# The effect of sand on knee load during a single leg jump task: implications for injury prevention and rehabilitation programmes.

# ABSTRACT

The purpose of the study was to determine potential differences in landing strategies and subsequent joint loads at the knee (knee abduction moment, anterior- posterior tibial translation and total knee shear force) when jumping onto sand and firm ground from both a level surface and a 30 cm height. Firm ground would act as the control for the study.

17 subjects (age: 23.6 ± 3.7 years; body mass: 67.7 ± 10.3 kg; height: 168.5 ± 7.4 cm) performed 3 single leg jumps on their dominant leg for each of the four conditions tested (ground level, sand level, ground height and sand height). A repeated measures design investigated the effect of sand on knee abduction moment, anterior-posterior~~AP~~ tibial translation and total knee shear force. Data was analyzed using magnitude-based inferences and presented as percentage change with 90 % confidence limits.

Results indicated that sand had a clear beneficial effect on knee abduction moment, which was possibly moderate during a drop jump (30 cm) and possibly small from a level jump. Sand also had a possibly moderate beneficial effect on anterior-posterior tibial translation from a level jump. The effect of sand on total knee shear force was unclear.

These results suggest that sand may provide a safer alternative to firm ground when performing jump tasks commonly used in ACL and PFJ injury prevention and rehabilitation programmes. Sand may also allow for an accelerated rehabilitation program, as jumping activities could potentially be implemented more safely at an earlier stage in the process.

**Key Words:** anterior cruciate ligament, patello-femoral joint, knee abduction moment, anterior-posterior tibial translation**.**

## INTRODUCTION

Over a 10-year study period, analysing 26 different sports, and 17397 patients, Majewski et al. (35) documented 19530 sporting injuries. 7769 related to the knee joint with over 20 % of these involving an anterior cruciate ligament (ACL) lesion. ACL injuries were most commonly associated with handball and volleyball activities. A high incidence of patellofemoral joint (PFJ) injuries has also been reported (9). As with ACL lesions, these can result in significant time lost from sport and future risk of osteoarthritis (44). Establishing an effective intervention to help prevent these injuries whilst at the same time enabling an acceleration of the rehabilitation process would be desirable.

To establish an intervention, it is essential to have a good understanding of the mechanisms and risk factors for PFJ and ACL injuries. The majority of these injuries are the result of a non-contact mechanism, with jump landing being the most frequently cited cause (1,7,22). Landing from a jump places high forces and moments on the knee joint. A component of knee joint force that can increase strain on the ACL is proximal tibia anterior shear force (50), given that it represents the most direct loading mechanism ~~of the ACL~~ (49). To estimate this loading of the ACL, anterior-posterior (AP) tibial translation is often used as an indirect measure (29). Another load mechanism commonly associated with the development of both PFJ and ACL injuries is knee valgus (8,23), with knee abduction moment (KAM) frequently recorded as a significant predictor of injury (42).

Interventions that can help the athlete to cope with these joint loads, specifically in jumping exercises should be integral to injury prevention and rehabilitation programmes for both ACL and PFJ injuries. To date, these have been carried out on firm surfaces, aiming to improve neuromuscular control of the lower limb (15). However, Binnie et al. (5) suggested that sand, as a less stable surface may be a viable option for such interventions. Most notably, its unique characteristics are thought to reduce impact forces through the body (2,6). Previous studies have also demonstrated a reduced rate and extent of musculoskeletal loading (28,38), alongside muscle activation strategies which provide more joint stability (47) when training on sand compared to firm surfaces. Furthermore, physiological (improved lactate threshold, aerobic capacity) and performance benefits (improved speed, agility, squat jump) on sand have been well documented (3,4,5,20,28,46) in both running and plyometric activities, and team sports. Moreover, evidence of improvements transferring to future firm ground performance in both running and agility tasks has been reported (20, 57). Although, the growing support for the use of sand in training interventions is evident the effects on common knee joint loads associated with ACL and PFJ injuries is unknown, and could have significant implications for the safety of both rehabilitation and injury prevention interventions.

To date, no study to our knowledge has examined the effects on knee joint loads, using a less stable sand surface compared to a firm surface during a jumping task. The purpose of this study was to determine whether differences were apparent in landing strategies and subsequent joint loads at the knee (KAM, AP tibial translation and total knee shear force) when hopping onto sand and firm ground from both a level surface and a 30 cm height. The functional test chosen for the jump task was a single leg hop (SLH) due to its use in a clinical setting to assess knee function (48).

