Can a single-legged squat provide insight into movement control and loading during dynamic sporting actions in athletic groin pain patients?

Abstract

Context: Chronic athletic groin pain (AGP) is common in field sports and has been associated with abnormal movement control and loading of the hip and pelvis during play. A single-legged squat (SLS) is commonly used by clinicians to assess movement control but whether it can provide insight into control during more dynamic sporting movements in AGP patients is unclear. ***Objective:*** To determine the relationships between biomechanical measures in a SLS and these same measures in a single-legged drop landing, single-legged hurdle hop and a cutting manoeuvre in AGP patients. ***Design:*** Cross-sectional study. ***Setting:*** Biomechanics laboratory. ***Patients:*** Forty recreational field sports players diagnosed with AGP. ***Intervention:*** A biomechanical analysis of each individual's SLS, drop-landing, hurdle hop and cut was undertaken. ***Main Outcome Measures:*** Hip, knee and pelvis angular displacement, and hip and knee peak moments. Pearson product moment correlations were used to examine relationships between SLS measures and equivalent measures in the other movements. ***Results:*** There were no significant correlations between any hip or pelvis measure in the SLS with these same measures in the drop landing, hurdle hop or cut (r range = 0.03 - 0.43, $P > 0.05$). Knee frontal and transverse plane angular displacement were related in the SLS and drop landing only, while knee moments were related in the SLS, drop-landing and hurdle hop (r range = 0.50 - 0.67, $P < 0.05$). ***Conclusion:*** For AGP patients, a SLS did not provide a meaningful insight into hip and pelvis control or loading during sporting movements that are associated with injury development. The usefulness of a SLS test in the assessment of movement control and loading in AGP patients is thus limited. The SLS provided a moderate insight into knee control while landing and therefore may be of use in the examination of knee injury risk.

Key Words: biomechanics, control, loading, cutting, landing

Introduction

Chronic groin pain is commonly experienced in a range of field sports including soccer,[1] Gaelic football[2] and rugby union.[3] There is also a significant morbidity associated with groin pain; it is behind only fracture and joint reconstruction in terms of time lost from sport.[3-5] While an array of descriptors of chronic groin injury currently exist, the term 'athletic groin pain' may be used to refer to a multitude of presenting symptoms of pain around the groin and lower abdomen. Athletic groin pain (AGP) may emanate from pathology of the adductor, hip flexor and lower abdominal musculature,[6] the hip joint and the pubic bone/symphysis.[7, 8] Although the specific aetiology of AGP is subject to much debate,[9-11] several authors have implicated abnormal movement control and loading in and around the hip and pelvis during play.[12-14] In light of this, sports clinicians frequently assess movement control in their AGP patients.

The single-legged squat (SLS) is a common test used in the assessment of movement control;[15, 16] it can be carried out with minimal space requirements and is undertaken at a speed that makes qualitative examination possible. While some authors suggest a SLS may be useful as an indicator of lumbo-pelvic hip control[16] and injury risk,[15, 17] others have questioned its validity,[18] or advised caution in extrapolating findings to more dynamic sporting movements.[19] From an ecological validity perspective, a major criticism of the SLS is that it does not involve the same speed or dynamic loading characteristics of field sport actions implicated in the aetiology of injury, [20, 21] such as cutting[22] and landing.[19] Thus, the

SLS may not provide an insight into movement control or loading during more dynamic sporting actions that are associated with AGP.

Few previous studies have comprehensively examined the relationship between the biomechanics of a SLS and the biomechanics of other more sport specific actions. Strensrud et al,[23] for example, found poor correlations between knee valgus angle in a SLS and single leg drop jump (Spearman rank 0.24-0.53), but no comparison of hip and pelvis measures was undertaken. While there is some evidence to suggest that a SLS may provide insight into hip biomechanics while straight line running,[24] it is change of direction cutting that is more commonly associated with groin pain.[4, 25] Besier et al[26] found that cutting places a much greater load and control challenge on the body than straight line running; frontal and transverse plane knee joint moments during a cut were considerably larger ($P < 0.05$). As far as we are aware no previous studies have examined relationships between a cut and a SLS in terms of movement control and loading.

