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Evolution of Core Stability, Athletic Performance, and ACL Injury Risk across a Soccer Season

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Abstract: Soccer athletic performance varies across a soccer season due to training and fatigue. In addition, it is known that core stability is linked with anterior cruciate ligament (ACL) injury risk but their variations over a season are unknown. The aim of the study was to determine the evolution of core stability, athletic performance, and ACL injury risk among young high-level soccer players at four key moments of a season: pre-season (PRE), start of season (START), mid-season (MID), and the end of the season (END). Core stability scores increased until mid-season, while ACL injury risk scores (measured during sidestep cuttings and single-leg landing) decreased thanks to an injury prevention program between START and MID. These results are in line with the literature, which demonstrates that a high level of core stability is linked to a low injury risk. Evolution of athletic performance was not consistent throughout the season, being dependent on the specific phases of training performed by the athletes. Therefore, assessing core stability, athletic performance, and ACL injury risk multiple times across a soccer season could help coaches to adapt their training programs properly.

Keywords: trunk control; longitudinal study; field testing; training; soccer

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1. Introduction

Numerous injuries are associated with soccer practice, and are mostly located at the thigh, knee, and ankle levels [1–3]. Anterior cruciate ligament (ACL) injury is one of the most debilitating injuries in soccer, as it often requires surgery [1,4] with a mean time to return to play around 250 days for professional players [4]. Non-contact ACL ruptures (i.e., without the intervention of external constraints), representing between 45% and 65% of ACL injuries in soccer [4,5], mainly occur during single-leg landing and sidestep cutting [6–8]. Typical lower limb mechanisms that lead to ACL rupture are hip adduction and internal rotation combined with knee abduction and internal or external rotation [9,10]. Moreover, trunk control impacts ACL injury risk. Indeed, a larger trunk frontal plane ipsilateral inclination moves the center of mass, increasing knee abduction moment and, therefore, ACL injury risk [10]. Moreover, trunk sagittal and transversal rotations also impact knee joint loading during both landing and sidestep cutting [10–12]. Therefore, adequately regulating the trunk position during such tasks is crucial to limiting ACL injury risk [11–13]. This adequate trunk control refers to core stability and is defined as the ability to control the position and the motion of the trunk over the pelvis to allow an optimal transfer of forces to terminal segments [14]. In addition to this strong theoretical relationship with knee injuries, the actual association between core stability and ACL injury risk in soccer has been proven via the implementation of core stability training programs. Indeed, core stability training improved knee kinetics and kinematics during landing and sidestep cutting tasks [15–19]. Moreover, prevention programs (including core stability exercises) have successfully helped to reduce ACL injury for male and female soccer players [20–22]. The impact of core stability on soccer performance has also been demonstrated in the literature, as core stability training has been associated with improved shooting speed [23], sprinting time [23], cutting time [24], and jump performance [25–27] in soccer.

Meanwhile, these physical parameters evolve during the competitive season in various sports (e.g., handball, softball, or soccer) [25,28–31]. For instance, it has been reported that during the pre-season period, soccer players mainly train using low-intensity aerobic exercises to develop endurance capacity, with force and speed exercises to improve sprint and jump capacities [25,29–31]. Then, soccer players raise their athletic level throughout midseason, as evidenced by improvements in jump height, sprint times, and agility level [25,29–31]. Finally, in the second part of the season, semiprofessional soccer players are used to maintaining their athletic level, e.g., countermovement jump height, 15 m sprinting, and Illinois testing [25], after reducing high-intensity training and focusing on aerobic at low intensity in order to prevent fatigue. However, the evolution of the estimated ACL injury risk and core stability throughout the season is still unknown. Thus, investigating core stability evolution in comparison with performance and ACL injury risk over a full soccer season could bring new insights on the effect of regular training on these major aspects of soccer practice and lead to better physical and sport-specific conditioning programs and evaluation recommendations. Therefore, the aims of this study were (i) to understand the evolution of core stability, performance, and ACL injury risk across a soccer season and (ii) to determine the relationship between the evolution of core stability, performance, and ACL injury risk, respectively. Firstly, we hypothesized that core stability and performance would evolve in the same way and in opposition to ACL injury risk factors. Secondly, we hypothesized a positive correlation between the evolution of core stability and performance and a negative correlation between core stability and ACL injury risk factors.

