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REVIEW ARTICLE

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Anterior Cruciate Ligament Force and Strain in Males and Females during Anticipated and Unanticipated Side-Stepping

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ABSTRACT

Females have a greater number of Anterior Cruciate Ligament (ACL) injuries per activity hours than males. The cause of this injury rate is speculated to be an increased strain on the ACL in performing a side-stepping manoeuvre. The purpose of this study was to determine the magnitude of ACL force and strain and the knee angle at initial foot contact during anticipated and unanticipated side-stepping. 12 male and 12 female, young, healthy, college-age, athletes were recruited for this study. 3D kinematics and kinetics were collected in each of anticipated and unanticipated conditions. A computational musculo-skeletal model was used to estimate the ACL force and strain. No differences were found between males and females in any of the ACL or knee angle parameters (P>0.05). However, there was a significant difference in ACL force and strain between anticipated and unanticipated side-stepping conditions with unanticipated force and strain greater than in the anticipated condition (P<0.05). These results support previous evidence that athletes may be at greater risk of injury during sidestepping tasks where planning time is reduced due to greater elongation of the ACL. Future research should focus upon investigating tasks to mitigate the high-risk strategies athletes use during unanticipated sports tasks.

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Introduction

Anterior Cruciate Ligament (ACL) injuries occur up to 250,000 times per year mainly between the ages of 15 and 25 years of age [1]. Studies in the literature also indicate that the risk for developing knee osteoarthritis increase significantly in those who have had an ACL injury [2]. A significant body of biomechanics literature has been dedicated toward understanding the underlying mechanisms of non-contact ACL injuries. Team-based sports often require athletes to perform such dynamic tasks as side-stepping under high temporal and visuospatial demands in response to external stimuli. These external stimuli may require rapid and precise reactions and, as such, may have constraints associated with these dynamic movements possibly leading to altered joint biomechanics and elevated loading of the knee and, in particular, the ACL. In fact, greater than 56% of ACL injuries in sporting activities occur during non-contact tasks such as side-stepping and within the first 40% of the support period [3,4]. In essence, these dynamic movements and the inability to plan safe movement strategies with adequate time may lead to loading the ACL that could result in an ACL rupture.

Team sports often require athletes to perform dynamic tasks under high temporal and visuospatial demands in response to external stimuli such as a reaction to a team member, an opponent or an implement such as a ball. These external stimuli require swift and precise reactions, and, as such, time constraints associated with these dynamic movements may lead to altered joint biomechanics and elevated loading at the knee. Such factors have been shown in unanticipated sidestepping tasks [5,6]. Understanding the effect of anticipation on postural adjustments is important to further the body of knowledge toward how both performance and safety can be enhanced during unanticipated sporting tasks.

It has been reported that female athletes who participate in jumping and cutting sports are 4–6 times more likely to sustain a serious knee injury than male athletes participating in the same sports [7-9]. Arendt and Dick reported that women have an ACL injury rate that is four times greater than their male counterparts. Based on the disproportionate incidence of injury, current research literature has investigated the biomechanical differences between males and females in sporting tasks [10].

Direct measurement of ACL loading in humans during sports tasks is invasive and it is not possible to directly measure ACL loading in vivo during manoeuvres often seen in athletic situations. Consequently, ACL injury risk has typically been quantified via surrogates such as externally applied knee joint moments, muscle activity and joint kinematics. However, in the past 15-20 years, open-source software and code, provided through OpenSim (http://simtk.org), has made it feasible to develop musculo-skeletal models via computer simulations. Such models have been used previously in several studies concerning ACL risk factors and different anticipated and unanticipated side-stepping manoeuvers [11-16]. However, several of these studies used relatively slow running speeds and used an anticipated task both of which are not truly representative of a game manoeuver.

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From a kinematic perspective, Zahradnik et al. reported that a significant risk factor for ACL injury was a straight leg landing [17]. Using a population of elite female volleyball players, they suggested that a single leg landing from a jump with a knee angle less than 30° would present a significant risk for an ACL injury. The single leg landing would be similar to a foot-ground contact during running.

