applied sciences

MDPI

Article

Influence of Dive Direction Uncertainty on Preparatory Posture, Coordination, and Kinematics in Elite Youth Goalkeepers

Salvatore Pinelli [1], Raffaele Zinno [2], Lorenzo Romano [1,*], Maria Scoppolini Massini [1], Giulio Senesi [1] and Laura Bragonzoni [1]

[1] Department for Life Quality Studies, University of Bologna, Corso D'Augusto 237, 47921 Rimini, Italy; salvatore.pinelli2@unibo.it (S.P.); maria.scoppolini2@unibo.it (M.S.M.); giulio.senesi2@unibo.it (G.S.); laura.bragonzoni4@unibo.it (L.B.)

[2] Department of Neuroscience and Rehabilitation, University of Ferrara, 44121 Ferrara, Italy; raffaele.zinno@unife.it

* Correspondence: lorenzo.romano12@unibo.it

Abstract

Soccer goalkeeper diving saves demand precise inter-segmental coordination to intercept shots under uncertainty, yet preparatory postures and kinematic adaptations between declared (D) and undeclared (ND) conditions remain underexplored in youth athletes. This study analyzed lower-limb kinematics and Continuous Relative Phase (CRP) in 10 elite youth male goalkeepers (14.3 ± 0.3 years) performing dives in different conditions using inertial sensors (Xsens MVN Awinda, 60 Hz) on a natural grass pitch. Data were time-normalized across the dive cycle and analyzed using Statistical Parametric Mapping 1D ANOVA to compare kinematic and coordination differences between conditions and preferred side. ND high dives showed significantly shorter total duration (1.02 ± 0.13 s vs. 1.09 ± 0.12 s) and take-off (0.19 ± 0.05 s vs. 0.21 ± 0.05 s) compared to the D condition. Pronounced laterality emerged in hip internal/external rotation (ipsilateral: 0–100%), with CRP alterations only in the ipsilateral ankle-hip/knee during preferred-side low dives (13–74%, $p < 0.001$), indicating tighter segmental coupling and reduced phase lag between joints from mid-stance to push-off. D condition appeared to favor mediolateral CoM shifts for reach optimization, while ND emphasized anteroposterior readiness. These findings highlight CRP's sensitivity to coordination under uncertainty and reveal laterality effects in preferred-side low dives.

Keywords: goalkeeping; continuous relative phase; inter-segmental coordination; diving performance; motor control; kinematic analysis; inertial sensors

1. Introduction

The soccer goalkeeper (GK) occupies a highly specialized position in soccer, demanding explosive whole-body actions in response to rapidly evolving game scenarios [1]. Consequently, GK should present unique physical, technical, and perceptual requirements that differentiate it from outfield players, with diving saves representing the most frequent and decisive defensive action, directly influencing match outcomes and talent identification [2].

The diving save constitutes a biomechanically intricate motor task, involving an explosive, multidirectional jump to intercept the ball within constrained reaction times. GK's require rapid force generation under uncertainty, particularly during multidirectional dives to intercept shots [3]. Elite GKs propel their center of mass (CoM) more directly and at higher velocities toward the ball compared to novices, prioritizing horizontal over

Check for updates

Received: 9 February 2026
Revised: 12 March 2026
Accepted: 16 March 2026
Published: 17 March 2026

vertical momentum for effective interception [1]. Moreover, success in diving saves relies on coordinated lower-limb push-offs. The contralateral leg (opposite the dive direction) generates predominant horizontal propulsion, while the ipsilateral leg facilitates initial stance widening and vertical adjustments to match ball height [1].

Previous biomechanical studies on GK dives were constrained by small samples, two-dimensional analyses, or laboratory setups limiting frontal-plane movements, thus compromising ecological validity [4]. Subsequent three-dimensional kinematic and inverse dynamics research revealed a proximal-to-distal, contralateral-to-ipsilateral sequencing of lower-limb joint powers, with contralateral hip extensors as primary contributors to CoM velocity [3]. Recent advances, including wearable sensors and principal component analysis, have enabled on-field assessments, highlighting side-specific asymmetries and the superiority of wider preparatory stances (75% leg length) for minimizing dive times and enhancing horizontal CoM trajectories [2].

