medicina

MDPI

Article

Differences in Kinematic and Muscle Activity between ACL Injury Risk and Healthy Players in Female Football: Influence of Change of Direction Amplitude. Cross-Sectional Case-Control Study.

Loreto Ferrández-Laliena[1], Lucía Vicente-Pina[1], Rocío Sánchez-Rodríguez[1], Graham J Chapman[2], José María Heredia-Jiménez[3], César Hidalgo-García[1*], José Miguel Tricás Moreno[1] and María Orosia Lucha-López[1*].

[1] Unidad de Investigación en Fisioterapia, Spin off Centro Clínico OMT-E Fisioterapia SLP, Universidad de Zaragoza, Domingo Miral s/n, 50009 Zaragoza, Spain; lfernadez@unizar.es (L.F.-L.); l.vicente@unizar.es (L.V.-P.); r.sanchez@unizar.es (R.S.-R.); jmtricas@unizar.es (J.M.T.-M.)

[2] Allied Health Research Unit, School of Health, Social Work and Sport, University of Central Lancashire, Preston, UK; GChapman2@uclan.ac.uk (G.C.)

[3] Departamento de Educación Física y Deportiva, Universidad de Granada, Ceuta, Spain; herediaj@ugr.es (J.M.H.-J.)

* Correspondence: orolucha@unizar.es (M.O.L.-L.); hidalgo@unizar.es (C.H.-G.) Tel.: +34-626-480-131 (M.O.L.-L.)

Abstract: *Background and Objectives*: Anterior cruciate ligament (ACL) injury rates remain high and have a significant impact on female football players. This study aims to evaluate knee kinematics and lower limb muscle activity in players at risk of ACL injury compared to healthy players during three side-cutting tests. It also investigates how the amplitude of change of direction influences stabilization parameters. *Materials and Methods*: A cross-sectional case-control study was conducted with 16 participants (23.93 ± 5.16 years), divided into Injured (n=8) and Healthy groups (n=8). Injured players had a history of non-contact knee injury involving valgus collapse, without undergoing surgical intervention. Three change of direction tests: Change of Direction and Acceleration Test (CODAT), Go Back Test (GOB), and Turn test (TURN) were used for evaluation. The peak and range of knee joint angles and angular velocities across three planes, along with the average rectified and peak envelope EMG signals of the Biceps Femoris (BF), Semitendinosus (ST), Vastus Medialis (VM), and Gastrocnemius Lateralis (GL), were recorded during the preparation and load phases. Group differences were analyzed using two-factor mixed-model ANOVA with pairwise comparisons. Statistical significance was set at $p < 0.05$. *Results*: Injured players demonstrated lower external tibial rotation angular velocity and a greater range of motion in tibial external rotation compared to Healthy players. Additionally, the Injured showed significantly higher average rectified muscle activity in VM and GL both increased by 4% during the load phase. The CODAT and TURN tests elicited higher Bf and VM muscle activity, compared to the GOB test. The TURN test also showed greater extension angular velocity in the sagittal plane. *Conclusions*: The results revealed differences in knee kinematics and muscle activity between players at risk of ACL injury and healthy players, influenced by the amplitude of directional changes. Players altered transverse plane mechanics and increased VM and LG activation during LOAD may reflect a dysfunctional motor pattern, while the greater sagittal plane angular velocity and VM and BF activation from CODAT and TURN highlight their higher potential to replicate ACL injury mechanisms compared to GOB.

Academic Editor: Firstname Lastname

Received: date
Revised: date
Accepted: date
Published: date

Citation: To be added by editorial staff during production.

Clinical Implications: This study highlights the importance of assessing kinematics in conjunction with specific muscle activity during functional tests that replicate ACL injury mechanisms, in order to better determine player risk profiles and design more effective prevention programs.

Keywords: Anterior cruciate ligament; biomechanics; electromyography; female football; injury prevention

1. Introduction

Anterior cruciate ligament (ACL) injury rates disproportionately affect females, who are 2-6 times more likely to suffer from an ACL injury compared to males with 0.7 injuries per squad per season and 0.1 injuries per 1,000 hours of play [1–3]. ACL injuries are significantly burdensome for the player with, on average, 38 days lost per 1,000 hours of exposure and 117 days of recovery [1]. Furthermore, 25-35% of players face re-injury within 2-5 years with females having a higher re-injury risk compared to males [4], with only 81% returning to their prior competition level post-rehabilitation [5,6].

Due to the severity and long-term impact of ACL injuries, current research focuses on identifying ACL risk factors to develop prevention strategies aimed at lowering injury thresholds [7]. Since non-contact mechanisms persist as the primary cause of ACL injuries, kinematic and kinetic analyses have traditionally focused on identifying biomechanical risk factors. Recent research has recognized the importance of addressing valgus collapse, characterized by hip adduction and internal rotation, and knee abduction, incorporating the function analysis of the transverse plane in prevention programs [8–10]. While most studies link increased internal tibial rotation to a higher risk of ACL injury, recent research suggests that excessive transverse plane movement may be the primary risk factor[11–17]. However, to date, there is no consensus whether excessive internal or external tibial rotation is a risk factor [16]. Consequently, recent studies advocate for incorporating new outcomes, such as angular velocity, into kinematic analyses, as it reflects the speed of joint movement, closely linked to motor control [11,12,16]. Therefore, it serves to characterize the direction and quality of control, based on movement velocity during the stabilization task.

Sensorimotor control, driven by muscle activity, directly influences the kinematic and kinetic factors associated with ACL injury mechanics [18]. Recent research has demonstrated altered muscle activity is related to ACL injured risk [10,13,19,20]. Most prevalent injury mechanism occurs during defensive actions, particularly during front-facing pressing situations, where the player must rapidly change direction to follow offensive opponent [21,22]. 21Therefore, recent studies suggest that functional tasks, such as change of direction tests, can be an effective strategy for assessing risk by replicating the mechanisms of ACL injuries [23,24]. However, it remains unclear which specific amplitude of directional change presents the greatest challenge to knee stabilization, thereby placing the maximum stress on its functional mechanisms [22].

Notably, most of ACL stabilization loading occurs in the sagittal plane, primarily involving the hamstrings, quadriceps, and gastrocnemius muscles [13,18,25]. Hamstrings play a crucial role as ACL synergist by counteracting anterior tibial translation during change of direction stabilization maneuvers [10,13,19]. Previous research highlights that altered hamstring activity, prior to initial ground contact, is associated with an increased risk of ACL injury [10,13,19,20,26]. Semitendinosus (ST) is particularly significant due to its role as a ‘knee adductor’, contributing to medial joint compartment compression and preventing valgus collapse [10,19,26]. Valgus collapse is often associated with increased quadricep activity, which has been suggested to increase anterior shear forces and places excessive strain on the ACL, particularly during the load phase when players re-establish their stability [13,19,26]. Additionally, recent studies have analyzed the role of the gastrocnemius in the stabilization process, identifying its function as ACL antagonist [18,25]. It may perform a posterior displacement of the femur that may contribute to anterior tibial translation, thereby enhancing the action triggered by quadricep contraction during the load phase [18,25].

Given the combined impact of the ACL incidence and its burdensome, along with the persistent sex-related prevalence disparities, improving evaluation strategies in female players remains essential [1,3]. Although previous studies have combined kinematic and motor control assessments, there is still a need to enhance sensitivity of movement quality evaluations and the specificity of muscle activity analysis during tasks that replicate ACL injury mechanisms. In this context, incorporating new kinematic variables, for example, angular velocity, which is more closely linked to motor control, alongside traditional joint angle measurements could enhance assessment specificity [11,12,16]. Similarly, by focusing on key muscles such as hamstrings and quadriceps and considering secondary muscles including gastrocnemius to analyze functionality, may help distinguish motor patterns between players at risk of ACL injury and healthy players [13,19,25]. Therefore, the first objective of this study was to evaluate angular velocity and joint angle kinematics of the knee, as well as muscle activity in hamstrings, quadriceps and gastrocnemius, in both players at risk of ACL injury and healthy players during three change of direction tests. The second objective was to evaluate how the amplitude of the change of direction angle involved in each test influences the knee stabilization pattern of the player, based on kinematic and muscle activity variables. It was hypothesized that players at risk of ACL injury will show differences in kinematic and muscle activity patterns compared to healthy players. Additionally, this study suggests that such differences will emerge during change of direction tasks and be influenced by amplitude of directional change.

