Manuscript Title: Stronger subjects select a movement pattern that may reduce ACL loading during cutting

Running Heading: Strength and cutting mechanics

Laboratory: Biomechanics Laboratory, Aspire Academy, Doha, Qatar

Authors: William T. Davies, National Sports Medicine Programme, Excellence in Football Project, Aspetar Orthopaedic and Sports Medicine Hospital, Doha, Qatar, email: williamdavies740@gmail.com

Joong Hyun Ryu, Sports Science Department, Aspire Academy, Doha, Qatar, email: joong.ryu@aspire.qa

Philip Graham-Smith, Sports Science Department, Aspire Academy, Doha, Qatar, email: phil.grahamsmith@aspire.qa

Jon E. Goodwin, Faculty of Sport Health and Applied Science, St Mary's University, Twickenham, London, email: goodwinjon76@gmail.com

Daniel J. Cleather, Faculty of Sport Health and Applied Science, St Mary's University, Twickenham, London, email: damiel.cleather@stmarys.ac.uk

Corresponding Author Details:

William Davies,

Telephone: +974 6615 8064

Email: Williamdavies740@gmail.com

Stronger subjects select a movement pattern that may reduce ACL loading during cutting

Abstract:

Increased strength has been suggested to reduce the incidence of anterior cruciate ligament (ACL) injury as part of wider neuromuscular training programs however the mechanism of this is not clear. Cutting is a high-risk manoeuvre for ACL injury, but limited research exists as to how strength affects sagittal plane biomechanics during this movement. Sixteen subjects were split into a stronger and weaker group based on their relative peak isometric strength in a unilateral squat (stronger: 29.0 ± 3.4 N/kg; weaker: 18.3 ± 4.1 N/kg). Subjects performed 45° cuts with maximal intent 3 times, at 3 different approach velocities (2, 4 and 6 $m.s^{-1}$). Kinematics and ground reaction forces were collected using optical motion capture and a force platform. The stronger group had lower knee extensor moments, larger hip extensor moments, and a greater peak knee flexion angle than the weaker group ($p < 0.05$). There was a trend for greater knee flexion at initial contact in the stronger group. There were no differences in resultant ground reaction forces between groups. The stronger group relied more on the hip than the knee during cutting and reached greater knee flexion angles. This could in turn reduce ACL loading by reducing the extensor moment required at the knee during weight acceptance. Similarly, the greater knee flexion angle during weight acceptance is likely to be protective of the ACL.

Key Words: kinetics, injury prevention, kinematics, anterior cruciate ligament, cutting

INTRODUCTION

Despite much research, the incidence of anterior cruciate ligament (ACL) injury appears not to be decreasing ([13,32]) and the mechanism of injury is still not fully understood ([5]). The ACL is under greatest strain when load is applied to the knee in all three planes of motion ([30]). However, it has been argued that anterior shear loading may deliver the most direct loading to the ACL ([43]) and an extended knee at initial contact when landing (>30°) has been observed in the majority of injury incidences ([17]). Resistance exercise modalities have demonstrated a likely prophylactic effect on the incidence of ACL injury ([36]), yet research into the effects of greater strength on sagittal plane biomechanics is limited, particularly in male populations, and results have been equivocal.

Increases in isometric and dynamic hip strength as a result of hip focused strengthening programs have been linked with increases in both peak knee flexion ([34]) and flexion at initial contact ([18]), with no change in average knee extensor moment ([34]). In contrast, a cross sectional study demonstrated that subjects with greater isometric hip strength demonstrated lower knee extensor moments with no difference in knee flexion angle ([22]). At the knee, increased dynamic extensor strength after 8 weeks of free weight resistance training was also associated with increases in peak knee flexion, as well as a reduction in knee extensor moments ([23]) in the absence of any changes in hip strength. However, increases in isometric knee and hip extensor strength as a result of 9 weeks of isolated band resisted training resulted in no kinetic or kinematic adaptations at the knee ([11]). Differences in program design, assessment modalities, and loading strategies make direct comparisons difficult and may explain the variation in results, and further research is warranted.

Considering the majority of non-contact ACL injuries have been reported to occur during side step cutting maneuvers in team sports, and often occur at high speeds ([3,38]), there is a paucity of research into the influence of strength on this particular movement pattern, at various approach velocities.

Only one study has attempted to evaluate the influence of resistance training on cutting performance ([2]) however, pre and post strength changes were not measured, making it hard to attribute any biomechanical adaptations to changes in strength alone. In another study, peak knee angle was increased in a group which demonstrated greater strength in a single leg isometric squat during a 45° cut ([33]), however, only peak knee angle was reported which perhaps does not give an accurate reflection of injury risk, as the mechanism for rupture likely occurs within the first 40ms after initial contact ([17]).

Therefore, the purpose of this study is to explore the influence that lower body strength has on sagittal plane knee and hip moments, and knee kinematics during a cutting maneuver at different approach velocities. It is hypothesized that athletes with greater isometric lower extremity strength will demonstrate reduced knee moments as a result of greater capacity to load the hip. It is also hypothesized that a deeper knee flexion angle will be observed at initial contact.