## METHODS

### Experimental Approach to the Problem

This study was designed to compare the effect of sand and firm ground surfaces on knee load during a single leg jumping task. To achieve this, subjects were required to perform three single leg jumps for each of the four different test conditions (A, B, C and D) on their dominant leg in a repeated measures design (Fig. 1, Fig. 2). Each individual participant decided leg dominance by asking which leg he or she took off with during a vertical jump. The four conditions were performed in a randomised order using a computer-generated system. This allowed the effects of the order of jumps to be counterbalanced preventing each condition from adversely influencing outcome measures. Each trial was separated by three minutes to eliminate carryover effects. KAM, AP tibial translation and total knee shear force were measured during each single leg jump. This arrangement allowed for a comparison of sand to firm ground on knee load.

***Figure 1. An illustration of the four test conditions (ground level, sand level, ground height, sand height). Picture with depicted marker set, used with permission from Vicon Motion Systems UK. (16)***

***Insert Fig. 1 here***

***Figure 2. An illustration of the experimental set up.***

***Insert Fig. 2 here***

### Subjects

Seventeen University students (14 females, 3 males; age: 23.6 ± 3.7 years; body mass: 67.7 ± 10.3 kg; height: 168.5 ± 7.4 cm) who participated in more than 3 hours of sporting activity per week were recruited for the study. All subjects had no history of ACL injury or other knee pathology, significant lower limb pathology, lower limb fracture or surgery and had been injury free for 3 months prior to data collection. All 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. The study received ethical approval by Teesside University's ethics committee (Ethics Number: SSSBLREC035), in accordance with the Declaration of Helsinki.

Procedures

Initial pilot work was conducted to assess the Az plane of the force plates to determine whether centre of pressure (COP) measures would remain accurate with the sand covering so that inverse dynamics could be performed. We found that comparisons between the data with and without the sand covering were a nearly perfect relationship ($p = 0.97$ and $p = 0.99$; for static and dynamic trials respectively).

Participants attended the laboratory on two occasions; firstly, for a familiarisation session and secondly for data collection. The familiarisation session allowed the subjects 3 to 5 practice trials of each of the 4 different hops on each surface, to orient themselves to these different conditions. The four conditions were hops on a level surface onto the laboratory floor (ground level), a level surface onto sand (sand level), from a 30 cm height onto the laboratory floor (ground height) and from a 30 cm height onto sand (sand height). The four conditions and experimental set up are shown in Figures 1 (A-D) and 2. The study took place within a laboratory setting at Teesside University at the same time of day (9-11am for each participant) to limit diurnal differences. Before testing, subjects were instructed to fast overnight and refrain from consuming caffeine for the previous 24 hours. All participants also had to refrain from strenuous muscular exercise for 48 hours prior to testing.

Prior to testing a standardised warm-up programme was performed which included 10 minutes on a stationary bike, stretching of the gluteus maximus, hamstrings, quadriceps and gastrocnemius (21, 55). Subjects were fitted with a heart rate monitor and asked to cycle at 60 % of their age predicted heart rate max. All muscle groups were stretched statically three times for a 30-second duration, with subjects instructed to stretch to the 'point just before pain'. The differences in kinematic and kinetic landing strategies of single leg hopping were investigated using the four conditions. Kinematic variables were collected using a commercially available six-camera motion capture system (Vicon MX13 and Vicon Nexus 1.7, Vicon Motion Systems, UK). The six-camera system is a passive video-based 3D motion capture system, which was calibrated prior to every session, following manufacturers' guidelines, to ensure image error was below 0.18 mm (34). Cameras for the six-camera system were set at a height of 1.9 m and a sampling frequency of 100 Hz. Throughout testing participants were required to wear tight fitting Velcro kinematic suits (Vicon Motion Systems, UK) to allow for placement of retro-reflective markers in accordance with the full-body plug-in-gait marker set (Vicon Motion Systems, UK), as previously used by Gehring et al. (19) when evaluating knee joint kinematics and kinetics during a landing task. This included markers placed on the head, arms, wrists, hands, trunk, pelvis, legs and feet, and has been outlined in detail previously (10,45) (Fig. 3). Marker trajectories were filtered using a Woltring Filter with a low-pass cut-off frequency of 10 Hz and stop-band frequency of 30 Hz. Kinematic and kinetic data were both processed using the Vicon's validated Plug-in Gait full body modelling software. Kinetic variables were collected using two force platforms (Kistler 9281CA Force Platforms, Kistler Instrument Corp., Switzerland) that were placed in the floor space of the laboratory and were collected concurrently with the motion capture system. The sand (particle size 0.02-0.2 mm) (Building Sand, Wickes, UK) was placed in a purpose-built pit with deformable sides and base, to allow lateral displacement of the sand, and the transmission of forces onto and from the force plate.

The sand was at a depth of 10 cm and placed directly on top of the force platforms in the laboratory (Fig.1, Fig. 2). When hopping onto the sand pit from the same level as the top of sand participants stood on a 10 cm plyometric box (Foam Plyometric Box, Perform Better Ltd., UK) (Fig. 1 B). When hopping onto the sand from a 30 cm height, a 40 cm box was used to account for the change in height (Fig. 1 D).

