STRATEGIES FOR A SELF-SELECTED UNANTICIPATED CHANGE OF DIRECTION MANEUVER AND THE RISK FOR ACL INJURY: FINDINGS FROM HAIE STUDY

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Abstract:

The purpose of the study was twofold: 1) to qualitatively investigate the different change of direction (COD) strategies used by females in an ecological situation; and 2) to evaluate the knee internal adduction moment and knee flexion during the first 30% of support as risk factors for anterior cruciate ligament (ACL) injury during these strategies. Ninety-four females, classified in ACTIVE and NON-ACTIVE groups performed five trials of a COD maneuver that were subsequently qualitatively evaluated. Kinematic and ground reaction force data were analyzed in the first 30% of support. To assess differences between strategies, we used a two-way repeated measures analysis of variance. Four strategies of 45° COD maneuvers were found. The different strategies involved either a cross-over with the right or left leg or had no cross-over. The statistical analysis revealed significant differences with a lesser knee internal adduction moment ($p<.05$) and a greater knee flexion angle during the strategies with a cross-over of the right foot compared to the other strategies ($p<.05$). Therefore, it is important to consider the potential effect of different strategies on ACL injury risk factors, as ACL injury risk factors may vary depending on the specific directional technique used.

Keywords: *knee moment, knee flexion, change of direction, COD strategies, anterior cruciate ligament*

Introduction

A sudden change of direction (COD) or cutting maneuver is often associated with non-contact anterior cruciate ligament (ACL) injuries in females (Pollard, Sigward, & Powers, 2007). The number of females participating in sport and exercise is increasing (Elliott-Sale, et al., 2021); thus, the higher number of active females is associated with potentially increased number of the ACL injuries. In addition, an ACL injury may lead to osteoarthritis later in life (Quatman & Hewett, 2009). To focus on preventing ACL injuries in females in high-risk sports, it is necessary to understand many strategies that could be used in performing the COD maneuver and to determine if these strategies are potentially risky.

The findings of studies in the literature have focused on biomechanical risk factors in relation to ACL injury during COD maneuvers focusing particularly on the knee adduction moment, knee flexion, menstrual cycle, laxity, and muscle activation (Fedie, Carlstedt, Willson, & Kernozek, 2010; Hanson, Padua, Blackburn, Prentice, & Hirt, 2008; Pollard, Braun, & Hamill, 2006; Wojtys, Huston, Boynton, Spindler, & Lindenfeld, 2002). Many of these studies constrain the strategy to be used and precise instructions are given to the participants to accomplish COD. However, there are many strategies that could be employed to accomplish a COD task. For example, Besier, Lloyd, Cochrane, and Ackland (2001) investigated several different methods of accomplishing COD maneuvers and found differences in several risk factors for ACL injury. However, the participants in this study were instructed on the methods to accomplish the COD maneuvers. A more ecological approach by letting the participants choose how to accomplish a COD task may be more informative as it relates to the risk of injury. It is certainly possible that the risk factors for ACL injury might be significantly affected by these different strategies used to perform the COD maneuver. However, there are few controlled studies that are ecological in nature allowing the participants to perform the task however they want.

Dempsey et al. (2007) and Dempsey, Lloyd, Elliott, Steele, and Munro (2009) demonstrated that different imposed techniques of a COD maneuver with focus on foot placement (i.e., foot wide, foot contact closer to the body's midline) resulted in increased peak valgus moments during weight acceptance phase of support. Besier et al. (2001) reported that different COD maneuvers elicited a combined load of flexion, valgus and internal rotation, whereas a cross-over technique had combined levels of flexion, varus and external rotation. So far, the above-mentioned studies had only been applied to men and had limited sample size. Moreover, these studies did not allow natural strategies, that is, a strategy chosen by the performer, in the performance of a COD maneuver and did not compare the types of different strategies often used in sports.

