The rate of groin injury is high in sports requiring repetitive change of direction, running at speed and kicking such as soccer, Australian Rules Football, rugby league and ice hockey.[1-4] Incidence of injury to the groin region in professional soccer ranks second to thigh strain, whilst in Australian Rules Football, it has been reported as one of the top three injury categories to result in lost playing time.[5, 6] Furthermore, these statistics under represent the impact of groin injury as it is confounded by a high rate of recurrence. Specifically, in Australian Rules Football, this has been reported as high as 22%.[7]

The assessment of hip muscle strength is an important component of screening for potential risk of groin injury.[8-10] Reduced bilateral isometric adductor strength has been reported in the weeks preceding onset of groin pain in junior Australian Rules Football athletes.[11] Additionally, national level ice hockey athletes with pre-season isometric hip adduction strength less than 80% of abduction values were 17 times more likely to sustain an adductor strain over the course of the season.[9] Therefore, a reliable and clinically feasible measure of these strength constructs is important as it may subsequently inform coaching and medical staff of potential risk of injury and development of preventative measures.

Activation of hip musculature also appears to be an important consideration with regard to presence of chronic groin pain and history of groin injury.[12-14] Specifically, elite, junior soccer athletes with a history of groin injury have demonstrated reduced surface electromyographic (sEMG) signals in the adductor longus (AL) during common clinical examination tests when compared to athletes without a past history. These tests included assessment of resisted bilateral and unilateral isometric adductor strength in various degrees of hip range of motion where a predominance of AL activity would normally be expected.[13] Additionally, decreased gluteus medius (GM) activation relative to AL during single leg standing and active hip flexion has been demonstrated in participants with chronic groin pain compared with activity matched, healthy controls.[14] However, the association between altered AL and GM activity and risk of future groin injury is yet to be explored. A reliable and feasible method of assessing sEMG in AL and GM in athletic populations might be of use to determine its association with risk of subsequent injury.

Screening protocols should include tests that are reliable and valid for the population in question, and wherever possible include tests that are also clinically feasible. Hand-held dynamometry (HHD) has demonstrated acceptable reliability in healthy adults and athlete populations for the assessment of hip abduction and adduction strength.[15, 16] For sEMG, assessment of activation of AL has demonstrated good inter-trial, intra-session reliability in athletes (ICC = 0.77)[13] however, inter-session reliability has not been reported. And yet, evaluating inter-session reliability is important because clinicians usually obtain repeated measures over time and if these measures are unreliable, then they are subsequently of no value.

The association between HHD and laboratory reference dynamometry has only been reported for hip flexion and extension contractions. Isometric strength measures of the hip flexor musculature in healthy adults were found to be significantly higher using HHD compared with isometric measurements using a laboratory dynamometer.[17] Additionally, medium to high correlations have been reported between HHD and isokinetic measures of isometric knee flexion and extension strength in professional football athletes.[18] However, the association between HHD and isometric measurements using a laboratory isokinetic dynamometer has not yet been established for hip ABD and ADD strength.

This aims of this study are twofold; firstly to evaluate the test-retest reliability of a HHD protocol assessing the maximal isometric strength of the hip ABD and ADD musculature and simultaneous sEMG activation of GM and AL in a population of elite, junior rugby league athletes. Secondly, to determine the association between HHD isometric strength measures and those obtained using a laboratory reference dynamometer, the Kin-Com (KC).

Methods

A convenience sample of 24 elite, male junior rugby league athletes from a single club with mean (range); age 18 (16 – 20) years, height 1.84 (1.74 - 1.97) m and mass 97.4 (81 – 112) kg were invited to participate and subsequently volunteered for testing. Testing was performed during the season of play (July 2013). All testing was conducted in the morning between the hours of six and nine, prior to any training sessions. This time within the athlete schedule was assigned to weights training and therefore athletes were familiar with performing strength exercises during these hours. A test-retest design was used whereby 17 of the participants returned for repeat testing on average (range) six (five to seven) days later. Four athletes were unable to attend repeat testing due to scheduling and transport difficulties. The timeframe between testing sessions allowed complete recovery from potential effects of testing without the possibility of substantial changes in muscle strength as a result of extraneous factors. Athletes were eligible for inclusion if they were free of pain and injury involving the trunk and/or lower limb and were fully training and competing at the time of testing. Athletes were excluded from repeat testing if they sustained a trunk or lower limb injury between sessions (three athletes excluded).