METHODS

Experimental approach to the problem

Research supports that increased strength at the hip and knee may result in alterations in lower extremity biomechanics that may in turn result in lowering ACL risk during landing tasks, however, relationships between strength gains and adaptations are often inconsistent, and no changes have also been reported ([11]). The disparities may be due to the lack of association between single joint strength tests, with multi joint movement patterns ([1]), as well as the unilateral mode of testing compared with the bilateral movement pattern that is being assessed. In addition, open chain exercises that are often used in strength assessments may not dynamically correspond to dynamic movements where vertical ground reaction forces are experienced by the performer ([35]).

Therefore, a more global measure of lower body strength, that is mechanically similar to the movement pattern being tested, may be warranted and may aid coaches in determining how traditional multi joint lower body strengthening exercises, with greater specificity, may influence lower body biomechanics. To differentiate stronger and weaker subjects, an isometric strength test was selected which was the same as one used in a previous study ([33]), and peak values achieved were normalised to body weight. Joint positions during this type of strength testing should be as close as possible to the dynamics of the movement to which it is being compared ([16]), in this case the plant phase of the cut. As the ACL is likely ruptured within the first 40ms after contact ([17]), and knee and hip angles at initial contact are reported within the ranges of 27°-42°, and ~37° respectively ([31,39]), angles of 40° for both joints were selected for the isometric strength test. Additionally, lower extremity joint contributions are comparable, with extensor moments at the hip and knee during cutting reported at 4.65 and 2.67 Nm/kg respectively ([10]), which closely corresponds to those observed during a maximal dynamic squat exercise (4.89 and 1.97 Nm/kg) ([8]). The majority of ACL injuries during sidestep manoeuvres occurring at cutting angles between 0-90°, and at both fast and moderate speeds prior to the cut ([38,3]) thus, a cut angle of 45°, and 3 different approach speeds ranging from a slow jog, to high speed running, were selected for the protocol. An a priori power analysis using G*power ([7]) revealed that a sample of 16 subjects would be sufficient to demonstrate a power 0.80, at the predetermined alpha level of 0.05 and with a moderate effect size (0.09).

Subjects

Sixteen male subjects (Table 1) with a minimum of 5 years previous experience, and who were currently practicing at least twice per week in team sports where cutting is prevalent, took part in the study. Exclusion criteria for the study included any lower extremity injury that kept the subject out of training for 3 weeks or more in the previous 6 months, or a previous ACL injury. Subjects abstained from exercise for 48 hours prior to each testing session. Leg dominance was identified by preferred kicking leg ([28]) and only participants who were right leg dominant participated in the study. Subjects above the 50th percentile were assigned to a stronger group (n=8) and those below the 50th percentile were assigned to the weaker (n=8) group based on relative peak force values from an isometric strength test. Relative strength between groups was significantly different, whereas subject height, weight and age were not different between the stronger and weaker groups (Table 1). The study was approved by the human research ethics committee at St Mary's University, as well as the internal review board at the Qatar anti-doping lab. Subjects were informed of the benefits and risks of the investigation prior to signing an institutionally approved informed consent document to participate in the study.

TABLE 1 ABOUT HERE

Procedures

Subjects were asked to take part in two testing sessions separated by at least 72 hours, and no longer than 14 days. The first testing session involved the assessment of strength in a single leg isometric squatting task. The subject was then taken to the lab for familiarization of the cutting protocols for the second testing session and performed a number of trials at different velocities until the subject felt comfortable with the task. The second testing session comprised the measurement of the participant's knee angle at initial contact and peak flexion, hip and knee extensor moment, as well as ground reaction force data during a 45° cutting manoeuvre at 3 different approach velocities.

Lower body strength was measured from the dominant limb using a single leg isometric squat on a custom made testing station (Figure 1), performed on a portable force plate (0.6m × 0.4m; Type 9286AA, Kistler, Winterthur, Switzerland) with a sampling rate of 1000Hz, and has demonstrated good reliability ([33]). The subject warmed up by performing 2 sets of squats at a self-selected weight that they considered they could lift for 8-10 repetitions. They were then moved to the rig where they performed 2 trials at ~80% and ~90% of maximal exertion to ensure that they were familiar with the technique and that the bar was set at the correct height before maximal testing. The test was then performed in the rig with knee and hip angles of 40°, measured using a goniometer. Subjects were asked to place the heel of the dominant leg directly under their centre of mass and apply as much upward force as possible for 5 seconds, for 3 trials, with 2 minutes recovery between each trial ([29]). Peak force was selected as the highest force achieved, but only if the second-best trial was within 10% of the highest, if not a further trial was recorded. An average measures, consistency, 2-way mixed effects model was used for calculating intra class correlation coefficient and giving a value of 0.97 for the dominant leg. The subjects were then given a 10-minute rest during which anthropometric measurements were taken (described below). Subjects then undertook a number of cutting trials at various velocities for familiarization until they felt comfortable with the technique required.