ACL injury is common in females due to many anatomic, hormonal, and neuromuscular risk factors. It is well known that females are predisposed to have greater quadriceps activation and lower hamstring activation in comparison to men (Harput, Soylu, Ertan, Ergun, & Mattacola, 2013). Moreover, anterior knee laxity is different between genders with females having significantly higher anterior knee laxity compared to males (Pollard, et al., 2006). Higher knee laxity may lead to higher internal knee adduction moments during a COD maneuver (Park, Stefanyshyn, Loitz-Ramage, Hart, & Ronsky, 2009). However, if male-based research is to be applied to females, there is a risk that the true potential risk for ACL injury in females will not be found. Dempsey et al. (2007, 2009) suggested that the results from the studies focusing only on men should not be applied to females. Presently, there are no controlled studies which evaluate ACL risk factors during different preferred strategies of COD maneuvers. Thus, it is necessary to conduct a controlled study that compares and/or evaluates different strategies of COD maneuvers in relation to possible risk factors for ACL injury in females.

To better the understanding of potential risk factors for ACL injury in females, it is necessary to focus on the individual and especially on different strategies that may be employed to perform a COD maneuver. Therefore, the first purpose of this study was to determine different strategies of an unanticipated COD maneuver used by females. This was accomplished by qualitatively classifying the different strategies used. The second purpose of this study was to compare specific biomechanical risk factors for ACL injury, that is, knee flexion (KF) angle in early support and the internal knee adduction moment (KIAM) according to the different strategies of COD maneuvers used by females. We hypothesized that the risk factors for ACL injury, knee flexion angle and the knee adduction moment during the first 30% of support would be different among the different strategies and that there would be no differences between ACTIVE and NON-ACTIVE participants in the risk factors for ACL injury.

Methods

Participants

An *a priori* sample size estimation was calculated based on key dependent variables (i.e., knee flexion and knee internal adduction moment) (Dempsey, et al., 2009). A power analysis for ANOVA (based on a pilot study of four types of direction changes) with minimal statistical power of 85% ($p=.05$) indicated that a total of 88 participants should be sufficient to expose statistically significant differences between each type of direction changes. A total 105 females were initially selected for this study. To be included in the study, ACTIVE participants ($n = 51$; age 22.8 ± 3.5 years; height 166.9 ± 6.0 cm; mass 59.9 ± 10.2 kg) had to be between 18 to 30 years of age, had at least five acceptable COD trials and participated in a moderate-intensity physical or sports activity at least 150 min per week or 75 min in high-intensity physical activity (World Health Organization, 2003). A NON-ACTIVE group ($n = 43$; age 23.3 ± 2.0 years; height 168.6 ± 2.6 cm; mass 63.0 ± 14.9 kg) had the same inclusion criteria as the active group with the exception that they did not regularly participate in a sports activity but could accomplish the COD task. The exclusion criteria for all eliminated individuals were them being smokers, pregnant or had a recent surgery, pain or illness. Eleven females were excluded from the study on the basis of incomplete data for the analysis of five trials of their COD maneuver. All participants signed an informed consent form that was approved by the Ethics and Research Committee of the University of Ostrava.

Experimental set-up

For kinetic and kinematic motion recording of COD maneuvers, we used a 10-camera high-speed motion analysis system (9x Oqus 700+ and 1x Oqus 510+, Qualisys, Inc., Gothenburg, Sweden) and large force plate (Kistler 9287CCAQ02, Kistler Instruments AG, Winterthur, Switzerland). A series of photocells (P-2RB/1, EGMedical, Ltd., Czech Republic) were aligned parallel to the approach runway to monitor the approach velocity prior the COD maneuver. A left path away from the force platform was outlined with the tape to define the direction at which the females had to accomplish a COD maneuver at an angle of 45°. The required unanticipated signal (i.e., left arrow or straight arrow) was displayed on the wall in front of a projector, which was used together with the timekeeper that triggered the signal at the end of the runway.

Protocol

After signing the informed consent, participants' height and body mass were measured prior to the initiation of data collection. Additionally, participants kicked a ball three times into a marked goal area to identify the dominant limb or the lower extremity that was used for most trials (Hoffman, Schrader, Applegate, & Koceja, 1998). Reflective markers were placed on thighs, shanks, feet and pelvis (McClay & Manal, 1999). All females were provided with neutral running shoes in which to perform the study. Before the COD maneuver, running and walking were used as a warm-up. Each participant completed a practice session which included several randomly cued trials of COD maneuvers on the dominant leg (the right limb for all participants). During the practice trials, the average approach running speed was measured and used as the target speed of analyzed trials. Following the practice trials, the first photocell was placed at a distance of 90% of the individual's stride length plus a distance for correction of the distance traveled in 0.2-s relative to participant's speed. In addition, the investigator triggered a random signal that was displayed in sufficient size at the end of the runway. Then several trials of the COD maneuvers were performed. The velocity was not standardized but did not fall below the values obtained from the practice session.