Prior to testing all participants were informed of potential risks of the procedures and written informed consent/assent was obtained from participants or parents/guardians. Participants also answered questions regarding demographics and leg dominance (kicking leg). Ethics approval was granted by the Institutional Ethics Review Board.

A standardised testing protocol was performed consisting of maximal isometric strength testing of the hip ABD and ADD musculature with simultaneous evaluation of sEMG of the AL and GM with HHD and unilateral tests were repeated using a reference laboratory dynamometer (KC).[19] All HHD testing was performed using a Lafayette Manual Muscle Tester, Model # 01163 (Lafayette Instrument Inc., Lafayette, Indiana) and involved unilateral maximal isometric strength testing of the right and left ABD and ADD musculature, and bilateral ADD muscle strength testing in the form of SQ tests in two different positions of hip flexion, 0 degrees (SQ 0) and approximately 45 degrees (SQ 45). A KC device (Chattecx

Corporation, Chattanooga, TN) was used as the laboratory criterion reference and all procedures are described in further detail in Figure 1. All testing was performed in the same order. Standardised instructions were verbally administered to participants prior to each test. Three trials of each test with at least 10 seconds rest between trials were performed. The maximal peak force (recorded in kg) of the three trials was used as the strength outcome measure. It was deemed unnecessary to convert force measures to torque (Nm), as the purpose of this study was to determine reliability of the measures and therefore only comparison of absolute values was performed. A single physiotherapist assessor with nine years of clinical experience performed all strength testing for both sessions and was blinded to the results of the previous session.

A Noraxon Telemyo DTS system with wireless electrodes was used for sEMG data collection. Bi-polar Ag/AgCl surface electrodes (Myotronics, Kent, Washington) were positioned over the muscle bellies, parallel to the direction of muscle fibres of the GM and AL that were firstly marked on each participant using a felt tipped pen prior to the commencement of testing. The positions were determined according to the guidelines provided by Surface EMG for the Non-Invasive Assessment of Muscles (SENIAM).[20] For the GM, this was 50% of the distance between the greater trochanter and the iliac crest. Whilst specific guidelines for the electrode placement for AL are not reported by SENIAM, a position one third the length of the medial aspect of the thigh (measured from the pubic symphysis to the medial femoral condyle) was chosen.[13] Prior to electrode placement, the skin of each participant was prepared according to SENIAM guidelines to reduce impedance. This involved shaving, lightly abrading and then swabbing the electrode site with an alcohol wipe.

The electrodes were wirelessly connected to the receiver system, sampling at 3000Hz, which output analogue voltage data to a National Instruments CompactDAQ with BNC9215 modules (National Instruments, Austin, Texas). A manual assessment of muscle activation was performed to confirm the EMG signal on a laptop via Bluetooth prior to commencing the HHD and KC protocol.

Customised Labview software (National Instruments, Austin, Texas) was used to collect and process the sEMG activity of the muscles, with data acquired through the DAQ device. All raw EMG signals were digitally filtered by the custom software program using a 10-500Hz bandpass filter. Raw sEMG was visually assessed. The maximal isometric ABD and ADD contractions performed by participants for HHD testing were used as reference maximal voluntary contractions (MVCs) to normalise the peak sEMG recordings for each test. For all sEMG signals, a root mean square (RMS) curve was calculated via a moving 50ms window (epoch) across each five second recording. Outcome measures for sEMG included absolute activation of GM and AL during HHD and KC to determine intra-session association. We investigated the reliability of the average of comparisons across the three trials for all sEMG outcome measures. Co-activation ratios of the R AL and GM were determined for: relative activation of the AL during ABD and; relative activation of the GM during ADD. Co-activation ratios were performed for this study as previous research has reported antagonist muscle activity to be an important factor for the maintenance of joint stability in athletic populations.[21] Whilst currently there is no evidence to suggest a link between co-activation strategies of the hip musculature and risk of groin injury, it was nonetheless deemed worthwhile to investigate.

All data analysis was performed using the Statistical Package for Social Sciences (SPSS, IBM Corporation, Chicago) version 20.0. Relative reliability for HHD, KC and sEMG was determined using Intraclass Correlation Coefficients, ICC$_{(2,1)}$ (95% CIs) and Spearman rho values. Point estimates of these correlations were interpreted based on parameters provided by Portney and Watkins[22] as follows: good to excellent (>0.75); moderate to good (0.50 - 0.75); or poor correlations (<0.50). Absolute reliability was determined using standard error of measurement (SEM) and minimum detectable change (MDC). SEM was calculated as the standard deviation (SD)/$\sqrt{n}$ and MDC was calculated as 1.96 x $\sqrt{2}$ x SEM. Intra-session association of HHD and KC including simultaneous sEMG for both sessions was determined using $ICC_{(2,1)}$ (95% CIs) and interpreted using the same point estimates described above. All values presented are means (±SD).