2. Materials and Methods

2.1. Participants

Potential participants were identified from professional female futsal teams (Real Federación de Fútbol de Ceuta). They were eligible if they held an active national futsal license, train for over 8 hours per week, competed in the Second Spanish National Futsal Division, and actively participated in competitions at the time of the study. Participants were excluded from the study if they had any lower limb injury which may affect the outcomes of this study or had received knee surgery and/or any other lower limb surgery.

A cross-sectional case-control study was conducted, and the recruitment was during 2022/2023 season. Participants were allocated to groups based on their clinical history. Injured players were defined as those who had previously sustained a non-contact knee injury resulting from a valgus collapse mechanism, without having undergone ACL surgical intervention. All injuries had to be fully recovered through conservative treatment by the time of the study in accordance with criteria used in previous research [4,9,27,28]. The control group consisted of players that were injury free and had not previously sustained a knee injury. Eight players were allocated in each group. The Research Ethics Committee of the Community of Aragón approved this study (code PI20/127), which adhered to the ethical principles of the Declaration of Helsinki [29]. All participants provided written informed consent prior to data collection commencement. For those participating players who were minors, it was also signed by their legal guardian.

2.2. Procedure

Participants took part in a single testing session and following a 10 minute warm up consisting of mobility exercises and variable intensity running with change of direction drills, were required to complete one trial under three different change of direction tasks; (1) CODAT [27,30,31], (2) GOB [32], and (3) TURN [24,33] (see Figure 1). These tests require performing a change of direction at maximal velocity, but each test involves different amplitudes of directional change. In CODAT and TURN, a 90º change of direction was recorded. However, in CODAT, this occurs after an initial 45º directional change and is followed by two additional consecutive changes of direction, requiring the player to continually adapt her trajectory. In contrast, the TURN test involves a single 90º change of direction, after which the player continues running straight to complete the task. In GOB test, a 180º change of direction was recorded, which includes a forward braking phase followed by running back towards where the participant started the task. Injured participants were instructed to use their injured limb and the healthy participants used their dominant limb as the stance limb for each change of direction test as the support limb, to replicate the injury mechanism associated with non-contact injuries [21]. Prior to data collection, participants completed a familiarization period to avoid learning bias [27]. Participants were given a unique anonymised study code to minimise any bias during data analysis.

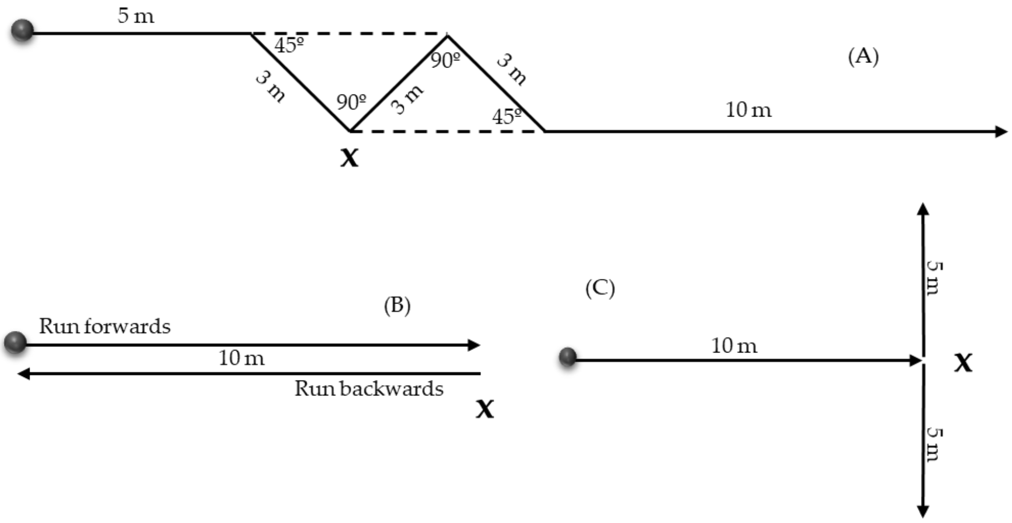

Figure 1. Functional change of direction test: CODAT test, GOB test and TURN test. The initial point of the test is drawn with a ball and the cross identifies the change of direction task that was recorded. (A) Change of Direction and Acceleration Test (CODAT), this test combines sprinting mechanics with the stabilization and acceleration required for change of direction movements. It consists of four diagonal change of direction tasks: two at 45° and two at 90°, interspersed with 3-meter sprints and culminating in a 10-meter sprint. (B) Go and Back test (GOB), this test involves a 10 m frontal sprint at maximum possible speed, followed by deceleration and a final backward sprint. It simultaneously incorporates a change of direction and a deceleration task, both of which are common mechanisms associated with ACL injuries. (C) TURN test, this test is a modified version of the T-test. It involves a frontal sprint followed by a single pre-planned 90º change of direction, performed once in each direction.

2.3. Marker and EMG sensor Placement

A total of twenty-six markers were placed on the anterior and posterior superior iliac spines, bilaterally on the greater trochanters, medial and lateral femoral epicondyles and medial and lateral malleoli. Non-orthogonal tracking clusters comprising of four markers were positioned on the lateral thighs and lateral shanks. The feet were modelled as single segments with four markers attached to each foot on the calcanei, 1st metatarsal, 5th metatarsal and midfoot. Kinematic data were captured at 250 Hz using a nine-camera 3D motion capture system (Qualisys AB, Göteborg, Sweden).

Surface EMG were recorded using four Trigno Avanti (Delsys Inc., USA) wireless sensors sampled at 1000 Hz positioned over the Biceps Femoris (BF), ST, Vastus Medialis (VM) and Lateral Gastrocnemius (LG) following the SENIAM guidelines [19,34]. Throughout data collection, regular checks of the signal-to-noise ratio were conducted to ensure good signal quality.

2.4. Data Analysis

Marker trajectories and EMG data were exported to C3D and imported into Visual 3D (C-Motion Inc., Germantown, USA) for analysis. Kinematic data were filtered using a 4th order zero-lag, 8Hz low-pass Butterworth filter [35]. Knee joint kinematics were calculated from the shank relative to the thigh using an XYZ cardan sequence [36]. Peak knee kinematics in the sagittal, coronal, and transverse planes were extracted [36]. EMG signals were filtered using a second-order Butterworth high-pass filter with a cut off frequency of 40 Hz to minimize movement artifacts [37] and then full wave rectified and low-pass filtered with a 15Hz cut off frequency [37]. The maximum observed signal from the filtered data across all trials and muscles was used to normalized the average and peak EMG signals during the preparation (PREP) phase, defined as 100ms prior to ground contact to the frame immediately before initial contact and the loading (LOAD) phase defined as initial contact to maximum knee flexion [13,38].

2.5. Sample Size

The sample size was calculated based on a minimum expected difference of 0.16 (SD 0.11) in BF muscle activity during PREP phase in a change of direction maneuver [38] using the GRANMO 8.0 calculator, considering an alpha risk of 0.05, a beta risk of 0.20, and a two-sided test. A target sample of 16 participants, eight per group, was required.

2.6. Statistical Analysis

Sharpiro-Wilk tests were performed to explore data normality. For normal distributed data, two factor Mixed Methods (2x2) ANOVA tests were used to explore kinematic differences between groups (Injured and Healthy) during the three different movement tasks (CODAT, GOB and TURN). For EMG measures, separate Mixed Methods ANOVAs were run for the PREP and LOAD phases. For significant main effects, pairwise comparisons were conducted to explore differences between groups and tasks. For significant interactions, separate one-way ANOVAs were performed. The significance level was set at $p < 0.05$ and all statistical analysis were performed using SPSS software v.25 (SPSS Inc., Chicago, IL, USA).