Participants were instructed to run and change direction as quickly as possible. Between each trial, approximately a one-minute interval was given to the participant in order to reduce the potential effect of fatigue. Individual trials continued until the five successful trials of the COD maneuver were completed. Trials were deemed successful if: 1) the right foot established contact with the force platform; 2) the following contact of the left foot was in the marked lane of a 45° angle; and 3) approach speed was not lower than in the practice trials.

The COD protocol was part of biomechanical protocol in a large study called 'Healthy Aging in Industrial Environment – Program 4 (4HAIE)' (Jandacka, et al., 2020). The main purpose of the larger study was to examine the impact of physical activity in a polluted environment. Data were collected from the participants during a two-day laboratory testing protocol. A part of the two-day testing protocol included biomechanical testing of running, walking and COD maneuvering. The full description of the experimental procedures and the kinematic and kinetic modelling approaches have been described previously (Jandacka, et al., 2020).

Data analysis

Five trials of COD maneuver for each female were qualitatively evaluated by two independent reviewers. To classify the COD strategies, the assessors evaluated three steps during COD: 1) the left foot in front of the force platform before the right foot contact with the force platform; 2) the right foot on the force platform; and 3) the subsequent step of the left foot outside of the force platform. The foot position was assessed from the coronal plane midline of the pelvis. After comparing the results of the qualitative evaluation of each trial, probable discrepancies were then discussed and evaluated by the two reviewers.

The maximum right knee adduction moment (KIAM) and the maximum right knee flexion angle (KF) were analyzed during the first 30% of support phase. Donnelly, Chinnasee, Weir, Sasimontonkul, and Alderson (2017) suggested that this was the period of support when the knee was most at risk for an ACL injury. The peak values of KIAM were normalized to body mass for the COD maneuvers.

Statistical analysis

For the second aim of this study, the distribution and the normality of dependent variables (i.e., right KIAM and right KF) were determined via a univariate analysis using strategy as an independent measure and by the Shapiro-Wilks test (α=.05). Depending on the distribution normality of the data, the differences between the types of direction changes for the mean of the five trials of each participant were assessed using two-way repeated measures analysis of variance (activity status X COD strategy X participants). If the data for the dependent measures were not normally distributed, a Kruskal-Wallis non-parametric test was used. The ANOVA was performed separately for both the KIAM and KF parameters. The criterion alpha level was set at 0.05. A Bonferroni correction was used for *post-hoc* tests when necessary.

Results

We identified four strategies of direction changes during the unanticipated COD maneuvers in which the right foot contacted the force platform (see Figure 1, Table 1). The COD strategies included two with a cross-over pattern (Strategies 2 and 4) and two without it (Strategies 1 and 3). The dependent measure KIAM was found to be non-normally distributed, while KF was normally distributed.

In the statistical analysis for KIAM, there was no statistically significant activity status X change in direction strategy interaction (p=.84, partial eta^2 = 0.002) nor was there a significant difference between the ACTIVE and NON-ACTIVE participants (p=.38, partial eta^2 = 0.002). The statistical analysis did reveal a statistically significant difference for KIAM across strategies (p=.001, partial eta^2 = 0.058). The *post-hoc* analysis revealed the main difference was between the types of direction