***Figure 3. The Marker placement of the Vicon Plug in Gait Model as presented from the manufacturers guidelines (Vicon Motion Systems, Oxford, UK).***

***Insert Fig. 3 here***

The SLH test has high reliability (ICC: r = 0.97, 95% CI; 0.9 – 0.99) (31) and also places high demand on the lower extremity to absorb ground reaction forces (13). Participants were instructed to stand on one leg and to position toes as close as possible to a predetermined floor marker (Fig. 2). The subject began the hop standing on one leg, keeping the hands static on the hips throughout the jump. Subjects were instructed to hop forward onto either the floor or sand during a level jump or hop down onto the floor or sandpit from a 30 cm height. A pre-determined floor marker 30 cm from the subjects starting position was used to standardise landing position (Fig. 2). A controlled landing was instructed for all test conditions by asking the subjects to land with a flat foot and hold the position on landing (43). Each condition was completed three times on the dominant leg. Trials in which the foot did not land completely on the force platform were discarded and subsequently repeated. Following each landing on the sand surface the sand was raked prior to the next jump to ensure an evenly distributed surface and a consistent 10 cm depth. During each condition, KAM, AP tibial translation and knee shear force were calculated throughout the complete movement. Data was exported, using a pipeline provided by the software manufacturers (Vicon Motion Systems, UK), into Microsoft

Excel so that data could be edited ready for analysis. Data from the initial 50 milliseconds immediately after contact with the force platforms was used for analysis as this time period provides the greatest risk of injury (33).

Statistical Analyses

Raw data, absolute and relative to body mass (kg), are presented as the mean ± SD. Using a custom-made spreadsheet (25) all data was logged transformed and then back transformed to obtain the percentage difference, with uncertainty of the estimates expressed as 90 % confidence limits between conditions for each outcome measure. Threshold values of 0.2, 0.6 and 1.2 represented small, moderate and large effects, respectively, with magnitude-based inferences subsequently applied (26). The probability of a substantial true population difference was assigned the following descriptors: <0.5 % most unlikely; 0.5-5 %, very unlikely; 5-25 % unlikely; 25-75 %, possibly; 75-95 %, likely; 95-99.5 %, very likely; >99.5 %, most likely (26). Clear mechanistic effects (<5 % chance of the CL overlapping both substantially positive and negative thresholds) were qualified as per Hopkins et al. (26).

## RESULTS

Descriptive statistics for the dependent variables are displayed in Table 1. Differences in dependent variables between surface conditions at two different heights are displayed in Table 2. Compared to landing on a firm surface from a 30 cm height, KAM was lower when landing on a sand surface. AP tibial translation was also lower on a sand surface, during a level jump. Effect sizes for these two conditions were moderate. There was no difference in knee shear force when landing on either surface at either height.

***Table 1: Raw data, presented as both absolute and relative to body mass (kg), (Mean ± SD) of the four conditions for the three outcome measures examined in this study***

***Insert Table 1 here***

***Table 2: Between condition differences for relative knee shear force, relative knee abduction moment and absolute anterior-posterior tibia translation***

***Insert Table 2 here*

## DISCUSSION

The purpose of this study was to determine whether differences were apparent in landing strategies and knee joint loads (KAM, AP tibial translation and total knee shear force) when hopping onto sand and firm ground from both a level surface and a 30 cm height. As these joint loads have been established as significant risk factors for ACL and PFJ injury, the study would help provide some initial data as to whether the use of sand in injury prevention and rehabilitation ~~programmes~~programmes may reduce these loads, and subsequent injury risk compared to a firm surface. The main findings of this study were that KAM was lower when undertaking a drop jump (30 cm) onto a sand surface compared to a firm one. AP tibial translation was also lower on a sand surface compared to a firm one, during a level jump. The magnitude of these effects was moderate and it is possible that these differences hold true for the population. These findings provide some initial support for the use of a less stable sand surface to reduce knee joint loads commonly associated with ACL and PFJ injury during both horizontal and vertical jumping tasks.