Results

The absolute values and reliability data for HHD and KC are presented in Table 1. Inter-session reliability for HHD was good to excellent ($ICC_{(2,1)}$ = 0.76 - 0.91) for all outcome measures and good to excellent for KC R ABD ($ICC_{(2,1)}$ = 0.80) and R ADD ($ICC_{(2,1)}$ = 0.88).

Mean intra-session, inter-trial reliability of sEMG activation of the R GM and AL was good to excellent for all HHD and KC strength tests ($ICC_{(2,1)}$ = 0.78 – 0.95). Similarly, inter-trial reliability of sEMG co-activation ratios for GM and AL was good to excellent ($ICC_{(2,1)}$ = 0.85 and 0.94 respectively). SEMG activation of these muscles expressed as a ratio SQ 45: SQ 0 demonstrated only moderate to good correlation ($ICC_{(2,1)}$ = 0.70 and 0.81 respectively).

Inter-session reliability data of the sEMG activation of the R and L AL and GM during SQ (expressed as a ratio of SQ 45: SQ 0) are reported in Table 2. Poor inter-session reliability was evident for both R and L ADD during both SQ tests ($ICC_{(2,1)}$ = 0.40 and 0.47 respectively).

The sEMG co-activation ratio values (mean ±SD) during HHD and KC and reliability data for session one and two are presented in Table 2. Inter-session reliability of sEMG co-activation of R AL during R ABD for HHD and KC was poor ($ICC_{(2,1)}$ = 0.11 and 0.36 respectively). SEMG co-activation of the R GM during R ADD for HHD and KC was also poor ($ICC_{(2,1)}$ = 0.22 and 0.14 respectively).

Data describing the relationship between HHD and KC devices of sEMG activation and co-activation ratios during strength tests for both sessions are reported in Table 2. Association of sEMG co-activation ratio of R AL when performing R ABD during HHD and KC was good to excellent for session one ($ICC_{(2,1)}$ = 0.97), however only moderate to good for session two

(ICC$_{(2,1)}$ = 0.57). Association between devices for sEMG co-activation of R GM during R ADD was poor for both session one and two (ICC$_{(2,1)}$ = -0.28 and 0.32 respectively). Association of sEMG activation for GM between HHD and KC devices for session one and two was poor (ICC$_{(2,1)}$ = 0.29 and 0.36 respectively), however was good to excellent for sEMG activation of AL during adduction for both sessions (ICC$_{(2,1)}$ = 0.89 and 0.78 respectively).

Correlations between HHD and KC devices expressed as ICC$_{(2,1)}$ (95% CIs) are presented in Table 1. The association between HHD and KC devices was poor for R ABD for session one (ICC$_{(2,1)}$ = 0.19), however was good to excellent for session two (ICC$_{(2,1)}$ = 0.79). For R ADD, the association between devices was good to excellent for both sessions (ICC$_{(2,1)}$ = 0.79 and 0.82 respectively).

Discussion

This is the first study to perform simultaneous sEMG of the GM and AL during maximal isometric strength testing of the hip ABD and ADD musculature in a cohort of elite, junior rugby league athletes and to evaluate the test-retest reliability of these outcome measures . Additionally, this study is the first to investigate the association between HHD and KC isometric strength assessment. The specific isometric strength tests chosen for this study are commonly used in the evaluation of groin injury in the clinical setting and some have also been reported to relate to risk of groin injury.[9, 11, 23]

We demonstrated good reliability of HHD for hip ABD and ADD. Previous studies have also reported good HHD reliability for isometric hip flexion and bilateral ADD in semi-professional adult soccer athletes,[15] however the reliability of unilateral strength tests for ABD and ADD was not investigated. In the present study the lowest reliability values were evident for bilateral SQ tests whereas higher reliability was evident for unilateral tests of hip ABD and ADD. The slightly lower reliability values and larger MDC values demonstrated during bilateral SQ tests favour the use of unilateral assessment of hip ABD and ADD.