FIGURE 1 ABOUT HERE

To record three-dimensional, lower extremity kinematics during the cutting manoeuvres, a 16 camera motion capture system (Vicon MX, Vicon Motion Systems Ltd, UK) was used with a sampling frequency of 250Hz. Sixteen 14mm hard markers encased in retro-reflective tape were attached to anatomical landmarks of the lower limb (Figure 2) in accordance with the Vicon lower-body Plug-in Gait model ([15]) which has been shown to be a reliable method to retrieve sagittal plane kinematics ([25]). Anthropometric measurements for leg length were taken from anterior superior iliac spine to medial malleoli, as well as ankle and knee girth. Ground reaction force (GRF) data during the cutting task was collected using a 0.6 × 0.9m force plate (Type 9287CA, Kistler, Winterthur, Switzerland) embedded into the floor and sampled at a frequency of 1000Hz. Cameras were synchronised to the force platforms so that joint moments could be calculated.

FIGURE 2 ABOUT HERE

On the second day of testing, subjects reported to the biomechanics lab where they were given lycra shorts to wear and asked to bring their own running shoes. Reflective markers were placed on their lower body ([15]), before subjects performed a 10-minute standardized warm up including a short familiarisation at the various cutting protocols. For the trials, subjects were asked to start on a marked line 15m from the centre of the force plate. The run-up area and force plate were covered with tartan running track and were the same for all subjects. To test the variations in lower body kinematics due to variations in the task, 3 different velocities (2, 4, and 6 $m.s^{-1}$) were selected to be performed at a cutting angle of 45°. The subject was asked to perform 3 trials for each of the conditions, making a total of 9 manoeuvres in the session, however, if the subject failed to achieve an approach velocity within ± 5% of the target, or the cutting manoeuvre appeared unnatural, or they 'hopped' during their plant step, they were asked to repeat the trial. To negate the effects of fatigue a minimum of 1-minute recovery was given between each trial. Approach velocity was measured for 3m, 8m from the force plate using light gates (Microgate Polifemo Light, Bolzano Bozen, Italy). Subjects were then asked to try to maintain this velocity through the second set of light gates until 2m before the force plate before attempting to complete the cut as quickly as possible. In the 2m leading up to the plate subjects were informed they could decelerate to a level whereby they felt safe performing the cut as quickly as possible, however no difference between groups were observed in approach velocity at foot contact during the cut ($p=0.82$, $\eta_p^2=0.004$). A third and fourth set of light gates were placed 2m after the force plate at a 45° angle to the plate, to measure completion time for the task (Figure 3). To ensure the correct cutting angle was achieved, tape marking was applied to the floor to guide the athletes with the fourth set of photocells set up 2m from the force plate and spaced 50cm either side of the marker tape to ensure the actual cut angle for the 45° trials would be between 35° and 55°. Subjects were asked to complete the movement as fast as possible.

FIGURE 3 ABOUT HERE

Data Analysis

The force platform was used to determine foot-strike and toe-off events to define the stance phase of the cutting. Resultant peak joint moments at the knee and hip were normalised to the subject's body weight and height, and ground reaction forces were normalised to the subject's body weight. Peak knee and hip extensor moments were taken in the time frame from initial foot contact to first peak of resultant ground reaction force. Initial contact knee angle was reported as the knee angle at foot strike, determined as the point at which ground reaction force exceeded 10N. Peak knee angle was taken as the deepest knee angle based on the kinematic data.

Instantaneous running velocity at foot contact was defined as the horizontal velocity of the centre of mass of the pelvis segment. To observe differences in performance between groups, post change of direction stride velocity was also determined from toe off from the force plate on the cutting leg, to heel strike on the first step after the change of direction using resultant velocity of centre of mass ([33]). The joint moments reported in this paper are external joint moments. An inverse dynamics procedure was used to calculate joint moments based on kinematic and force plate data.

All orientation angles were calculated using a Cardan Y-X-Z (mediolateral, anteroposterior, and vertical) rotation sequence except for ankle angles which are calculated in order Y-Z-X. Y-X-Z Cardan angles were compared using relative orientation of 2 segments, using data from previous studies ([6,14]), with positive rotation representing flexion at the hip and knee. The 'Plug-in Gait' model in Vicon was used to calculate joint kinetics. Both marker trajectories and force data were filtered using a Woltring filter quintic spline routine in mean square error mode with a smoothing factor of 10 in order to avoid the creation of artificial peaks in the computed result joint moments ([19]).

Statistical Analysis

The main dependent variables in this study were measures of knee flexion, and hip and knee moments. A 2 (Strength Group) x 3 (Velocity Condition) mixed design analysis of variance (ANOVA) was used to determine any significant effects of strength at different approach velocities. Post Hoc unpaired *t*-tests were used to identify any differences at specific velocities, using a Bonferroni correction method to control the family wise error rate. Statistical significance was set at $p \leq 0.05$ (determined a priori) with all data reported as mean and standard deviation (sd). Partial Eta squared values (n_p^2) were reported as a measure of effect size, where the following descriptors were used: 0.01 (small), 0.09 (moderate) and 0.25 (large) ([21]). All data analysis was completed using a statistical software package (SPSS, Version 22).