Most ACL and PFJ injuries occur during non-contact activities such as jumping and landing (1,7,22) on different surfaces, although little data exists regarding knee joint loads when training on these surfaces. Hence, there is no data to directly compare the effects of sand on knee joint loads. Furthermore, the value of ~~-~~KAM and amount of AP tibial translation on landing which becomes significant in terms of creating the injury risk is also unknown. Previous KAM values of 18.4 ± 15.6 N.m during the landing of a 30 cm drop jump in uninjured female athletes participating in high-risk sports for ACL injury (soccer, basketball, volleyball) have been reported (23). Our results, show similar values of 17.3 ± 5.9 N.m for a firm surface with a reduction to 14.8 ± 5.2 N.m when landing on a sand surface from a 30 cm height. Increased KAM during landing has been significantly correlated with an increase in lower extremity valgus alignment (23,32,42). The link between increased knee valgus and resultant ACL strain and PFJ injuries has been widely documented through both cadaver and in vivo research (7,18,24,33,36). It is therefore likely that the reduction in KAM observed when landing on the sand surface from a 30 cm height would lead to a reduction in valgus loading compared to a firm surface, and a subsequent decrease in ACL and PFJ injury risk. Given that knee valgus on landing is also a common technique flaw amongst athletes, and can be reliably used to screen landing performance (37), the reduction in KAM provides some early support for considering the use of a less stable sand surface in both rehabilitation and prevention programmes, for individuals who are considered to be at a heightened risk.

Regarding AP tibial translation, previous average values ranging from 8.5 mm to 13 mm for uninjured ACLs have been reported using cadaveric specimens, and on participants with and without anaesthesia (14,30,39). Our results, although in more dynamic conditions, showed similar values ranging from 11.8 ± 4.0 mm to 14.4 ± 5.6 mm across the four conditions measured, with a reduction from 12.6 ± 3.7 mm to 11.8 ± 4.0 mm on sand during a horizontal jump. Landing on a sand surface therefore during jumping exercises would appear to have two major benefits. Reduced AP tibial translation is evident on horizontal jump landings and reduced KAM is evident when landing from a drop jump.

Although KAM and AP tibial translation data is limited, a number of other studies have demonstrated biomechanical data on changes occurring resulting from landing on various surfaces. Moritz and Farley (41) demonstrated that humans alter kinematics and/or muscle activation 3-76 ms before landing, when expecting a surface stiffness change. Subjects landed with more knee flexion and increased their muscle activation 24-76 % during the 50 ms before landing on the expected hard surface compared to a consistently soft surface. Leg stiffness was also 47 % lower on the expected hard surface than on the consistently soft surface immediately after touchdown. However, for unexpected surface changes, they demonstrated that hoppers use passive mechanics to change leg stiffness, compensate for the new surface soon after landing and before any changes in neural activity occur. These mechanical reactions to landing, caused by intrinsic muscle properties termed ‘preflexes’, and passive dynamics of the body’s linked segments, are thought to contribute to adjustments for new surfaces more rapidly than reflexes (41). This suggests that neural feedback is not a prerequisite for a change in leg stiffness, and was further supported by the findings of Van der Krogt et al (54) for both unexpected hard and unexpected soft surfaces. Although leg stiffness and neural activity were not directly measured in our study, the subjects were not blinded to the surface for each hop. This increases the likelihood that neural anticipation rather than passive mechanics played a significant role in subjects adapting their landing strategy for the expected surface change, when hoping onto both the firm and less stable sand surface. It is possible that these adaptations on the firm and sand surface may account for some of the differences in both KAM and AP tibial translation reported.

With unexpected perturbations, previous work by Daley et al. (12) demonstrated a proximo-distal gradient in limb neuromuscular performance and motor control. They demonstrated that the proximal muscles at the hip and knee joints of a helmeted guinea fowl were controlled primarily in a feedforward manner and exhibited load-insensitive mechanical performance at ground contact. However, the distal muscles at the ankle and tarsometatarso-phalangeal (TMP) joints were highly load-sensitive, due to intrinsic mechanical effects and rapid, higher gain proprioceptive feedback. The hip also maintained the same mechanical role regardless of limb loading, whereas the ankle and TMP switched between spring-like function with an increased amount of knee flexion at ground contact and damping function as the knee became more extended at ground contact. Whether or not this proximo-distal gradient in limb neuromuscular performance and motor control would be evident with an expected perturbation in humans, such as a jump onto an anticipated less stable sand surface is unclear, and warrants further investigation.