The extent to which movement control and loading in a SLS is indicative of control and loading in more dynamic sporting conditions associated with AGP is of significance but has yet to be fully examined. The primary aim of our study was to determine the relationships between relevant biomechanical measures in a SLS and these same measures in field sport related movements in AGP patients. A single-legged drop landing, a single-legged hurdle hop and a cutting manoeuvre were examined. A comparison of variable magnitudes across each of the four movement tests was also undertaken to determine the extent to which movement technique and loading differed. In addition, the relationships between biomechanical measures in the drop landing, hurdle hop and cut were also compared. It was hypothesised that a SLS would not provide a meaningful insight into dynamic movement control and loading in AGP patients due to a lack of movement specificity. The findings of this study should facilitate a more informed decision on the use of a SLS screening test to assess dynamic movement control in AGP patients.

Methods

Design

A cross-sectional study design was employed. The independent variables were the movement tests of interest, that is, a SLS, a drop landing, a hurdle hop and a cut. The dependent variables were hip, knee and pelvis angular displacement (range of motion, °), peak moments at the hip and knee ($Nm\cdot kg^{-1}$), peak ground reaction forces ($N.kg^{-1}$) and the duration of the eccentric phase (ms).

Patients

We recruited forty (n = 40) recreational field sports players diagnosed with chronic athletic groin pain from patients at the xxxxxxxxxxxx (mean ± *SD*: age, 27.8 ± 6.3 years; height, 180.2 ± 6.1 cm; mass, 83.1 ± 10.7 kg; time with groin pain, 53.8 ± 39.1 weeks). Participants had presented with exercise-related pain in the proximal medial thigh, proximal anterior thigh, lower abdominal, inguinal and/or perineal regions. A diagnosis was obtained based on diagnostic tests (a SLS, hip joint range of motion, the flexion adduction internal rotation test (FADER), the flexion abduction external rotation test (FABER), squeeze tests, resisted sit up, resisted straight leg raise, Thomas test) and palpation reproducing the athletes' pain. A SLS is used on clinical assessment, in part as a pain provocation test, but we are unaware if it can provide an insight into movement control during more dynamic movements. The majority of participants were diagnosed with pubic aponeurosis pathology (80%, n = 32) followed by hip pathology (18%, n = 7) and hip flexor pathology (2%, n = 1), while 13% (n = 5) had combined hip and pubic aponeurosis pathology. 80% (n = 32) of participants experienced unilateral AGP while the remainder (20%, n = 8) experienced bi-lateral pain. The majority of participants played Gaelic football (60%), hurling (18%), soccer (10%) and rugby (8%). All participants provided written informed consent as required by the xxxxxxxxxxx Ethics Committee.

Procedures

Prior to testing, we recorded participants' height and weight using an electronic scale (Seca 876) and stadiometer (Seca 213). Participants then undertook a standardised warm-up which consisted of five body weight squats and five sub-maximal countermovement jumps (instructed to jump at 50% of perceived maximal intensity). Testing involved three trials (both left and right side) of a SLS, a single-legged drop landing, a single-legged hurdle hop, and a running cut. We acknowledge that landing, land-and-go and cutting movements such as these have yet to be truly validated as determinants of AGP. However, we suggest that these performance tests are likely candidates for biomechanical assessment protocols as they are dynamic multi-joint activities that challenge hip, pelvis and groin control and are commonly undertaken in field sports such as soccer, gaelic football and rugby union where AGP is prevalent.[1-3] During each test participants made foot contact with one of two identical force platforms. The floor of the 3D biomechanics laboratory is an artificial grass surface (polyethylene mono filament, Condor Grass, Holland) which is permanently and firmly fixed to the force plates (Sanctuary Synthetic Adhesive, Ireland). Participants wore brief shorts and their own athletic footwear.