2. Materials and Methods

2.1. Participants

The sample size was estimated based on a power analysis (GPower software, v3.1.9.7), using the effect sizes reported for injury risk [32] and athletic performance [32,33] measured after a training period (i.e., effect sizes of 1.95, 0.51, and 0.25 for dynamic knee valgus angle, sprinting time, and jump height, respectively). Therefore, for repeated measures ANOVA with 4 measurement times, at least 24 participants were needed to reach an effect size of 0.25 with a power of 80% and an alpha criterion of 0.05. To anticipate unavailability of players through the season, thirty-five soccer players were recruited for this study. They had six to eight training sessions per week and played in the U17 or U19 French national championships. All participants were healthy and had not suffered from any injury over the two months prior to the study. However, due to occurrence of injuries during the measurement period, some players missed one or more measurement sessions (Figure 1). The final results are presented on the 26 players (age 15.9 $\pm$ 0.2 years, height 174.5 $\pm$ 6.9 cm, body mass 63.0 $\pm$ 7.3 kg) that performed all measurement sessions. Prior to testing, all participants were informed about possible risks and gave written informed consent. The study was conducted in accordance with the Declaration of Helsinki and approved by the ethics committee Sud Mediterranee III (approval reference: 2018.07.03 bis).

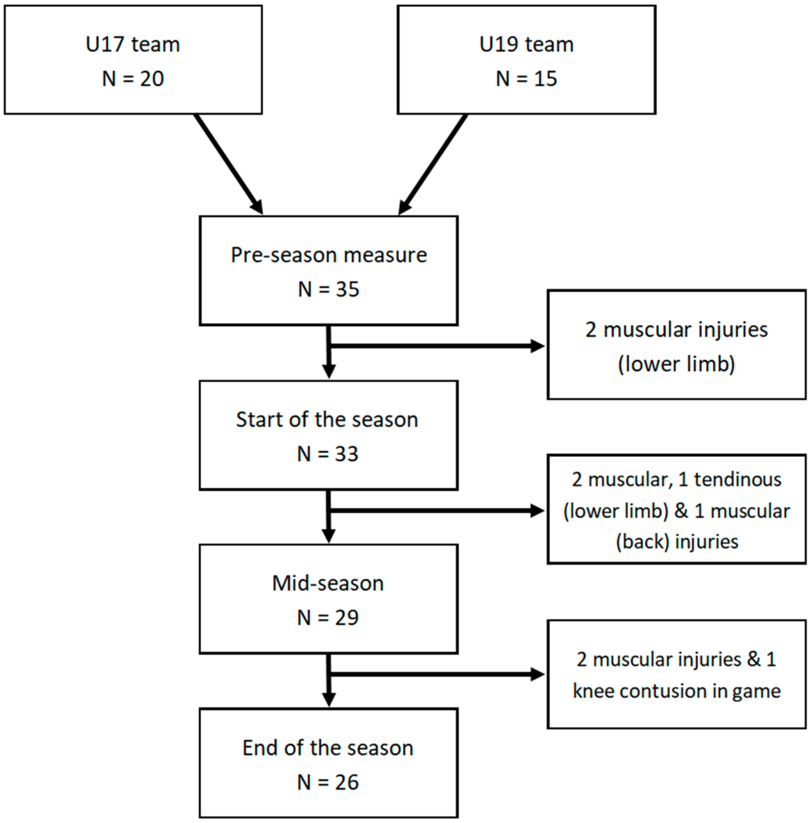

Figure 1. Flow chart of study population throughout all stages of the protocol.

2.2. Study Design

This longitudinal study was carried out during the 2022/2023 season with 4 measurement times: pre-season (PRE), start of the season (START), mid-season (MID), and end of the season (END). During the four weeks prior to the pre-season training, players had three to four training sessions per week. These were based on running exercises, going progressively from low pace to interval training. Pre-season training (PRE to START) lasted eight weeks and was based on general physical preparation with exercises to develop explosivity, speed, and strength capacities. After the start of the season, feedback about the injury risk of the players was provided to the physical trainer according to their evaluations. Therefore, between the start of season and mid-season (17 weeks), specific exercises focusing on muscles such as trunk external obliques and transverse, hip external rotators and knee abductors and on technical corrections during landing and cutting were added to the regular training program aiming at development of technique, tactical football skills, and force capacity. For the latter half of the season (MID-END; 19 weeks), physical training was orientated to limit accumulated fatigue with lighter physical training sessions, mostly based on bodyweight exercises. This training phase also considered mid-season evaluation feedback about the injury risk of the players.

2.3. Evaluations

The evaluations consisted of core stability including a close kinetic chain lower extremity stability test (CKCLEST), lower quarter Y-balance Test (LQ-YBT), and lateral step down (LSD), athletic performance tests, and injury screening, performed in a counter-balanced order.

