Malaysian Journal of Movement, Health & Exercise, 9(1), 77-88, 2020

REFLECTING ON SIDE-CUTTING VARIABILITY ON ACL INJURY RISK: A CASE STUDY

Muhammad Hamdan[1] and Raja Mohammed Firhad Raja Azidin[1, 2*]

[1]Faculty of Sports Science and Recreation, UiTM Shah Alam
[2]National Football Academy UiTM-MOHE-FAM, UiTM Shah Alam

[*]Email: firhad@salam.uitm.edu.my
(Received 12 June 2019; accepted 1 July 2019; published online 1 January 2020)

To cite this article:*Hamdan, M. & Raja Azidin, R. M. F. (2020). Reflecting on side-cutting variability on ACL injury risk: A case study. Malaysian Journal of Movement, Health & Exercise,9(1), 77-88. https://doi.org/10.15282/mohe.v9i1.400*
Link to this article: *https://doi.org/10.15282/mohe.v9i1.400*

Abstract

This case study aims to discuss a proposal for identifying anterior cruciate ligament injury (ACL) risk by observing the variability of side cutting kinematics with respect to the development of fatigue. One participant (n=1) sustained an ACL injury while performing a side-cutting task during the latter stages of a soccer match a few months after a recorded laboratory session. Data from his laboratory session were then compared to matched samples of seventeen healthy, uninjured participants (n=17). The injured participant was found to have performed his side-cutting task with a lower deviation than mean variability before the later stages of the second half of simulated soccer match-play. Over time, the participant performed side-cutting tasks with increasing variability in sagittal plane kinematics, suggesting that compensatory actions may have been implemented to facilitate the task execution. This elevated variability may be indicative of an increased risk of ACL injury. Further prospective investigation is warranted to gain a deeper understanding of how variabilities may play a role in task execution performance with respect to injury mechanisms.

Keywords: Anterior Cruciate Ligament, Side-cutting, Soccer, Fatigue, Biomechanics,Variability

Introduction

The knee is one of the most commonly injured regions among athletes (Wahab et al., 2015). In soccer, ligament ruptures and strains such as the anterior cruciate ligament (ACL) injury comprise nearly a third of knee injuries, making them the most likely injury to be sustained by an athlete (Herrero et al., 2014). Epidemiological observations have indicated that most ACL injuries have been non-traumatic in nature (Agel et al., 2007; Boden et al., 2000; Brophy et al., 2010; Faunø & Wulff, 2006; Griffin et al., 2000; Waldén et al., 2011). According to Agel et al. (2007) and Ekstrand et al. (2011), the likelihood of an athlete sustaining a non-traumatic ACL injury can increase up to six-fold during matches in comparison to practice. High intensity physical exertion thus forms a crucial factor in increasing non-traumatic ACL injury risk among players. Recent advances in ACL injury risk screening research have thus implemented repeated, sports-specific physical exertions into various markers of ACL injury risk to seek further understanding on how fatigue induced from these sports-specific exertions may play a role in escalating the injury risk (Cone et al., 2012; Cortes et al., 2013; Cortes et al., 2012; Greig, 2009; Raja Azidin et al., 2015; Sanna & O’connor, 2008; Shultz et al., 2013; Shultz et al., 2015). This study presents a non-traumatic ACL injury suffered by an athlete while performing a side-cutting task during a soccer match and discusses the prospect of identifying variabilities in task execution patterns as a predictive marker of ACL injury risk.

Case Study

Injury Case

One male athlete (age: 24 years; height: 1.63 m; body mass: 61 kg) performed a series of side-cutting trials in a laboratory. The university ethics committee approved the study. The participant was instructed to run an overground simulated soccer match-play consisting of multidirectional acceleration and deceleration components intermittently to replicate physical and physiological exertions observed in soccer matches. Further details of the overground simulated soccer match-play protocol can be found elsewhere (Barreira et al., 2016; Raja Azidin et al., 2013). At selected time points during the simulation (Time: 0min, 45min, 60min, 105min), the participant was required to perform five anticipated, 45˚ side-cutting tasks. Each task was video recorded for analysis.