Therefore, the purpose of this study was to ascertain if there were differences in peak ACL force (F_{ACL}) and strain (ε_{ACL}) and knee flexion angle during the loading portion of anticipated (ANT) and unanticipated (UnANT) side-stepping. We hypothesized that the F_{ACL} and ε_{ACL} values would be greater in females relative to males suggesting that females would be at a greater risk for ACL injury than males. We further hypothesized that peak F_{ACL} and ε_{ACL} would be greater during the UnANT condition in the loading portion of the support phase of the support limb thus indicating that the UnANT manoeuvre would have a greater risk for ACL injury than the ANT condition. We also hypothesized that the knee angle at initial contact would be less than 30° in the limb in which the cutting manoeuvre was initiated in both males and females and in the UnANT versus the ANT condition. The loading phase of support was chosen as it has been suggested that this is the period when the ACL is under the highest strain.

Methods

Participants

Twenty-four collegiate, team sport athletes (12 male, 12 female) participated in a single biomechanical testing session. The participant characteristics are presented in Table 1. This cohort of female field hockey and male soccer players was chosen because ACL injuries typically occur in team sport athletes and this cohort would also be familiar with sidestepping sporting tasks. A power analysis from previous research revealed that to achieve 80% power at an alpha criterion level of 0.05, a minimum of 12 participants were required for comparison [12,18]. All participants were free from injury at the time of testing and had no history of serious lower extremity injury or surgery within the previous year. Approval for this research was gained from the University Institutional Review Board and written informed consent for all participants was obtained.

Table 1- Participant characteristics

	Age (years)	Height (m)	Body Mass (kg)
Female (N=12)	19 ± 1.2	1.63 ± 0.04	58.1 ± 5.88
Male (N=12)	20 ± 1.3	1.83 ± 0.08	75.03 ± 9.19

Experimental Set-up

Kinematic data were recorded using an 11-camera motion capture system (Qualysis, Inc., Gothenburg, Sweden) sampling at 240 Hz synchronously with ground reaction forces from a 1.2×0.6m force platform at 1200 Hz (AMTI, Watertown, MA). Participants were fitted with 42 14mm retro-reflective markers as per a customized trunk and lower limb kinematic marker set and model [19,20]. Markers placed on the medial and lateral femoral condyles were used alongside a functional knee axis to define knee joint centers and knee axes orientation [21]. A functional method was also used to define hip joint centers [20]. Anatomical landmarks of the lower limb were tracked using rigid marker clusters placed on the thigh and leg [22]. All participants wore standardized indoor soccer footwear provided by the laboratory.

Protocol

Participants were asked to complete a random series of anticipated and unanticipated run, run-stop and sidestepping tasks using their dominant limb. Their dominant limb was determined by asking participants which leg they would kick a soccer ball with or land from a jump. All participants were right limb dominant. Run and run-stop tasks were used for task randomization to limit predictability of the unanticipated sidestepping tasks and were not used formally in analysis. Symbols representing these tasks (i.e., arrow or stop sign) were displayed on a 1.65m television screen at the end of a 20m runway. Participants were instructed to run at 4.0 ± 0.5m•s^{-1} down the runway and perform the task displayed on the screen. During these tasks, the screen either displayed the task prompt before the initiation of the run (ANT) or it appeared at ipsilateral limb toe-off prior to contacting the force platform with the dominant leg to perform the task (UnANT). An UnANT task prompt was triggered by the athlete running through a set of timing gates (see Figure 1).