For the SLS, we instructed participants to place their hands across their chest, place the non weight bearing foot behind them (with an approximate 90° knee bend) and then squat as low as possible with an upright trunk.[15] For the drop landing, participants stood on top of a 30cm step (in the same preparatory position described for the squat), landed and held the landing position for 2 seconds.[27] We took care to ensure participants dropped directly from the 30cm height rather than jumping vertically and thus landing from a greater height. The hurdle hop involved a lateral hop over a 15cm hurdle and then an immediate hop back to the initial starting position. We instructed participants to undertake the hop as quickly as possible, and while the free leg was in the same orientation as described for the SLS, the arms were free to move. The lateral distance travelled between foot contacts in the hurdle hop was approximately 40cm, that is, the distance between force plate centres. The landing from the first hop over the hurdle was analysed. The hurdle hop task was included in the testing battery as it may place a different control challenge on the body than the predominately sagittal plane single leg landing.[28]

For the running cut, participants ran as fast as possible for five meters toward a marker placed on the floor, made a single complete foot contact in a 40X60cm area in front of the marker (the force plate), and performed an approximate 75° cut before running maximally for another five meters to the finish (figure 1). Participants were instructed to plant with the outside foot (when cutting left plant with the right and vice versa). Through clinical experience we have observed that acute cutting angles in the region of 75° are often provocative in athletic groin pain patients. We instructed participants to complete the task as quickly as possible. The initial and final foot contact in the running cut initiated and stopped a timing device (Games Education – Hotspot, UK).

Figure 1

Testing was carried out in the order of SLS, drop landing, hurdle hop and running cut, and all six trials of one movement were completed before moving on to the next new movement. Tests were carried out in the order of lowest to highest intensity exercise in a further attempt to minimize potential fatigue effects. The order of leg testing (left versus right) was randomized. Participants undertook two practice trials of each movement (submaximal practice trials for the cut) before test trials were captured. A recovery of 30s was allocated between repetitions of the SLS, drop landing and hurdle hop with 1 minute allocated between trials of the running cut.

We used an eight camera 3D motion analysis system (Vicon - Bonita B10, UK), synchronized with two 40x60cm force platforms (AMTI – BP400600, USA), to collect kinematic and kinetic data. We placed reflective markers (1.4cm diameter) at bony landmarks on the lower limbs and pelvis according to Plug in Gait marker locations (Vicon, UK): second toe, heel, lateral malleolus, shank, knee, thigh, anterior superior iliac spine and posterior superior iliac spine. Pilot work revealed that the anterior superior iliac spine markers were often occluded during the tests therefore two additional markers were placed on the iliac crests. On occasions where an ASIS marker became occluded, we calculated its location from the locations of the five other pelvic markers by assuming a rigid pelvis. Vicon Nexus software controlled simultaneous collection of motion and force data at 200Hz and 1,000Hz, respectively. We filtered both marker and force data using a fourth order Butterworth filter with a cut-off frequency of 15Hz to avoid impact artefacts.[29] The Vicon Plug in Gait modelling routine (Dynamic Plug in Gait) defined rigid body segments (foot, shank, thigh and pelvis) and the joint angles between these segments. The model then used standard inverse dynamics techniques to calculate segmental and joint kinetics.[30]

Kinetic and kinematic variables of interest were measured during the loading phase of each movement. In the SLS the loading phase began with the initial lowering of the centre of mass and ended when the centre of mass returned to standing height. For the single leg drop landing the loading phase began at initial foot contact with the force platform and ended when the subjects' centre of mass returned to standing height (as obtained in the SLS). For the hurdle hop and running cut, initial foot contact and toe-off on the force platform marked the start and end of the loading phase, respectively. To compare the movement times of each task we decided to utilize eccentric phase duration as opposed to total movement time; the drop landing has a relatively long pause at the end of the eccentric phase which does not allow a like-for-like comparison using total movement time. The eccentric phase duration was defined as the time between the start of the loading phase and the time at which the centre of mass was at its lowest vertical position for the SLS and drop landing, or at its most lateral or anterior position for the hurdle hop and running cut, respectively. The location of the centre of mass was measured relative to the global coordinate system of the laboratory.

Statistical Analysis

Our analysis utilized the mean of each participant's three trials on the symptomatic side, or for those with bi-lateral groin pain (n = 8), the side that was most symptomatic. To check the normality of distribution of data we used Shapiro-Wilks tests. To examine the relationship between a given biomechanical measure in the SLS with the equivalent measure in each of the three other movement tests, we used Pearson product moment correlations. The same techniques were used to compare relationships in the drop landing, hurdle hop and cut. The measures used in the correlation analysis were hip, knee and pelvis angular displacement (movement control) and maximum hip and knee moments (joint loading). The principle direction of joint movements in the SLS was: knee flexion, valgus and internal rotation; hip flexion, adduction and internal rotation; pelvis anterior tilt, contralateral drop and external rotation. When undertaking joint angular displacement comparisons between the SLS and the other movements in question, care was taken to ensure that the same direction of joint displacement was being compared.