Participants performed three evaluations of core stability. First, they underwent the CKCLEST developed by Arikan et al. [34] (Figure 2) to evaluate core strength and lower limb explosivity. The soccer player maintained a prone plank position on forearms, shoulder-width apart, with a 33 cm wide and 7.5 cm height box placed between the feet to settle the distance between them. From this position, the subject had to touch the ground in the outer side of one foot with the other, return to the initial position, and then repeat the same movement with the other foot. The instruction given to the participant was to perform maximum touches over 15 s. The testing protocol took inspiration from Degot et al. [35]. This exercise was repeated three times, with 45 s recovery between each set. In addition, the exercise was performed over 60 s to assess the endurance capacity in addition to core strength and lower limb explosivity. The corresponding endurance index was obtained via dividing half the number of touches over the last 30 s by the mean of the second and third sets of 15 s, multiplied by 100 [35].

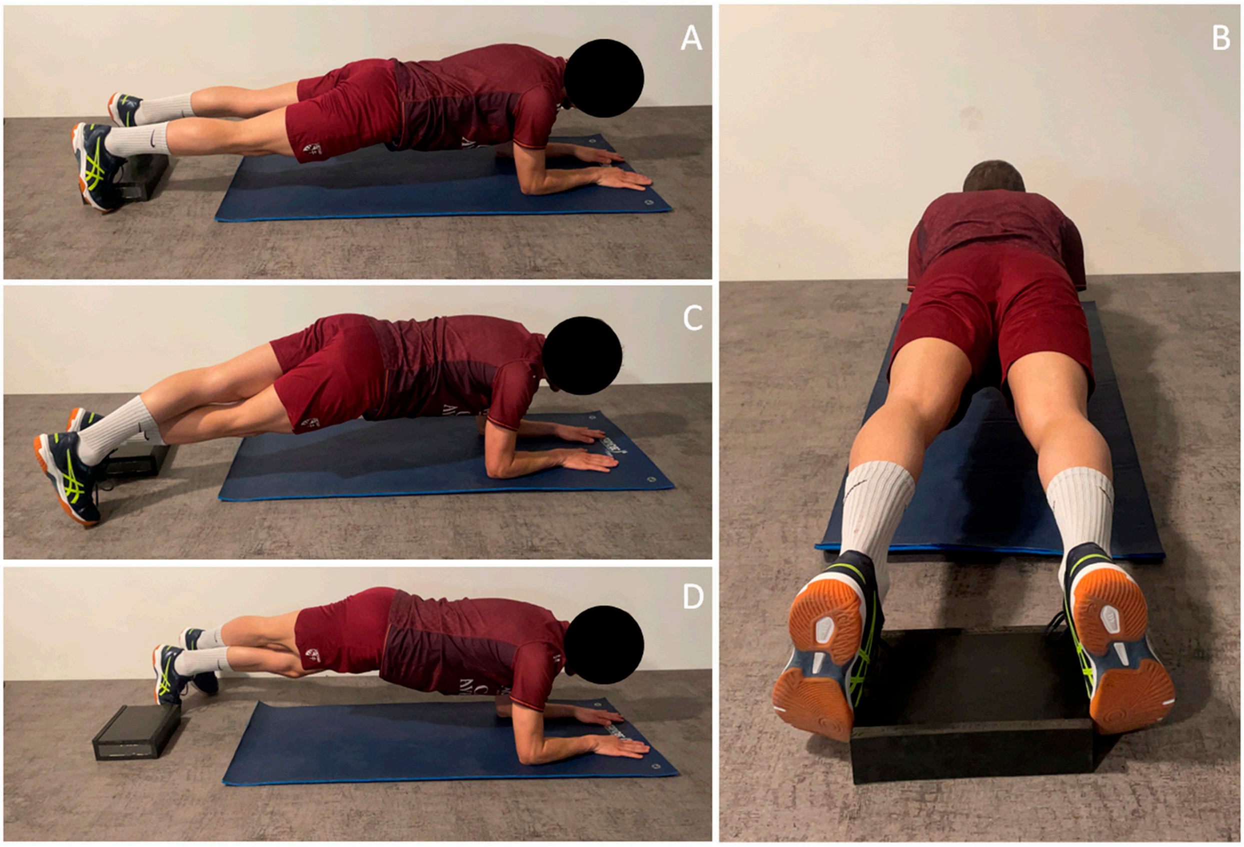

Figure 2. Close kinetic chain lower extremity stability test: lateral (**A**) and back (**B**) view of starting position and the two successive touching positions (**C**,**D**).