RESULTS

Knee extensor moment was significantly lower, and hip extensor moment higher, for the stronger group during the weight acceptance phase (Table 2). Figure 4a displays extensor moment differences between the strong and weak group at each approach velocity. A significant difference for knee extensor moment was observed at 2, 4 and 6 $m.s^{-1}$ ($p = 0.004$, $\eta_p^2 = 0.460$; $p = 0.004$, $\eta_p^2 = 0.458$ and $p = 0.042$, $\eta_p^2 = 0.263$ respectively). Hip extensor moment was significantly greater for the stronger group at 2 $m.s^{-1}$ ($p = 0.046$, $\eta_p^2 = 0.256$) but not at 4 or 6 $m.s^{-1}$ ($p = 0.116$, $\eta_p^2 = 0.167$ and $p = 0.085$, $\eta_p^2 = 0.197$). Peak GRF during weight acceptance was not different between the groups (Table 2).

TABLE 2 ABOUT HERE

A significant main effect for peak knee flexion angle was observed, with subjects in the stronger group demonstrating deeper peak knee flexion angles (Table 2). Post hoc analysis found significant differences at both 4 and 6 $m.s^{-1}$ ($p = 0.033$, $\eta_p^2 = 0.305$ and $p = 0.042$, $\eta_p^2 = 0.282$ respectively) but not at 2 $m.s^{-1}$ ($p = 0.075$, $\eta_p^2 = 0.223$; Figure 4b). No significant differences were observed in knee flexion angle at initial contact, although a moderate effect size was observed for deeper flexion in the stronger group (Table 2). There were no differences in total knee excursion between groups (peak flexion angle minus initial contact angle; $p=0.46$, $\eta_p^2= 0.040$), and there were no significant differences between groups for post cut stride velocity ($p=0.86$, $\eta_p^2=0.003$).

FIGURE 4 ABOUT HERE

DISCUSSION

In support of the first hypothesis, the stronger group had lower knee extensor moments during the weight acceptance phase of a cutting manoeuvre, as well as greater hip extensor moments. Previous research in female populations show reduced knee extensor moments during landing in subjects with greater isometric hip ([22]), and dynamic quadricep ([23]) strength, however the present study reports this difference in a more reactive movement during weight acceptance. Although both studies were conducted in female populations, there is increasing evidence to suggest that direct comparisons may be valid. Recent studies have shown no differences in sagittal plane kinetics between men and women, with similar experience, during cutting maneuvers ([10,31]). In addition, when strength is matched between gender groups, previously observed differences in muscle activation were not prevalent ([27]). Knee extensor moments have been associated with anterior shear forces (r=0.91) ([42]) which in turn have been associated with ACL strain ([40]). Lower relative contributions from the quadriceps during weight acceptance could reduce anterior pull on the tibia from the patella tendon, thus reducing anterior shear forces and associated ACL strain. The present study adds to the literature by indicating that this potentially protective mechanism is also present during cutting movements.

In addition to lower knee extensor moments, greater hip extensor moments were also observed in the stronger group. Greater hip contributions to landing tasks have been observed in female cohorts after a free weight training programs ([4]) and proximal strength training programmes (focussed on landing) ([34]). Taken together, it is reasonable to suggest that the greater hip extensor moments observed in the stronger group may be as a result of an increased capacity to absorb load at the hip, potentially as a result of adaptations such as increased gluteal pre activity ([23]), or greater musculotendinous stiffness ([20]) which have been observed as a result of strength training. This would allow capacity for more load to be absorbed at the hip early in the weight acceptance phase, which in turn requires lower quadriceps activity to contribute towards the absorption of GRF. Thus, knee extensor moments can be lower during the initial stages of landing. As the demands of the activity were increased (via faster approach velocities), knee extensor moments remained lower in the stronger group, yet was only significant at 2 $m.s^{-1}$ for hip extensor moments. High variability, and low subject numbers may have prevented significant results at 4 and 6 $m.s^{-1}$, as similar magnitudes were observed. This trend indicates a general movement strategy that favours force absorption at the hip during cutting tasks.