Approximately two months after the laboratory session, the participant sustained a knee injury on his dominant leg following a side-cutting maneuver around the last 5 minutes of a soccer match. Upon clinical inspection by an orthopedic specialist, the injury was diagnosed as a complete rupture of the ACL. The anterior Drawer test was positive and magnetic resonance imaging (MRI) confirmed the diagnosis. Before the current injury, the participant had normal foot function and no injury of the lower limbs, and especially in the knee region, in the previous 8 months.

Biomechanical Model

The participants in this study were required to wear tight-fitting compression wear. Five spherical markers were attached to selected bony landmarks depicting sagittal plane movements of the hip and knee joint, as well as to aid in initial contact identification (Figure 1). The hip angle was formed by two lines originating from the acromion process and the lateral femoral epicondyle and intersected at the greater trochanter, whereas the knee angle was formed by two lines originating from the greater trochanter and the lateral malleolus and intersecting at the lateral femoral epicondyle (Dingenen et al., 2015a; Dingenen et al., 2015b). A fifth marker was attached to the fifth metatarsophalangeal joint for initial contact identification.

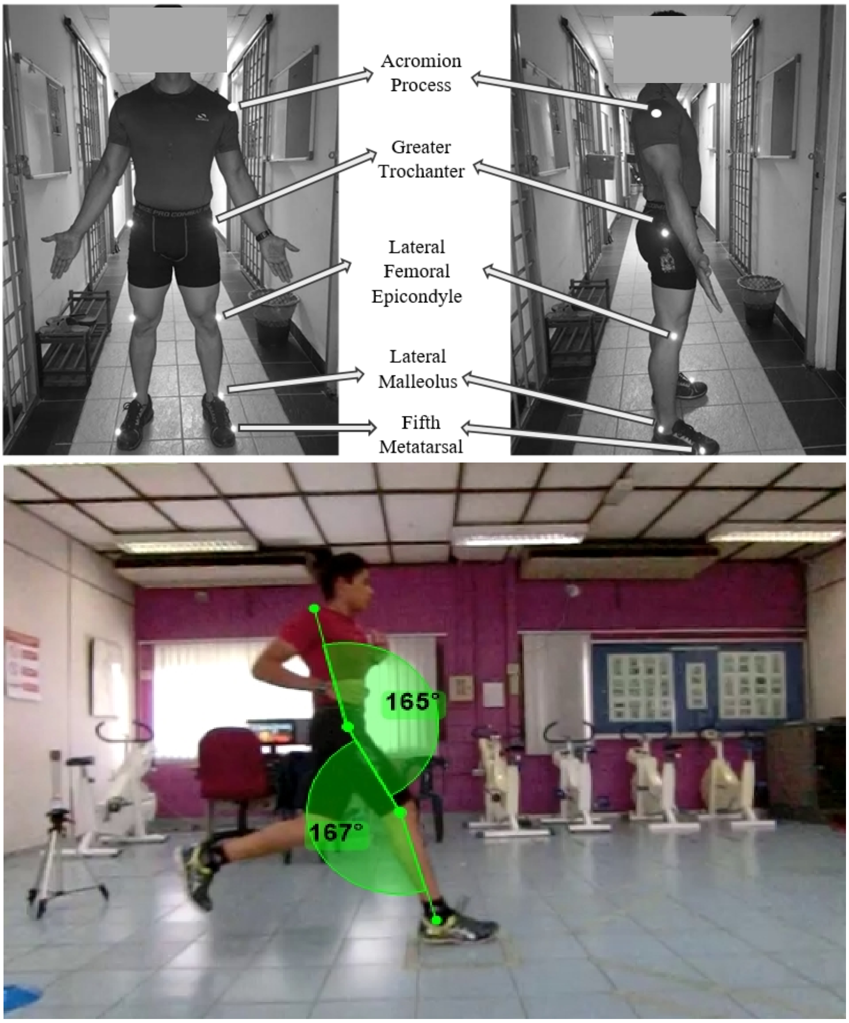

Figure 1: Marker placements on selected bony landmarks (left) and hip and knee angles (right).