Preparatory posture influences CoM projection over the base of support (BoS), directly affecting the direction and magnitude of subsequent ground reaction forces. In explosive sport tasks, anticipatory postural adjustments (APAs) reposition the center of pressure and modulate joint configuration prior to movement initiation, optimizing force vector alignment and dynamic stability [5–8]. APAs have been documented across a range of sport-like explosive actions, including cutting maneuvers in football, fencing lunges, and football kicks, where trunk orientation, stance width, and support-leg activity are organized in advance to enable rapid yet controlled CoM displacement. In these tasks, the CoM is typically projected centrally, or slightly toward the intended direction of movement, within the BoS, balancing postural stability with the need for rapid motion initiation [9–11].

Elite GKs naturally adopt a suboptimal narrow width stance (~33% leg length) and reduced hip/knee flexion (~63°). This yields slower dives than a wider stance (75% leg length), which optimizes contralateral push-off and reduces vertical CoM excursions [2]. Stance width of 75% positions the CoM forward (~75% foot length) and aligns ground reaction force vectors for efficient horizontal propulsion, minimizing countermovement in high dives and vertical velocity ranges in low dives [2].

Another key variable influencing dive performance is the uncertainty of ball direction. Experimental paradigms commonly distinguish between "declared (D)" condition, in which ball direction is known in advance and allows anticipatory motor planning, and "undeclared (ND)" condition, in which direction is revealed only at ball release, requiring real-time perceptual–motor adjustments. From a motor control perspective, D conditions primarily engage in feedforward control mechanisms and predictive internal models, enabling advanced organization of preparatory posture [12]. In contrast, the ND condition increases sensorimotor uncertainty and necessitates rapid movement decisions through perception–action coupling. Within ecological dynamics frameworks, ND conditions more closely simulate match realism by preserving informational uncertainty and constraining action through emergent affordances rather than pre-planned responses. Under uncertainty, coordination strategies may reorganize to balance stability and reaction time.

Therefore, comparing D and ND conditions provides insight into how GKs adapt lower-limb coordination and preparatory posture when shifting from predictive to more reactive control strategies, which is an ability that is critical for high-level defensive performance [13].

Investigating differences in terms of inter- and intra-limb coordination pattern between these conditions (D vs. ND) elucidates real-time motor control, informing targeted training to enhance CoM projection under uncertainty [1]. The Continuous Relative Phase (CRP), according to Dynamical Systems Theory (DST), serves as a variable for quantifying the human dynamic system and describing inter- and intra-limb coordination by measuring the phase space relation between two coupling segments as the movement evolves [14,15]. CRP provides a phase-based representation of coordination by combining position (displacement) and velocity data into a single measure [16].

Therefore, CRP is particularly suited for examining coordination under uncertainty, as it captures changes in phase stability, variability, and segmental coupling over time. Within coordination dynamics frameworks, stable movement patterns are often interpreted as attractor states, whereas shifts in phase relationships may reflect adaptive reorganization in response to task constraints. Under uncertain conditions, coordination may transition toward more flexible or metastable regimes, allowing rapid adjustments between functional movement solutions [17]. In this framework, skilled performance reflects an optimal stability–flexibility trade-off: robust attractor states support consistent execution, while sufficient functional variability enables adaptation to evolving constraints, such as uncertainty in dive direction. This adaptive capacity is supported by degeneracy, whereby multiple coordination patterns can achieve the same performance outcome [17–19].

Changes in CRP patterns therefore provide insight not only into kinematic differences, but also into how the motor system balances stability and flexibility to maintain performance under uncertainty [14].