The second hypothesis stated that knee flexion angles at initial contact would be deeper in the stronger group during a cutting task. Although a trend for increased flexion was observed at each approach velocity of approximately 5°, and carried a moderate effect size, significance was not reached, possibly due to the low sample numbers. Some previous studies that have reported associations between initial contact angle and strength in males using isolated knee extensor strength protocols on a dynamometer ([26,41]) whereas the present study used a more global measure of lower extremity strength. This may demonstrate a limitation of the current protocol's sensitivity to detect significant changes in knee flexion at initial contact. On the other hand, peak flexion angle was greater in the stronger group, which was significant, and supports the data from a cutting study which used the same multi-joint strength protocol ([33]). Relationships between knee flexion angle and ACL strain suggest greater flexion may have a moderating effect for injury risk ([37]). More extended knee positions create greater strain in the ACL via two primary mechanisms. Firstly, there is an increase in the elevation angle, and reduction in length of the ACL as the knee moves into flexion due to the changing geometry of the tibiofemoral joint space, thus reducing strain on the ligament ([24]). Secondly, the patella's relationship with the tibia means that as the knee flexes, the orientation of the patella tendon relative to the longitudinal axis of the tibia changes from being anteriorly to posteriorly directed ([12]) meaning that at deeper knee flexion angles tension in the patella tendon will tend to unload the ACL.

Previous research has shown that subjects with greater dynamic gluteal strength demonstrated deeper knee flexion at initial contact in females during a rebound jump task ([18]). The ability of the stronger group to absorb load at the hips, and associated reduced knee moments, may reduce the force production requirements of the quadriceps at a given knee flexion angle, potentially allowing a deeper knee flexion for the same effort. In addition, females demonstrating an increased peak knee flexion during a jump landing has also been observed during a landing task after 8 weeks of strength training which was observed alongside dynamic quadriceps strength, in the absence of increased hip strength ([23]), and may demonstrate that increased quadriceps strength may also contribute to the increased knee flexion in the present study. However, in the absence of individual joint contribution measures during the squatting task, these proposals should be observed with caution. Strikingly, no difference in excursion between the stronger and the weaker group were observed, and taken together, the trend for greater flexion at initial contact, and deeper peak knee angle may imply a relationship between the two, which is supported by Wu et al. ([41]).

There are a number of confounding variables in this study which make interpretation difficult. Firstly, the low numbers within each group make for low statistical power which reduces the ability to identify differences. In addition, the task of cutting itself has high variability due to its high perceptual-motor demands compared to movements such as landing. Attempts to reduce this were made by incorporating a familiarisation session, and giving the subject narrow velocity parameters, however a certain level of variability was still observed which may have greater impact on data with low subject numbers. Although all subjects were currently at a recreational level of performance in their team sport, there was a broad range of previous playing experience, as well as weight training experience which may have influenced coordination patterns, and the mechanical properties of the muscle, that were not related to greater strength but may have influenced lower extremity biomechanics. Previous studies have also shown peak strength outputs in an isometric leg press for a given individual may occur at different angles ([9]) and this was not accounted for in the present study. Instead a pre-set joint angle based on the demands of the cutting task was used, which may have affected the groups into which subjects were categorized. In addition, the use of isometric testing to assess differences in a dynamic movement may not correspond as closely as a dynamic strength test, and other strength qualities, such as reactive or eccentric, may better reflect how force is applied during a cutting movement. Finally, it is important to acknowledge that non-contact ACL injuries are likely highly related to mechanics that are outside the sagittal plane but were not explored in this study, due to the questionable validity of Plug in Gait method in transverse and frontal planes ([25]).

PRACTICAL RECOMMENDATIONS

The data from this cross-sectional study supports the premise that stronger individuals develop a movement strategy during cutting which increases hip, yet reduces knee, extensor moments during the early phase of foot contact. This movement strategy is likely to entail less loading of the ACL, and so this study provides support for the contention that strength training of the lower limb can reduce ACL injury risk. In addition, stronger subjects tend to select a movement pattern that has a deeper peak knee flexion angle, which may allow for a deeper knee angle at initial contact, whilst maintaining the same overall knee excursion, and could also contribute to reducing ACL load. The strength protocol used may indicate that unilateral, multi joint isometric strength training, involving postures that are specific to those seen during the plant step of a cutting manoeuvre, may help to alter lower extremity biomechanics that moderate ACL load. More research involving such interventions are required to confirm this.

ACKNOWLEDGMENTS

No funding was received for this study. There are no conflicts of interest. The results of this study are presented clearly, honestly and without fabrication, falsification, or inappropriate data manipulation and do not constitute endorsement by the NSCA.

REFERENCES

1. Anderson, MA, Gieck, JH, Perrin, DH, et al. The relationship among isometric, isotonic, and isokinetic concentric and eccentric quadriceps and hamstring force and three components of athletic performance. *J Orthop Sports Phys Ther* 14 (3): 114-20, 1991.
2. Cochrane, JL, Lloyd, DG, Besier, TF, et al. Training affects knee kinematics and kinetics in cutting maneuvers in sport. *Med Sci Sports Exerc* 42(8): 1535-1544, 2010.
3. Cochrane, JL, Lloyd, DG, Buttfield, A, Seward, H, McGivern, J. Characteristics of anterior cruciate ligament injuries in Australian football. *J Sci Med Sport* 10: 96-104, 2007.
4. Czasche, MB, Goodwin, J, Bull, AM, Cleather, DJ. Effects of an 8-week strength training intervention on tibiofemoral joint loading during landing: a cohort study. *BMJ Open Sport & Exerc Med*. 2018. https//doi:10.1136/bmjsem-2017-000273
5. Dai, B, Mao, D, Garrett, WE, Yu, B. Anterior cruciate ligament injuries in soccer: Loading mechanisms, risk factors and prevention programs. *J Sports Health Sci* 3: 299-306, 2014.
6. Davis III, RB, Ounpuu, S, Tyburski, D, Gage, JR. A gait analysis collection and reduction technique. *Human Mov Sci* 10: 575-87, 1991.
7. Faul, F, Erdfelder, E, Lang, AG, Buchner, A. G*Power 3: a flexible statistical power analysis program for the social sciences. *Behav Res Methods* 39(2): 175-191, 2007.