Side-cutting Kinematics Assessment

Side cutting tasks were selected during the laboratory session because its maneuvers mimic the most commonly reported kinematics and demands of the lower limb during ACL injury occurrence (Faunø & Wulff, 2006; Hawkins et al., 2001; Mclean et al., 2004). Further reports on the reliability of side cutting kinematics have been published and presented elsewhere (Hamdan et al., 2017a; Hamdan et al., 2018b; Hamdan et al., 2017c; Sankey et al., 2015). All side cutting tasks were performed inside a 0.30 × 0.30 m box marked on the ground with two high-speed cameras (Exilim ZR-800, Casio, USA) set at 240 frames per second (fps) and a pixel resolution of 512 × 384 placed perpendicularly to both sides (sagittal plane) of the side cutting box. The height and distance of the cameras were adjusted accordingly to fit the full model of the markers into the recorded display in order to ensure that the markers were all visible for processing.

The speed of the side cutting tasks was standardized using timing gates (Swift Performance, USA) which were set up 2 m apart and 2 m from the designated landing box for the side cutting task execution. The approach speed range was set at 4 – 5 ms^{-1} to ensure a safe approach speed to approach the cutting maneuver with representative kinematic data for injury risk assessment (Vanrenterghem et al., 2012). Trials with approach speeds not within the set range were excluded from the analysis. The side cutting tasks utilized were anticipated in nature and consists of a 45˚ change of direction. Cones were also placed at 45˚ of deviation from the runway in addition to floor markings representing a target gate for exiting the 45˚ side cutting task. The participant performed five successful trials of side cutting for the dominant limb at all selected time point.

Kinematic Changes of Hip and Knee Angles at Initial Contact Following Simulated Soccer Match-play

Repeated measures analysis of variance revealed that both the hips and knees were oriented at a more extended at initial contact of side cutting maneuvers as the simulated soccer match-play progresses and these findings have been published and presented elsewhere (Hamdan et al., 2017b, 2018a; Hamdan et al., 2018b). These findings are in line with previous studies (Greig, 2009; Raja Azidin et al., 2015; Sanna & O'connor, 2008) and suggest that fatigue from soccer-specific exertions may play a role in increasing ACL injury risk.

Kinematic Comparisons of the Injured Participant versus Uninjured Participants

Data are presented in terms of mean and standard deviations (SD). A similar procedure of the side-cutting kinematics assessment was performed by 17 other male participants (Age: 23.1 ± 4.7 years; Height: 1.7 ± .1 m; Mass: 70.6 ± 10.4 kg) and matched against the injured participant's trials. Hip and knee extension normalized root-mean-square deviations (NRMSD) were computed to compare variabilities between datasets with different sizes (N = 17 vs. n = 1). Normalized root-mean-square deviations were defined as the SD denominated by the range of the measured data (i.e. hip and knee extension; (Ris et al., 1999; Zambresky, 1989)).

$$NRMSD = \frac{SD}{x_{max} - x_{min}} \qquad \text{[Eq. 1]}$$

Table 1 and Figure 2 show the means, NRMSD and mean variabilities for hip and knee angles at initial contact during side cutting tasks for all participants in comparison to the injured participant's trials. As we were interested in exploring the variabilities in task execution, each participant's individual hip and knee extension SDs were treated as the observed data to calculate mean variability, which was calculated by getting the sum of SD of all participants and with the number of participants (N = 17) as demonstrated below:

$$Mean\ Variability = \frac{\sum_{i=1}^{N} SD}{N} \qquad \textit{[Eq. 2]}$$

Table 1: Mean and variabilities for hip and knee angles at initial contact between uninjured and injured participant during side-cutting trials.

Joint Angle		Mean Uninjured (Mean Injured)	NRMSD Uninjured (NRMSD injured)	Mean Variability Uninjured (SD injured)
Hip Angle	0min	152.6° (156.8°)	0.333 (0.386)	5.5° (5.2°)
	45min	154.4° (159.8°)	0.306 (0.435)	5.5° (5.1°)
	60min	157.0° (161.2°)	0.314 (0.373)	3.9° (2.2°)
	105min	157.4° (157.2°)	0.302 (0.454)	4.2° (6.1°)
Knee Angle	0min	162.3° (163.4°)	0.362 (0.373)	3.7° (2.7°)
	45min	163.9° (163.6°)	0.320 (0.394)	3.8° (2.6°)
	60min	165.3° (165.4°)	0.316 (0.434)	3.4° (2.6°)
	105min	164.8° (162.8°)	0.333 (0.404)	3.7° (4.1°)