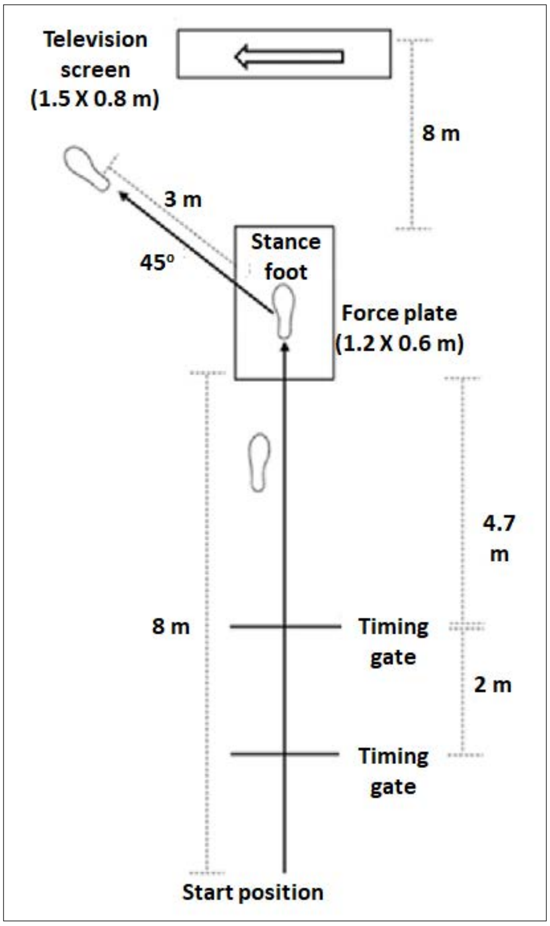

Figure 1: Experimental Set Up for Sidestepping Trials [35]

Participants were given approximately 30 seconds of rest between tasks to minimize any effects of fatigue. End-point variability/task completion was controlled for both ANT and UnANT sidestepping tasks such that results could only be interpreted with reference to condition and not task execution. As such, sidestepping trials were considered successful if the athletes' average approach velocity was 4.0 ± 0.5m•s^{-1} and they contacted a black line ± 10° marked on the ground at 45° with the contralateral limb upon exit of the sidestep manoeuver [24].

Data Reduction

Kinematic trajectories and ground reaction forces were filtered with a zero-lag fourth-order low pass Butterworth filter at 14 Hz. This cut-off frequency was selected based on residual analysis and visual inspection. Three-dimensional kinematic and kinetic data were calculated using a customized lower body model compliant with the International Society of Biomechanics (ISB) standards for the reporting of data [25]. Data processing was performed using Visual 3D software (C-motion, Inc., and Rockville.MD).

Data Analysis

Marker trajectories and GRF data served as inputs used to drive the 14-segment, 37 degree-of-freedom, muscle tendon actuated, participant-specific simulations in OpenSim [26]. The ACL model used in this study was enhanced from the original knee model in OpenSim using an established approach [27]. Our model was actuated by 92 muscle-tendon units to represent 76 muscles in the lower extremity and torso with an ACL added. Descriptions regarding the model can be found in the OpenSim documentation and previous studies [26, 27]. While previous studies have mainly estimated ACL force and strain using knee joint moments, joint reaction forces, and muscle forces, the model used in the current study enabled us to directly compute changes in ACL length (F_L), and respectively F_{ACL} and ε_{ACL} [12]. The musculoskeletal model was scaled using each participant's anthropometric data based on experimentally collected data during static trials. The joint angles were estimated using inverse kinematics toolbox. This approach uses a weighted least squares method to reproduce the experimentally collected marker trajectories. Similarly, joint moments were then computed using the inverse dynamics toolbox. Static optimization was employed to estimate the muscle activation and force data. The optimization routines were set to minimize the sum of squared muscle activation levels. For static optimization, residual and reserve actuators were appended to the model to account for lack of consistency between the actual participant and the participant that was used to create the model. The actuators were only used to provide extra torque in case the simulated models were unable to produce sufficient acceleration to satisfy the experimental data [28,29]. Inverse kinematic results, ground reaction forces, static optimization results, and ACL insertion coordinates (on tibia and femur) were used as inputs to estimate changes in the F_L during each trial using the Analyze toolbox in OpenSim. A customized MATLAB code (MATLAB R2021b, The MathWorks, Inc., Natick, MA) was used for further analysis. F_{ACL} was computed using F_L and the ACL's linear elastic stiffness (Equation 1). The ACL linear elastic stiffness was set to 240 N/mm obtained from study by Woo et al. [30].

$$F_{ACL}(t) = 240 \times \left(F_L(t) - F_{L_0}{}^{*}\right) \qquad \text{(Equation 1)}$$

where F_L is the ACL length and F_{L0} is the ACL resting length obtained from each participant's scaled model. ACL strain (ε_{ACL}) was then calculated as (Equation 2):

$$\varepsilon_{ACL}(t) = \left(\frac{F_{ACL}(t)}{F_{L_0}}\right) * 100 \qquad \text{(Equation 2)}$$