Then, the LQ-YBT was carried out on the dominant leg (i.e., the preferred leg for kicking a ball) to evaluate core motor control during a single-leg stance. Participants stood on their leg, barefoot (to remove any effect of shoe drop), with hands on the hips. The instruction was to move an indicator as far as possible with the free leg and come back to the starting position, along three axes: anterior, posteromedial, and posterolateral. An attempt was considered successful if (1) the foot did not touch the ground, (2) the indicator was pushed, not kicked, (3) hands did not move from the hips, and (4) the participant was able to return to the starting position. Participants performed three attempts per axis. The maximum reach, in centimeters, was registered and a composite score was computed by summing the three best distances divided by three times the leg length [36].

Finally, LSD was evaluated in order to assess pelvic motor control. Participants stood on their dominant leg on the lateral edge of a wooden box of 31 cm height with their arms crossed on their chest. They had to touch the ground with the heel of their free leg without weight transfer to the ground and return to the initial position. The instruction was to "touch the ground while trying to keep your pelvis straight". The test was performed five times and was captured using a camera (Hero 7, GoPro, San Mateo, CA, USA) at 120 Hz, placed 1.90 m in front of the subject. The scoring method for movement execution performance developed by De Blaiser et al. [37] was used to assess the movement with three criteria, i.e., dynamic balance, knee valgus/hip internal rotation, and pelvic control, ranging from 0 (lowest mark) to 3 (highest mark). The overall score was therefore on a 9-point scale.

Athletic performance was assessed through sprinting, jumping, and shooting performance. Sprinting performance was measured over a single 20 m-sprint [24,38]. Players started 1 m behind the start line and the time (seconds) was measured using two photoelectric cells (Witty, Microgate, Mahopac, NY, USA).

A countermovement jump (CMJ; three trials) was performed to evaluate jumping performance. Jump height was determined based on the flight time recorded on a force plate (AccuGait, Advanced Mechanical Technology Inc., Watertown, MA, USA) and served as a performance variable.

A test composed of a reactive sidestep cutting task and a shooting task was performed to evaluate soccer-specific performance. The experimental setup is illustrated in Figure A1. The player started with a 6 m acceleration run and crossed two photoelectric cells (Witty, Microgate, Mahopac, NY, USA) that triggered an arrow in front of him, indicating randomly the direction of the sidestep cutting (either left or right). After the cut, the player had to kick a ball placed on the penalty spot in one of the two 1 m areas next to each goal post. Ball speed, measured via radar (100 Hz, Stalker Acceleration Testing System, Stalker Sport, Richardson, TX, USA), and precision score (i.e., number of times the target was reached divided by the total number of shots) were used to assess performance. Participants performed six runs, with three cuts in each direction.

ACL injury risk was estimated during the aforementioned sidestep cutting task, as well as during landings. During the sidestep, two cameras (120 Hz, Hero 7, GoPro, San Mateo, CA, USA) were placed in the sagittal and frontal planes to assess the cutting maneuver assessment score (CMAS), evaluating the ACL injury risk [39,40].

A single-leg triple hop (TH; three trials) test was also used for ACL injury risk estimation. Participants realized the TH on the force plate while equipped with an inertial measurement unit (Ultium Motion, Noraxon, Scottsdale, AZ, USA) placed on C7 and T10 vertebrae, sacrum, thighs, and shin plates. Sampling frequencies were set at 1000 Hz for the force plate and 200 Hz for IMUs. Peak knee valgus and ipsilateral trunk flexion between initial contact and maximum knee flexion were measured during TH to estimate ACL injury risk [6].

Prior to each measurement session, a 15 min standard soccer warm up was conducted (joint mobilization, active stretching, cardiovascular activation) to ensure maximal performance during the evaluation. Also, before each test, a familiarization period was planned to avoid any learning effect.

2.4. Statistical Analysis

All variables were averaged across the trials for each participant. Normality of the data was controlled using the Shapiro–Wilk test. As most variables did not follow a normal distribution, results are presented as median and interquartile range. To evaluate differences between measurement times (PRE vs. START vs. MID vs. END) for core stability, performance, and injury risk parameters, Friedman analyses of variance were computed. In case of a significant main effect, a post hoc analysis was carried out using the Wilcoxon signed rank tests between the consecutive measurement sessions. A Bonferroni correction was adopted. In addition, the difference between two consecutive measurement times was computed for each variable to express its variation across the season. Spearman's correlations were computed to link core stability variations with performance and injury risk variations. Significant level was set at $p < 0.05$. Statistical analyses were performed with Rstudio software (version 4.3.2, Posit Software, PBC, Boston, MA, USA).