To our knowledge, we are the first to report simultaneous measurement of GM and AL sEMG activation during isometric strength testing for both HHD and KC in an athletic population. Delahunt et al.[23] has reported AL activation during a series of squeeze tests (at 0, 45 and 90 degrees of hip flexion), and found the highest sEMG activity in the 45 degree test position, and also reported that this coincided with the greatest pressure values (measured using a sphygmometer). However, the study did not report reliability of these measurements. The results of our study indicate that whilst inter-trial, intra-session reliability for activation and co-activation ratios of GM and AL during the HHD and KC strength tests was acceptable, inter-session reliability was poor for both activation and co-activation data. Additionally, the MDC values for all sEMG measurements were large, including intra-session results and even intra-session, inter-trial data should be used with caution. The good intra-session reliability concurs with previous research investigating sEMG of the AL which reported good to excellent intra-session reliability during SQ 0 testing.[13] However, inter-session reliability was not reported. Similarly, Sener et al.[12] evaluated the sEMG of AL during a selection of hip adduction strengthening exercises in healthy, elite soccer athletes, and reported intra-session reliability of the measurements to be excellent for the majority of exercises. Poorer intra-session reliability was reported for exercises involving isometric actions.[12] Again, inter-session reliability was not reported. Oskouei et al.[24] reported inter-day reliability of forearm surface SEMG during various hand grip forces.[24] In agreement with the present study, average measures intra-session reliability was excellent, however, removal and subsequent replacement of electrodes inter-day produced poor reliability.[24] These results and those of the present study therefore suggest there is no use for sEMG as a screening tool for measurement of AL and GM activation.

Results of the present study indicate that HHD measures correlate with those derived using a criterion reference laboratory device. Good to excellent association between devices for R ABD and ADD was demonstrated for the second testing session. However, it should be noted that the association of session one R ABD was poor. This aberrant result is certainly a limitation of the present study. One potential reason is inadequate participant familiarization with the KC device. It was anticipated that athletes were highly familiar with the HHD protocol and specific movement patterns associated with maximal isometric testing of the hip ABD and ADD musculature, having undergone the HHD procedure regularly. However, lack of familiarity with the KC device may yet have influenced the poor session one result that was no longer evident in session two.

The present study has some limitations which should be noted. There are a number of issues that have been widely reported to affect the accuracy of sEMG measurements that may have affected the present study. These include inexperience of the researcher identifying the correct position on the musculature and application of the electrodes, soft tissue displacement affecting electrode placement, as well as movement of electrodes between placement on the participant and positioning for testing.[25] Wherever possible, it was attempted to minimise the effect of these issues. Furthermore, an additional tests that might have enhanced sEMG location on the correct musculature such as ultrasound analysis, were not performed. Additionally, it should be noted that whilst electrode placement for GM was standardised according to SENIAM guidelines, it is likely that the only the activation of primarily the anterior fibres of GM would have been measured.[26] Activation of other hip abductors such as the tensor fascia late and the gluteus maximus would have been accounted for with the HHD results and not with GM sEMG data. Accordingly, this should be acknowledged when interpreting the results of the study, particularly with respect to the usefulness of sEMG for indicating activation of the hip abductor musculature system as a whole. Whilst participant-specific differences such as skin conductivity, cross talk from adjacent musculature and amount of adipose tissue overlying musculature can affect comparison between participants, attempts were made to minimise their impact by analysis of ratio data and normalising data to MVCs.

Future research should examine the comparison of hip strength in participants with and without a past history of significant pain or injury to the hip and groin region, and prospectively whether there is any association between the relevant strength measurements and future risk of injury over the course of a competitive season. This is especially the case for hip ABD strength which is yet to be investigated with respect to risk of future groin injury for some athletic populations. Additionally, the reliability of alternative EMG assessment techniques such as in-dwelling electrodes or analysis during submaximal contractions may be considered.

Conclusion

The current study presents a clinically feasible HHD strength testing protocol for the hip ABD and ADD musculature that is reliable and has potential for use in large-scale screening. Whilst sEMG of the GM and AL demonstrated good inter-trial reliability and may be used for within session comparisons of muscle activation, poor inter-session reliability negates its use for screening purposes.

Practical applications

- HHD is a reliable clinical tool that can be used with minimal set up requirements to measure hip ABD and ADD strength in elite, junior rugby league athletes.
- Weakness of the hip ADD musculature has been previously been associated with risk of groin injury and this HHD protocol may be used to potentially identify at-risk athletes.
- Inter-session reliability of sEMG signals for GM and AL using our technique was poor and therefore its use as a screening tool is not recommended. .