Similar to our study but using running tasks, Pinnington et al. (47) and Thomas and Derrick (52) demonstrated alterations to kinematics on irregular surfaces. Thomas and Derrick (52) found that runners demonstrated increased knee flexion at heel contact on an irregular surface, with greater impact attenuation reported compared with a firm surface. Similarly, Pinnington et al. (47) found that hip and knee flexion at initial foot contact (IFC), mid support (MS) and flexion maximum were all greater when running on sand compared with firm surfaces at 8 and 11 km/h. Although joint angles were not analysed in the current investigation, it is possible that the subjects landed with a greater degree of knee and hip flexion on the more unstable sand surface in an attempt to improve stability on landing. As increased hip and knee flexion has been shown to reduce anterior tibiofemoral shear force during a jumping task (53), these kinematic changes may explain the reductions in AP tibial translation observed on the less stable sand surface. Pinnington et al. (47) also demonstrated that the EMG of the hamstring muscles was greater on sand during the late swing phase, which could be associated with a need for greater eccentric control over the rate of knee extension, so that the knee remains more flexed at IFC. EMG activity in the Hamstrings, Vastus Lateralis, Vastus Medialis, Rectus Femoris and Tensor Fascia Latae were also greater than the firm surface measures during the stance phase in the 8 km/h trials. These EMG findings suggest that repeated exposure to sand or other less stable surfaces may lead to the development of muscle activation strategies that promote stability and kinaesthetic sense during exercise, and subsequently reduce injury risk. However, these changes were observed during running activities, and muscle activation strategies may be different during the landing of jumping tasks on different surfaces. The role of muscle control in protecting against ACL and PFJ injury has been previously established with the importance of hamstring to quadriceps strength ratio and gastrocnemius strength frequently cited (17,23,40,51). Further investigation of muscle activation strategies during the four conditions tested here would be beneficial. This would help establish whether muscles which are known to be important in reducing ACL injury risk have greater activation on a sand compared to a firm surface during different jumping tasks.

Despite our findings, it is important to highlight potential limitations. We chose to use KAM and AP tibial translation, as they were significant risk factors for PFJ and ACL injury. However, as knee valgus has the greatest link to injury and can be screened clinically (7,18,33,36,37), future studies which analyse knee valgus specifically, when comparing jump landings onto sand and firm ground would be beneficial. To determine the effect of sand specifically, rather than a less stable surface compared with a firm one, we acknowledge that future studies should also include a more unstable control such as a pliable grass surface.

We used inverse dynamics to calculate the forces experienced by the subjects. This approach does not consider individual muscle forces and their contributions to joint loading, so reduces the accuracy in assessing the true forces acting on the joint. However, methods that accurately measure individual muscles forces are not yet readily available, leaving inverse dynamics as a suitable means of estimating joint forces at present. Although our pilot study showed that centre of pressure measures would remain accurate with a sand covering on the force plate, we acknowledge that the small offset between the depth of the footprint and the force plate may have had some effect on our inverse dynamics calculations. Despite, the plug-in gait marker set we used being widely utilised in biomechanical analysis for examining knee mechanics (27,56), the authors feel that alternative marker sets may have been more appropriate for the explosive nature of the movements being examined, for example those employed by Cappozzo and colleagues (11) and Morgan and colleagues (40). We used a valid sampling frequency of 100 Hz for kinematic analysis of dynamics of the knee during loading, however we feel a greater sampling frequency would have added strength to our study. A higher frequency would have allowed the capture of all the forces during the weight-acceptance phase. These rapidly rising forces (during the first 50 ms) are likely to be higher on the firm surface rather than the sand. Hence, had we used a greater sampling frequency then the differences in KAM could well have been even more apparent, further supporting the potential reduction in injury risk on the less stable sand surface.

Sand characteristics such as granulation, moisture content, depth and consistency of the substratum can contribute to different levels of stiffness and may affect results (46). As we only used one type of sand under single lab-controlled conditions future work should quantify the effects of different sand conditions on knee joint loads. Finally, use of state of the art expensive technology such as the 3D V~~v~~icon system to quantify the kinetics observed lacks ecological validity for practitioners, and would not be available in the clinical environment. However, the Kinect is a valid and reliable tool for analysis (34).

Practical Applications

The present study adds to current understanding, showing some initial support for the use of a less stable sand surface to reduce common knee joint loads associated with ACL and PFJ injury during landing of both a drop (30 cm) and level jump. The data set is an initial step towards determining whether sand may provide a safer alternative to firm ground in ACL and PFJ injury prevention and rehabilitation programmes, which involve a jumping component. We showed that both KAM and AP tibial translation were lower on sand compared to a firm surface during drop and horizontal jump landings respectively. Strength and Conditioning professionals and clinicians may therefore wish to consider the use of a less stable sand surface when planning ACL or PFJ injury prevention or rehabilitation programmes which involve a dynamic jumping component. The reduced loads in sand may have the potential to reduce ACL and PFJ injury risk, whilst also enabling an accelerated rehabilitation program, as jumping activities could potentially be implemented more safely at an earlier stage in the process. Further research is required however, before any firm conclusions regarding the safety of a sand surface can be made. We hope our study catalyses further research in this field.

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## REFERENCES

1. Agel, J, Arendt, EA, and Bershadsky, B. Anterior cruciate ligament injury in National Collegiate Athletic Association basketball and soccer: a 13-year review. *The American Journal of Sports Medicine* 33(4): 524-531, 2005.