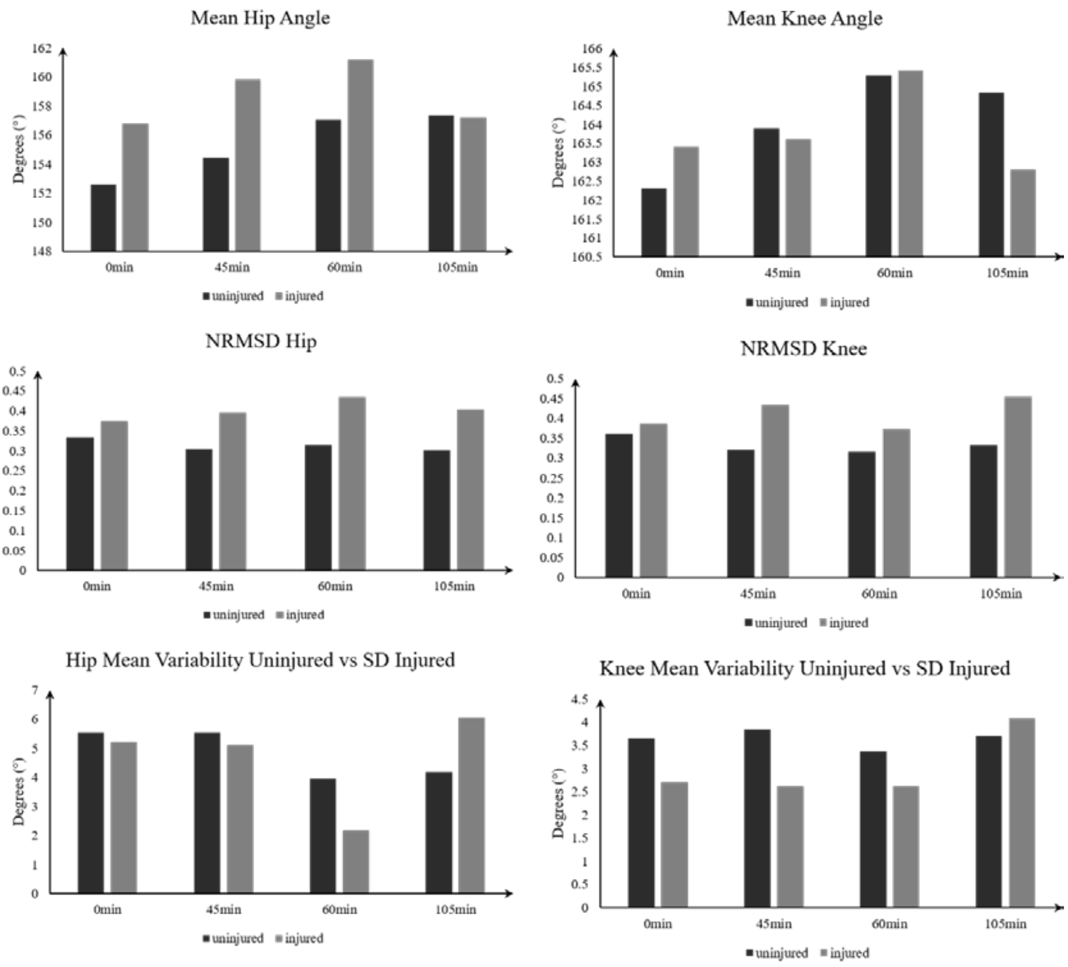

Figure 2: Mean hip angles (top left), knee angles (top right) with their corresponding NRMSD (middle) and mean variabilities (bottom).

Figure 2 shows a graphical representation of the mean and variabilities of the hip and knee angles at initial contact of side cutting tasks throughout the soccer match-play simulation.

Discussion

The aim of this paper was to discuss the prospect of identifying variabilities in task execution patterns as a predictive marker of ACL injury risk.

