BIOMECHANICS AND JOINT COORDINATION IN ANTERIOR CRUCIATE LIGAMENT-INJURED FEMALE FOOTBALLERS DURING A 90° CHANGE OF DIRECTION

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The purpose of this study was to investigate the biomechanical predictors of Anterior Cruciate Ligament (ACL) injury in female football players by means of 3D motion capture with vector coding. Women's first-division healthy football players (n=16) performed a series of 90° change of directions. Biomechanics was collected through a marker-based optoelectronic system. In the next 2 consecutive football seasons, 4 ACL injuries were registered. Vector cording technique was used to compare angle-angle coordination between ACL-injured and non-injured players. ACL-injured players showed greater knee valgus (p=0.029) and internal rotation (p=0.017), external hip rotation (p=0.003), ankle eversion (p<0.001), and pelvic drop (p<0.001). Differences in angle-angle coordination were found on frontal and sagittal planes. The presented methodological approach can be used to get a deeper insight into ACL injury in primary prevention.

KEYWORDS: ACL, Biomechanics, Joint coordination, Women football, Injury prevention

INTRODUCTION: Women's football participation has progressively increased in the last years. Unfortunately, increasing rates and earlier occurrence of severe non-contact injury, such as Anterior Cruciate Ligament (ACL) rupture, have also been reported(Beck et al., 2017). Since a higher ACL injury risk has been reported in women with respect to their male counterparts, deeper comprehension of the ACL injury biomechanics has been advocated to target preventative interventions and mitigate the injury risk (Silvers & Mandelbaum, 2007; Silvers-Granelli, 2021).
Recent studies highlighted a series of ACL injury risk factors, underlining a complex full-body mechanism (Lucarno et al., 2021). Dedicated methodologies are therefore required to obtain objective measurements of players' movement quality and identify the ACL injury predictors. The 3D motion capture is the gold standard for biomechanical assessment of high-demanding tasks. Given the complex nature of the movements and the injury mechanisms under investigation, innovative comprehensive approaches, such as the vector coding technique, have been proposed to investigate intra- and inter-joint coordination and coordination variability alongside the 1D-biomechanics(Hamill et al., 2012; Weir et al., 2019). Joint coordination provides information on the relative movement of two body segments or of two anatomical planes of the same joint and can be used to determine the presence of "dangerous" or "efficient" biomechanical patterns (Hamill et al., 2012; Weir et al., 2019). These aspects are relevant to get new insights on players' motion during high-dynamics sport-specific tasks. Currently, no prospective studies investigated the ACL injury risk predictors through a coupled biomechanics/coordination approach in women's football. The purpose of this study was to investigate the biomechanical predictors of Anterior Cruciate Ligament (ACL) injury during a 90° change of direction (COD) task in a prospective cohort of young female football players by means of 3D motion capture and vector coding technique. The hypothesis was that, before ACL injury occurred, both biomechanical and coordination differences existed between ACL-injured and non-injured players.

METHODS: A cohort of players from a women's first-division football team (n=16) was enrolled in this prospective pilot study. At the time of the data collection, all the players were free from

musculoskeletal injury (median age 19.5 years, range 18-22). Every player performed a series of pre-planned 90° COD tasks at the maximum speed possible in a laboratory equipped with artificial turf. Each player performed a 5 minutes warm-up and a at least 2 unrecorded repetitions per leg to get confident with the environment. Three valid repetitions per leg were recorded. A sports physician specialized in orthopedic biomechanics instructed the players and checked the execution of each movement trial.
Players' biomechanics was collected through a set of 10 optoelectronic cameras (frame rate 120Hz) and 42 retroreflective markers (VICON Nexus, Vicon Motion Systems Ltd, Oxford, UK) placed according to the Plug-in-Gait protocol.
The markers' trajectories were digitally filtered using a fourth-order Butterworth filter in the VICON Nexus software environment. Full body kinematics was computed using a Cardan sequence of rotation (X-Y-Z) and imported for post-processing in Matlab (The MathWorks, Natick, US). The ultimate foot contact before the change of direction was isolated and the lower-limb 3D biomechanics was normalized over the stance phase (0-100%).
The players were prospectively followed in the next two consecutive football seasons. The ACL injuries that occurred during the seasons were registered. Overall, 4 out of 16 players (25%, all aged 18 years old) experience a complete ACL rupture with non-contact mechanism (i.e., no direct tackle from an opponent, according to Lucarno et al. (Lucarno et al., 2021)). All ACL injuries happened during regular football matches. The injury was confirmed both through MRI and clinical examination.
Coupling angles were derived according to McErlain-Naylor (McErlain-Naylor, 2020; Weir et al., 2019) using the vector cording technique with circular statistics. The following angle couples were investigated: hip flexion/knee flexion, hip rotation/knee flexion, knee varus-valgus/knee flexion, hip rotation/knee varus-valgus, knee varus-valgus/ankle inversion-eversion, and knee flexion/ankle flexion. Joint coordination and coordination variability were derived for each angle couple. The student's t-test ($p<0.05$) was used to compare continuous biomechanics, joint coordination, and coordination variability between the ACL-injured (ACL-injured leg) and non-injured (dominant leg) players through Statistical Parametric Mapping (SPM). The frequency of proximal/distal and in-phase/anti-phase coordination was also compared among the groups (Mann-Whitney U-test) for all the joint couples.