For example, in jumping studies, CRP is extensively applied to analyze coordination, typically involving segments such as the thigh, shank, foot, and trunk, across various jump types like the squat jump and single-leg jump [14]. Furthermore, it is also used for its sensitivity to detect coordination changes induced by biological factors (e.g., pathology, age) and task factors (e.g., fatigue and jumping types) [14,20]. By analyzing changes in CRP between D (predictable) and ND (uncertain) conditions, the present study sheds light on how GKs modulate these dynamics to optimize diving movement.

The aim of this study was to evaluate the kinematic patterns of GK soccer players while performing different dive saves (high/low, preferred/ non-preferred) in different conditions (D/ND) in terms of CRP. We hypothesized that ND conditions will exhibit greater CRP (larger absolute deviation from 0°) reflecting more out-of-phase (less synchronized) coordination patterns between joints compared to D conditions.

2. Materials and Methods

2.1. Research Design

This study employed a within-subject experimental design with three experimental factors: dive height (high vs. low), side (preferred vs. non-preferred leg), and condition (D vs. ND). Each participant performed two trials per condition (2 heights $\times$ 2 sides $\times$ 2 conditions = 16 trials total), with trial order randomized across participants. The primary outcome measures included lower-limb kinematics, CRP between joints, and CoM projection onto the BoS.

2.2. Participants

This study involved 10 male GKs from an elite youth soccer team (Italian Primavera 2, season 2023/24) (14.3 $\pm$ 0.3 years old; 179.7 $\pm$ 6.5 cm height; 10 right leg dominance). The inclusion criteria required active involvement in soccer training, no history of lower-limb injuries or surgeries within the past six months, and a willingness to participate in all testing sessions. The exclusion criteria included any current injuries or conditions that could affect performance during the tests. Ethical approval was granted by the University of Bologna Bioethics Committee (protocol No. 0025861) in accordance with the principles of the Declaration of Helsinki. Since the participants were <18 years old, players' parents or legal guardians signed informed consent before enrolment. To maintain the subject's privacy, all data were anonymized before the analysis.

https://doi.org/10.3390/app16062879

2.3. Experimental Setup

The data collection was performed in a regular soccer goal (7.32 m × 2.44 m) on a natural grass soccer pitch. The tests were conducted on 17 June 2024, under stable environmental conditions. The mean ambient temperature was 21.0 °C (range: 13.3 °C to 28.5 °C), with a relative humidity of 74%. The weather was clear and sunny throughout the testing period.

Before the measurements, the participants completed a GK-specific warm-up routine with their coaches, including several diving saves to familiarize themselves with the experimental setup. Each participant was then instructed to perform dives in response to an acoustic stimulus, aiming to intercept balls shot by a cannon positioned at the penalty mark (ball shot at ~70 cm medially from the goal post, and ∼30 cm high for low balls and ∼190 cm high for high balls) [21]. The ball cannon was calibrated to ensure that the ball reached the target positions in approximately 1.2 ± 0.1 s, consistent with previous studies [1]. Calibration targeted standardized impact points, with minimal variability in final ball position [21].

2.4. Data Collection

Kinematic data were acquired at a sampling rate of 60 Hz using the MVN Awinda system (Xsens Technologies BV, Enschede, The Netherlands) featuring 17 inertial measurement units, a transmission pack, and a battery. Anthropometric measurements were incorporated to scale the proprietary biomechanical model within the Xsens Motion Tracking System, facilitating motion capture calibration via Xsens MVN Analyze software (version 2023.2). As documented in the literature, this sampling rate proved sufficient for high-dynamic tasks [22,23], including angular velocity estimation and CRP computation during continuous vertical jumps [24], or running analysis in ACL-reconstructed individuals [25]. Although the system has demonstrated fair to excellent accuracy in the sagittal plane, previous studies have also reported acceptable accuracy in the frontal plane for lower-limb joint angles during dynamic activities [26]. Specifically, concurrent validity has been confirmed for explosive tasks involving frontal/transverse plane demands, such as 90° changes of direction, using the Xsens MVN Awinda system at 60 Hz sampling [27]. The system demonstrated fair-to-excellent agreement for frontal plane kinematics (r = 0.55–0.96; CMC = 0.63–0.96) and transverse plane kinematics (r = 0.45–0.84; CMC = 0.59–0.90) [27].