2. Barrett, RS, Neal, RJ, and Roberts, LJ. The dynamic loading responses of surfaces encountered in beach running. *Journal of Science and Medicine in Sport* 1(1): 1-11, 1998.

3. Binnie, MJ, Dawson, B, Pinnington, H, Landers, G, and Peeling, P. Effect of training surface on acute physiological responses after interval training. *Journal of Strength and Conditioning Research* 27: 1047-1056, 2013a.

4. Binnie, MJ, Dawson, B, Pinnington, H, Landers, G, and Peeling, P. Part 2: Effect of training surface on acute physiological responses after sport-specific training. *Journal of Strength and Conditioning Research*, 27: 1057-1066, 2013b.

5. Binnie, MJ, Dawson, B, Arnot, MA, Pinnington, H, Landers, G, and Peeling, P. Effect of sand versus grass training surfaces during an 8-week pre-season conditioning programme in team sports athletes. *Journal of Sports Sciences* 32(11): 1001-1012, 2014.

6. Bishop, D. A comparison between land and sand-based tests for beach volleyball assessment. *Journal of Sports Medicine and Physical Fitness* 43: 418-423, 2003.

7. Boden, BP, Dean, GS, Feagin, JA, and Garrett, WE. Mechanisms of anterior cruciate ligament injury. *Orthopaedics* 23(6): 573-578, 2000.

8. Boling, MC, Padua, DA, Marshall, SW, Guskiewicz, K, Pyne, S, and Beutler, A. A prospective investigation of biomechanical risk factors for patellofemoral pain syndrome: the Joint Undertaking to Monitor and Prevent ACL Injury (JUMP-ACL) cohort. *The American Journal of Sports Medicine* 37(11): 2108-2116, 2009.

9. Boling, M, Padua, D, Marshall, S, Guskiewicz, K, Pyne, S, and Beutler, A. Gender differences in the incidence and prevalence of patellofemoral pain syndrome. *Scandinavian Journal of Medicine & Science in Sports* 20(5): 725-730, 2010.

10. Clark, RA., Pua, YH, Fortin, K, Ritchie, C, Webster, KE, Denehy, L, and Bryant, AL. Validity of the Microsoft Kinect for assessment of postural control. *Gait & Posture* 36(3): 372-377, 2012.

11. Copozzo, A, Catani, F, Della Croce, U, and Leardini, A. Position and orientation in space of bones during movement: anatomical frame definition and determination. *Clinical biomechanics,* 11(2): 90-100, 1996.

12. Daley, MA, Felix, G, and Biewener, AA. Running stability is enhanced by a proximo-distal gradient in joint neuromechanical control. *Journal of Experimental Biology*, 210(3): 383-94, 2007.

13. Decker, MJ, Torry, MR, Wyland, DJ, Sterett, WI, and Steadman, JR. Gender differences in lower extremity kinematics, kinetics and energy absorption during landing. *Clinical Biomechanics* 18(7): 662-669, 2003.

14. DeMorat, G, Weinhold, P, Blackburn, T, Chudik, S, and Garrett, W. Aggressive quadriceps loading can induce noncontact anterior cruciate ligament injury. *The American Journal of Sports Medicine* 32(2): 477-483, 2004.

15. Di Stasi, S, Myer, GD, and Hewett, TE. Neuromuscular training to target deficits associated with second anterior cruciate ligament injury. *Journal of Orthopaedic & Sports Physical Therapy* 43(11): 777-A11, 2013.

16. Docs.vicon.com. (2017). *Full body modeling with Plug-in Gait - Nexus 2.6 Documentation – Documentation VICON*. [online] Available at: https://docs.vicon.com/display/Nexus26/Full+body+modeling+with+Plug-in+Gait [Accessed 14th Oct. 2017].

17. Donnell-Fink, LA, Klara, K, Collins, JE, Yang, HY, Goczalk, MG, Katz, JN, and Losina, E. Effectiveness of knee injury and anterior cruciate ligament tear prevention programs: A meta-analysis. *PloS one 10(12): e0144063*, 2016.

18. Fukuda, Y, Woo, SL, Loh, JC, Tsuda, E, Tang, P, McMahon, PJ and Debski, RE. A quantitative analysis of valgus torque on the ACL: a human cadaveric study. *Journal of Orthopaedic Research*, 21(6):1107-12, 2003.

19. Gehring, D, Melnyk, M, and Gollhofer, A. Gender and fatigue have influence on knee joint control strategies during landing. *Clinical Biomechanics 24*(1): 82-87, 2009.

20. Gortsila, E, Theos, A, Smirnioti, A, and Maridaki, M. The effect of sand-based training in agility of pre-pubescent volleyball players. In *16th annual congress of the European college of sports science*, Liverpool, United Kingdom. *Book of Abstracts* (p. 643), 2011.