Previous studies by Greig (2009), Hamdan et al. (2018a), Raja Azidin et al. (2015), and Sanna and O'Connor (2008) have looked into mean extension angles of the hip and knees during cutting maneuvers over the course of fatigue development during soccer-specific maneuvers. The hips and the knees have universally been observed to be significantly more extended at initial contact during cutting maneuvers, proposing that fatigue may have implications on hamstrings and quadriceps co-activation synchrony during the task maneuver, leading to an increased shear force acting on the ACL. This situation, combined with an elevated ACL angle from an extended knee (Blackburn & Padua, 2008), and a posteriorly shifted centre of mass due to an erect orientation at the hips could easily load the ACL beyond its breaking point.

Based on the mean hip and knee angles of the injured participant, we can observe a pattern of increasing extension in both joints at initial contact during side-cutting tasks as the participant accumulates fatigue. This corresponds well in comparison to all other participants' side-cutting kinematics and appears to be in an agreement with previous studies, suggesting an increased risk of injury. There were notable reductions in hip and knee angles of the injured participant. We speculate that this may be the outcome of compensatory measures in landing strategies implemented by the participant following repeated exertions. This speculation will be further discussed in parallel to the variability observations reported.

Normalized root-mean-square deviations reveal that the injured participant had notably higher variability in hip and knee extension execution during side cutting. These variabilities appear to be incremental throughout the progression of fatigue (hip: 0min - 105min; knee: 0min – 45min, 60min – 105min). These variabilities may be indicative of an existing characteristic predisposing the participant to greater injury risk. Although the increased variability contradicts the findings by Falla et al. (2014), the discrepancies in the observations may be due to the parameters measured in the respective studies. This study attempted to observe the characteristics of biomechanical orientations presented by a future-injured participant while Falla et al. (2014) observed variabilities in muscle activities among injured participants.

From the perspective of functional stability, A study by Greig and Walker-Johnson (2007) noted that balance performance was not affected by soccer-specific fatigue; however, they also noted deflections off the stabilometer surface, which they attributed to a change in the postural control strategy. Adlerton et al. (2003) explained that postural control strategies from the ankle to the hip may be altered from a habitual strategy to produce compensatory corrections in order to maintain functional stability. From the sagittal plane, these corrections may be produced by reducing or increasing joint extension angles at the hips and the knees and (Greig & Walker-Johnson, 2007). Another noteworthy explanation for this fatigue-induced compensation phenomena could be the reduced distribution variation of muscle activity across the quadriceps and hamstrings during the execution of a side-cutting task. Falla et al. (2014) reported that reduced variability in muscles activation distribution has been observed to be consistently present among participants who suffer muscle pain and this condition may pose detrimental implications for the provocation of injury due to fatigue attributed to repeated tasks. Another muscle activation impairment has also been proposed by Hashemi et al. (2011), suggesting that fatigue may inhibit and impair co-contraction of the muscles. This impairment may lead to an unstable orientation in the joint where the muscles are attached to and may inhibit the ability of an antagonist muscle to negate the shear force produced by the agonist muscle, rupturing the ligaments holding the joint in place.

As these alterations occur during the bouts of fatigue from repeated high-intensity physical exertions, joint stability may be compromised. It should be noted that whilst balance performance is maintained, these fatigue-induced alterations in strategy may place an athlete in a more vulnerable position and increase his susceptibility to injury (Greig & Walker-Johnson, 2007). This corresponds to increased anterior-posterior laxity observed with physical exertions observed among athletes as demonstrated by Shultz et al. (2015), specifically promoting greater hip external and knee internal rotation and knee valgus during landing.

In the case of our injured participant, we can observe an increased variation in knee extension angles beyond the variability observed among our uninjured participants as represented by the standard deviations of the knee angle. Note that the deviation in the variability of hip and knee angle started to occur at the end of the second half of the soccer match-play simulation (105 min), approximately the similar time whence the participant sustained his injury during an actual match. This may be indicative of the change in postural control strategy to compensate and accommodate functional stability, as explained by Adlerton et al. (2003), triggering a chain of disruptions in his landing biomechanics.