8. Flanagan SP, Salem GJ. Lower extremity joint kinetic responses to external resistance variations. *J Appl Biomech* 24: 58-68, 2008.
9. Hahn, D, Olvermann, M, Richtberg, J, Seiberi, W, Schwirtz, A. Knee and ankle torque-angle relationship of multi-joint leg extension. *J Biomech* 44: 2059-2065, 2011.
10. Havens, KL, Sigward, SM. Joint and segmental mechanics differ between cutting maneuvers in skilled athletes. *Gait & Posture* 41: 33-38, 2015.
11. Herman, DC, Weinhold, PS, Guskiewicz, KM, et al. The effects of strength training on the lower extremity biomechanics of female recreational athletes during a stop-jump task. *Am J Sports Med* 36(4): 733-40, 2008.
12. Herzog, W, Read, LJ. Lines of action and moment arms of the major force carrying structures crossing the human knee joint. *J Anat* 182 (part 2): 213-30, 1993.
13. Hootman, JM, Dick, R, Agel, J. Epidemiology of collegiate injuries for 15 sports: Summary and recommendations for injury prevention initiatives. *J Ath Train* 42(2): 311-19, 2007.
14. Kadaba, MP, Ramakrishnan, HK, Wootten, ME. Measurement of lower extremity kinematics during level walking. *J Ortho Res* 8: 383-92, 1990.
15. Kadaba, MP, Ramakrishnan, HK, Wootten, ME, et al. Repeatability of kinematic, kinetic, and electromyographic data in normal adult gait. *J Orthop Res* 7(6): 849-60, 1989.
16. Kawamori, N, Rossi, SJ, Justice, BD, et al. Peak force and rate of force development during isometric and dynamic mid-thigh clean pulls performed at various intensities. *J Strength Cond Res* 20(3): 483-91, 2006.
17. Koga, H, Nakamae, A, Shima, Y, et al. Mechanisms for non contact cruciate ligament injuries. *Am J Sports Med* 38(11): 2218-26, 2010.

18. Kondo, H, Someya, F. Changes in ground reaction force during a rebound-jump task after hip strength training for single-sided ankle dorsiflexion restriction. *J Phys Ther Sci* 28: 319-25, 2016.

19. Kristianslund, E, Krosshaug, T, van den Bogert, AJ. Effect of low pass filtering on joint moments from inverse dynamics: Implications for injury prevention. *J Biomech* 45: 666-71, 2012.

20. Kubo, K, Kanehisa, H, Fukunaga, T. Effects of resistance training and stretching training programmes on the viscoelastic properties of human tendon structures in vivo. *J Phys* 538(1): 219-26, 2002.

21. Lakens, D. Calculating and reporting effect sizes to facilitate cumulative science: a practical prime for t-tests and ANOVAs. *Front Psychol* 4: 1-12, 2013.

22. Lawrence, RK, Kernozek, TW, Miller, EJ, Torry, MR, Reuteman, P. Influences of hip external rotation strength on knee mechanics during single-leg drop landings in females. *Clin Biomech* 23(6): 806-13, 2008.

23. Lephart, SM, Abt, JP, Ferris, CM, et al. Neuromuscular and biomechanical characteristic changes in high school athletes: a plyometric versus basic resistance program. *Br J Sports Med* 39: 932-39, 2005.

24. Li, G, DeFrate, LE, Rubash, HE, Gill, TJ. In vivo kinematics of the ACL during weight-bearing knee flexion. *J Orthop Res* 23: 340-4, 2005.

25. McGinley, JL, Baker, R, Wolfe, R, Morris, ME. The reliability of three-dimensional kinematic gait measurements: A systematic review. *Gait & Posture* 29: 360-9, 2009.

26. Nagai, T, Sell, TC, House, AJ, Abt, JP, Lephart, SM. Knee proprioception and strength and landing kinematics during a single leg stop jump task. *J Ath Train* 48(1): 31-8, 2013.

27. Nimphius, S, McBride, JM, Rice, PE, Goodman-Capps, CL, Capps, CR. Comparison of quadriceps and hamstring muscle activity during an isometric squat between strength-matched men and women. *J Sports Sci Med* 18: 1010-108, 2019.