Differences in variable magnitudes between the movement tests were compared using repeated measure ANOVAs with Bonferroni post-hoc analysis. The aforementioned measures were also examined in this analysis, as were the following additional measures: the duration of the eccentric phase and maximal ground reaction forces. Statistical significance was set at $P < 0.05$ and all statistical analyses were carried out using IBM SPSS Statistics (version 21).

Results

All variables exhibited normal distribution as evidenced by non-significant ($P > 0.05$) Shapiro-Wilk tests in the SLS, drop landing, hurdle hop and running cut (mean [95% confidence intervals (CIs)]: 0.948 [0.941, 0.954], 0.947 [0.942, 0.953], 0.944 [0.936, 0.949] and 0.941 [0.936, 0.946], respectively).

A comparison of the magnitudes of biomechanical measures in each of the movement tests is provided in Table 1. The SLS tended to have smaller magnitudes of loading (moments and ground reaction forces) than the other tests. Peak vertical ground reaction forces, for example, were 37%, 63% and 68% lower in the SLS in comparison to the cut, drop landing and hurdle hop, respectively. The SLS had the longest eccentric phase duration (1532ms) followed by the increasingly quicker drop landing (261ms), hurdle hop (152ms) and cut (100ms). Hip and pelvis transverse plane angular displacement was significantly greater in the cut than in the other movement tests but hip and knee moments tended to be greater in the hurdle hop and drop landing ($P < 0.05$). The hurdle hop exhibited significantly greater ($P < 0.05$) frontal plane knee joint moments and medial/lateral ground reaction forces than the drop landing.

The results of the correlation analysis which examined relationships between biomechanical measures in the SLS and equivalent measures in the drop landing, hurdle hop and cut are detailed in Table 2. There were no significant correlations between any hip or pelvis measure in the SLS with these same measures in the drop landing, hurdle hop or cut. Knee frontal and transverse plane angular displacement were significantly related ($P < 0.05$) in the SLS and drop landing only. Knee peak moments (sagittal, frontal, transverse) in the hurdle hop and drop landing were significantly correlated ($P < 0.05$) with these same measures in the SLS, but there were no significant relationships between any joint moments in the SLS and the cut.

The correlation analysis between biomechanical measures in the drop landing, hurdle hop and cut is displayed in table 3. There were six significant correlations ($P < 0.05$) between the drop landing and the hurdle hop, two between the hurdle hop and the cut and none between the drop landing and the cut.

Discussion

Athletic groin pain (AGP) is common in field sports and has been associated with abnormal movement control and loading of the hip and pelvis during play. A single-legged squat (SLS) is commonly used by practitioners to assess movement control but whether it can provide insight into control during more dynamic sporting movements in AGP patients is unclear. Our study examined this by determining the relationship between biomechanical measures in a SLS, a drop landing, a hurdle hop and a cutting manoeuvre, in AGP patients.

There were no significant correlations between the SLS and the other movement tests for any biomechanical measures at the hip and pelvis (r range: 0.03-0.32, $P > 0.05$, Table 2). These findings suggest that a SLS test cannot provide insight into movement control and loading at the hip and pelvis during landing and cutting actions in AGP patients. DiMattia et al[18] also queried the validity of the SLS. They found that hip adduction angle in a SLS, which had previously been thought to provide an insight into control of the hip abductors,[31] did not correlate with hip abductor strength ($r = 0.21$, $p = 0.14$). While Willson & Davis[24] observed a level of consistency in hip angle results between a SLS and more dynamic tasks (straight line running and repeated vertical jumps), these tasks were primarily uni-planar in nature, and the apparent consistency was not examined statistically. In addition, the patient group utilised by Willson & Davis,[24] patellofemoral pain patients, differed to the AGP patients utilised herein.