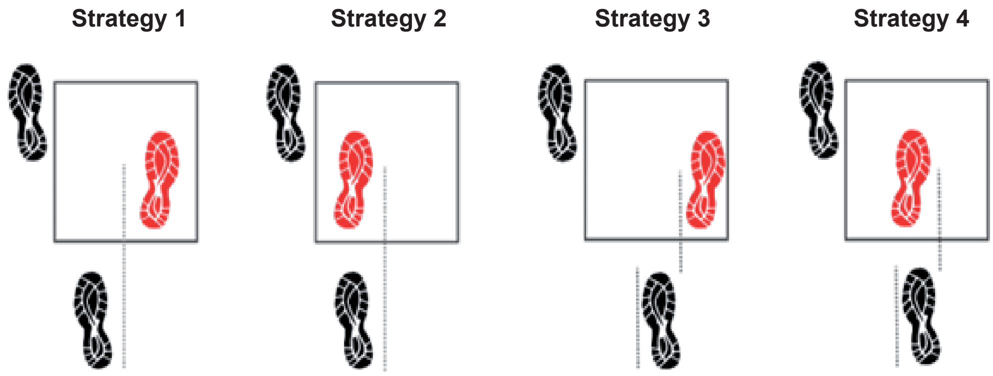

Figure 1. The types of strategies used by participants when given no instructions on how to accomplish a change of direction maneuver (left foot – black; right foot – red): 1) left foot without cross-over and the right foot without cross-over; 2) left foot without cross-over and right foot with cross-over; 3) left foot with cross-over and right foot without cross-over; and 4) left foot with cross-over and right foot with cross-over. Strategies 2 and 4 were considered cross-over strategies, while 1 and 3 were not. The contact of the foot on the force platform is illustrated. The square represents the force platform.

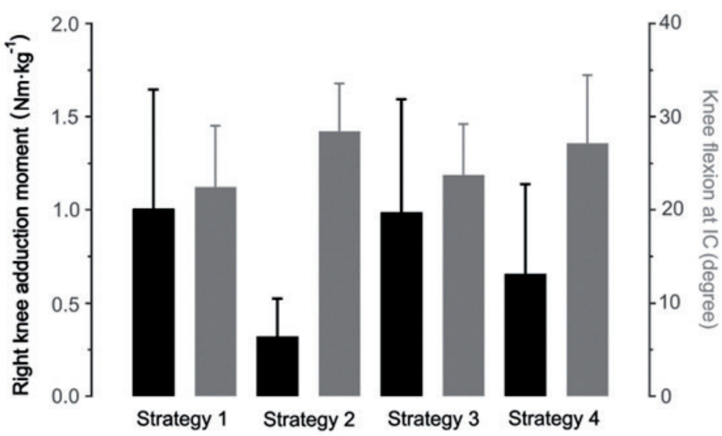

Figure 2. The graph illustrates the average peak magnitude of the right knee internal adduction moment normalized to body mass (black) and right knee flexion angle during the first 30 % of support phase (grey) across different types of direction changes during an unanticipated change of direction maneuver.

Table 1. Descriptive mean values (±standard deviation) of the variables during the change of direction maneuver for the different strategies

	Strategy 1		Strategy 2		Strategy 3		Strategy 4	
Variable	ACTIVE	NON-ACTIVE	ACTIVE	NON-ACTIVE	ACTIVE	NON-ACTIVE	ACTIVE	NON-ACTIVE
Frequency of occurrence	149	91	2	11	65	56	39	57
Knee adduction moment	1.03±0.69[a]	0.97±0.54[d,f]	0.49±0.18	0.29±0.20[c,d]	1.05±0.68[b]	0.91±0.50[c,e]	0.66±0.46[a,b]	0.65±0.50[e,f]
Knee flexion	22.37±6.97	22.60±5.91	32.09±0.24	22.77±5.34	24.24±5.77	23.14±5.14	28.62±9.01	26.14±5.80
Approach velocity	4.28±0.52[g]	3.96±0.48[i,j]	3.56±0.65	3.71±0.47[j]	4.06±0.46[k]	4.06±0.46[k]	4.20±0.44[g,h]	3.94±0.42[i,k]

Note. Means with the same superscript are statistically different in pairwise comparison analysis between strategies ($p<.05$). Knee adduction moment ($Nm•kg^{-1}$); velocity ($m•s^{-1}$); knee flexion (degrees).

changes without cross-over of the right foot (Type 1 and Type 3) with types of direction changes when the right foot did a cross-over (Type 2 and Type 4) ($p=.001$, partial $eta^2 =.002$).

For the KF parameter, again there was no statistically significant activity status X COD strategy interaction ($p=.308$, partial $eta^2 = 0.008$) nor was there a significant difference between the ACTIVE and NON-ACTIVE groups ($p=.151$, partial $eta^2 = 0.004$). However, there was a significant difference between the COD strategies ($p=.001$, partial $eta^2 = 0.087$). The *post-hoc* analysis revealed that KF was largest with the cross-over of the right foot (Type 2) indicating that the knee was in a more flexed or less extended position. However, when the right foot did not cross-over (Type 1 and Type 3), the KF angle was less (i.e., more extended) than in the strategies with the cross-over of the right foot (Type 2 and Type 4) (p=.001, partial eta^2 = 0.077).