RESULTS: The ACL-injured players showed greater ($p<0.05$) knee valgus and knee internal rotation during the weight acceptance (first 25% of the stance phase), external hip rotation during the propulsion (70-90% of the stance phase), ankle eversion (from midstance to propulsion), and pelvic contralateral drop (entire stance phase). The time normalized waveforms with SPM significance were reported in Figure 1.

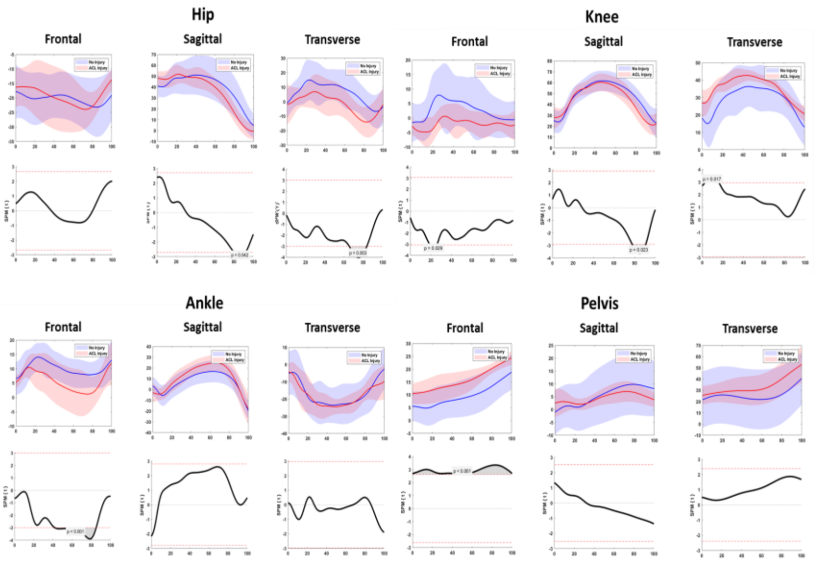

Figure 1: Hip, knee, ankle, and pelvis joint kinematics in the three anatomical planes for the ACL-injured (red) and non-injured (blue) players. SPM statistics (t-test) is reported below each graph.

Different coordination patterns were found both on the frontal and sagittal plane between ACL-injured and non-injured players (Table1).

Table 1: Coordination pattern frequencies between ACL-inured and non-injured players.

Joint couple	Pattern in ACL-injured players
Hip flexion / Knee flexion	Anti-phase distal (knee) dominance
Hip rotation / Knee flexion	In-phase distal dominance (hip external rotation + knee extension)
Hip rotation / Knee varus-valgus	Anti-phase (hip internal rotation + knee valgus)
Knee varus-valgus / Knee flexion	Anti-phase distal dominance (knee valgus during knee flexion)
Knee flexion / Ankle flexion	Distal (ankle) dominance
Knee varus-valgus / Ankle inversion-eversion	Distal (ankle) dominance

Knee dominance was noted in all the hip/knee couples on both the sagittal and frontal/transverse planes. Ankle distal dominance was also noted on both frontal and sagittal planes in knee/ankle couples. Anti-phase coordination was more frequent in ACL-injured players (Figure 2).
Moreover, the ACL-injured players showed lower coordination variability for all the joint couples ($p<0.001$).