2.5. Data Processing

All kinematic analyses were carried out using custom software in Python (Python Software Foundation; Python Language Reference, version 3.13.5).

An automated event-detection algorithm was developed to segment GK dive maneuvers from Xsens motion-capture data. The accuracy of the automated detections was subsequently verified through manual inspection performed by an experienced biomechanics researcher (S.P.). Using this algorithm, several key events were identified [4,28] and described as follows.

The preparatory posture was operationally defined as the static stance frame preceding any dives, in which the GK exhibited flexed hips and knees with the arms close to the body [29]. This frame was identified using a window-wise (10-frame) filtering approach that detected the period of minimal joint displacement across all joints. Within this window, the median frame was selected as the representative preparatory posture.

All kinematic events quantify the purely mechanical phase of the dive, deliberately excluding perceptual processing or unmeasurable reaction time components. The following key kinematic events were identified during dive execution (Figure 1). Ipsilateral foot toe-off (IF-TO) marked the start of the contralateral foot (CF) single support phase. Ipsilateral foot initial contact (IF-IC) corresponded to re-contact of the ipsilateral foot (IF) with the ground and the start of the IF stance phase. Contralateral foot toe-off (CF-TO) indicated the beginning of the push phase and single-leg support on the ipsilateral limb. Ipsilateral foot toe-off push-off (IF-TO push-off) represented the transition from the TO phase to the flight phase of the dive. Finally, fall was defined as the instant of pelvis sensor impact detection with the ground.

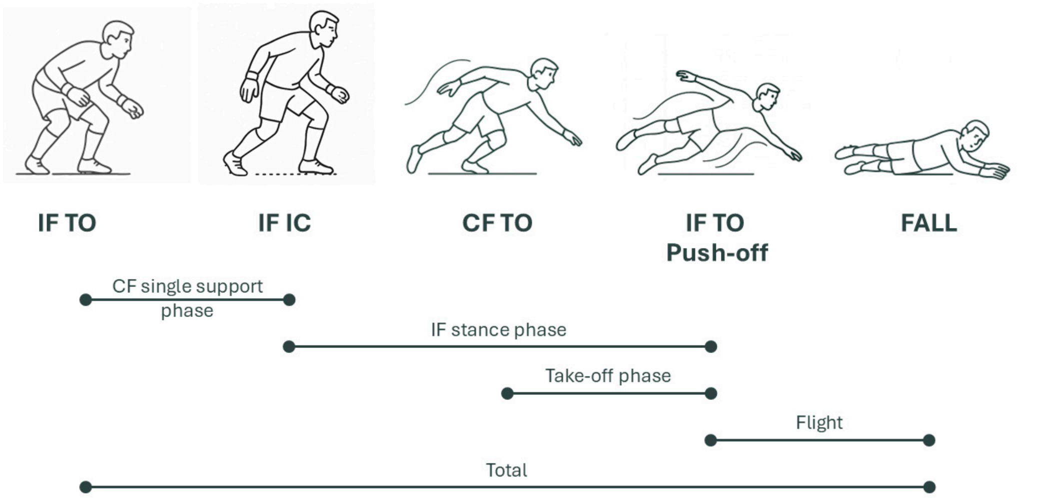


Figure 1. Schematic representation of the dive phase segmentation and the corresponding key events: Ipsilateral foot toe-off (IF-TO), ipsilateral foot initial contact (IF-IC), contralateral foot toe-off (CF-TO), ipsilateral foot toe-off push-off (IF-TO push-off), and Fall.