Acknowledgements

The authors wish to acknowledge the support of the team from which the recruiting occurred. Specifically the head strength and conditioning coach, Adrian Jiminez and assistant coaches.

References

1. Ekstrand J, Hilding J. The incidence and differential diagnosis of acute groin injuries in male soccer players. *Scan J Med Sci Sports.* 1999; 9(2):98-103.
2. Orchard J, Wood T, Seward H, et al. Comparison of injuries in elite senior and junior Australian football. *J Sci Med Sport.* 1998; 1(2):83-88.
3. Agel J, Dompier TP, Dick R, et al. Descriptive epidemiology of collegiate men's ice hockey injuries: National Collegiate Athletic Association Injury Surveillance System, 1988–1989 through 2003–2004. *J Athl Training.* 2007; 42(2):241.
4. Gabbett TJ, Jenkins DG. Relationship between training load and injury in professional rugby league players. *J Sci Med Sport.* 2011; 14(3):204-209.
5. Hagglund M, Walden M, Ekstrand J. Previous injury as a risk factor for injury in elite football: a prospective study over two consecutive seasons. *Br J Sports Med.* 2006; 40(9):767-772.
6. Orchard J, Seward H. Injury report 2010: Australian football league. *Sport Health.* 2011; 29(2):15.
7. Orchard JW, Seward H, Orchard JJ. Results of 2 decades of injury surveillance and public release of data in the Australian Football League. *Am J Sports Med.* 2013:0363546513476270.
8. Hölmich P. Long-standing groin pain in sportspeople falls into three primary patterns, a “clinical entity” approach: a prospective study of 207 patients. *Br J Sports Med.* 2007; 41(4):247-252.
9. Tyler TF, Nicholas SJ, Campbell RJ, et al. The association of hip strength and flexibility with the incidence of adductor muscle strains in professional ice hockey players. *Am J Sports Med.* 2001; 29(2):124-128.
10. Thorborg K, Branci S, Nielsen MP, et al. Eccentric and Isometric Hip Adduction Strength in Male Soccer Players With and Without Adductor-Related Groin Pain An Assessor-Blinded Comparison. *OJSM.* 2014; 2(2).
11. Crow JF, Pearce AJ, Veale JP, et al. Hip adductor muscle strength is reduced preceding and during the onset of groin pain in elite junior Australian football players. *J Sci Med Sport.* 2010; 13(2):202-204.
12. Serner A, Jakobsen MD, Andersen LL, et al. EMG evaluation of hip adduction exercises for soccer players: implications for exercise selection in prevention and treatment of groin injuries. *Br J Sports Med.* 2013.
13. Lovell GA, Blanch PD, Barnes CJ. EMG of the hip adductor muscles in six clinical examination tests. *Phys Ther Sport.* 2012; 13(3):134-140.
14. Morrissey D, Graham J, Screen H, et al. Coronal plane hip muscle activation in football code athletes with chronic adductor groin strain injury during standing hip flexion. *Man Ther.* 2012; 17(2):145-149.
15. Fulcher ML, Hanna CM, Raina Elley C. Reliability of handheld dynamometry in assessment of hip strength in adult male football players. *J Sci Med Sport.* 2010; 13(1):80-84.
16. Thorborg K, Petersen J, Magnusson S, et al. Clinical assessment of hip strength using a hand-held dynamometer is reliable. *Scan J Med Sci Sports.* 2010; 20(3):493-501.
17. Li RC, Jasiewicz JM, Middleton J, et al. The development, validity, and reliability of a manual muscle testing device with integrated limb position sensors. *Arch Phys Med Rehabil.* 2006; 87(3):411-417.
18. Whiteley R, Jacobsen P, Prior S, et al. Correlation of isokinetic and novel hand-held dynamometry measures of knee flexion and extension strength testing. *J Sci Med Sport.* 2012; 15(5):444-450.
19. Stark T, Walker B, Phillips JK, et al. Hand-held dynamometry correlation with the gold standard isokinetic dynamometry: a systematic review. *PM&R.* 2011; 3(5):472-479.