3. Results

Eight participants were allocated to the Injured group, and eight to the Healthy group, based on their clinical history. The average age was 23.93 ± 5.16 years with an average height of 1.61 ± 0.05 m, demographic characteristics are summarized in Table 1.

Table 1. Demographic characteristics of the players

	Total (n=16)	**Injured (n=8)**	**Healthy (n=8)**
Aged (years)	23.93 ± 5.16	23.00 ± 4.04	24.75 ± 6.13
Position (Goalkeper : Back: Wing : Pivot)	3 : 4 : 7 : 2	1 : 3 : 3 : 1	2 : 1 : 4 : 1
Height (cm)	161.24 ± 5.41	162.71 ± 5.87	159.95 ± 4.97
Limb dominance (Right : Left)	13 : 3	6 : 2	7 : 1
Football Experience		15.75 ± 1.98	16.63 ± 1.19
Injury limb (Dominant Limb : Non-Dominant Limb)	4 : 4	4 : 4	

Table 2 shows the descriptive statistics, main effects and interactions for sagittal, coronal and transverse plane knee kinematics. No differences were reported in the coronal plane for task or group. In the sagittal plane, Mixed Methods ANOVA revealed a significant main effect of task for peak knee flexion-extension angular velocity (p = 0.049) (Table 2). Post-hoc pairwise comparisons showed the CODAT and GOB demonstrated significantly higher knee extension angular velocity compared to TURN task (p = 0.035, and p = 0.046, respectively) (Table 5).

Table 2. Mean (SDs), and the two-factor mixed linear model statistics for peak sagittal, coronal and transverse plane knee kinematics during the CODAT, GOB and Turn tasks.

	CODAT		**GOB**		**TURN**		**Task p value**	**Injured p value**	**Interaction effect**
	Injured	**Healthy**	**Injured**	**Healthy**	**Injured**	**Healthy**			
Variables									
Sagittal Plane									
Joint Angle									
Minimum Knee Flexion Angle	19.06 ±4.49	23.64 ±8.77	20.10 ±4.49	21.22 ±11.96	22.65 ±2.26	23.83 ±9.11	0.599	0.307	0.741
Peak Knee Flexion-Extension Angle	-53.64 ±8.46	54.30 ±12.04	-62.26 ±10.18	59.46 ±8.18	-60.01 ±10.69	58.41 ±14.88	0.150	0.696	0.884
Knee Flexion-Extension Angle ROM	-34.59 ±9.05	30.66 ±11.17	42.16 ±10.04	38.23 ±10.91	37.36 ±11.57	34.59 ±9.05	0.134	0.265	0.986
Angular Velocity									
Minimum Knee Flexion Angular Velocity	-517.30 ±127.17	-501.68 ±126.55	-462.53 ±64.01	-471.95 ±11.96	-536.92 ±109.41	-485.78 ±124.02	0.380	0.556	0.710
Peak Knee Flexion-Extension Angular Velocity	46.24 ±140.89	143.81 ±224.30	11.79 ±50.65	58.63 ±77.11	7.32 ±18.88	-3.85 ±19.01	**0.049* ()**	0.201	0.164
Knee Flexion-Extension Angular Velocity ROM	562.06 ±201.87	643.98 ±197.75	471.74 ±77.73	524.55 ±163.86	534.60 ±110.51	464.36 ±119.65	0.184	0.628	0.264
Coronal Plane									

Joint Angle									
Minimum Knee Abduction Angle	-6.67 ±5.59	-7.87 ±4.24	-4.42 ±5.37	-8.80 ±6.96	-7.07 ±5.81	-6.65 ±4.99	0.942	0.289	0.511
Peak Knee Abduction/Adduction Angle	0.90 ±3.39	-2.25 ±3.99	2.68 ±5.72	2.91 ±7.55	0.67 ±3.54	1.76 ±6.80	0.173	0.698	0.385
Knee Abduction-Adduction Angle ROM	7.58 ±4.37	5.62 ±2.52	7.09 ±2.78	11.71 ±5.50	-7.73 ±2.92	8.41 ±3.87	0.152	0.320	0.086
Angular Velocity									
Minimum Knee Abduction Angular Velocity	-118.01 ±76.41	-114.89 ±37.91	-138.28 ±77.59	-133.43 ±45.78	-154.99 ±137.08	-105.27 ±51.92	0.672	0.405	0.721
Peak Knee Adduction Angular Velocity	196.10 ±73.84	140.87 ±98.07	183.62 ±73.92	175.43 ±85.87	244.57 ±97.19	179.37 ±91.62	0.388	0.097	0.601
Knee Abduction-Adduction Angular Velocity ROM	314.11 ±123.82	255.76 ±127.85	321.90 ±148.60	308.86 ±92.26	399.56 ±223.63	284.64 ±108.42	0.557	0.145	0.636
Transverse Plane									
Joint Angle									
Minimum Knee External Rotation Angle	-1.55 ±8.45	-0.97 ±8.48	-6.89 ±9.86	-4.18 ±9.51	-6.16 ±9.22	-2.44 ±7.35	0.386	0.365	0.867
Peak Knee Internal Rotation Angle	11.55 ±7.96	8.19 ±7.33	6.54 ±6.65	7.92 ±8.63	11.15 ±6.23	6.19 ±5.76	0.626	0.269	0.435
Knee Internal-External Rotation Angle ROM	13.11 ±5.21	9.16 ±4.40	13.43 ±5.09	12.10 ±5.54	17.31 ±7.37	8.63 ±5.14	0.558	**0.006***	0.223
Angular Velocity									
Minimum Knee External Rotation Angular Velocity	-96.61 ±92.06	-164.32 ±145.82	-173.90 ±120.09	-254.06 ±134.48	-109.27 ±58.56	-176.00 ±96.89	0.129	**0.034***	0.983
Peak Knee Internal Rotation Angular Velocity	253.16 ±155.06	215.68 ±126.86	270.14 ±124.14	233.24 ±115.39	366.58 ±200.39	215.80 ±88.08	0.552	0.071	0.461
Knee Internal-External Rotation Angular Velocity ROM	349.77 ±225.48	380.00 ±249.73	444.04 ±116.70	487.30 ±221.62	475.85 ±206.39	391.81 ±141.91	0.411	0.952	0.564

*denotes significance

In the transverse plane, Mixed Methods ANOVA showed a significant main effect of group on knee internal-external rotation range of motion (p = 0.006) and minimum knee external rotation angular velocity (p = 0.034). Post-hoc pairwise comparisons revealed that the Injured demonstrated significantly increased knee internal-external rotation range of motion (p=0.006) and significantly decreased external rotation angular velocity (p=0.034). (Table 5). These kinematic post-hoc pairwise comparisons were graphically represented in Figure 2, in the sagittal plane for task comparison, and in Figure 3, in the transverse plane for group comparison.