The preparatory posture event was used exclusively to compute parameters related to preparatory posture (i.e., BoS and CoM projection; see Section 2.5.2). Kinematic data were time-normalized from the final preparatory step (IF-TO, 0%) to the TO initiating the propulsive dive push-off (IF-TO push-off, 100%). Although dives represent discrete maneuvers, this interval captures repeatable intra-limb push-off coordination, suitable for dynamical systems analysis of non-cyclic movements [15].

2.5.1. Continuous Relative Phase Calculation

The CRP was derived from joint phase angles of the lower limbs, with phase information obtained by applying the Hilbert transform to the relevant time-series signals [30]. Specifically, only flexion-extension angles of the ankle, knee, and hip joints were considered for the coupling analysis [15]. The calculation involves determining the phase angle of each segment by the arctangent of the normalized angular displacement relative to its velocity, which indicates the state of that joint in a phase space [14]. Then, the CRP is calculated by subtracting the phase angle of the proximal segment from the distal segment.

Common calculation methodologies include those based on phase portraits and those utilizing the Hilbert transformation, the latter potentially providing a better fit for non-sinusoidal original data. Regarding interpretation, a value of 0° indicates an in-phase state, whereas 180° (or −180°) represents an anti-phase state; increasing distance from 0° signifies an out-of-phase change [14]. The CRP curve is a graphical tool where a positive (negative) slope suggests that the distal segment is leading (lagging) the proximal segment, enabling the analysis of synchronization and lead-lag relationships between joints over time.

2.5.2. Projection of the CoM on the BoS During Preparatory Posture

For Xsens data, MVN Studio recorded and stored all kinematic data in a proprietary file format (.mvn), which was subsequently exported into two file formats (.c3d and .mvnx). Foot position data were extracted from the .c3d files. For each landmark, three-dimensional coordinates were acquired, but only the positions of four-foot landmarks were used in the present analysis: pLeftToe, pLeftHeelFoot, pRightToe, and pRightHeelFoot. The quadrilateral defined by these landmarks was used to approximate the BoS, following the procedure described by Guo et al. [31] for Xsens-based BoS estimation. In particular, the present task mainly involves static or near-static positions, which fall within the conditions under which Xsens-based BoS estimates have been shown to exhibit acceptable accuracy.

The whole-body CoM position was obtained from the .mvnx files provided by the Xsens biomechanical model. For each trial, the CoM projection on the BoS was computed for the preparatory posture frame. The data were normalized relative to the CoM position as follows: the mediolateral (ML) score ranged from −1 (CoM fully over the contralateral foot) to +1 (CoM fully over the ipsilateral foot), while the anteroposterior (AP) score ranged from −1 (heels) to +1 (toes) (Figure 2).

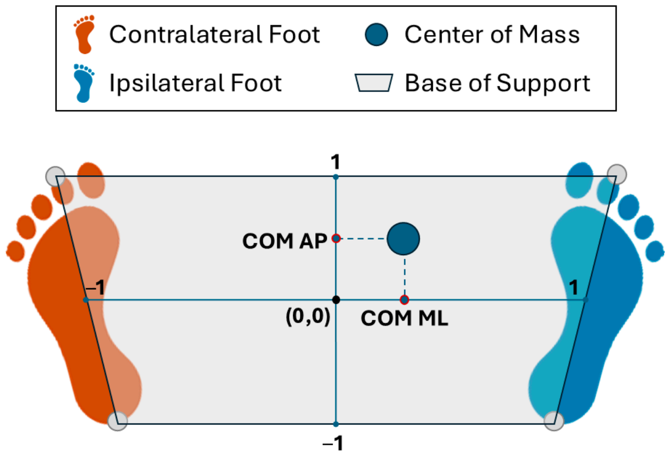


Figure 2. Schematic representation of the base of support (BoS) approximation (quadrilateral formed by ipsilateral and contralateral foot landmarks) and the projection of the center of mass (CoM) onto the BoS in the anteroposterior (AP) and mediolateral (ML) directions during the preparatory posture. The origin (0, 0) corresponds to the BoS centroid.