This case report proposes a prospective utility of the sagittal plane side-cutting variability as a possible marker for identifying ACL injury risk. To our knowledge, this is the first study to explore the variabilities of the side cutting kinematics at IC with an actual injury mimicking that observed during the laboratory session happening in an actual match. However, these observations do suffer from certain limitations. Limited information was available from the frontal and transverse plane motions during the laboratory trials and the actual match, thus a three-dimensional (3D) motion analysis may allow for such information plus a more aggressive observation compared to a 2D motion analysis with a more standard variability in degrees of freedom (DOF). In addition to hip and knee angles at initial contact, several other parameters should be included in the observation such as peak flexion angles or flexion range of motions. This information may be crucial in adding a critical understanding of how the variability of side-cutting motion may play a role in identifying ACL injury risk. Furthermore, a proper, prospective study with a greater sample size should be conducted to seek proper justification to this proposal of a marker of ACL injury risk, as n = 1 data should be carefully approached.

Conclusion

This paper discusses the utility of variability in task execution kinematics as a predictive marker of ACL injury risk. At the time corresponding to the injury, the participant performed a side-cutting task with increased variability, suggesting an array of impairments in muscle activation due to fatigue inhibition alongside several compensatory measures to maintain functional stability while performing the task. However, limited information is available regarding the role of kinematic variabilities with respect to injury mechanisms as well as the proper tool in comparing n = 1 variability to population variabilities. To our knowledge, this case study is the first to approach side cutting kinematic variability as a potential marker for injury risk screening. This paper contributes knowledge to the body of literature and raises a debate on the prospective utility of kinematic variabilities in identifying ACL injury risk over the development of fatigue.

References

Adlerton, A. K., Moritz, U., & Moe-Nilssen, R. (2003). Forceplate and accelerometer measures for evaluating the effect of muscle fatigue on postural control during one-legged stance. *Physiotherapy Research International, 8*(4), 187-199. https://doi.org/10.1002/pri.289

Agel, J., Evans, T. A., Dick, R., Putukian, M., & Marshall, S. W. (2007). Descriptive epidemiology of collegiate men's soccer injuries: National collegiate athletic association injury surveillance system, 1988-1989 through 2002-2003. *Journal of Athletic Training (National Athletic Trainers' Association), 42*(2), 270-277.

Barreira, P., Robinson, M. A., Drust, B., Nedergaard, N., Raja Azidin, R. M. F., & Vanrenterghem, J. (2016). Mechanical player load™ using trunk-mounted accelerometry in football: Is it a reliable, task-and player-specific observation? *The Journal of Sports Sciences*, 1-8. https://doi.org/10.1080/02640414.2016.1229015

Blackburn, J. T., & Padua, D. A. (2008). Influence of trunk flexion on hip and knee joint kinematics during a controlled drop landing. *Journal of Clinical Biomechanics, 23*(3), 313-319. https://doi.org/10.1016/j.clinbiomech.2007.10.003

Boden, B. P., Dean, G. S., Feagin, J. A., & Garrett, W. E. (2000). Mechanisms of anterior cruciate ligament injury. *Orthopedics, 23*(6), 573-578. https://doi.org/10.3928/0147-7447-20000601-15

Brophy, R., Silvers, H. J., Gonzales, T., & Mandelbaum, B. R. (2010). Gender influences: The role of leg dominance in acl injury among soccer players. *The British Journal of Sports Medicine, 44*(10), 694. https://doi.org/10.1136/bjsm.2008.051243

Cone, J. R., Berry, N. T., Goldfarb, A. H., Henson, R. A., Schmitz, R. J., Wideman, L., et al. (2012). Effects of an individualized soccer match simulation on vertical stiffness and impedance. *The Journal of Strength & Conditioning Research, 26*(8), 2027-2036. https://doi.org/10.1519/JSC.0b013e31823a4076

Cortes, N., Greska, E., Kollock, R., Ambegaonkar, J., & Onate, J. A. (2013). Changes in lower extremity biomechanics due to a short-term fatigue protocol. *Journal of Athletic Training, 48*(3), 306-313. https://doi.org/10.4085/1062-6050-48.2.03

Cortes, N., Quammen, D., Lucci, S., Greska, E., & Onate, J. (2012). A functional agility short-term fatigue protocol changes lower extremity mechanics. *The Journal of Sports Sciences, 30*(8), 797-805. https://doi.org/10.1080/02640414.2012.671528