Statistical Analysis

A two-way repeated measures analysis with one group factor (males versus females) and one repeated factor (ANT versus UnANT) was performed to test the hypotheses that the peak F_{ACL}, ε_{ACL} and the knee flexion angle at initial contact over 0-40% of the loading phase of the support period were different between ANT and UnANT tasks. Measures of skewness, kurtosis and normality were tested using the Shapiro-Wilkes test. The criterion alpha level was set at 0.05 for all statistical tests. All statistical analysis was performed using SPSS software (IBM SPSS Statistic 29.0, IBM Corp, Armonk NY).

Results

There were no significant Condition X Gender interactions for any of the ACL parameters (see Table 2). There was also no statistically significant difference between males and females for any of the ACL parameters (see Table 2). However, for each of the ACL parameters (peak ε_{ACL}, mean F_{ACL}, ε_{ACL} there was a significant difference between the ANT and UnANT conditions ($p < 0.004$, < 0.006 and < 0.018 respectively) (see Figure 2). In each ACL force parameter, females had a higher magnitude than the males in both the ANT and UnANT conditions although this difference was not statistically significant ($p > 0.05$). However, this was not the case for ε_{ACL} where there was no difference between the strain magnitudes for males and females. Figure 3 represents an exemplar F_{ACL} profile for one female participant, and one male participant for ANT and UnANT side-stepping conditions across the loading period (0-100%).

Table 2: Peak anterior cruciate ligament parameters during 0-40% of loading phase of support

	Men		Women		Gender	Condition	Condition*Gender
	ANT	UnANT	ANT	UnANT	p-value	p-value	p-value
Peak ACL Force	7.47 ± 1.62	9.68 ± 2.80	7.87 ± 2.28	10.16 ± 2.31	0.547	0.004*	0.962
Mean ACL Force	6.03 ± 1.68	7.93 ± 3.02	6.53 ± 2.28	8.54 ±1.60	0.407	0.006*	0.944
Average ACL Strain	5.24 ± 1.69	6.55 ± 2.26	5.07 ± 1.17	6.38 ±1.31	0.748	0.018*	0.997

*indicates a statistically significant difference; force – N; strain – percent.

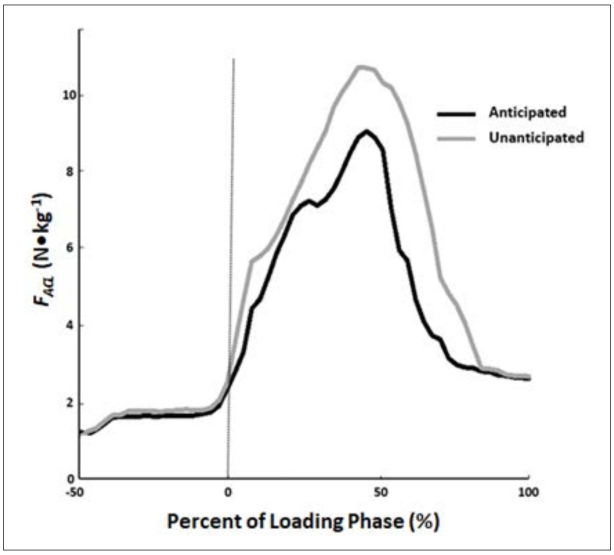

Figure 2: Exemplar ACL Force Profile for One Female Participant for Anticipated and Unanticipated Side-Stepping Conditions across the Loading Phase (0-100%). from -50% to 0% Indicates Pre-Contact. The Vertical Line Indicates Foot Strike.