Our study found relatively few significant correlations between biomechanical measures in the SLS and drop landing (5/15), fewer still in the hurdle hop (3/15) and none in the running cut (0/15). Thus, it would appear that as the movements in question became more multi-planar in nature, the ability of the SLS (a primarily sagittal plane task) to provide an insight into movement control and loading reduced. Similar trends were observed in the correlation findings between the drop landing, hurdle hop and cut (Table 3). The drop landing had six significant correlations with the hurdle hop but none with the cut. Indeed the hurdle hop test was the only movement to have any significant correlations ($P < 0.05$) with the cut and both of these were only moderate; knee frontal plane angular displacement ($r = 0.50$) and knee sagittal plane peak moment ($r = 0.50$). These findings further reinforce the notion that screening tests should aim to be as specific as possible to the injury mechanism they are examining.[21]

Eight significant correlations were observed between the SLS and the drop landing and hurdle hop, which all pertained to the knee (r range = 0.50-0.69, $P < 0.05$, Table 2). This suggests that the SLS may provide a moderate insight into control of the knee in single-legged landings. This is relevant to population groups other than AGP patients as single-legged landing activities are, at least in part, implicated in knee injuries such as anterior cruciate knee ligament injury.[29] Unlike our findings, Stensrud et al[23] found that knee frontal plane angles were poorly related between a SLS and a single leg drop jump (Spearman rank 0.24-0.53). However, the drop height used by Stensrud et al[23] was only 10cm and participants tended to land with small knee flexion angles. The authors suggested that this may have limited their investigation of frontal plane knee control.

A common criticism of the SLS is that it does not involve the same speed or loading magnitudes of typical sporting conditions implicated in the aetiology of AGP such as landing and cutting.[21] The results of our study, which appears to be the first to investigate this empirically, support these suggestions. Hip and knee moments and whole body ground reaction forces were typically lower ($P < 0.05$) in the SLS than in the drop landing, hurdle hop or cut (Table 1). Speed of movement (as measured by the eccentric phase duration) also differed between tests with the SLS having by far the longest eccentric phase duration (Table 1). This appears to be as a result of the relatively large sagittal plane angular displacement (flexion) at the hip and pelvis in the SLS in comparison to the other movement tests (Table 1). These relatively large sagittal plane ranges in the SLS may have little relevance in rehabilitation assessment however, as it is excessive twisting and turning movements that are more typically associated with AGP.[25, 28] Together, the differences in magnitude of loading and speed of movement that exist between the SLS and the other movement tests appears to explain why the SLS does not provide a thorough insight into movement control in these more sport specific movements.

The cut exhibited significantly greater ($P < 0.05$) hip and pelvis transverse plane angular displacement than either the hurdle hop or the drop landing (Table 1). However, transverse plane hip moments were not greater in the cut in comparison to the other movements. This may be relevant as Kernozek et al[32] suggest that larger joint angles with lower respective joint moments may increase the risk of injury; lower moments being unable to support the increasing joint angle. As such our findings may go some way to explaining why cutting actions are particularly implicated in the aetiology of AGP.

On comparing the magnitudes of kinetic factors in the hurdle hop and drop landing (Table 1), there appeared to be a tendency toward greater frontal plane loading in the former. Peak frontal plane knee moment and peak medial/lateral ground reaction force, for example, were both significantly ($P < 0.05$) greater in the hurdle hop in comparison to the drop landing. However, we found no significant differences in frontal plane hip moments in these movements. This is surprising given the frontal plane nature of the hurdle hop. Perhaps the relatively small lateral distance travelled during this test (approximately 40cm), was not large enough to overload frontal plane neuromuscular capacity at the hip. The fact that there was no significant difference ($P > 0.05$) in frontal plane hip angular displacement between the hurdle hop and drop landing appears to support this suggestion (Table 1).