3. Results

Descriptive results with median and interquartile range are presented below for core stability (Figure 3), performance (Figure 4), and ACL injury risk tests (Figure 5).

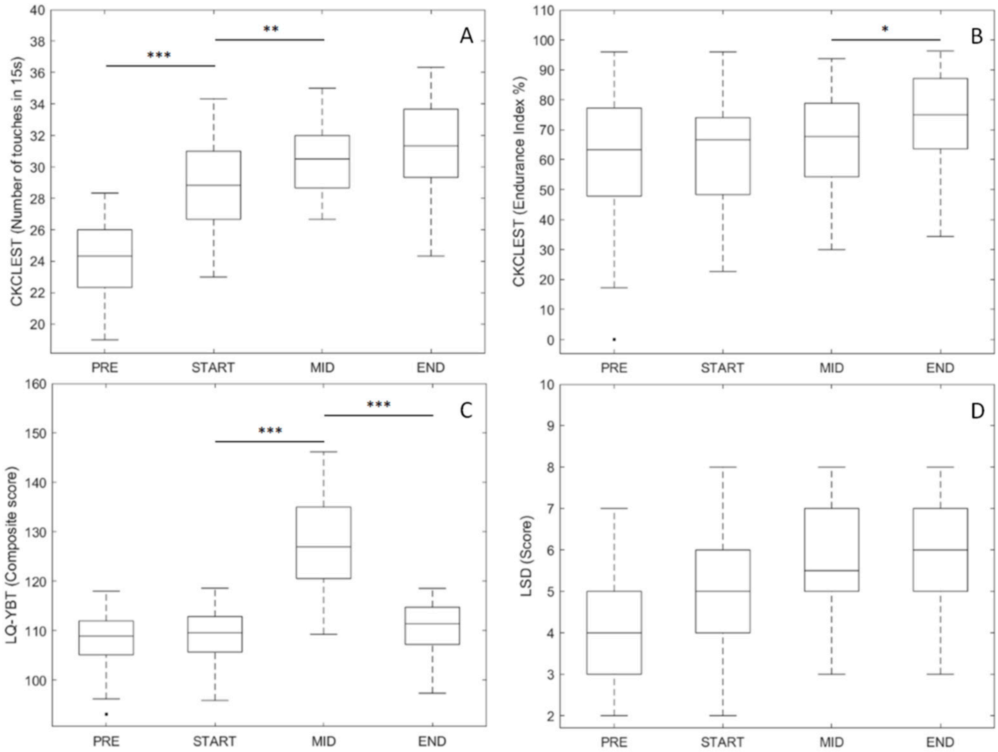

Figure 3. Boxplot of core stability test results at each measurement time representing (**A**) CKCLEST score for sets of 15 s, (**B**) CKCLEST endurance index, (**C**) LQ-YBT composite score, and (**D**) lateral step-down score. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$ indicate significant difference between two measurement times.

For core stability tests, a significant effect of the measurement time was found for the CKCLEST ($X^2(3) = 55.5$, $p < 0.001$). Pairwise comparison revealed a significant increase in touches between PRE and START ($p < 0.001$) and START and MID ($p = 0.003$). Moreover, the endurance index of the CKCLEST significantly evolved over the training season ($X^2(3) = 13.8$, $p = 0.003$). In particular, a significant increase in the endurance index was found between MID and END ($p = 0.044$). For the LQ-YBT, results indicated a significant difference over the season ($X^2(3) = 48.8$, $p < 0.001$). In particular, the LQ-YBT score was larger at MID compared with START and END ($p < 0.001$). No significant differences were found for the lateral step-down test.

A significant main effect was found for the 20 m sprint ($X^2(3) = 36.8$, $p < 0.001$). Pairwise comparison showed a significant reduced sprint time between PRE and START ($p < 0.001$) and an increased time between START and MID ($p < 0.001$). Jump height demonstrated a significant influence of the measurement time ($X^2(3) = 9.46$, $p = 0.024$). Indeed, post hoc analysis revealed a decrease in jump height between PRE and START ($p = 0.009$). Significant differences were also found for shooting speed and accuracy ($X^2(3) = 13.8$, $p = 0.003$ and $X^2(3) = 15.6$, $p = 0.001$, respectively). Speed was significantly lower at END compared to MID ($p = 0.031$) and accuracy was reduced during pre-season training ($p = 0.013$).