21. Greenberger, HB, and Paterno, MV. Relationship of knee extensor strength and hopping test performance in the assessment of lower extremity function. *Journal of Orthopaedic & Sports Physical Therapy* 22(5): 202-206, 1995

22. Griffin, LY, Albohm, MJ, Arendt, EA, Bahr, R, Beynnon, BD, DeMaio, M, Dick, RW, Engebretsen, L, Garrett, WE, Hannafin, JA, and Hewett, TE. Understanding and preventing noncontact anterior cruciate ligament injuries a review of the Hunt Valley II meeting, January 2005. *The American Journal of Sports Medicine* 34(9): 1512-1532, 2006.

23. Hewett, TE, Myer, GD, Ford, KR, Heidt, RS, Colosimo, AJ, McLean, SG, Van den Bogert, AJ, Paterno, MV, and Succop, P. Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes a prospective study. *The American Journal of Sports Medicine* 33(4): 492-501, 2005.

24. Hewett, TE, Torg, JS, and Boden, BP. Video analysis of trunk and knee motion during non-contact anterior cruciate ligament injury in female athletes: lateral trunk and knee abduction motion are combined components of the injury mechanism. *British Journal of Sports Medicine* 43(6): 417-422, 2009.

25. Hopkins, WG. Spreadsheets for analysis of controlled trials with adjustment for a predictor. *Sportscience* 10: 46-50, 2006.

26. Hopkins, W, Marshall, S, Batterham, A, and Hanin, J. Progressive statistics for studies in sports medicine and exercise science. *Medicine and Science in Sports and Exercise* 41(1): 3, 2009.

27. Hughes, G, and Watkins, J. Lower Limb Coordination and Stiffness During Landing from Volleyball Block Jumps. *Research in Sports Medicine*, 16(2): 138-154, 2008.

28. Impellizzeri, FM, Rampinini, E, Castagna, C, Martino, F, Fiorini, S, and Wisloff, U. Effect of plyometric training on sand versus grass on muscle soreness and jumping and sprinting ability in soccer players. *British Journal of Sports Medicine* 42: 42-46, 2008.

29. Imran, A, and O'Connor, JJ. Control of knee stability after ACL injury or repair: interaction between hamstrings contraction and tibial translation. *Clinical Biomechanics* 13(3): 153-162, 1998.

30. Kilinc, BE, Kara, A, Haluk Celik, YO, and Camur, S. Evaluation of the accuracy of Lachman and Anterior Drawer Tests with KT1000 ın the follow-up of anterior cruciate ligament surgery. *Journal of Exercise Rehabilitation* 12(4): 363, 2016.

31. Kockum, B, and Heijne, AILM. Hop performance and leg muscle power in athletes: Reliability of a test battery. *Physical Therapy in Sport* 16(3): 222-227, 2015.

32. Kristianslund, E, Faul, O, Bahr, R, Myklebust, G, and Krosshaug, T. Sidestep cutting technique and knee abduction loading: implications for ACL prevention exercises. *British Journal of Sports Medicine* 48(9): 779-783, 2014.

33. Krosshaug, T, Nakamae, A, Boden, BP, Engebretsen, L, Smith, G, Slauterbeck, JR, Hewett, TE, and Bahr, R. Mechanisms of anterior cruciate ligament injury in basketball video analysis of 39 cases. *The American Journal of Sports Medicine* 35(3): 359-367, 2007.

34. Macpherson, TW, Taylor, J, McBain, T, Weston, M, and Spears, IR. Real-time measurement of pelvis and trunk kinematics during treadmill locomotion using a low-cost depth-sensing camera: A concurrent validity study. *Journal of biomechanics* 49(3): 474-478, 2016.

35. Majewski, M, Susanne, H, and Klaus, S. Epidemiology of athletic knee injuries: A 10-year study. *The Knee* 13(3): 184-188, 2006.

36. Markolf, KL, Burchfield, DM, Shapiro, MM, Shepard, MF, Finerman, GA and Slauterbeck, JL. Combined knee loading states that generate high anterior cruciate ligament forces. *Journal of Orthopaedic Research*, 13(6): 930-5, 1995.

37. Mayhew, L, Johnson, MI, Francis, P, Snowdon, N and Jones, G. Inter-rater reliability, internal consistency and common technique flaws of the Tuck Jump Assessment in elite female football players. *Science and Medicine in Football*, 1(2): 139-144, 2017.

38. Miyama, M, and Nosaka, K. Influence of surface on muscle damage and soreness induced by consecutive drop jumps. *Journal of Strength and Conditioning Research* 18: 206-211, 2004.

39. Monaco, E, Labianca, L, Maestri, B, De Carli, A, Conteduca, F, and Ferretti, A. Instrumented measurements of knee laxity: KT-1000 versus navigation. *Knee Surgery, Sports Traumatology, Arthroscopy* 17(6): 617, 2009.