Discussion and conclusions

The first purpose of this study was to identify different types of direction changes during an unanticipated COD maneuver. When we visually inspected the data, we found that there were four main types of strategies commonly used by the participants (see Figure 1), two strategies that employed a cross-over technique and two that did not. The second purpose of this study was to compare the maximum of the knee internal adduction moment and knee flexion angle at the initial foot contact according to the different strategies of the COD maneuvers used by the participants and between the ACTIVE and NON-ACTIVE groups. We hypothesized that there would be difference in the knee internal adduction moment or the knee flexion angle at initial contact between the COD strategies but not between the groups. The main finding of the present study suggests that the types of direction changes with a cross-over of the right foot (Strategies 2 and 4) showed significantly lower knee internal adduction moments and higher knee flexion angles at the initial contact than the types without cross-over of the right foot (Strategies 1 and 3) and that activity status did not affect the COD strategy results.

The results of the current study for the knee adduction moment and knee flexion angle at the initial contact were similar to those in studies that used an unanticipated COD maneuver (Beaulieu, Lamontagne, & Xu, 2009; Kim, et al., 2014). Unlike other quasi-experimental studies, these results were achieved using an ecological design allowing the performance of a self-selected COD maneuver by participants (i.e., females) who generally are at a greater risk of ACL injury compared to men (Dempsey, et al., 2007; Dos'Santos, Thomas, Comfort, & Jones, 2021; Hewett, et al., 2005). The values of KIAM during Type 1 (1.02 ± 0.61 Nm•kg^{-1}) and Type 3 (0.99 ± 0.59 Nm•kg^{-1}) in this study were comparable to the values of experienced athletes (0.9 ± 0.6 Nm•kg) (Sigward & Powers, 2006). For the KF angle during the first 30% of support, Vanrenterghem, Venables, Pataky, and Robinson (2012) reported an angle of 14.9 ± 4.1° of KF for the same COD angle running at a speed of 4.0 m•s^{-1} or approximately the speed used by the participants in our study. Similar results were reported by Beaulieu et al. (2009) where the KF angle was reported as 18.0 ± 6.8° at 4.0 to 5.0 m•s^{-1} in an unanticipated COD maneuver. These KF angles are less than the angles observed in the current study (angles ranging from 22.4 to 28.2°). However, the authors in the previous studies did not address the cross-over situations, which had the lowest KF angles in our study. It was also not clear whether the trials in Vanrenterghem et al. (2012) were unanticipated or anticipated, which certainly could affect the results of KF. Unlike the above-mentioned studies, higher knee flexion values (e.g., 29.3 ± 6.2°) were found at 90° COD (Sheu, Gray, Brown, & Smith, 2015). It appears that a higher angle of COD or cross-over may increase knee flexion (i.e., knee is more flexed) and thus possibly less risk for ACL injury. Regardless of crossing over or not or increasing the direction angle, all strategies found in this study exhibited a risk for ACL injury.

There are several strategies that can be used for performing a sudden unanticipated COD maneuver. These options were the possible strategies for the execution of a sudden change of direction used by females in the current study. Sigward and Powers (2006) reported that beginners and experienced female athletes employed different neuromuscular control strategies during a COD maneuver, thus, beginners may adopt a protective strategy during this maneuver. Dos'Santos et al. (2021) and Potter et al. (2014) analyzed a maneuver in which the left foot crossed over and found no differences between experienced and non-experienced participants. While not all participants in our study engaged regularly in sports activities that included a COD maneuver, we did not find that there were differences in the risk factors between ACTIVE and NON-ACTIVE participants.