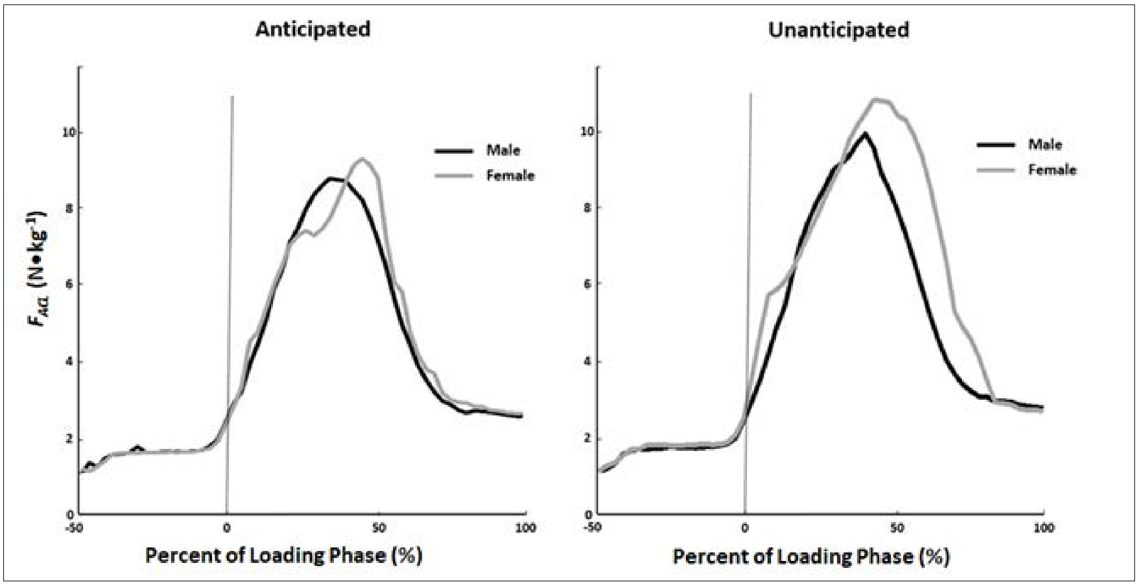

Figure 3: Exemplar ACL Force Profile for One Male and Female Participant for Anticipated (Left) and Unanticipated (Right) Side-Stepping Conditions across the Loading Phase (0-100%). from -50% to 0% Indicates Pre-Contact. The Vertical Line Indicates Foot Strike.

There were no significant Condition X Gender interactions (p = 0.443 and p=0.436) nor were there significant differences between the ANT and UnANT conditions for the knee angle parameters (see Table 3). However, there was a large non-significant difference in the knee flexion angle between the ANT and UnANT conditions between initial contact and at the end of the loading phase. Figure 2 shows an exemplar comparison of a male and female participant in both the ANT and UnANT conditions.

Table 3: Peak Knee Angle Values in Degrees During the Loading Period ((0-40% of Support)

	Men		Women		Condition	Condition*Gender
	PSS	UPSS	PSS	UPSS	p-value	p-value
At initial contact	17.61 ± 6.91	18.76 ± 8.38	15.67 ± 6.38	20.23 ± 5.58	0.081	0.287
At 40% of support	33.33 ± 4.65	33.17 ± 6.29	32.92 ± 11.04	36.33 ± 4.65	0.459	0.416

Discussion

The purpose of this study was to investigate if there were differences in F_{ACL}, ε_{ACL} and the knee flexion angle during the loading phase of support in males and females during anticipated and unanticipated side-stepping. We hypothesized that there would be a difference between males and females in both the ANT and UnANT. However, the results of our study could not support this hypothesis. We found no statistically significant difference between males and females for any of the ACL or knee angle parameters. We also hypothesized that F_{ACL} and ε_{ACL} would be greater during the UnANT condition than in the ANT condition during the initial 40% of the loading phase of support. The main finding of this study was that this hypothesis was supported in that the magnitudes of the F_{ACL} and ε_{ACL} values were greater in the UnANT versus the ANT conditions. The values of peak FACL, mean F_{ACL} and ε_{ACL} were increased by 22.7%, average ACL force of 23.7% and ACL strain of 20.3% in the UnANT condition over the ANT condition. We also hypothesized that the knee angle at initial contact would be less than 30° in the landing limb in both males and females and in the UnANT versus the ANT conditions. However, we must reject this hypothesis since our results showed that there was no statistically significant difference between males and females and between the UnANT and ANT conditions.