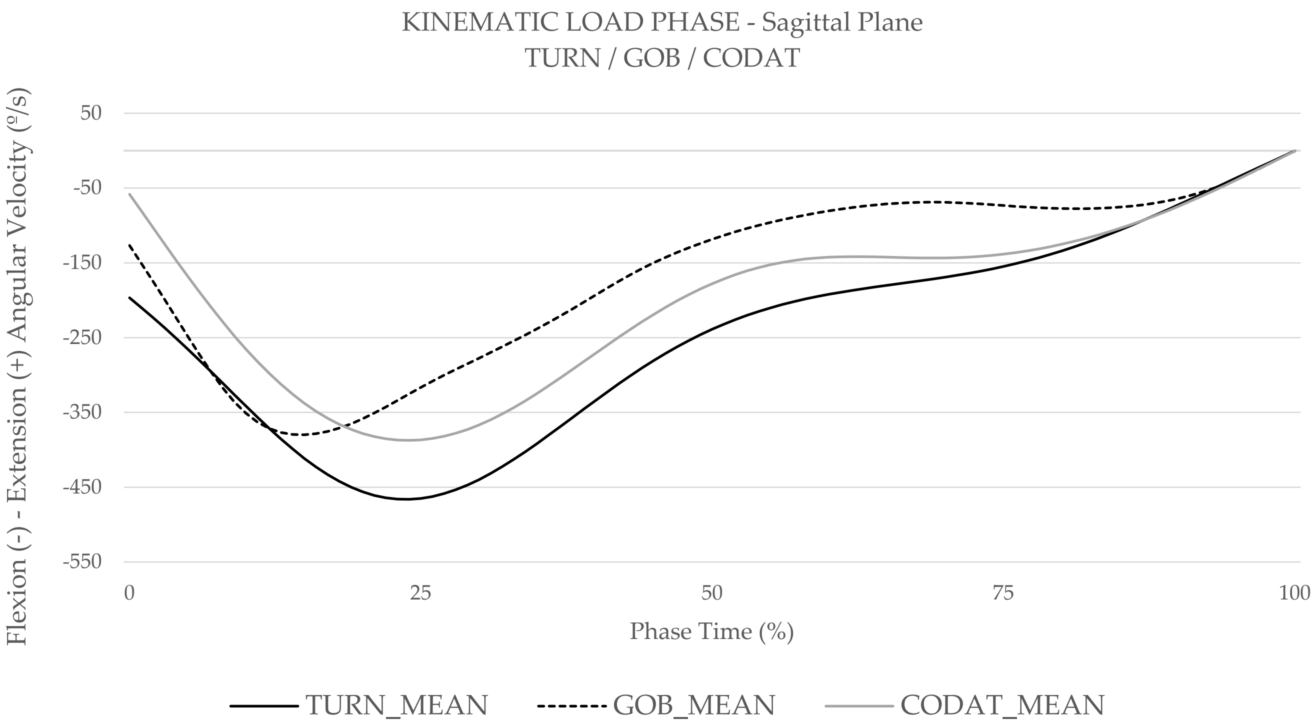

Figure 2. Sagittal plane for TURN, GOB and CODAT test mean values angular velocity during the LOAD phase.

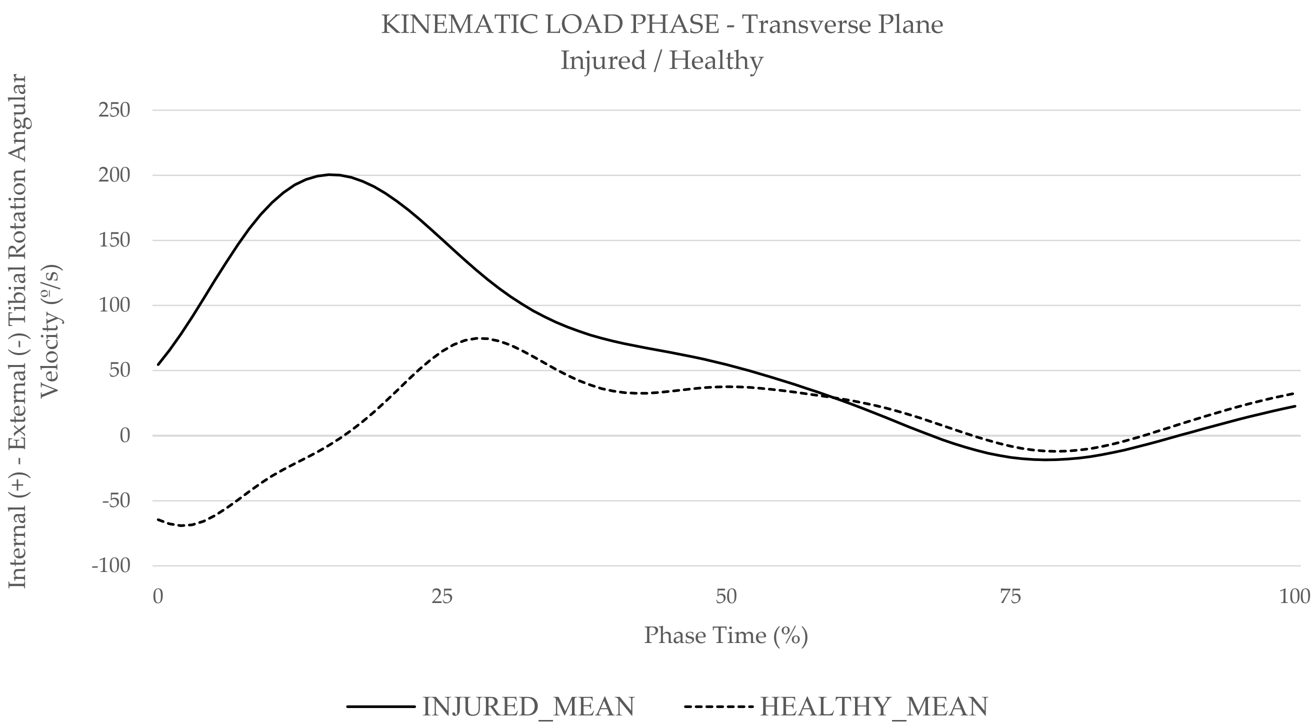

Figure 3. Transverse plane for Injured and Healthy players based on mean data from functional test (CODAT, GOB and TURN) players angular velocity in the CODAT test during the LOAD phase.

Table 3 and 4 show the Mixed Methods ANOVA results for average and peak muscle activity for the PREP and LOAD phases, respectively. There were no significant between group differences or main effect of task for EMG measures during the PREP phase (p >

0.05) (Table 3). In the LOAD phase, Mixed Model ANOVA showed a significant interaction between group and task for peak lateral gastrocnemius muscle activity (p = 0.025). Post-hoc one way ANOVA revealed peak LG muscle activity was significantly higher for Injured compared to Healthy under the TURN task (p = 0.022) (Table 6). There were no between group differences either the GOB or CODAT tasks for LG muscle activity (p>0.05) (Table 6).

Table 3. Mean (SDs) and the two-factor mixed linear model statistics for peak and average muscle activity for Biceps Femoris, Semitendinosus, Vastus Medialis and Lateral Gastrocnemius during the CODAT, GOB and Turn tasks during preparation phase.

	CODAT		GOB		TURN		Task p value	Group p value	Interaction effect
	Injured	Healthy	Injured	Healthy	Injured	Healthy			
Variables									
Average Biceps Femoris	0.14 ±0.05	0.13 ±0.11	0.12 ±0.04	0.10 ±0.07	0.15 ±0.05	0.14 ±0.12	0.326	0.483	0.893
Peak Biceps Femoris	0.63 ±0.24	0.59 ±0.37	0.51 ±0.12	0.38 ±0.25	0.68 ±0.26	0.53 ±0.42	0.122	0.206	0.842
Average Semitendinosus	0.17 ±0.09	0.15 ±0.05	0.19 ±0.05	0.16 ±0.06	0.19 ±0.08	0.14 ±0.07	0.791	0.097	0.887
Peak Semitendinosus	0.71 ±0.33	0.75 ±0.23	0.68 ±0.20	0.63 ±0.22	0.78 ±0.24	0.63 ±0.18	0.656	0.403	0.576
Average Vastus Medialis	0.11 ±0.06	0.08 ±0.05	0.08 ±0.03	0.07 ±0.04	0.10 ±0.05	0.07 ±0.05	0.335	0.092	0.867
Peak Vastus Medialis	0.49 ±0.18	0.43 ±0.31	0.47 ±0.21	0.33 ±0.18	0.53 ±0.23	0.46 ±0.25	0.420	0.197	0.850
Average Lateral Gastrocnemius	0.08 ±0.06	0.08 ±0.06	0.06 ±0.04	0.07 ±0.04	0.05 ±0.02	0.05 ±0.04	0.217	0.618	0.959
Peak Lateral Gastrocnemius	0.40 ±0.18	0.48 ±0.31	0.26 ±0.19	0.35 ±0.25	0.38 ±0.25	0.31 ±0.29	0.274	0.612	0.633

*denotes significance

Table 4. Mean (SDs) and the two-factor mixed linear model statistics for peak and average muscle activity for Biceps Femoris, Semitendinosus, Vastus Medialis and Lateral Gastrocnemius during the CODAT, GOB and Turn tasks during load phase.