40. Morgan, KD, Donnelly, CJ, and Reinbolt, JA. Elevated gastrocnemius forces compensate for decreased hamstrings forces during the weight-acceptance phase of single-leg jump landing: implications for anterior cruciate ligament injury risk. *Journal of Biomechanics*, 47: 3295-3302, 2014.

41. Moritz, CT and Farley, CT. Passive dynamics change leg mechanics for an unexpected surface during human hopping. *Journal of Applied Physiology*, 97(4):1313-1322, 2004.

42. Myer, GD, Ford, KR, Khoury, J, Succop, P, and Hewett, TE. Biomechanics laboratory-based prediction algorithm to identify female athletes with high knee loads

that increase risk of ACL injury. *British Journal of Sports Medicine* 45: 245-252, 2011.

43. Neeter, C, Gustavsson, A, Thomeé, P, Augustsson, J, Thomeé, R, and Karlsson, J. Development of a strength test battery for evaluating leg muscle power after anterior cruciate ligament injury and reconstruction. *Knee Surgery, Sports Traumatology, Arthroscopy* 14(6): 571-580, 2006.

44. Øiestad, BE, Engebretsen, L, Storheim, K, and Risberg, MA. Knee osteoarthritis after anterior cruciate ligament injury a systematic review. *The American Journal of Sports Medicine* 37(7): 1434-1443, 2009.

45. Orendurff, MS, Segal, AD, Klute, GK, and Berge, JS. The effect of walking speed on centre of mass displacement. *Journal of Rehabilitation Research and Development* 41(6A):829, 2004.

46. Pinnington, HC, and Dawson, B. The energy cost of running on grass compared to soft dry beach sand. *Journal of Science and Medicine in Sport* 4: 416-430, 2001.

47. Pinnington, HC, Lloyd, DG, Besier, TF, and Dawson, B. Kinematic and electromyography analysis of submaximal differences running on a firm surface compared with soft, dry sand. *European Journal of Applied Physiology* 94: 242-253, 2005.

48. Rudolph, KS, Axe, MJ, and Snyder-Mackler, L. Dynamic stability after ACL injury: who can hop? *Knee Surgery, Sports Traumatology, Arthroscopy* 8(5): 262-269, 2000.

49. Sakane, M, Livesay, GA, Fox, RJ, Rudy, TW, Runco, TJ, and Woo, SY. Relative contribution of the ACL, MCL, and bony contact to the anterior stability of the knee. *Knee Surgery, Sports Traumatology, Arthroscopy* 7(2): 93-97, 1999.

50. Sell, TC, Ferris, CM, Abt, JP, Tsai, YS, Myers, JB, Fu, FH, and Lephart, SM. Predictors of proximal tibia anterior shear force during a vertical stop-jump. *Journal of Orthopaedic Research* 25(12): 1589-1597, 2007.

51. Souza, RB, and Powers, CM. Differences in hip kinematics, muscle strength, and muscle activation between subjects with and without patellofemoral pain. *Journal of Orthopaedic & Sports Physical Therapy* 39(1): 12-19, 2009.

52. Thomas, JM, and Derrick TR. Effects of step uncertainty on impact peaks, shock attenuation, and knee/subtalar synchrony in treadmill running. *Journal of Applied Biomechanic*s, 19(1):60-70, 2003.

53. Tsai, LC, Ko, YA, Hammond, KE, Xerogeanes, JW, Warren, GL, and Powers, CM. Increasing hip and knee flexion during a drop-jump task reduces tibiofemoral shear and compressive forces: implications for ACL injury prevention training. *Journal of Sports Sciences*, 35(24): 2405-11, 2017.

54. Van Der Krogt, MM, De Graaf, WW, Farley, CT, Moritz, CT, Casius, LR and Bobbert, MF. Robust passive dynamics of the musculoskeletal system compensate for

unexpected surface changes during human hopping. *Journal of Applied Physiology*, 107(3): 801-8, 2009.

55. Wilk, KE, Romaniello, WT, Soscia, SM, Arrigo, CA, and Andrews, JR. The relationship between subjective knee scores, isokinetic testing, and functional testing in the ACL-reconstructed knee 1. *Journal of Orthopaedic & Sports Physical Therapy* 20(2): 60-73, 1994.

56. Wulf, G, and Dufek, JS. (2009). Increased jump height with an external focus due to enhanced lower extremity joint kinetics. Journal of Motor Behavior, 41(5): 401-409, 2009.

57. Yigit, SS, and Tuncel, F. A comparison of the endurance training responses to road and sand running in high school and college students. *Journal of Strength and Conditioning Research* 12: 79-81, 1998.