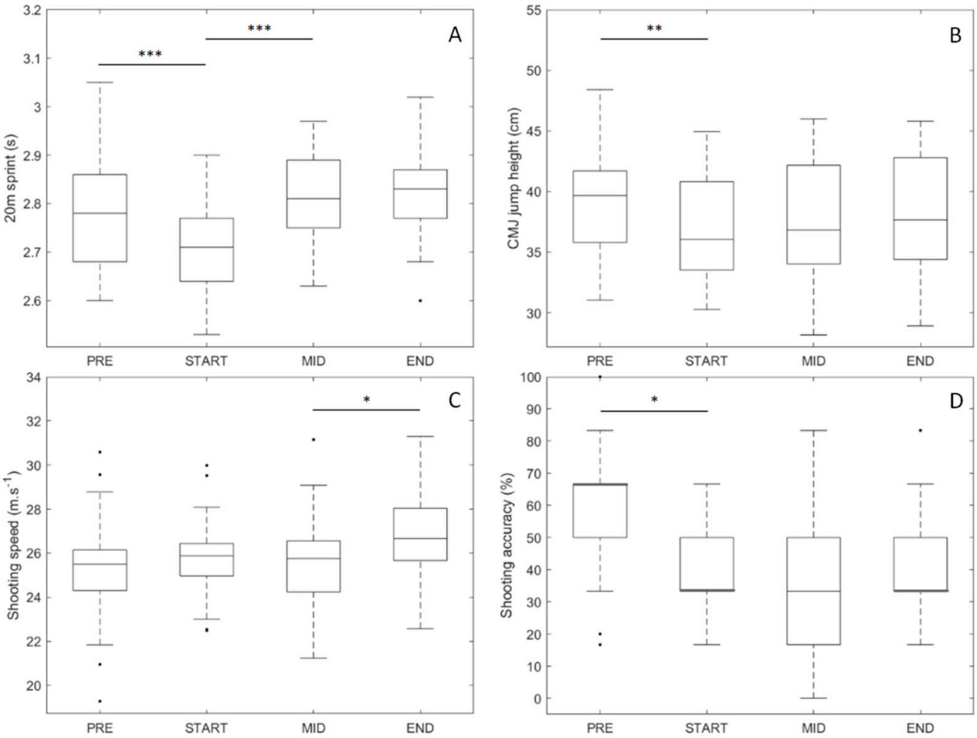

Figure 4. Boxplot of performance tests results at each measurement time representing (**A**) sprint time, (**B**) countermovement jump (CMJ) height, (**C**) shooting speed, and (**D**) shooting accuracy. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$ indicate significant difference between two measurement times.

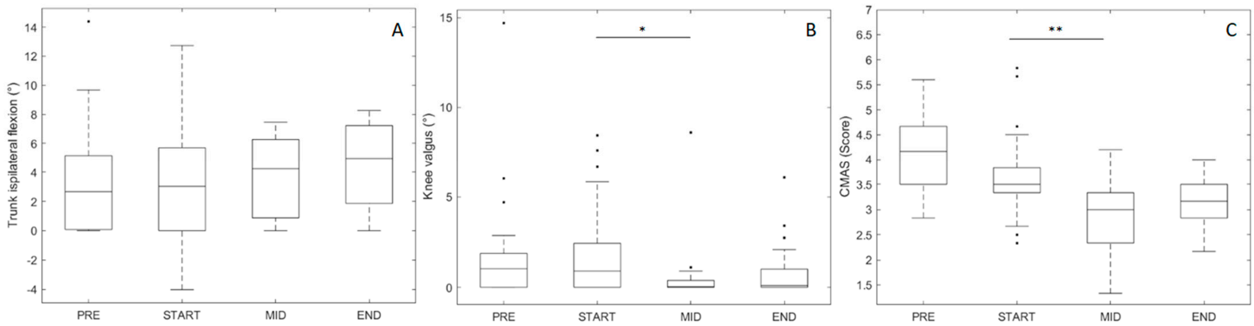

Figure 5. Boxplot of ACL injury risk test results at each measurement time representing (**A**) peak trunk ipsilateral flexion and (**B**) peak knee valgus during weight acceptance of triple hop (TH) and (**C**) CMAS score. * $p < 0.05$, ** $p < 0.01$ indicate significant difference between two measurement times.

Regarding ACL injury risk tests, a significant decrease in TH knee valgus ($X^2(3) = 11.0$, $p = 0.012$) and CMAS ($X^2(3) = 27.6$, $p < 0.001$) score was noted. Knee angle and CMAS score were significantly smaller between START and MID ($p = 0.013$ and $p = 0.004$, respectively). No differences between measurement times were found for TH trunk ipsilateral flexion.