20. Hermens HJ, Freriks B, Merletti R, et al. *European recommendations for surface electromyography*, Roessingh Research and Development The Netherlands; 1999.
21. Aagaard P, Simonsen E, Andersen J, et al. Antagonist muscle coactivation during isokinetic knee extension. *Scan J Med Sci Sports.* 2000; 10(2):58-67.
22. Watkins MP, Portney L. *Foundations of clinical research: applications to practice*, Pearson/Prentice Hall; 2009.
23. Delahunt E, Kennelly C, McEntee BL, et al. The thigh adductor squeeze test: 45° of hip flexion as the optimal test position for eliciting adductor muscle activity and maximum pressure values. *Man Ther.* 2011; 16(5):476-480.
24. Hashemi Oskouei A, Paulin MG, Carman AB. Intra-session and inter-day reliability of forearm surface EMG during varying hand grip forces. *J Electromyogr Kinesiol.* 2013; 23(1):216-222.
25. Basmajian J, Deluca C. Muscles Alive. In: Baltimore M, ed. 5th ed ed: Williams & Wilkins; 1985.
26. Flack NAMS, Nicholson HD, Woodley SJ. A review of the anatomy of the hip abductor muscles, gluteus medius, gluteus minimus, and tensor fascia lata. *Clin Anat.* 2012; 25(6):697-708.

Figure Legends

Figure 1: Testing positions for each of the handheld dynamometry (HHD) and Kin-Com (KC) isometric strength tests. Prior to testing the position of the force transducer for HHD was marked both five centimetres proximal to the mid-point of the medial malleolus and five centimetres proximal to the mid-point of the lateral malleolus using a felt tipped pen. A familiarisation trial in each movement direction was performed until participants were comfortable with the procedures and the tester was satisfied with correct performance. Three trials each of all tests for each side were performed with at least 10 seconds between trials. The maximal peak force (in kilograms) of the three tests was recorded.

1A: HHD unilateral hip ABD. Participant in supine with the contralateral leg positioned laterally off the edge of the plinth and the participant instructed to hold the edge of the plinth at waist level to stabilise the trunk. Testing leg positioned with the hip joint in anatomical position (zero degrees of flexion and extension). The dynamometer force transducer is positioned 5cm proximal to the lateral malleolus. The participant is instructed to gradually build towards a maximal contraction, "pushing as hard as possible" against the assessor and hold this contraction for three seconds. A "make" test was applied whereby the assessor matches the maximal muscular contraction a participant is able to perform.[16]

1B: HHD unilateral hip ADD. Identical participant positioning as for 1A, however, the dynamometer force transducer is positioned 5cm proximal to the medial malleolus.

1C: HHD bilateral hip adduction with hips in 0 degrees knee flexion/extension (SQ 0). Participant in supine with the lower limbs parallel, knees extended and hips in a neutral position. The assessor positions the dynamometer between the right and left medial epicondyles of the femur. Participant is instructed to build towards "squeezing as hard as possible with both knees" against the dynamometer and hold for three seconds. Participant instructed to maintain the hips and knees extended during testing.

1D: HHD bilateral hip ADD with hips in approximately 45 degrees knee flexion (SQ 45). Participant in supine with the lower limbs parallel with the knees extended and hips in a neutral position. Assessor positions the right hip in flexion by placing the heel of the foot in line with the contralateral medial femoral condyle. Contralateral heel is placed adjacent to the already positioned limb such that the hips are in approximately 45 degrees of flexion. Although it is acknowledged that this is not an exact angle, the position is nonetheless standardised for each participant and is quick and easy to administer in the clinical setting. The assessor positions and maintains the HHD between the medial femoral epicondyles. Participant instructed to build towards “squeezing as hard as possible with both knees” against the dynamometer and hold for three seconds.

1E: Kin-Com unilateral hip ABD and ADD. Only the right side was evaluated for KC testing as a substantial number of maximal strength tests were performed within a single session, and we did not intend to impose unnecessary time or fatigue burden on the subject. Additionally, only unilateral ABD and ADD were assessed as it was not possible to replicate squeeze testing using the KC. The starting position was identical for ABD and ADD with the participant in supine with the left leg off the lateral edge of the plinth. Three stabilising belts are firmly attached to the participant; two diagonally across the trunk in each direction and a third horizontally across the pelvis. The right hip and knee are positioned in neutral with the ankle firmly fixated to the dynamometer resistance pad using straps five centimetres proximal to the medial and lateral malleolus. Identical instructions as for HHD ABD and ADD (described previously) are administered.

Table 1 Intra-rater reliability and correlation of HHD and KC session 1 and 2.