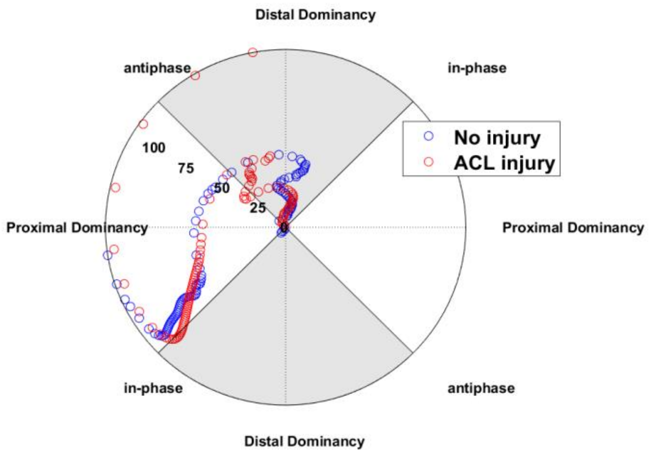

Figure 2: Hip flexion/Knee flexion average coupling angle. Example of difference in coordination pattern with greater anti-phase distal (knee) dominance in ACL-injured players.

DISCUSSION: The present prospective pilot study was the first to investigate the risk predictors for the ACL injury through a coupled biomechanics/coordination approach in a cohort of first-division women's football players. A significant difference between ACL injured and non-injured players emerged both in terms of continuous biomechanical data and coordination patterns.
Although the ACL-injured players were healthy at the time of the data collection, their biomechanics and coordination patterns were strongly consistent with the ACL injury mechanism underlined in a recent video-analysis study on elite female players(Lucarno et al., 2021). In the latter study, the injury mechanism reported was the following: knee dynamic valgus, hip internal rotation, limited hip and knee flexion, pelvis and trunk tilt, and foot eversion. Such a profile is thought to cause knee overloading and lead to ACL rupture(Lloyd, 2021). In the present study, many of these biomechanical predictors were found in the cohort of ACL-injured players: dynamic valgus was noted in the initial stance phase (weight acceptance),

limited hip and knee flexion was noted during the late stance phase (propulsion), and different pelvic strategy (greater contralateral drop) was found in the entire stance phase.
Furthermore, the analysis of coordination patterns underlined interesting aspects of the joint motion: knee valgus coupled with hip internal rotation and knee flexion, distal dominance between hip and knee and between knee and ankle, anti-phase coordination (Table 1). These aspects are, in part, in agreement with the aforementioned ACL injury predictors. Knee distal dominance is also thought to overload the knee as the principal mover in the hip-knee joint couple (Hamill et al., 2012; Weir et al., 2019). Joint coordination variability was also lower in all the joint couples in the ACL-injured players. A lower coordination variability has been proposed to increase the risk for both overuse and traumatic musculoskeletal injury (Hamill et al., 2012; Weir et al., 2019). The analysis of joint coordination is relatively new in the biomechanical assessment of severe non-contact injuries. Due to the novelty of the present analysis, the best practice for its application in this sports biomechanics area are yet to be identified. The joint coordination analysis allows to inspect the occurrence of multiple ACL injury predictors (e.g., knee valgus and limited knee flexion) during the motion without focusing on single risk factors alone, as recently suggested (Hamill et al., 2012; Weir et al., 2019). The aspects could improve the regular monitoring of football players in terms of primary ACL injury prevention.
The ACL-injured players in the present study's cohort were all 18 years old. Despite the small sample size of the investigated cohort, this data recalls the last evidence on the earlier occurrence of ACL injury in women's football, which is now among 15-19 years (Beck et al., 2017). Particular attention should be paid to the biomechanical risk factors for ACL injury in this high-risk population. Awareness should rise in women's football: methodological advancement could boost the comprehension of dangerous patterns and inform sports practitioners and ACL professionals on the preventative strategies.
In the present study, the adoption of a coupled biomechanics/coordination approach (through vector coding technique) offered precious predictive insights towards the non-contact ACL injury risk. Such an approach might increase the level of detail of players' quantitative assessment in light of the complex mechanisms below the severe non-contact injuries. Future investigations should provide evidence on wider prospective cohorts of female footballers and investigate high-demanding tasks in sport-specific environments to account for the influence of context-specific external stimuli.

CONCLUSION: The present study underlined differences in biomechanics and coordination patterns in a prospectively investigated cohort of female football players. A coupled biomechanics/coordination assessment was used to depict the predictors of the ACL injury. The sports practitioners and ACL professionals might benefit from this approach to better understand the biomechanical profiles of high-risk players. Increased awareness in the women's football community on the risks of severe non-contact injuries and the possible counteractions is strongly advisable. Broader adoption of instrumented evaluations and targeted training might help prevent or delay the occurrence of primary ACL injury in women's football.

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