Dingenen, B., Malfait, B., Nijs, S., Peers, K. H., Vereecken, S., Verschueren, S. M., et al. (2015a). Can two-dimensional video analysis during single-leg drop vertical jumps help identify non-contact knee injury risk? A one-year prospective study. *Journal of Clinical Biomechanics, 30*(8), 781-787. https://doi.org/10.1016/j.clinbiomech.2015.06.013

Dingenen, B., Malfait, B., Vanrenterghem, J., Robinson, M. A., Verschueren, S. M., & Staes, F. F. (2015b). Can two-dimensional measured peak sagittal plane excursions during drop vertical jumps help identify three-dimensional measured joint moments? *The Knee*, *22*(2), 73-79. https://doi.org/10.1016/j.knee.2014.12.006

Ekstrand, J., Hägglund, M., & Waldén, M. (2011). Epidemiology of muscle injuries in professional football (soccer). *American Journal of Sports Medicine, 39*(6), 1226-1232. https://doi.org/10.1177/0363546510395879

Falla, D., Gizzi, L., Tschapek, M., Erlenwein, J., & Petzke, F. (2014). Reduced task-induced variations in the distribution of activity across back muscle regions in individuals with low back pain. *PAIN®, 155*(5), 944-953. https://doi.org/10.1016/j.pain.2014.01.027

Faunø, P., & Wulff, J. B. (2006). Mechanism of anterior cruciate ligament injuries in soccer. *International Journal of Sports Medicine, 27*(1), 75-79. https://doi.org/10.1055/s-2005-837485

Greig, M. (2009). The influence of soccer-specific activity on the kinematics of an agility sprint. *The European Journal of Sport Science, 9*(1), 23-33. https://doi.org/10.1080/17461390802579129

Greig, M., & Walker-Johnson, C. (2007). The influence of soccer-specific fatigue on functional stability. *Physical Therapy in Sport, 8*(4), 185-190. https://doi.org/10.1016/j.ptsp.2007.03.001

Griffin, L. Y., Agel, J., Albohm, M. J., Arendt, E. A., Dick, R. W., Garrett, W. E., et al. (2000). Noncontact anterior cruciate ligament injuries: Risk factors and prevention strategies. *Journal of the American Academy of Orthopaedic Surgeons, 8*(3), 141-150. https://doi.org/10.5435/00124635-200005000-00001

Hamdan, M., Ismail, S. I., Hassan, H., Ismail, H., Bukry, S. A., & Raja Azidin, R. M. F. (2017a). *How reliable is kinovea vs. Templo in knee and hip kinematics assessment during side cutting tasks?* Paper presented at the 4th Movement, Health & Exercise (MoHE), Johor, Malaysia.

Hamdan, M., Ismail, S. I., Hassan, H., Ismail, H., & Raja Azidin, R. M. F. (2017b). *The effects of 45 min overground soccer match-play simulation on hip extension angles during anticipated side-cutting tasks*. Paper presented at the XXVI Congress of the International Society of Biomechanics (ISB 2017), Brisbane, Australia.

Hamdan, M., Ismail, S. I., Hassan, H., Ismail, H., & Raja Azidin, R. M. F. (2018a). The effects of a 90-minute simulated soccer match-play on knee and hip kinematics. *Movement, Health & Exercise (MoHE), 7*(1). https://doi.org/10.15282/mohe.v7i1.164

Hamdan, M., Mohd Noh, S. N., Hasan, H., Ismail, H., & Raja Azidin, R. M. F. (2018b). Knee and hip extension responses to prolonged simulated soccer match-play: A 2d study. *International Journal of Engineering and Technology (UAE), 7*(4), 6-14. https://doi.org/10.15282/mohe.v7i1.164

Hamdan, M., Mohd Noh, S. N., Hassan, H., Ismail, S. I., Ismail, H., & Raja Azidin, R. M. F. (2017c). *The reliability of the measurement of knee and hip extension in two-dimensional video analysis during anticipated side cutting tasks*. Paper presented at the 4th Movement, Health & Exercise (MoHE), Johor, Malaysia.