Estimates of the F_{ACL} values reported for the same period were slightly less than in the current paper [11,12]. Weinhandl et al. reported a 1.38 N•kg^{-1} increase in the UnANT over the ANT condition while we found an increase in the UnANT over the ANT condition of 2.21 N•kg^{-1} and 2.29 N•kg^{-1} for the males and females respectively. However, the shape and timing of the ACL force profile was similar in both papers [12].

The differences in the FACL values in the current study and in the referenced papers may have been a result of the difference models. The Weinhandl model, for example, estimated ACL force using a musculoskeletal model with extra degrees of freedom (DoF) for the knee joint and no knee ligaments [12]. Therefore, only increasing knee joint DoF without the presence of ligament structures may cause increased muscle forces to compensate for passive forces [27,31]. In addition, the Weinhandl model used EMG and scaled each participant's isometric force to each participant's peak isometric strength. The ACLs for both knees were added to the model used in the current paper which enabled us to estimate ligament force directly from changes in ligament length during each trial.

It has been proposed that elongation of the ACL (i.e., ε_{ACL}) during the loading phase of a single leg landing or, as in a side-stepping movement, may result in a partial or complete rupture of the ACL [18,31]. In the current study, there was a significant difference in ε_{ACL} of 1.33 and 1.31 percent between the UnANT and ANT conditions for both males and females respectively. ε_{ACL} in the UnANT was 1.25 times the strain in the ANT condition for both males and females. These results suggest that the UnANT condition was more precarious to the ACL than the ANT condition.

It was surprising there were no differences in the ACL parameters between males and females since the number of non-contact ACL injuries in females is much greater than for males [32]. However, because the two groups were made of up elite athletes who had similar significant exposure time to training, it can be assumed that the training prepared both groups for side-stepping manoeuvres. Thus, even though females may have a greater number of risk factors for ACL injuries, in this particular study, the risk for an ACL injury was equal between the groups.

Zahradnik et al. suggested that a single leg landing with an angle less than 30° may be a significant risk factor for an ACL injury [17]. Our results indicated that the initial foot-ground contact knee angle was well below the 30° level suggested as an injury risk factor compromising the athlete. This was the case in both the ANT and UnANT conditions. However, by the end of the loading period, the knee angles in both conditions were just over the 30° angle mark. With the ACL force parameters greater in the UnANT condition and the knee angle less than 30° at initial foot-ground contact, it would appear this would be a situation that should be avoided in both males and females during a side-stepping maneuvre.

Based on the results presented here and that of, it is evident that future studies should incorporate UnANT sidestepping over ANT sidestepping when investigating ACL injury mechanisms [12,17]. Future studies should also attempt to integrate more sport-relevant factors such as unexpected perturbations within experimental testing environments. Such approaches may provide further insights into causative factors of non-contact ACL injury, facilitating development of more effective and adaptable prevention methods.

There are several limitations to this study that should be considered in the interpretation of these data. It has been established that the cross-sectional area of the ACL is different in males and females [33]. We did not scale the ACL cross-sectional area accordingly. It is not known how the effects of such scaling would affect the level of the forces necessary to cause an injury could be a topic for future study [34]. The results must be taken into context with task completion and the variability of the change of direction angle. Although pre-contact velocities were matched between tasks, there was a statistically significant difference for the change of direction angle which may have influenced our results. This difference was, however, less than 5° which is comparable to that in other studies [18]. While the data collection protocol has been used in many other studies, the results of the analysis were used in a musculo-skeletal model which had a number of assumptions that could have affected the results. Finally, this analysis was only tested in healthy, team sport athletes retrospectively.

Conclusions

The results of this study suggest that, while there were no differences in males and females, the changes in ACL force and strain are greater during UnANT compared to ANT conditions. In addition, increased elongation of the ACL, as observed in the estimated ACL strain values, during rapid changes of direction in sports tasks may be a pre-cursor of a partial or complete rupture of the ACL that may result in a significant loss of time in an athlete's activity period. Therefore, future research should focus upon investigating movements to mitigate the high-risk strategies athletes use during unanticipated sports tasks and/ or evaluate how we can improve an athlete's planning time via their perceptual strategies [35].

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