28. Norcross, MF, Lewek, MD, Padua, DA, et al. Lower extremity energy absorption and biomechanics during landing, part I: sagittal-plane energy absorption analysis. *J Ath Train* 48(6): 748-56, 2013.

29. Nuzzo, JL, Mcbride, JM, Cormie, P, McCaulley, GO. Relationship between countermovement jump performance and multijoint isometric and dynamic tests of strength. *J Strength Cond Res* 22(3): 699-707, 2008.

30. Quatman, CE, Quatman-Yates, CC, Hewett, TE. A ‘plane’ explanation for anterior cruciate ligament injury mechanisms. A systematic review. *Sports Med* 40(9): 729-42, 2010.

31. Schreurs, MJ, Benjamese, A, Lemmink, KAPM. Sharper angle, higher risk? The effect of cutting angle on knee mechanics in invasion sport athletes. *J Biomech* 63: 144-150, 2017.

32. Shaw, L, Finch, CF. Trends in pediatric and adolescent anterior cruciate ligament injuries in Victoria, Australia 2005-2015. *Int J Environ Res Public Health* 14: 599-609, 2017.

33. Spiteri, T, Cochrane, JL, Hart, NH, Haff, G, Nimphius, S. Effect of strength on plant foot kinetics and kinematics during a change of direction task. *Eur J Sport Sci* 13(6): 646-52, 2013.

34. Stearns, KM, Powers, CM. Improvements in hip muscle performance result in increased use of the hip extensors during a landing task. *Am J Sports Med* 42: 602-09, 2014.

35. Suarez, DG, Wagle, JP, Cunanen, AJ, Sausaman RW, Stone, MH. Dynamic correspondence of resistance training to sport: a brief review. *Strength Cond J* 41(4): 80-88, 2019.

36. Sugimoto, D, Myer, GD, Barber Floss, KD, Hewett, TE. Specific exercise effects of preventive neuromuscular training intervention on anterior cruciate ligament injury risk

reduction in young females: meta-analysis and subgroup analysis. *Br J Sports Med* 49: 282-89, 2015.

37. Taylor, KA, Cutcliffe, HC, Queen, RM, et al. In vivo measurement of ACL length and relative strain during walking. *J Biomech* 46(3): 478-83, 2013.
38. Walden, M, Krosshaug, T, Bjorneboe, J, et al. Three distinct mechanisms predominate in non-contact anterior cruciate ligament injuries in male professional football players: a systematic video analysis of 39 cases. *Br J Sports Med*. 2015. https://doi:10.1136/bjsports-2014-094573
39. Weinhandl, JT, Earl-Boehm, JE, Ebersole, KT, et al. Reduced hamstrings strength increases anterior cruciate ligament loading during anticipated sidestep cutting. *Clin Biomech*. 2014 doi: 10.1016/j.clinbiomech.2014.05.013.
40. Withrow, TJ, Huston, L, Wojtys, EM, Ashton Miller, JA. The relationship between quadriceps muscle force, knee flexion and anterior cruciate ligament strain in an in vitro simulated jump landing. *Am J Sports Med*. 34(2): 269-74, 2006.
41. Wu, X, Zhang, S, Liu, Y, Zhang, D, Xie, B. Do knee concentric and eccentric strength and sagittal-plane knee joint biomechanics differ between jumpers and non-jumpers in landing. *Human Mov Sci* 32: 1299-1309, 2013.
42. Yu, B, Lin, C-F, Garrett, WE. Lower extremity biomechanics during the landing of a stop jump task. *Clin Biomech* 21: 297-305, 2006.
43. Yu, B, Garrett, WE. Mechanisms of non-contact ACL injuries. *Br J Sports Med* 41(suppl 1): 47-51, 2007.

LIST OF TABLES:

Table 1: Mean (sd) characteristics of subjects by strength

	Stronger (n=8)	Weaker (n=8)
Strength (N/kg)	29.0 (3.4)*	18.3 (4.1)
Age (years)	34.2 (5.0)	36.0 (4.9)
Height (cm)	177.2 (7.1)	178.1 (8.0)
Body Mass (kg)	79.3 (10.1)	76.3 (12.6)

***indicates significant difference between groups.**
s = seconds, cm = centimeters, N/kg = Newtons/kilogram.

	Weaker	Stronger	P value	η_p^2
Peak Knee Extensor Moment (Nm/kg.ht)	0.023 ± 0.010 (0.016 – 0.029)	0.008 ± 0.006* (0.002 – 0.014)	0.003	0.476
Peak Hip Extensor Moment (Nm/kg.ht)	0.036 ± 0.010 (0.024 – 0.047)	0.053 ± 0.019* (0.041 – 0.065)	0.041	0.265
Initial Contact Knee Angle (°)	40.4 ± 6.7 (34.9 – 45.8)	45.4 ± 4.4 (39.9 – 50.8)	0.184	0.122
Peak Knee flexion Angle (°)	59.6 ± 8.6 (54.2 – 64.9)	67.7 ± 6.7* (62.3 – 73)	0.037	0.275
Peak Resultant GRF (N/kg)	3.93 ± 1.32 (3.01 – 4.78)	3.63 ± 0.88 (2.78 – 4.48)	0.601	0.020