	CODAT		GOB		TURN		Task p value	Group p value	Interaction effect
	Injured	Healthy	Injured	Healthy	Injured	Healthy			
Variables									
Average Biceps Femoris	0.16 ±0.06	0.13 ±0.09	0.10 ±0.03	0.08 ±0.07	0.15 ±0.04	0.13 ±0.08	**0.042***	0.208	0.884
Peak Biceps Femoris	0.78	0.69	0.59	0.47	0.71	0.67	0.188	0.376	0.946

	±0.25	±0.31	±0.25	±0.40	±0.26	±0.34			
Average Semitendinosus	0.11 ±0.06	0.14 ±0.07	0.10 ±0.02	0.10 ±0.05	0.13 ±0.07	0.11 ±0.05	0.264	0.755	0.653
Peak Semitendinosus	0.64 ±0.35	0.74 ±0.24	0.52 ±0.12	0.63 ±0.28	0.59 ±0.27	0.73 ±0.26	0.395	0.143	0.969
Average Vastus Medialis	0.20 ±0.05	0.12 ±0.07	0.13 ±0.05	0.10 ±0.07	0.17 ±0.06	0.16 ±0.09	**0.052***	**0.031***	0.153
Peak Vastus Medialis	0.91 ±0.14	0.73 ±0.31	0.68 ±0.25	0.49 ±0.32	0.71 ±0.23	0.81 ±0.32	**0.051***	0.253	0.245
Average Lateral Gastrocnemius	0.15 ±0.07	0.14 ±0.07	0.12 ±0.07	0.08 ±0.04	0.15 ±0.08	0.08 ±0.04	0.174	**0.036***	0.433
Peak Lateral Gastrocnemius	0.69 ±0.28	0.86 ±0.23	0.52 ±0.31	0.60 ±0.35	0.79 ±0.26	0.46 ±0.25	0.096	0.770	**0.025***

*denotes significance

There was also significant main effects of task on average BF muscle activity (p = 0.042) between tasks. Post-hoc pairwise comparisons that CODAT and TURN tasks significantly increased average BF (p = 0.034 and p = 0.040, respectively) compared to GOB (Table 4).

There was also significant main effect of group on average VM and peak LG muscle activity (p = 0.031 and 0.036, respectively) (Table 3). For group condition, post-hoc pairwise comparisons showed that the Injured demonstrated significantly increased average VM and LG muscle activity compared to Healthy (p = 0.031 and p = 0.036, respectively) (Table 4).

Table 5. Knee kinematic and EMG pairwise comparisons for significant main effects of injured condition and task.

Variable – Knee kinematic		**Mean Difference**	**p value**	**95% Confidence Intervals for Differences**	
				Lower Bound	**Upper Bound**
Sagittal Plane *(Significant Main effects of Task)*					
Peak Knee Flexion-Extension Angular Velocity	CODAT and GOB	59.82	0.247	-46.12	165.76
	CODAT and TURN	93.29	**0.035***	3.55	82.00
	GOB and TURN	33.47	**0.046***	2.18	208.61
Transverse Plane *(Significant Main effects of Group)*					
Knee Internal-External Rotation Angle ROM	Injured and Healthy	4.66	**0.006***	1.42	7.89
Minimum Knee External Rotation Angular Velocity	Injured and Healthy	71.54	**0.034***	5.92	137.15
Variable – Muscle Activity EMG					
(Significant Main effects of Task)					
Average Biceps Femoris Load Phase	CODAT and GOB	0.05	**0.034***	0.00	0.10
	CODAT and TURN	0.01	0.812	-0.05	0.06
	GOB and TURN	-0.05	**0.040***	-0.09	-0.00
Average Vastus Medialis Load Phase	CODAT and GOB	0.04	**0.030***	0.01	0.08

	CODAT and TURN	-0.01	0.711	-0.05	0.04
	GOB and TURN	-0.05	**0.046***	-0.10	-0.00
	CODAT and GOB	0.24	**0.018***	0.05	0.43
Peak Vastus Medialis Load Phase	CODAT and TURN	0.06	0.535	-0.13	0.25
	GOB and TURN	-0.18	0.080	-0.39	0.02
(Significant Main effects of Group)					
Average Vastus Medialis Load Phase	Injured and Healthy	0.04	**0.031***	0.00	0.08
Average Lateral Gastrocnemius Load Phase	Injured and Healthy	0.04	**0.036***	0.00	0.08

*denotes significance

Table 6. Pairwise comparison for significant main effect of limb for each task for Peak Lateral Gastrocnemius during the load phase.

Variable *Peak Lateral Gastrocnemius load phase*		**Mean Difference**	**p value**	**95% Confidence Intervals for Differences**	
				Lower Bound	**Upper Bound**
CODAT	Injured and Healthy	-0.17	0.203	-0.45	0.10
GOB	Injured and Healthy	-0.09	0.616	-0.44	0.27
TURN	Injured and Healthy	0.33	**0.022***	0.05	0.60

*denotes significance

4. Discussion

This study investigated the differences in kinematic and muscle activity outcomes associated with ACL injury mechanisms during functional change of direction tasks, comparing players at risk of ACL injury with healthy players. Additionally, it examined whether these differences were influenced by the amplitude of the angle involved in each different change of direction test. The findings support the hypothesis that players at risk of ACL injury, defined as those with a history of valgus collapse-related knee injury, demonstrate altered functional motor pattern compared to healthy players, as reflected by movement quality and motor control. Moreover, both knee kinematics and muscle activity were also influenced by the amplitude of the angle required in each functional change of direction test.

Injured showed significant differences for kinematics exclusively in the transverse plane, where exhibited higher internal-external tibial rotation range of motion and decreased external rotation angular velocity compared to Healthy. This altered kinematic pattern amplifies the rotational load on the ACL, especially in the internal rotation direction, which is critical during pivot shift maneuvers that involve knee abduction and internal tibial rotation, thereby increasing ACL injury risk [39,40]. This aligns with Bates et al., who explained that the ACL primarily stabilizes anterior tibial translation in the sagittal plane (87%) while also resists torsional forces (13%) from movements in the transverse and coronal planes [39,41]. Additionally, Hewett et al. outlined how axial forces increase compression on the lateral knee side during valgus collapse [42], which combined with the posterior slope of the lateral tibial plateau, enhances internal tibial rotation [15]. This increased internal rotation corresponds with the motor pattern observed in Injured, highlighting kinematic dysfunctions directly associated with the ACL injury mechanism. Our findings align with these studies, as the Injured group demonstrated reduced external tibial rotation angular velocity, particularly during the early LOAD phase (Figure 3), when main stabilization adjustments are essential to avoid excessive strain in the ACL [13]. These are consistent with research that identified greater rotation motion, impaired in internal rotation direction, in players at risk of ACL [12,43,44]. Consequently, Injured may be more likely to exhibit high risk ACL kinematic profiles, particularly in the transverse plane, compared to Healthy.

Group differences in muscle activity were observed exclusively during the LOAD phase. Kinematic profile differences, particularly in the transverse plane, may influence muscle activity during load absorption, explaining the lack of differences during the airborne PREP phase. Injured players demonstrated significantly higher average VM and LG muscle activity, 4% more than Healthy, and only during the TURN, 33% higher peak LG activity. Quadriceps-dominant strategies during LOAD phase increase anterior tibial shear forces, contributing to excessive ACL strain and higher injury risk [10,13]. As Murphy et al. explains VM, as a uni-articular muscle, plays a key role in knee stabilization [45]. Therefore, the increased VM activity in Injured may reflect greater neuromuscular demand for rapid stabilization, potentially resulting from impaired motor control. In addition, LG anatomical position enables posterior femoral translation and posterior knee compression [13,18,25], which, in synergy with quadriceps activity, generates anterior tibial shear forces, further increasing ACL strain [13,18,25]. As noted by Nasseri et al., this interaction reaches its peak early in the LOAD phase, along with the previously mentioned kinematic imbalances [13] (Figures 2 and 3). Our findings highlight this dysfunctional neuromuscular mechanism in Injured, where elevated VM and LG activation promotes anterior tibial displacement, thereby increasing ACL strain and significantly raising injury risk. This Injured pattern, according to Picot et al., could be attributed to muscle compensation related to dysfunctional hamstrings muscle activity, key stabilizers of knee rotation [10,19]. Despite the absence of significant differences in hamstring muscle activity between groups or between BF and ST, the presence of transverse plane kinematic differences suggest that Injured compensates through VM and LG EMG to maintain rotational stability, highlighting a potentially dysfunctional strategy that could underline the increased ACL injury risk explained. This pattern may raise immediate ACL injury risk and contribute to long-term vulnerability [4,13,19].