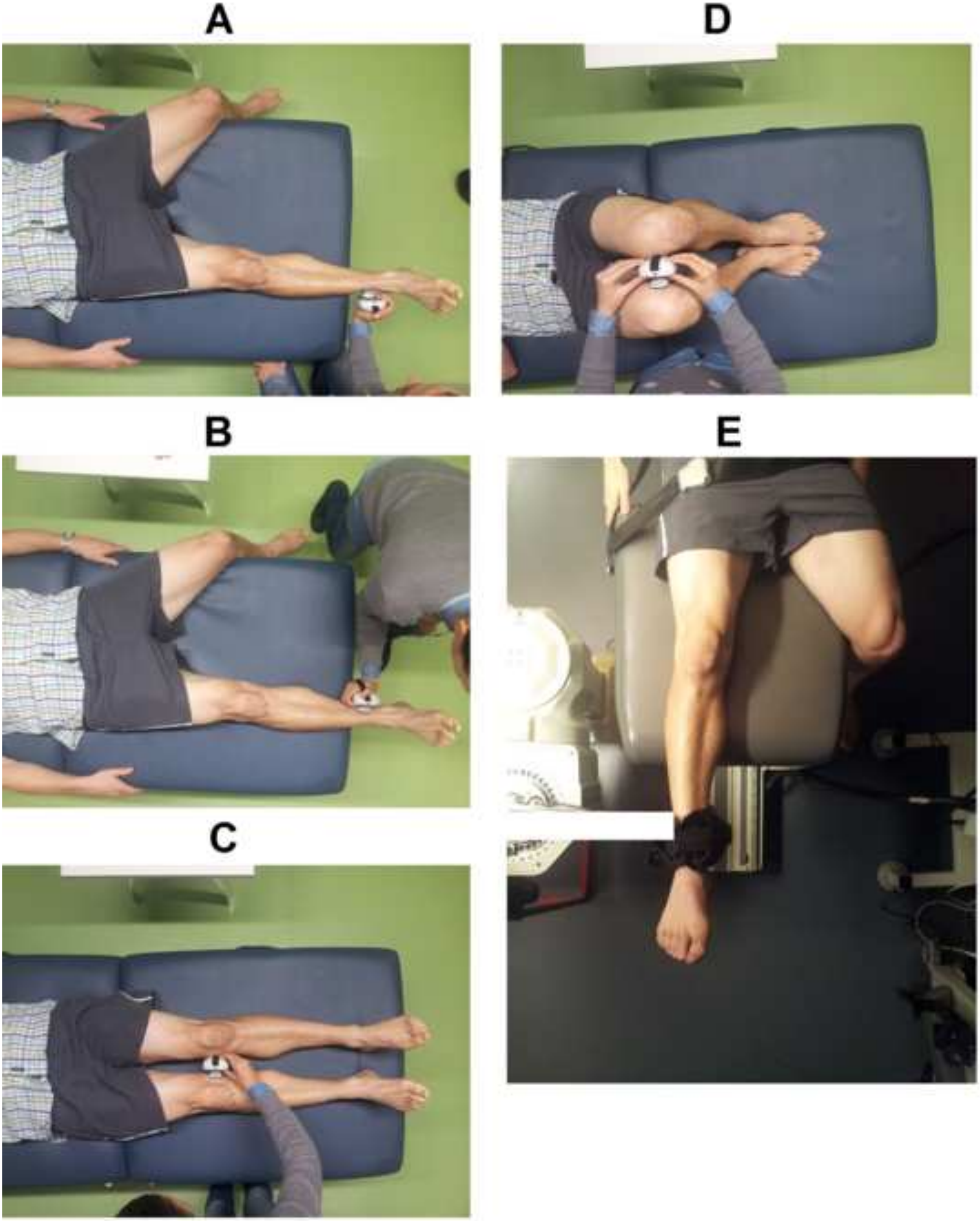
Outcome measure	HHD(±SD)	KC(±SD)	ICC$_{(2,1)}$ (95%CI)
Right Abduction (Kg)			
Session 1	21.4 (3.1)	19.0 (3.3)	0.19 (-1.00-0.67)
Session 2	20.5 (3.4)	19.3 (3.5)	0.79 (0.41-0.93)
ICC$_{(2,1)}$ (95%CI)	0.87 (0.65-0.95)	0.80 (0.46-0.93)	
SEM	1.1	1.5	
MDC	3.1	4.1	
Spearman R *	0.69*	0.75*	
Left Abduction (Kg)			
Session 1	19.7 (3.2)	-	-
Session 2	18.9 (3.3)	-	-
ICC$_{(2,1)}$ (95%CI)	0.90 (0.73-0.96)	-	
SEM	1.0	-	
MDC	2.8	-	
Spearman R *	0.78*	-	
Right Adduction (Kg)			
Session 1	25.4 (5.7)	23.5 (5.7)	0.79 (0.49-0.92)
Session 2	24.7 (5.1)	22.7 (6.8)	0.82 (0.49-0.94)
ICC$_{(2,1)}$ (95%CI)	0.88 (0.66-0.96)	0.88 (0.67-0.95)	
SEM	2.0	2.0	
MDC	5.5	5.6	
Spearman R *	0.76*	0.73*	
Left Adduction (Kg)			
Session 1	26.1 (5.8)	-	-
Session 2	26.2 (6.5)	-	-
ICC$_{(2,1)}$ (95%CI)	0.91 (0.76-0.97)	-	
SEM	1.7	-	
MDC	4.7	-	
Spearman R *	0.90*	-	
Squeeze 0 (Kg)			
Session 1	34.6 (8.9)	-	-
Session 2	34.2 (8.9)	-	-
ICC$_{(2,1)}$ (95%CI)	0.83 (0.52-0.94)	-	
SEM	3.7	-	
MDC	10.2	-	
Spearman R *	0.81*	-	
Squeeze 45 (Kg)			
Session 1	27.1 (6.9)	-	-
Session 2	27.1 (5.9)	-	-
ICC$_{(2,1)}$ (95%CI)	0.76 (0.36-0.91)	-	
SEM	3.4	-	
MDC	9.3	-	
Spearman R *	0.69*	-	