2.6. Statistical Analysis

Continuous variables were reported as mean and standard deviation. All statistical analyses were performed using Python 3.13.5 (Python Software Foundation) with NumPy 2.1.3, SciPy 1.15.3, Pandas 2.2.3, spm1d 0.4.53, power1d 0.1.15, and statsmodels 0.14.4. Results were considered statistically significant a priori at $p < 0.05$. Discrete variables were analyzed using linear mixed-effects models, whereas time-continuous kinematic variables were analyzed using Statistical Parametric Mapping (SPM1D). The specific statistical procedures applied to each outcome are detailed in the following subsections.

2.6.1. Time Performance

Diving time and sub-phases were compared between conditions (D vs. ND) using separate linear mixed models for high and low dives, estimated via restricted maximum likelihood (REML), with participant as a random effect to account for repeated measures. Model explanatory power was quantified using marginal R^2 (variance explained by fixed effects) and conditional R^2 (variance explained by fixed + random effects) [32]. These metrics assess overall model fit and the relative contribution of predictors versus the participant-specific random intercept [33]. Effect sizes were classified as trivial (<0.05), small (0.05–0.13), medium (0.13–0.26), or large (>0.26) [34].

2.6.2. Projection of the CoM on the BoS During Preparatory Posture

The position of the CoM in the ML and AP planes, alongside foot distance (% leg length), was analyzed using a linear mixed model (participant as random effect) to assess differences between conditions (D vs. ND).

2.6.3. Lower Limb Kinematics

Continuous kinematic variables (joint angles and lower-limb CRP) were analyzed using SPM1D, based on Random Field Theory as described by Pataky et al. [35]. To account for the repeated-measures design, a two-level hierarchical random-effects approach was implemented. [36,37]. At the first level, trial-level data for each participant were averaged within each condition and variable to obtain representative within-subject means, reducing intra-subject variability. At the second level, these within-subject means were used to perform group-level ANOVAs to assess differences across conditions (D vs. ND) and sides (preferred vs. non-preferred).

Pairwise comparisons between conditions were conducted using Student's *t*-tests with Bonferroni correction for multiple comparisons. Post hoc power analysis was conducted using Power1D [38] to evaluate sensitivity for observed effects. Variables with a mean power $\geq$0.80 across significant clusters were retained for reporting and interpretation, whereas underpowered variables (<0.80) were not reported.

3. Results

Of the 160 dives recorded across all participants, 154 trials (96.25%) were retained for kinematic analysis following data quality checks, while six trials (1 D, 5 ND) were excluded due to motion capture artifacts (e.g., sensor signal dropout or incomplete recordings that prevented reliable event detection).

3.1. Time Performance

Linear mixed models revealed distinct condition-specific effects on dive kinematics between D and ND conditions (Tables 1 and 2).

For high dives, ND conditions demonstrated consistently shorter durations across propulsion and aerial phases compared to D conditions. Total dive duration was significantly reduced (β = −0.067 s, p = 0.011, R^2_m = 0.15), alongside shorter flight time (β = −0.044 s, p = 0.032, R^2_m = 0.18) and TO phase (β = −0.022 s, p = 0.035, R^2_m = 0.07).

For low dives, the ND condition required prolonged preparatory phases, with significantly longer CF single support (β = +0.036 s, p = 0.020, R^2_m = 0.18) and shorter IF stance duration (β = −0.056 s, p = 0.003, R^2_m = 0.11) compared to D.

Table 1. Duration (mean ± SD, in seconds) of dive performance phases across conditions (Declared and Undeclared) and dive height (High, Low).