Tasks analysis indicates that the amplitude of directional change significantly impacts kinematic strategies, particularly in the sagittal plane. This highlights this plane load component as the primary involved in change of direction tasks, supporting functional test specificity, as most ACL loading occurs in the sagittal plane during the LOAD phase [13,20,25,39]. The results revealed that both CODAT and GOB exhibited significantly higher knee extension angular velocity compared to TURN. In our study the maximum knee flexion marking the end of the LOAD phase [13,38,46]. In this way, CODAT and GOB highly extension angular velocity appears at the end of LOAD phase (Figure 2). According to Thomas et al., increased knee flexion during the LOAD phase aids in achieving an optimal body position at final contact, characterized by a lower center of mass, which enhances force absorption and control of external disturbances [46]. The higher extension angular velocity observed in CODAT and GOB during this phase suggests a more efficient transition from stabilization, increased then decreased flexion angular velocity, to propulsion, extension angular velocity. In contrast, TURN appears to present a greater stabilization challenge, potentially delaying this transition and reducing extension angular velocity. Therefore, TURN may better replicate functional injury mechanisms in defense football context, as it allows players to perform the maneuver at high intensity, preceded and followed only by straight-line sprinting [22].

Significant differences in muscle activity between tasks were observed only during the LOAD phase. This suggests that the amplitude of directional change during the functional change of direction maneuver does not influence muscle activity in the PREP phase. Both CODAT and TURN tasks resulted in higher average BF and VM muscles compared to GOB. Murphy et al. highlight that the hamstrings and quadriceps are the primary controllers of knee stability [45]. This is because most of the knee stabilization load occurs in the sagittal plane, which is the primary axis of action for the hamstrings and quadriceps functioning in an agonist–antagonist balance [10,13]. Therefore, CODAT and TURN, that involve greater activation of these muscle groups, suggest that 90° change of direction maneuvers implicates a greater stabilization challenge for the knee compared to other task as GOB that involving other amplitude angle. Supporting this, Markström et al., report that 90º directional changes are associated with more specific and demanding functional patterns than other directional amplitudes [40]. These results, when considered alongside the kinematic data, suggest that tasks involving 90° directional changes may offer a more effective means of evaluating knee stability. Overall, the increased muscle demands and coordination required during these tasks may better reflect functional challenges faced during high-risk movements, such as those related to ACL injury mechanisms.

Future research should investigate the transferability of these findings to other sports, as change of direction is a common functional task across various disciplines. It would be valuable to examine whether similar kinematic and muscle activity patterns are present in athletes exposed to valgus collapse knee injury mechanisms in different sporting contexts. This exploration could enhance the development of cross-sport prevention strategies. Additionally, further research should focus on the design and implementation of specific training programs based on the kinematic and muscle activity patterns identified in players at risk of ACL injury. These interventions should aim to reduce the magnitude of these risk-related variables, reverse the dysfunctional knee stabilization patterns observed, and ultimately prevent ACL injuries.

4.1. Limitations

This study presented some limitations. The assessor(s) in the present study were not blinded during data collection. However, participants were given a unique, anonymized study code to mitigate potential bias during data and statistical analyses. Although this study was powered appropriately, the sample size small and the results should be interpreted with caution. However, these findings do support the use of kinematics, angular velocity and muscle activity to explore differences between those at risk of ACL injury and healthy participants during change of direction tests. Additionally, potential covariates such as player age, years of sport participation, and injury type were not included in the a priori statistical plan. Future research may want to appropriately power a study to explore these factors. Methodological limitation of this study is its exclusive focus on knee kinematics, as knee motion is influenced by the kinematics of the entire lower limb. Future research may want to include hip and ankle kinematics and/or muscle activity to gain a more comprehensive understanding of functional differences between players at risk of ACL injury. Furthermore, incorporating gluteal muscle activity analysis would be valuable, as these muscles play a key role in controlling hip movement, which in turn affects knee stability, particularly in the transverse plane.

4.2. Clinical contributions

This study highlights the growing trend of incorporating muscle activity analysis, as neuromuscular factor related to motor control, into ACL injury risk identification studies. In synergy with kinematic variables such as angular velocity may provide more sensitive information to identify players at risk of ACL injury, based on quality of movement analysis. Furthermore, since the study involved active players who had previously suffered an injury due to valgus collapse and had fully recovered, it is plausible that the observed risk patterns reflect dysfunctional compensatory mechanisms. Our findings show that players at risk of ACL injury exhibited greater angular velocity and range of motion in the transverse plane, along with heightened VM and LG muscle activity compared to healthy players. These alterations in movement quality and motor control reinforce the hypothesis of a dysfunctional compensatory motor pattern. Therefore, these risk patterns should be leveraged to design more targeted injury prevention programs that address these movement strategies and mitigate long-term risk factors.

5. Conclusions

This study identified differences in knee angular velocity, and muscle activity between players at risk of ACL injury and healthy players. These differences were influenced by the amplitude and direction of the change of direction indicating that CODAT and TURN tasks, that involving 90° directional changes, may offer a more effective means of evaluating knee stability. Players at risk of ACL injury exhibit increased range of motion and angular velocity in the transverse plane, along with elevated VM and LG muscle activity during the LOAD phase, compared to healthy players. Conversely, the TURN and CODAT tests are characterized by greater angular velocity in the sagittal plane, which is associated with increased activation of the VM and BF muscles. Therefore, the increased angular velocity and range of motion in the transverse plane, along with elevated VM and LG muscle activity during the LOAD phase, may reflect an underlying dysfunctional motor pattern. This highlights the importance of assessing kinematics alongside specific muscle activity during functional tests, replicating ACL injury mechanisms, to better determine player risk profiles and design more effective prevention programs.

Author Contributions: Loreto Ferrández-Laliena and María Orosia Lucha-López; Data curation, Lucía Vicente-Pina and Rocío Sánchez-Rodríguez; Formal analysis, Graham J Chapman; Funding acquisition, José Miguel Tricás Moreno; Investigation, Loreto Ferrández-Laliena, Lucía Vicente-Pina, Rocío Sánchez-Rodríguez and José María Heredia-Jiménez; Methodology, Graham J Chapman and María Orosia Lucha-López; Project administration, José María Heredia-Jiménez and María Orosia Lucha-López; Resources, Lucía Vicente-Pina and César Hidalgo-García; Software, Loreto Ferrández-Laliena and Graham J Chapman; Supervision, Graham J Chapman; Validation, César Hidalgo-García, José Miguel Tricás Moreno and María Orosia Lucha-López; Visualization, Rocío Sánchez-Rodríguez; Writing – original draft, Loreto Ferrández-Laliena; Writing – review & editing, Graham J Chapman and María Orosia Lucha-López.

Funding: This research received no external funding.

Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki, and approved by the Research Ethics Committee of Community of Aragón (protocol code PI20/127; date of approval: 18 March 2020).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study. Written informed consent has been obtained from the patient(s) to publish this paper.

Data Availability Statement: The datasets presented in this study are available on request from the corresponding author. All data covered by this study are included in this manuscript.