We acknowledge that our study participants were tested prior to the commencement of their rehabilitation and the majority (35/40) experienced some degree of pain during at least one of the movement tests [SLS (15/40); drop landing (6/40); hurdle hop (7/40); cut (29/40)]. Pain may affect a given individuals' movement pattern but from an ecological validity perspective our findings can be readily applied by rehabilitators working with AGP patients. Interestingly, while the findings of the current study question the ability of a SLS screen to provide an insight into more dynamic movement control, the SLS may still be useful as a pain provocation test. The authors also acknowledge that while abnormal biomechanical factors during dynamic sporting movements such as cutting are thought to be associated with AGP development, further research is required to specifically support the notion that these movements are determinants of this injury. A potential limitation of our study is that the SLS is typically not well practiced, and therefore may not be as 'natural' a movement as the other tasks examined. In addition the lateral distance between hurdle hops was not normalized which may have affected the results due to its influence on initial impact speed and loading (similar to the influence of running speed on kinetics and kinematics).[33]

Conclusion

Our findings indicated that a SLS did not provide a meaningful insight into hip and pelvis movement control or loading in AGP patients during landing and cutting. The usefulness of a SLS test as an indicator of dynamic movement control in AGP patients thus appears limited. This is due, at least in part, to the notable differences between the SLS and the other movement tests in terms of magnitude of loading and speed of movement. Our study also demonstrated that a SLS may be able to provide a moderate insight into movement control and loading at the knee while landing. However, further studies utilizing different patient population groups are required to confirm this hypothesis. Future studies may also look to repeat our analysis over the course of a rehabilitation protocol with healthy controls to determine whether the absence of injury affects the findings.

Acknowledgment

Thanks to David Breen who assisted in the collection of data and Shane Gore who assisted in data processing. Our study has emanated from research supported in part by a research grant from Science Foundation Ireland (Dublin, Ireland) under Grant Number SFI/12/RC/2289.

Conflict of interest

None

References

1. Walden M, Hagglund M, Ekstrand J. Football injuries during European Championships 2004-2005. *Knee Surg Sports Traumatol Arthrosc.* 2007;15(9):1155-62.

2. Murphy JC, O'Malley E, Gissane C, Blake C. Incidence of injury in Gaelic football: a 4-year prospective study. *Am J Sports Med.* 2012;40(9): 2113-2120.

3. Brooks J, Fuller C, Kemp S, Reddin D. Epidemiology of injuries in English professional rugby union: part 1 match injuries. *Br J Sports Med*. 2005;39(10):757-766.

4. Falvey EC, Franklyn-Miller A, McCrory PR. The groin triangle: a patho-anatomical approach to the diagnosis of chronic groin pain in athletes. *Br J Sports Med.* 2009;43(3):213-220.

5. Brooks J, Fuller C, Kemp S, Reddin D. Epidemiology of injuries in English professional rugby union: part 2 training injuries. *Br J Sports Med*. 2005;39(10):757-766.

6. 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.

7. Verrall GM, Hamilton IA, Slavotinek JP, et al. Hip joint range of motion reduction in sports-related chronic groin injury diagnosed as pubic bone stress injury. *Aust J Sci Med Sport*. 2005;8(1):77-84.

8. Verrall G, Slavotinek J, Fon G. Incidence of pubic bone marrow oedema in Australian rules football players: relation to groin pain. *Br J Sports Med.* 2001;35(1):28-33.

9. Lloyd DM, Sutton CD, Altafa A, et al. Laparoscopic inguinal ligament tenotomy and mesh reinforcement of the anterior abdominal wall: a new approach for the management of chronic groin pain. *Surg Laparosc Endosc Percutan Tech.* 2008;18(4):363-368.

10. Philippon M, Schenker M, Briggs K, Kuppersmith D. Femoroacetabular impingement in 45 professional athletes: associated pathologies and return to sport following arthroscopic decompression. *Knee Surg Sport Tr A*. 2007;15(7):908-914.

11. Shortt CP, Zoga AC, Kavanagh EC, Meyers WC. Anatomy, pathology, and MRI findings in the sports hernia. *Semin Musculoskelet Radiol.* 2008;12(1):54-61.

12. Rabe SB, Oliver GD. Athletic Pubalgia: Recognition, Treatment, and PreventionA Review of the Literature. *Athletic Training and Sports Health Care*. 2010; 2(1):25-30.

13. Pizzari T, Coburn PT, Crow JF. Prevention and management of osteitis pubis in the Australian Football League: a qualitative analysis. *Phys Ther Sport.* 2008;9(3):117-125.

14. Holmich P, Uhrskou P, Ulnits L, et al. Effectiveness of active physical training as treatment for long-standing adductor-related groin pain in athletes: randomised trial. *Lancet.* 1999;353(9151):439-443.