HHD = Hand held dynamometry; KC = Kincom; SD = standard deviation; * indicates significance at $p < 0.05$; ICC = intraclass correlation coefficient; SEM = standard error of measurement reported for session 1; MDC = minimal detectable change reported for session 1.

Table 2 Intra-rater reliability and correlation of EMG co-activation ratios during HHD and KC session 1 and 2.

Outcome measure	EMG HHD(±SD)	EMG KC(±SD)	ICC$_{(2,1)}$ (95%CI)
Co-activation R ADD during R ABD			
Session 1	12.8 (10.9)	8.3 (5.5)	0.97 (0.93-0.99)
Session 2	14.7 (21.6)	12.4 (11.0)	0.57 (-0.96-0.83)
ICC$_{(2,1)}$ (95%CI)	-0.11 (-2.3-0.63)	0.36 (-0.99-0.80)	
SEM	10.92	4.37	
MDC	30.26	12.12	
Spearman R *	-0.19	0.24	
Co-activation R ABD during R ADD			
Session 1	11.0 (10.4)	9.7 (5.7)	-0.28 (-1.5-0.58)
Session 2	9.7 (5.1)	9.7 (5.1)	0.32 (-7.14-0.73)
ICC$_{(2,1)}$ (95%CI)	0.22 (-1.3-0.74)	0.14 (-2.21-0.77)	
SEM	10.42	5.27	
MDC	28.87	14.62	
Spearman R *	0.17	-0.12	
Activation R ABD during R ABD [a]			
Session 1	340.2 (183.7)	326.1 (183.1)	0.29 (-0.71-0.71)
Session 2	279.2 (120.0)	285.4 (166.1)	0.36 (-0.61-0.75)
Activation R ADD during R ADD [a]			
Session 1	372.5 (167.5)	472.8 (231.2)	0.89 (0.73-0.96)
Session 2	600.0 (448.0)	597.0 (483.3)	0.78 (0.44-0.91)
Squeeze 45: Squeeze 0 activation R ADD			
Session 1	118.1 (47.2)	-	-
Session 2	178.3 (113.1)	-	-
ICC$_{(2,1)}$ (95%CI)	-0.40 (-2.84-0.50)	-	
SEM	57.30	-	
MDC	158.8	-	
Spearman R *	-0.39	-	
Squeeze 45: Squeeze 0 activation L ADD			
Session 1	116.1 (63.9)	-	-
Session 2	172.4 (103.3)	-	-
ICC$_{(2,1)}$ (95%CI)	0.47 (-0.47-0.81)	-	
SEM	47.98	-	
MDC	133.01	-	
Spearman R *	0.47	-	

HHD = Hand held dynamometry; KC = Kincom; SD = standard deviation; * indicates significance at $p < 0.05$; R = right; L = left; ABD = abduction; ADD = adduction; ICC = intraclass correlation coefficient; SEM = standard error of measurement reported for session 1; MDC = minimal detectable change reported for session 1; [a] = only ICC's are presented for this data.


A
D
B
E
C