Acknowledgments: The authors have reviewed and edited the output and take full responsibility for the content of this publication.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

ACL	Anterior Cruciate Ligament
EMG	Electromyography
ST	Semitendinosus
BF	Biceps Femoris
VM	Vastus Medialis
LG	Lateral Gastrocnemius
PREP	Preparation phase
LOAD	Load phase

References

1. Hallén, A.; Tomás, R.; Ekstrand, J.; Bengtsson, H.; Van den Steen, E.; Hägglund, M.; et al. UEFA Women's Elite Club Injury Study: a prospective study on 1527 injuries over four consecutive seasons 2018/2019 to 2021/2022 reveals thigh muscle injuries to be most common and ACL injuries most burdensome. *Br. J. Sports Med.* **2024,** 58, 128–136. https://doi.org/10.1136/bjsports-2023-107133
2. Lima, Y.L.; Collings, T.J.; Hall, M,; Bourne, M.N.; Diamond, L.E. Injury Prevention Programmes Fail to Change Most Lower Limb Kinematics and Kinetics in Female Team Field and Court Sports: A Systematic Review and Meta-Analysis of Randomised Controlled Trials. *Sports Med.* **2024** 54, 933–952. https://doi.org/10.1007/s40279-023-01974-2
3. Larruskain, J.; Lekue, J.A.; Angulo P.; Santisteban J.M.; Diaz-Beitia G.; Martin-Garetxana I.; et al. An injury burden heat map of all men's and women's teams of a professional football club over a decade. *Sports Med.* **2024** 32, 740–750. https://doi.org/10.1080/15438627.2023.2228959
4. Ferrández-Laliena, L.; Sánchez-Rodríguez, R.; Vicente-Pina, L.; Lucha-López, M.O.; Ambrus, M.; Hidalgo-García, C. et al. Comparative Analysis of Neuromuscular Activation Patterns Associated with Force between Semi-Professional Female Soccer Players with Previous Anterior Cruciate Ligament Surgery and Healthy Players in Thigh Musculature Related to Valgus Collapse. *Appl. Sci.* **2024** 14, 6869. https://doi.org/10.3390/app14166869
5. Ramachandran, A.K.; Pedley J.S.; Moeskops S.; Oliver J.L.; Myer G.D.; Lloyd R.S. Changes in Lower Limb Biomechanics Across Various Stages of Maturation and Implications for ACL Injury Risk in Female Athletes: a Systematic Review. *Sports Med.* **2024** 54, 1851-1876. https://doi.org/10.1007/s40279-024-02022-3
6. Hamoongard, M.; Letafatkar, A.; Thomas, A.C. The Effect of Neurocognitive Training on Biomechanical Risk Factors Related to Anterior Cruciate Ligament Injury in Athletes: A Narrative Review. *J. Sport Rehabil.* **2024** 33, 485–494. https://doi.org/10.1123/jsr.2023-0428
7. Alenezi, F.; Herrington, L.; Jones, P.; Jones, R. Knee valgus angle and loading across common athletic tasks; reference values and gender differences in a healthy population. *Br. J. Sports Med.* **2017** 5, 286. https://doi.org/10.1136/bjsports-2016-097372.6
8. Chia, L. Myer, G.D.; Hewett, T.E.; McKay, M.J.; Sullivan, J.; Ford, K.R.; et al. When puberty strikes: Longitudinal changes in cutting kinematics in 172 high-school female athletes. *J. Sci. Med. Sport*. **2021** 24, 1290–5. https://doi.org/10.1016/j.jsams.2021.07.011
9. Dix, C.; Arundale, A.; Silvers-Granelli, H.; Marmon, A.; Zarzycki, R.; Snyder-Mackler, L. Biomechanical measures during two sport-specific tasks differentiate between soccer players who go on to anterior cruciate ligament injury and those who do not: a prospective cohort analysis. *Int. J. Sports. Phys. Ther.* **2020** 15, 928-935. https://doi.org/10.26603/ijspt20200928
10. Zebis, M.K.; Aagaard, P.; Andersen, L.L.; Hölmich, P.; Clausen, M.B.; Brandt, M. et al. First-time anterior cruciate ligament injury in adolescent female elite athletes: a prospective cohort study to identify modifiable risk factors. *Knee Surg. Sports Traumatol. Arthrosc.* **2022** 30, 1341. https://doi.org/10.1007/s00167-021-06595-8
11. Aoki, A.; Kubota, S.; Morinaga, K.; Zheng, N.N.; Wang, S.S.; Gamada, K. Detection of knee wobbling as a screen to identify athletes who may be at high risk for ACL injury. *Int Biomech.* **2021** 8, 30–41. https://doi.org/10.1080/23335432.2021.1936175
12. Wakabayashi, K.; Ogasawara, I.; Suzuki, Y.; Nakata, K.; Nomura, T. Exploring pre-impact landing kinematics associated with increase and decrease in the anterior cruciate ligament injury risk. *J. Biomech.* **2022** 145, 111382. https://doi.org/10.1016/j.jbiomech.2022.111382

13. Nasseri, A.; Lloyd, D.G.; Bryant, A.L.; Headrick, J.; Sayer, T.A.; Saxby, D.J.; Mechanism of Anterior Cruciate Ligament Loading during Dynamic Motor Tasks. *Med. Sci. Sports Exerc.* **2021** 53,1235–44. https://doi.org/10.1249/MSS.0000000000002589
14. Nagano, Y.; Ida, H.; Akai, M.; Fukubayashi, T. Biomechanical characteristics of the knee joint in female athletes during tasks associated with anterior cruciate ligament injury. *Knee*. **2009** 16, 153–158. https://doi.org/10.1016/j.knee.2008.10.012
15. Kikuchi, N.; Kanamori, A.; Kadone, H.; Kajiwara, M.; Okuno, K.; Hyodo, K.; et al. Relationship Between Posterior Tibial Slope and Lower Extremity Biomechanics During a Single-Leg Drop Landing Combined With a Cognitive Task in Athletes After ACL Reconstruction. *Orthop. J. Sports Med*. **2022** 10(7). https://doi.org/10.1177/23259671221107931
16. Jeong, J.; Choi, D.H.; Shin, C.S. Association Between the Medial-Lateral Quadriceps and Hamstring Muscle Thickness and the Knee Kinematics and Kinetics During Single-Leg Landing. *Sports Health*. **2023** 15, 519–526. https://doi.org/10.1177/19417381231152476
17. Hewett, T.E.; Myer, G.D.; Ford, K.R.; Heidt, R.S.; Colosimo, A.J.; McLean, S.G.; et al. Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: A prospective study. *Am. J. Sports Med.* **2005** 33, 492–501. https://doi.org/10.1177/0363546504269591
18. Mokhtarzadeh, H.; Yeow, C.H.; Hong-Goh, J.C.; Oetomo, D.; Malekipour, F.; Lee, P.V.S. Contributions of the Soleus and Gastrocnemius muscles to the anterior cruciate ligament loading during single-leg landing. *J Biomech*. **2013** 46, 1913-1920. https://doi.org/10.1016/j.jbiomech.2013.04.010
19. Picot, B.; Lempereur, M.; Morel, B.; Forestier, N.; Rémy-Néris, O. Lack of Proprioceptive Strategy Modulation Leads to At-Risk Biomechanics for Anterior Cruciate Ligament in Healthy Athletes. *Med. Sci. Sports Exerc.* **2024** 56, 942–952. https://doi.org/10.1249/MSS.0000000000003378
20. Behnke, A.L.; Parola, L.R.; Karamchedu, N.P.; Badger, G.J.; Fleming, B.C.; Beveridge, J.E. Neuromuscular function in anterior cruciate ligament reconstructed patients at long-term follow-up. *Clin. Biomech*. **2021** 81, 105231. https://doi.org/10.1016/j.clinbiomech.2020.105231
21. Lucarno, S.; Zago, M.; Buckthorpe, M.; Grassi, A.; Tosarelli, F.; Smith, R.; et al. Systematic Video Analysis of Anterior Cruciate Ligament Injuries in Professional Female Soccer Players. *Am. J. Sports Med.* **2021** 49, 1794-802. https://doi.org/10.1177/03635465211008169
22. Ebner, C.; Granacher, U.; Gehring, D. Effects of Anticipation and Dual-Tasking on Lower Limb Biomechanics While Performing Change-of-Direction Tasks in Physically Active Individuals: A Systematic Review with Meta-Analysis. *Sports Med.* **2025** 55, 857-876. https://doi.org/10.1007/s40279-025-02182-w
23. Bencke, J.; Zebis, M.K. The influence of gender on neuromuscular pre-activity during side-cutting. *J. Electromyogr. Kinesiol*. **2011** 21, 371-375. https://doi.org/10.1016/j.jelekin.2010.10.008
24. Di Paolo, S.; Bragonzoni, L.; Della-Villa, F.; Grassi, A.; Zaffagnini, S. Do healthy athletes exhibit at-risk biomechanics for anterior cruciate ligament injury during pivoting movements? *Sports Biomech.* **2022** 2, 1-14 https://doi.org/10.1080/14763141.2022.2080105
25. Navacchia, A.; Ueno, R.; Ford, K.R.; DiCesare, C.A.; Myer, G.D.; Hewett TE. EMG-Informed Musculoskeletal Modeling to Estimate Realistic Knee Anterior Shear Force During Drop Vertical Jump in Female Athletes. *Ann. Biomed. Eng.* **2019** 47, 2416–2430. https://doi.org/10.1007/s10439-019-02318-w
26. Zebis, M.K.; Andersen, L,L.; Bencke, J.; Kjær, M.; Aagaard, P. Identification of athletes at future risk of anterior cruciate ligament ruptures by neuromuscular screening. *Am. J. Sports Med.* **2009** 37, 1967–1973. https://doi.org/10.1177/036354650933500
27. Ferrández-Laliena, L.; Vicente-Pina, L.; Sánchez-Rodríguez, R.; Orantes-González, E.; Heredia-Jimenez, J.; Lucha-López, M.O.; et al. Diagnostics Using the Change-of-Direction and Acceleration Test (CODAT) of the Biomechanical Patterns Associated with Knee Injury in Female Futsal Players: A Cross-Sectional Analytical Study. *Diagnostics.* **2023** 13, 928. https://doi.org/10.3390/diagnostics13050928
28. Arundale, A.J.H.; Bizzini, M.; Giordano, A.; Hewett, T.E.; Logerstedt, D.S.; Mandelbaum, B.; et al. Exercise-based knee and anterior cruciate ligament injury prevention. *J. Orthop. Sports Phys. Ther.* **2018** 48, *A1–A42*. https://www.jospt.org/doi/10.2519/jospt.2018.0303
29. Ethical principles for medical research involving human subjects. *Eur. J. Emerg. Med.* **2001** 8, 221–223.
30. Brophy, R.H.; Stepan, J.G.; Silvers, H.J.; Mandelbaum, B.R. Defending Puts the Anterior Cruciate Ligament at Risk During Soccer: A Gender-Based Analysis. *Sports Health* **2015** 7, 244. https://doi.org/10.1177/194173811453518
31. Lockie, R.G.; Schultz, A.B.; Callaghan, S.J.; Jeffriess, M.D.; Berry, S.P. Reliability and Validity of a New Test of Change-of-Direction Speed for Field-Based Sports: the Change-of-Direction and Acceleration Test (CODAT). *J. Sports Sci. Med.* **2013** 12, 88-96. PMID: 24149730