15. Chmielewski TL, Hodges MJ, Horodyski M, Bishop MD, Conrad BP, Tillman SM. Investigation of clinician agreement in evaluating movement quality during unilateral lower extremity functional tasks: a comparison of 2 rating methods. *J Orthop Sports Phys Ther.* 2007;37(3):122-129.

16. Brukner P, Kahn K. *Clinical sports medicine.* Third ed. New South Wales: McGraw-Hill; 2006.

17. Graci V, Van Dillen LR, Salsich GB. Gender differences in trunk, pelvis and lower limb kinematics during a single leg squat. *Gait & Posture.* 2012;36(3):461-466.

18. DiMattia MA, Livengood AL, Uhl TL, Mattacola CG, Malone TR. What are the validity of the single-leg-squat test and its relationship to hip-abduction strength? *J Sport Rehabil.* 2005;14(2).

19. Myer GD, Ford KR, Palumbo JP, Hewett TE. Neuromuscular training improves performance and lower-extremity biomechanics in female athletes. *J Strength Cond Res.* 2005;19(1):51-60.

20. de Marche Baldon R, Lobato DFM, Carvalho LP, Santiago PRP, Benze BG, Serrão FV. Relationship between eccentric hip torque and lower-limb kinematics: gender differences. *J Appl Biomech.* 2011;27:223-232.

21. Ageberg E, Bennell KL, Hunt MA, Simic M, Roos EM, Creaby MW. Validity and inter-rater reliability of medio-lateral knee motion observed during a single-limb mini squat. *BMC Musculoskelet Disord.* 2010;11:265.

22. Anderson K, Strickland SM, Warren R. Hip and groin injuries in athletes. *Am J Sports Med.* 2001;29(4):521-533.

23. Stensrud S, Myklebust G, Kristianslund E, Bahr R, Krosshaug T. Correlation between two-dimensional video analysis and subjective assessment in evaluating knee control among elite female team handball players. *Br J Sports Med.* 2010; 45(7):589-95.

24. Willson JD, Davis IS. Lower extremity mechanics of females with and without patellofemoral pain across activities with progressively greater task demands. *Clin Biomech.* 2008;23(2):203-211.

25. Falvey E, Franklyn-Miller A, McCrory P. A 3G approach to a 3-dimensional problem. *Br J Sports Med.* Feb 2009;43(2):145.

26. Besier TF, Lloyd DG, Cochrane JL, Ackland TR. External loading of the knee joint during running and cutting maneuvers. *Med Sci Sports Exerc.* 2001;33(7):1168-1175.

27. Zazulak BT, Ponce PL, Straub SJ, Medvecky MJ, Avedisian L, Hewett TE. Gender comparison of hip muscle activity during single-leg landing. *J* Orthop Sports Phys Ther. 2005;35(5):292-299.

28. Hickey KC, Quatman CE, Myer GD, Ford KR, Brosky JA, Hewett TE. Methodological report: dynamic field tests used in an NFL combine setting to identify lower-extremity functional asymmetries. *J Strength Cond Res.* 2009;23(9):2500-2506.

29. Kristianslund E, Faul O, Bahr R, Myklebust G, Krosshaug T. Sidestep cutting technique and knee abduction loading: implications for ACL prevention exercises. *Br J Sports Med.* 2014; 48(9):779-83.

30. Winter DA. *Biomechanics and motor control of human movement.* Fourth ed. New Jersey: J. Wiley; 2009.

31. Zeller BL, McCrory JL, Kibler WB, Uhl TL. Differences in kinematics and electromyographic activity between men and women during the single-legged squat. *Am J Sports Med.* 2003;31(3):449-456.

32. Kernozek TW, Torry MR, H VANH, Cowley H, Tanner S. Gender differences in frontal and sagittal plane biomechanics during drop landings. *Med Sci Sports Exerc.* 2005;37(6):1003-1012.

33. Brughelli M, Cronin J, Chaouachi A. Effects of running velocity on running kinetics and kinematics. *The Journal of Strength & Conditioning Research.* 2011;25(4):933-939.

Legends to figures

Figure 1. Running cut layout for a right footed plant and cut left. Participants ran as fast as possible toward a cone placed next to the force plate, made a single complete foot contact on

the force plate, and performed an approximate 75° cut before running maximally to the finish.