No significant correlation was found between any core stability variations between measurement times and the respective variations in performance and injury risk variables.

4. Discussion

The aims of the present study were to determine the evolution of core stability, athletic level, and ACL injury risk over a complete soccer season and the relationships between their evolutions. The main findings were the improvement of core stability and decrease of ACL injury risk over time, especially when the prevention program was realized. No significant correlation was found between the evolution of core stability and performance or injury risk.

4.1. Effects of Soccer Training Program on Core Stability

The improvement of the CKCLEST score was in line with the training program that players carried out over the season. Indeed, CKCLEST performance depends on lower limb explosivity and core stability, which were part of the training, especially during the PRE to START phase. Then, during the first half of the season, due to the first matches and the prevention program, players strengthened their core and improved lower limb explosivity. This is likely to explain why core strength, expressed by CKCLEST score, improved until mid-season with the potential help of the prevention program. Afterwards, soccer players undertook less explosive training and more aerobic training, explaining why CKCLEST levelled off but potentially in favor of the endurance index improvement between MID and END. Regarding LQ-YBT, pre-season training did not impact the score, but the prevention program, established between START and MID, led to significantly better LQ-YBT performance. So, prevention training, mostly based on trunk and lower limb proprioception and on lower limb strength, influenced core stability. These results are in line with previous studies reporting greater performance in the LQ-YBT after 8 weeks of proprioceptive training [41,42] and core training [43]. However, unlike core strength and endurance, core motor control performance decreased between MID and END, which shows the importance of specific and regular training to maintain this capacity.

Contrary to Bagherian et al. [43], no significant evolution of the LSD score was observed. This difference might come from the specific core training protocol and/or from the constraints induced by the box height. Indeed, in their study, the box was 15 cm high while, in the present study, it was 31 cm high (based on De Blaiser et al. [37]), probably leading to higher constraints that could not be overpassed with classic in-season training. Overall, to evaluate core stability in football, CKCLEST and LQ-YBT seem to be the most suitable tests as they reflect the physical training throughout the full season. Lateral step down could be used as pre-season screening test to examine pelvic and knee control, and multiple testing throughout the season would therefore not be needed.

Overall, the core stability test performances, in particular for the CKCLEST and LQ-YBT, were improved through the soccer training because they were chosen to be as functional as possible for football. As recommended by Vera-Garcia et al. [44], the test battery had to be the most ecological in regard to the sport assessed.

4.2. Core Stability and Atheltic Performance

Athletic performance mainly evolved significantly during pre-season training with a decrease in jump height and shooting accuracy and an improvement of sprinting time. In line with previous studies [25,30,31], soccer pre-season training improved sprinting. However, contrary to those studies, CMJ height significantly decreased. One hypothesis explaining this decrease in performance could be the accumulation of fatigue during pre-season training with the intensity of the first "friendly" games, in line with the findings of Spyrou et al. [45] for futsal players.

During the first part of the season (i.e., from START to MID), higher sprint times were observed. Previous studies showed heterogenous results about sprint times in the same period. Caldwell et Peters [31] demonstrated that sprinting was improved by specific sprint training during the first part of the season, while, without specific sprinting training, Meckel et al. [30] observed a decrease in sprinting. Thus, our results are in line with the aforementioned research. With the start of the championship matches, field training was more based on technico–tactical aspects, strength development, and the prevention program. Consequently, sprint training was not as present as in pre-season training, leading to worse sprinting performance. In addition, this result supports the absence of correlation between core stability and sprinting performance. Indeed, improvement of core strength (measured by CKCLEST) from PRE to MID and motor control (measured by LQ-YBT) from START to MID did not help to maintain or improve sprint times. Interestingly, core stability (measured in laboratory settings) and performance, when studied regardless of their seasonal evolution, seemed to be correlated, as sprinting and jumping performances were associated with better core stability [46]. Therefore, specific core stability training would have been more likely to lead to correlation between the evolutions of the different factors [24].

Finally, during the latter half of the season, shooting speed was improved. This is a surprising result because we could hypothesize that due to the season fatigue, shooting speed would decrease. Indeed, during the second half of the season, fatigue has been reported to impact physiological parameters (e.g., VO_2) and neuromuscular performance [25,31]. This would also be in line Torreblanca-Martinez et al. [47], who reported a decrease in shooting speed right after a specific fatiguing task. However, our performance results did not indicate any potential fatigue, as our athletic measurements remained stable. Therefore, this fatigue hypothesis is not supported by our data.