32. Di Paolo, S.; Zaffagnini, S.; Tosarelli, F.; Aggio, F.; Bragonzoni, L.; Grassi, A.; et al. A 2D qualitative movement assessment of a deceleration task detects football players with high knee joint loading. *Knee Surg. Sports Traumatol. Arthrosc.* **2021** 29, 4032-4404 https://doi.org/10.1007/s00167-021-06709-2
33. Chattanta, V.; Verma, N.; Mehra, P. Quantifying the difference between male and female agility in football players: A cross-sectional study. *Phys. Ther. Sport.* **2024** 1, 90–94. https://doi.org/10.1016/j.ptsp.2024.10.002
34. Hermens, H.J.; Freriks, B.; Disselhorst-Klug, C.; Rau, G. Development of recommendations for SEMG sensors and sensor placement procedures. *J. Electromyogr. Kinesiol.* **2000** 10, 361–374. https://doi.org/10.1016/S1050-6411(00)00027-4
35. Watcharakhueankhan, P.; Chapman, G.J.; Sinsurin, K.; Jaysrichai, T.; Richards, J. The immediate effects of Kinesio Taping on running biomechanics, muscle activity, and perceived changes in comfort, stability and running performance in healthy runners, and the implications to the management of Iliotibial band syndrome. *Gait Posture*. **2022** 91, 179–185. https://doi.org/10.1016/j.gaitpost.2021.10.025
36. Hanzlíková, I.; Richards, J.; Hébert-Losier, K.; Smékal, D. The effect of proprioceptive knee bracing on knee stability after anterior cruciate ligament reconstruction. *Gait Posture*. **2019** 67, 242–247. https://doi.org/10.1519/JSC.0000000000001783
37. Karacan, I.; Topkara-Arslan, B.; Karaoglu, A.; Aydin, T.; Gray, S.; Ungan, P.; et al. Estimating and minimizing movement artifacts in surface electromyogram. *J. Electromyogr. Kinesiol*. **2023** 70, 102778. https://doi.org/10.1016/j.jelekin.2023.102778
38. Ruan M, Zhang Q, Wu X. Acute effects of static stretching of hamstring on performance and anterior cruciate ligament injury risk during stop-jump and cutting tasks in female athletes. *J. Strength Cond. Res.* **2017** 31, 1241-1250. https://doi.org/10.1519/JSC.0000000000001783
39. Bates, N.A.; Schilaty, N.D.; Nagelli, C.V.; Krych, A.J.; Hewett, T.E. Multiplanar Loading of the Knee and Its Influence on Anterior Cruciate Ligament and Medial Collateral Ligament Strain During Simulated Landings and Noncontact Tears. *Am. J. Sports Med.* **2019** 47, 1844–1853. https://doi.org/10.1177/0363546519850165
40. Markström, J.L.; Grinberg, Y.; Sole, G.; Häger, C.K. Strategies for knee stabilising and pivot-shift avoidance in a step-down and cross-over task observed sub-acutely after anterior cruciate ligament reconstruction. *Clin. Biomech*. **2024** 1, 115. https://doi.org/10.1016/j.clinbiomech.2024.106255
41. Bates, N.A.; Nesbitt, R.J.; Shearn, J.T.; Myer, G.D.; Hewett, T.E. The influence of internal and external tibial rotation offsets on knee joint and ligament biomechanics during simulated athletic tasks. *Clin. Biomech*. **2018** 1, 109-116
42. Hewett, T.E.; Torg, J.S.; Boden, B.P. 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. *Br. J. Sports Med*. **2009** 43, 417–422. https://doi.org/10.1136/bjsm.2009.059162
43. McBurnie, A.J.; Dos'Santos, T.; Jones, P.A. Biomechanical Associates of Performance and Knee Joint Loads During A 70-90˚Cutting90˚Cutting Maneuver in Subelite Soccer Players. *J. Strength. Cond. Res.* **2019** 35, 3190-3198. https://doi.org/10.1519/JSC.0000000000003252
44. Di Paolo S.; Grassi, A.; Tosarelli, F.; Crepaldi, M.; Bragonzoni, L.; Zaffagnini, S. et al. Two-Dimensional and Three-Dimensional Biomechanical Factors During 90° Change of Direction are Associated to Non-Contact ACL injury in Female Soccer Players. *Int J Sports Phys Ther*. **2023** 18, 887. https://doi.org/10.26603/001c.84308
45. Murphy, C; Landry, S.; Urquhart, N.; Coady, C.; Rutherford, D. Drop landing between subjects post anterior cruciate ligament reconstruction and uninjured controls: A biomechanical and neuromuscular analysis. . *Clin. Biomech*. **2025** 124. https://doi.org/10.1016/j.clinbiomech.2025.106504
46. Thomas, C.; Dos'Santos, T.; Comfort, P.; Jones, P.A Male and female soccer players exhibit different knee joint mechanics during pre-planned change of direction. *Sports Biomech.* **2024** 23, 118-131. https://doi.org/10.1016/j.clinbiomech.2025.106504