KIAM was different with regard to the type of direction changes during the unanticipated COD maneuver. This study showed that types of direction changes with cross-over of the right foot decreased the knee internal adduction moment compared to the strategies that did not use a cross-over. Studies by Besier et al. (2001) and Kim et al. (2014) showed greater knee valgus moments during side-step techniques compared to cross-over techniques. Unlike those studies, our study was conducted with females who had a greater risk of ACL injury at higher speeds when injury is more likely (Vanrenterghem, et al., 2012; McLean, Myers, & Walters, 1998). Dos'Santos, McBurnie, Thomas, Comfort, and Jones (2019) reported that when the foot crossed the body midline, the ground reaction force vector was positioned medial to the knee thus generating a knee varus or adduction moment. In contrast, in a maneuver without a cross-over, the ground reaction force vector was positioned lateral to the knee creating a knee valgus or abduction moment. With respect to knee adduction moment, this technique (cross-over) appeared to be a safety strategy for ACL injury for an unplanned COD. This finding suggests that the cross-over strategy may be important to include in training. Relative to ACL injuries, the COD without a cross-over appears to be a higher risk compared to the cross-over technique.

As KF increases, that is the knee becomes less extended, this occurs with the strategies that included a cross-over. KF angles ranged from 22.37°, 28.16°, 23.77°, 26.69° for strategy 1 to strategy 4 (see Table 1). Zahradnik, Jandacka, Farana, Uchytil, and Hamill (2017) suggested that a KF angle less than 30° (i.e., with a straighter, more extended leg) placed the athlete in a precarious position for an ACL injury. It certainly appears that the strategies categorized in this study may place the participant in a position that could lead to an ACL injury. The results of the current study support the notion that, with a cross-over strategy, ACL risk may be reduced by an increased knee flexion angle (Benjaminse, Otten, Gokeler, Diercks, & Lemmink, 2017). Studies by McGovern et al. (2015) and Schreurs, Benjaminse, and Lemmink (2017) confirmed that females displayed less KF than males during a typical COD maneuver. Additionally, a higher KF angle was found during cross-over cuts compared to side-step cuts (McGovern, et al., 2015; Potter, et al., 2014). These findings are similar to those in our study. We can speculate that the differences in KF values (a less extended knee) between Type 2 and Type 4 compared to Beaulieu et al. (2009) and Vanrenterghem et al. (2012) may be higher due to a crossover strategy.

There are some limitations of our study that should be acknowledged. This study only considered a 45° moment maneuver in which we gave no instructions to the participant in how to perform the movement. The left foot was not analyzed with regard to the ground reaction force. Specifically, in strategy 2, the left foot may have been more loaded in terms of the reaction forces with respect to the ACL. Additionally, we evaluated only two risk factors considered to be the most prevalent (internal knee adduction moment and knee flexion angle during the first 30% of support) as indicators of ACL injury risk. While these are two of the more prevalent risk factors for ACL injury, there are others that we did not assess (e.g., the internal and external rotation of foot relative to the knee, which is the next most prevalent cause of ACL injury) (Schreurs, et al., 2017). Lastly, we did not directly measure running speed. It has been suggested that the appropriate speed for evaluating knee loading mechanisms in females in a 45° side COD maneuver should be approximately 4 $m{\bullet}s^{-1}$ (Vanrenterghem, et al., 2012). The approach velocities in our study were 4.14 ± 0.53 $m{\bullet}s^{-1}$, 3.60 ± 0.43 $m{\bullet}s^{-1}$, 4.11 ± 0.51 $m{\bullet}s^{-1}$, and 4.00 ± 0.41 $m{\bullet}s^{-1}$ for Type 1, Type 2, Type 3, and Type 4, respectively. With the exception of strategy type 2, all velocities were in the suggested range.

To conclude, our results suggest that females may use at least four different methods to accomplish an unanticipated COD task. We also found that two of the main risk factors for ACL injury (e.g., knee adduction moment and knee flexion angle at the initial contact) may be different with regard to the four strategies of the COD maneuver performed. The KF angle increased with the presence of a cross-over in COD while the knee adduction moment decreased with the presence of the cross-over strategy. In both cases, the risk of an ACL injury was decreased in the strategies with a cross-over. Change of direction maneuvers without a cross-over of the right foot may be associated with an increased biomechanical loading (e.g., higher knee adduction moments) of the ACL compared to other strategies for accomplishing COD tasks in females possibly placing these females at risk for ACL injury. These results also suggest that it may not be possible to compare knee kinematics/kinetics from one study to the next unless that type of strategy in each study is the same. In future studies, it may be prudent to define the COD task explicitly or explain directly which type of change of direction strategy was used.