Hashemi, J., Breighner, R., Chandrashekar, N., Hardy, D. M., Chaudhari, A. M., Shultz, S. J., et al. (2011). Hip extension, knee flexion paradox: A new mechanism for non-contact acl injury. *The Journal of Biomechanics, 44*(4), 577-585. https://doi.org/10.1016/j.jbiomech.2010.11.013

Hawkins, R. D., Hulse, M. A., Wilkinson, C., Hodson, A., & Gibson, M. (2001). The associated football medical research programme: An audit of injuries in professional football. *The British Journal of Sports Medicine, 35*, 43-47. https://doi.org/10.1136/bjsm.35.1.43

Herrero, H., Salinero, J. J., & Del Coso, J. (2014). Injuries among spanish male amateur soccer players: A retrospective population study. *American Journal of Sports Medicine, 42*(1), 78-85. https://doi.org/10.1177/0363546513507767

Mclean, S. G., Lipfert, S. W., & Van Den Bogert, A. J. (2004). Effect of gender and defensive opponent on the biomechancs of sidestep cutting. *Journal of Medicine and Science in Sports and Exercise, 36*(6), 1008. https://doi.org/10.1249/01.MSS.0000128180.51443.83

Raja Azidin, R. M. F., Sankey, S. P., Drust, B., Robinson, M. A., & Vanrenterghem, J. (2015). Effects of treadmill versus overground soccer match simulations on biomechanical markers of anterior cruciate ligament injury risk in side cutting. *The Journal of Sports Sciences, 33*(13), 1332-1341. https://doi.org/10.1080/02640414.2014.990491

Raja Azidin, R. M. F., Sankey, S. P., Robinson, M. A., & Vanrenterghem, J. (2013). Treadmill versus overground soccer-specific fatigue: The effect on hamstring and quadriceps strength and frontal plane peak knee joint moments in side-cutting.

Ris, R., Holthuijsen, L., & Booij, N. (1999). A third-generation wave model for coastal regions: 2. Verification. *Journal of Geophysical Research: Oceans, 104*(C4), 7667-7681. https://doi.org/10.1029/1998JC900123

Sankey, S. P., Azidin, R. M. F. R., Robinson, M. A., Malfait, B., Deschamps, K., Verschueren, S., et al. (2015). How reliable are knee kinematics and kinetics during side-cutting manoeuvres? *Gait & Posture, 41*(4), 905-911. https://doi.org/10.1016/j.gaitpost.2015.03.014

Sanna, G., & O'connor, K. M. (2008). Fatigue-related changes in stance leg mechanics during sidestep cutting maneuvers. *Journal of Clinical Biomechanics, 23*(7), 946-954. https://doi.org/10.1016/j.clinbiomech.2008.03.065

Shultz, S. J., Schmitz, R. J., Cone, J. R., Copple, T. J., Montgomery, M. M., Pye, M. L., et al. (2013). Multiplanar knee laxity increases during a 90-min intermittent exercise protocol. *Journal of Medicine and Science in Sports and Exercise, 45*(8), 1553-1561. https://doi.org/10.1249/MSS.0b013e31828cb94e

Shultz, S. J., Schmitz, R. J., Cone, J. R., Henson, R. A., Montgomery, M. M., Pye, M. L., et al. (2015). Changes in fatigue, multiplanar knee laxity, and landing biomechanics during intermittent exercise. *Journal of Athletic Training, 50*(5), 486-497. https://doi.org/10.4085/1062-6050-49.5.08

Vanrenterghem, J., Venables, E., Pataky, T., & Robinson, M. A. (2012). The effect of running speed on knee mechanical loading in females during side cutting. *The Journal of Biomechanics, 45*(14), 2444-2449. https://doi.org/10.1016/j.jbiomech.2012.06.029

Wahab, S. A., Ampofo-Boateng, K., Mohd Sharif, S. A., Othman, S. I. R., Abdul Aziz, R., Ismail, H., et al. (2015). *Injury profiles in malaysia elite athletes*. Paper presented at the International Conference on Movement, Health, and Exercise 2015, Penang, Malaysia.

Waldén, M., Hägglund, M., Werner, J., & Ekstrand, J. (2011). The epidemiology of anterior cruciate ligament injury in football (soccer): A review of the literature from a gender-related perspective. *Journal of Knee Surgery, Sports Traumatology, Arthroscopy*, *19*(1), 3-10. https://doi.org/10.1007/s00167-010-1172-7

Zambresky, L. (1989). *A verification study of the global wam model: December 1987-november 1988*: na.