Table 2. Main effects for kinetic and kinematic data between strength groups with approach velocity collapsed, mean ± sd (95% CI)

***p<0.05 vs weak. Nm/kg.ht – Newtonmeters/kilogram.height, ° = degrees, N/kg = Newtons/kilogram**

LIST OF FIGURES

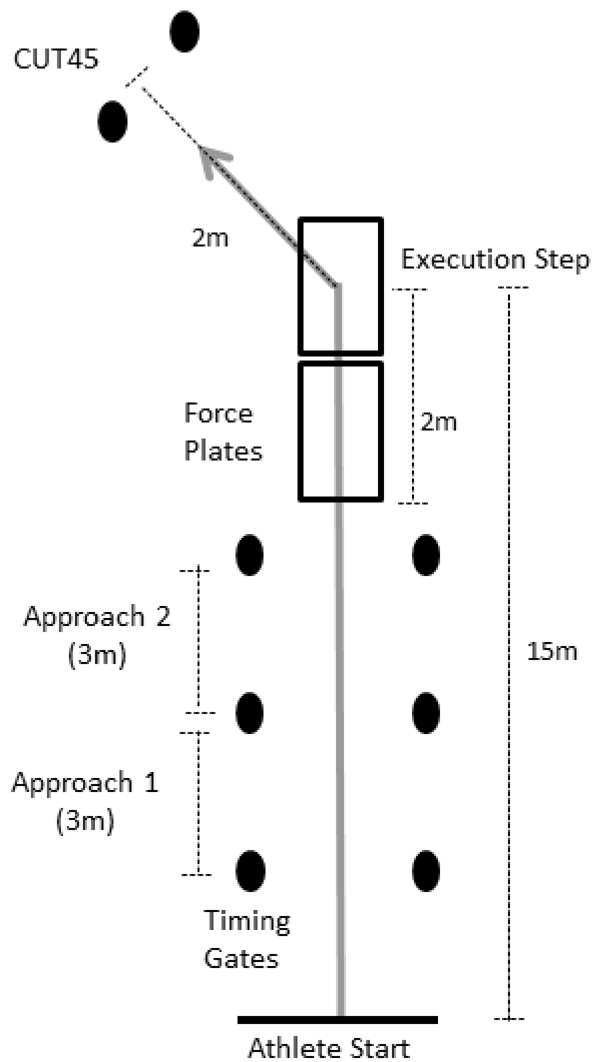

Figure 1. Experimental setup for the cutting task. Solid line arrow represents line of motion with two cutting angles at the end. The light timer was triggered from 8m before force plate, and again 5m before the force plate.

Figure 2: Adopted subject positioning for the unilateral isometric strength test. Squat rack was bolted to the floor, and had custom made stoppers connecting the barbell to the rack.

Figure 3: Subject positioned for standing calibration trial with retro-reflective marker placed at relevant sites (heel and PSIS are posteriorly positioned). This is to establish local coordinate system relative to global that is marked via static and dynamic calibration with the wand.

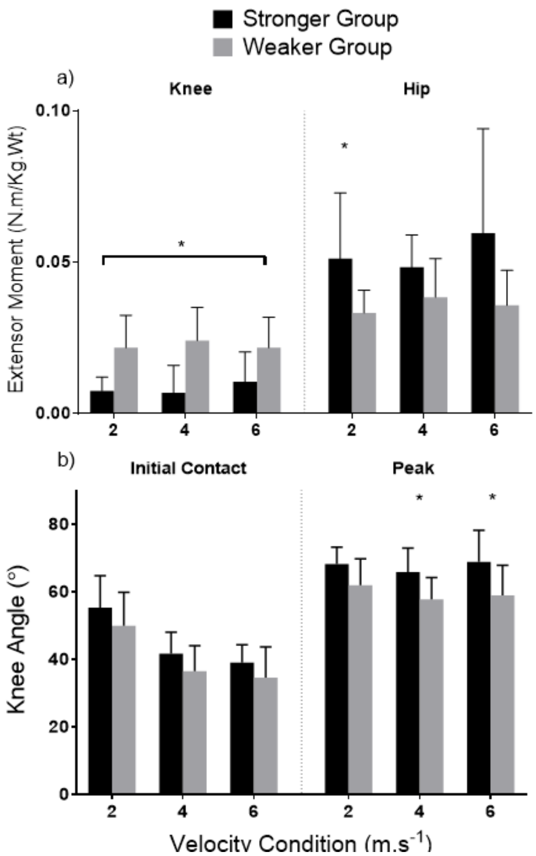

Fig 4. Comparison between strength groups at 3 different approach velocities (2, 4 and 6 m.s^{-1}) for variables; a) body weight and height normalised knee vs hip extensor moments, b) knee angle at initial contact vs peak knee angle. *denotes significant differences between strength groups ($p < 0.05$).