References

Beaulieu, M.L., Lamontagne, M., & Xu, L. (2009). Lower limb muscle activity and kinematics of an unanticipated cutting manoeuvre: A gender comparison. *Knee Surgery, Sports Traumatology, Arthroscopy, 17*(8), 968-976. doi: 10.1007/s00167-009-0821-1

Benjaminse, A., Otten, B., Gokeler, A., Diercks, R.L., & Lemmink K. (2017). Motor learning strategies in basketball players and its implications for ACL injury prevention: A randomized controlled trial. *Knee Surgery, Sports Traumatology, Arthroscopy, 25*(8), 2365-2376. doi: 10.1007/s00167-015-3727-0

Besier, T.F., Lloyd, D.G., Cochrane, J.L., & Ackland, T.R. (2001). External loading of the knee joint during running and cutting maneuvers. *Medicine and Science in Sport and Exercise, 33*(7), 1168-1175. doi:10.1097/00005768-200107000-00014

Dempsey, A.R., Lloyd, D.G., Elliott, B.C., Steele, J.R., Munro, B.J., & Russo, K.A. (2007). The effect of technique change on knee loads during sidestep cutting. *Medicine and Science in Sport and Exercise*, *39*(10), 1765-1773. doi: 10.1249/mss.0b013e31812f56d1

Dempsey, A.R., Lloyd, D.G., Elliott, B.C., Steele, J.R., & Munro, B.J. (2009). Changing sidestep cutting technique reduces knee valgus loading. *American Journal of Sports Medicine*, *37*(11), 2194-2200. doi: 10.1177/0363546509334373

Donnelly, C.J., Chinnasee, C., Weir, G., Sasimontonkul, S., & Alderson, J. (2017). Joint dynamics of rear- and fore-foot unplanned sidestepping. *Journal of Science and Medicine in Sport*, *20*(1), 32-37. doi: 10.1016/j.jsams.2016.06.002

Dos'Santos, T., McBurnie, A., Thomas, C., Comfort, P., & Jones, P.A. (2019). Biomechanical comparison of cutting techniques: A review and practical applications. *Journal of Strength and Conditioning Research*, *41*(4), 40-54. doi: 10.1519/SSC.0000000000000461

Dos'Santos, T., Thomas, C., Comfort, P., & Jones, P.A. (2021). Biomechanical effects of a 6-week change-of-direction technique modification intervention on anterior cruciate ligament injury risk. *Journal of Strength and Conditioning Research*, *35*(8), 2133-2144. doi: 10.1519/JSC.0000000000004075

Elliott-Sale, K.J., Minahan, C.L., de Jonge X., …, & Hackney, A.C. (2021). Methodological considerations for studies in sport and exercise science with women as participants: A working guide for standards of practice for research on women. *Sports Medicine*, *51*(5), 843-861. doi: 10.1007/s40279-021-01435-8

Fedie, R., Carlstedt, K., Willson, J.D., & Kernozek, T.W. (2010). Effect of attending to a ball during a side-cut maneuver on lower extremity biomechanics in male and female athletes. *Sports Biomechanics*, *9*(3), 165-177. doi: 10.1080/14763141.2010.502241

Hanson, A.M., Padua, D.A., Blaskburn, J.T., Prentice, W.E., & Hirt, C.J. (2008). Muscle activation during side-step cutting maneuvers in male and female soccer athletes. *Journal of Athletic Training*, *43*(2), 133-143. doi: 10.4085/1062-6050-43.2.133

Harput, G., Soylu, A.R., Ertan, H., Ergun, N., & Mattacola, C.G. (2013). Effect of gender on the quadriceps-to-hamstrings coactivation ratio during different exercises. *Journal of Sport Rehabilitation*, *23*(1), 36-43. doi: 10.1123/JSR.2012-0120

Hewett, T.E., Myer, G.D., Ford, K.R., …, & Succop, P. (2005). Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: A prospective study. *American Journal of Sports Medicine*, *33*(4), 492-501. doi:10.1177/0363546504269591

Hoffman, M., Schrader, J., Applegate, T., & Koceja, D. (1998). Unilateral postural control of the functionally dominant and nondominant extremities of healthy subjects. *Journal of Athletic Training*, *33*(4), 319-322.