Condition	High/Low Dive	CF Single Support	IF Stance	Take Off	Flight Time	Total Duration	Time to CoM Peak Velocity
D	High	0.22 ± 0.06	0.33 ± 0.06	0.21 ± 0.05	0.54 ± 0.10	1.09 ± 0.12	0.52 ± 0.11
	Low	0.22 ± 0.06	0.31 ± 0.09	0.18 ± 0.09	0.28 ± 0.11	0.81 ± 0.15	0.56 ± 0.10
ND	High	0.22 ± 0.07	0.31 ± 0.05	0.19 ± 0.05	0.50 ± 0.10	1.02 ± 0.13	0.51 ± 0.11
	Low	0.26 ± 0.09	0.26 ± 0.08	0.15 ± 0.06	0.30 ± 0.12	0.81 ± 0.16	0.53 ± 0.13

Note: Acronymous: Declared (D), Undeclared (ND), Contralateral Foot (CF), Ipsilateral Foot (IF), Center of Mass (CoM).

https://doi.org/10.3390/app16062879

Table 2. Linear mixed model results comparing dive conditions (Declared vs. Undeclared) separately for high and low heights.

High/Low Dive	Phase	β	SE	*p*-Value	R^2_m	R^2_c
High	CF single support	−0.001	0.011	0.925	0.26	0.60
	If Stance	−0.022	0.012	0.068	0.14	0.33
	Take Off	−0.022	0.011	0.035 *	0.07	0.13
	Flight Time	−0.044	0.021	0.032 *	0.18	0.39
	Total Duration	−0.067	0.026	0.011 *	0.15	0.31
	Time to CoM peak velocity	−0.023	0.017	0.169	0.33	0.72
Low	CF single support	0.036	0.016	0.020 *	0.18	0.40
	If Stance	−0.056	0.019	0.003 **	0.11	0.15
	Take Off	−0.027	0.016	0.091	0.13	0.30
	Flight Time	0.025	0.020	0.216	0.24	0.53
	Total Duration	0.002	0.031	0.949	0.13	0.34
	Time to CoM peak velocity	−0.027	0.021	0.197	0.20	0.46

Note: β represents the difference (negative values indicate shorter ND durations), SE represents the standard error, *p*-values: * $p < 0.05$, ** $p < 0.01$, $R^2_{m/c}$: marginal (fixed effects) and conditional (fixed + random effects) variance explained. Acronymous: Declared (D), Undeclared (ND), Contralateral Foot (CF), Ipsilateral Foot (IF), Center of Mass (CoM).

3.2. Projection of the CoM on the BoS During Preparatory Posture

As presented in Table 3, results revealed a highly significant main effect of condition on CoM 2D position in the ML direction (β = −0.057, SE = 0.017, $p = 0.001$; R^2m = 0.13, R^2c = 0.26), but not in the AP direction (β = 0.040, SE = 0.026, $p = 0.130$; R^2m = 0.41, R^2c = 0.86). No statistical differences were observed between groups for foot distance normalized to leg length (β = −0.189, SE = 1.220, $p = 0.877$; R^2m = 0.36, R^2c = 0.78).

Table 3. Linear mixed model results comparing dive conditions (Declared vs. Undeclared).

CoM Position	β	SE	*p*-Value	R^2_m	R^2_c
ML	−0.057	0.017	0.001 **	0.13	0.26
AP	0.040	0.026	0.130	0.41	0.86
Foot distance (% leg length)	−0.189	1.220	0.877	0.36	0.78

Note: β represents the difference (negative values indicate shorter ND durations), SE represents the standard error, *p*-values: ** $p < 0.01$, $R^2_{m/c}$: marginal (fixed effects) and conditional (fixed + random effects) variance explained. Acronymous: Center of Mass (CoM), Mediolateral (ML), Anteroposterior (AP).

In D condition, the CoM was positioned more laterally toward the ipsilateral limb, whereas ND condition showed more centered ML positioning but greater anterior projection (Table 4 and Figure 3).

Table 4. Posture parameters for Declared and Undeclared conditions.