4.3. Core Stability and Injury Risk

Between START and MID measurement times, the specific prevention training resulted in a significant reduction of the injury risk, (i.e., smaller knee valgus angles during landing and lower CMAS score), lasting until the end of the season. Some studies have already demonstrated this link with core training or global prevention programs (e.g., Fifa 11+) during similar at-risk tasks [17,22,48]. This reduced injury risk was supported by a significant increase in CKCLEST and LQ-YBT composite scores, ensuring the efficiency of the prevention training to positively impact core stability. Both core stability tests were theoretically linked to the movement that was assessed to determine injury risk during landing and sidestep cutting. Indeed, the CKCLEST involves a high level of trunk control with dynamic leg movements, and the LQ-YBT relies on trunk control during a single-leg stance [49]. However, no significant correlation was found between core stability and injury risk, despite the established relationship between core stability and ACL injury risk [17,22,48]. We could hypothesize that there was no evolution present for low-risk players (representing 34.5% of the players), which explained the absence of correlation. Indeed, our population had different levels of estimated risk of injury (i.e., low, moderate, and high risk), based on CMAS score for sidestep cutting and peak ipsilateral trunk flexion and knee valgus angle for landing. Therefore, low-risk athletes might not have had better scores during landing and sidestep cutting but could have increased their core stability, blurring potential correlations between factors. Furthermore, the prevention program's effects on ACL injury risk were maintained until the end of the season, suggesting that specific prevention training might not be needed throughout the full soccer season when prevention programs last at least four months [50].

5. Conclusions

In conclusion, this is the first study to compare the evolution of core stability, athletic performance, and injury risk along a complete season of high-level soccer. Two core stability tests (CKCLEST and LQ-YBT) reflected the evolution of the training during the season. In addition, the prevention training program conducted during the first half of the season probably improved core stability and helped reducing ACL injury risk by decreasing knee valgus and CMAS score, respectively, during landing and sidestepping. These results can be used to advise physical trainers, coaches, and athletes to choose adequate core stability tests to assess physical levels and underline that the benefits of the ACL injury risk prevention program can be evaluated through specific and functional tests. Future research must investigate these patterns of evolution among female, adult, and recreational soccer players.

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Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki and approved by the Sud Mediterranee III ethics committee (approval reference 2018.07.03 bis).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data that support the findings of this study are available from the corresponding author upon reasonable request.

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

Appendix A

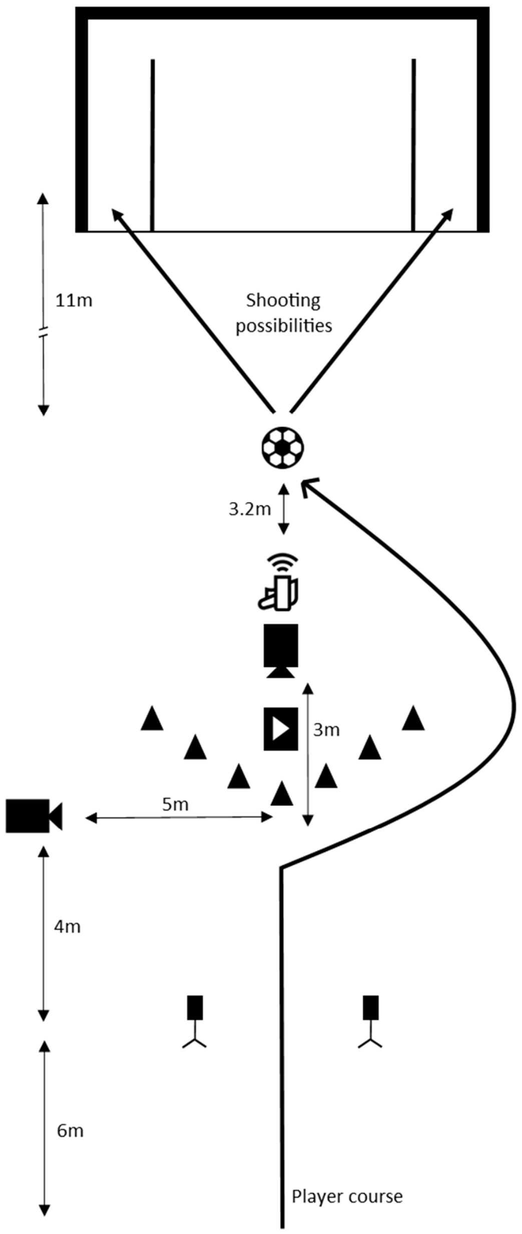

Figure A1. Diagram of the specific soccer test describing the player course, shooting possibilities, and hardware placement for measurement.

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