Jandacka, D., Uchytil, J., Zahradnik, D., ..., & Hamill, J. (2020). Running and physical activity in an air-polluted environment: The biomechanical and musculoskeletal protocol for a prospective cohort study 4HAIE (Healthy Aging in Industrial Environment—Program 4). *International Journal of Environmental Research and Public Health*, *17*(23), 9142. doi: 10.3390/ijerph17239142.

Kim, J.H., Lee, K.K., Kong, S.J., An, K.O., Jeong, J.H., & Lee, Y.S. (2014). Effect of anticipation on lower extremity biomechanics during side- and cross-cutting maneuvers in young soccer players. *American Journal of Sports Medicine*, *42*(8), 1985-1992. doi: 10.1177/0363546514531578

McClay, I.S., & Manal, K. (1999). Three-dimensional kinetic analysis of running: Significance of secondary planes of motion. *Medicine and Science in Sports and Exercise*, *31*(11), 1629-1637. doi: 10.1097/00005768-199911000-00021

McGovern, A., Dude, C., Munkley, D., ..., & Garbalosa, J.C. (2025). Lower limb kinematics of male and female soccer players during a self-selected cutting maneuver: Effects of prolonged activity. *Knee*, *22*(6), 510-516. doi:10.1016/j.knee.2015.05.005

McLean, S.G., Myers, P.T., & Walters, M.R. (1998). A quantitative analysis of knee joint kinematics during the sidestep cutting maneuver. Implications for non-contact anterior cruciate ligament injury. *Bulletin Hospital for Joint Diseases (New York)*, *57*(1), 30-38.

Park, S.K., Stefanyshyn, D.J., Loitz-Ramage, B., Hart, D.A., & Ronsky, J.L. (2009). Alterations in knee joint laxity during the menstrual cycle in healthy women leads to increases in joint loads during selected athletic movements. *American Journal of Sports Medicine*, *37*(6), 1169-1177. doi: 10.1177/0363546508330146

Pollard, C.D., Braun, B., & Hamill, J. (2006). Influence of gender, estrogen and exercise on anterior knee laxity. *Clinical Biomechanics*, *21*(10), 1060-1066. doi: 10.1016/j.clinbiomech.2006.07.002

Pollard, C.D., Sigward, S.M., & Powers, C.M. (2007). Mechanisms of ACL injury: Current perspectives. *Journal of Biomechanics*, *40*, 254. doi:10.1016/S0021-9290(07)70250-6

Potter, D., Reidinger, K., Szymialowicz, R., ..., & Garbalosa, J.C. (2014). Sidestep and crossover lower limb kinematics during a prolonged sport-like agility test. *International Journal of Sports Physical Therapy*, *9*(5), 617-627.

Quatman, C.E., & Hewett, T.E. (2009). The anterior cruciate ligament injury controversy: Is "valgus collapse" a sex-specific mechanism? *British Journal of Sports Medicine*, *43*(5), 328-335. doi: 10.1136/bjsm.2009.059139.

Schreurs, M.J., Benjaminse, A., & Lemmink, K. (2017). Sharper angle, higher risk? The effect of cutting angle on knee mechanics in invasion sport athletes. *Journal of Biomechanics*, *63*, 144-150. doi: 10.1016/j.jbiomech.2017.08.019

Sheu, C.L., Gray, A.M., Brown, D., & Smith, B.A. (2015). Sex differences in knee flexion angle during a rapid change of direction while running. Orthopaedic Journal of Sports Medicine, 3(12):1-5. doi: 10.1177/2325967115617932

Sigward, S., & Powers, C.M. (2006). The influence of experience on knee mechanics during side-step cutting in females. *Clinical Biomechanics*, *21*(7), 740-747. doi: 10.1016/j.clinbiomech.2006.03.003

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

Wojtys, E.M., Huston, L.J., Boynton, M.D., Spindler, K.P., & Lindenfeld, T.N. (2002). The effect of the menstrual cycle on anterior cruciate ligament injuries in women as determined by hormone levels. *American Journal of Sports Medicine*, *30*(2), 182-188. doi: 10.1177/0363546505282624

World Health Organization. (2003). Physical activity. Primary Health Care, 13, 1-8.

Zahradnik, D., Jandacka, D., Farana, R., Uchytil, J., & Hamill, J. (2017). Identification of types of landings after blocking in volleyball associated with risk of ACL injury. *European Journal of Sport Science*, *17*(2), 241-248. doi: 10.1080/17461391.2016.1220626

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