Condition	ML Position	AP Position	Foot Distance (% Leg Length)
D	0.08 ± 0.12	0.18 ± 0.33	63.90 ± 12.78
ND	0.02 ± 0.10	0.23 ± 0.32	63.45 ± 12.01

Acronymous: Medio-Lateral (ML), Anterio-Posterior (AP), Declared (D), Undeclared (ND).

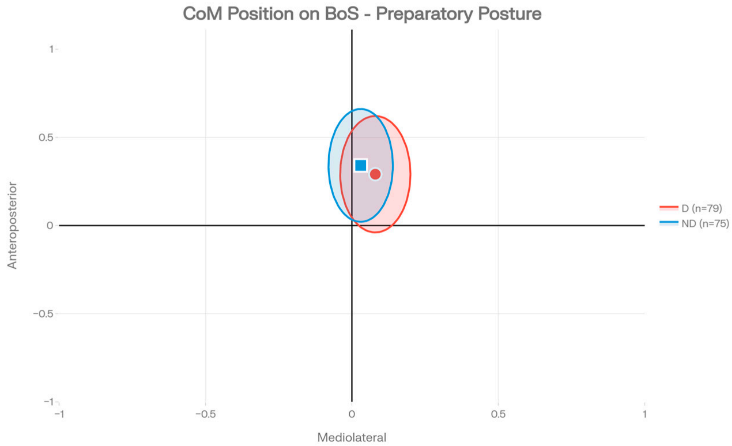


Figure 3. Mean (±1 SD, ellipse) center of mass position on the base of support during preparatory posture by player condition (Declared, [red circle, n = 79]; Undeclared, [blue square, n = 75]). Mediolateral axis: −1 = contralateral foot, +1 = ipsilateral foot; Anteroposterior axis: −1 = heels, +1 = toes.

3.3. Lower Limb Kinematics

3.3.1. Joint Angle

SPM1D analysis revealed significant kinematic alterations during both High and Low Dive conditions (Table 5, Appendix A.3). In High Dive (Appendix A.1), ipsilateral Hip Internal/External Rotation exhibited differences across the entire movement cycle (0–100%), with consistent post hoc differences between Preferred vs. Non-Preferred sides, D vs. ND conditions. Specifically, NP side dives maintained approximately 10° of ipsilateral hip external rotation throughout the cycle, whereas P dives began internally rotated, peaked near neutral at IF-TO, and concluded with slight external rotation (~5°) during push-off.

Ipsilateral Knee Abduction/Adduction showed differences during early loading (0–18%) and late push-off (57–80%, near CF-TO). Contralaterally, Ankle Abduction/Adduction exhibited prolonged differences from mid-stance to push-off completion (52–100%, spanning IF-IC to final IF-TO).

In Low Dive, ipsilateral Hip Internal/External Rotation remained significantly altered nearly full cycle (0–94%), with extensive group differences. Contralateral Knee Abduction/Adduction displayed the most prolonged differences (0–43%, through IF-IC). Hip movements consistently showed significant dual regions across limbs and conditions.

In summary, consistent kinematic patterns emerged across dive heights, with pronounced differences in hip internal/external rotation (ipsilateral: High 0–100%, Low 0–94%; contralateral: High 0–34; 63–100%, Low 0–23; 61–93%).

Table 5. SPM1D results summary for joint kinematics during High and Low dives. Only variables with significant ANOVA results ($p < 0.05$) and post hoc power > 0.8 are shown. Significant clusters are reported as time intervals (% movement cycle) with minimum p-value in parentheses.

High /Low Dive	Limb	Joint	Movement	ANOVA	P ND vs. NP ND	P D vs. NP D	P D vs. P ND	NP D vs. NP ND	Power
High	I	Hip	Int/Ext Rot	0–100% ***	0–30% **	0–81% ***	40–85% ***	-	0.98
	C	Knee	Ab/Ad	0–16% **	6% *	0–4% **	-	-	0.82
		Ankle	Ab/Ad	52–100% ***	59–85% ***	57–99% ***	-	-	0.97
Low	I	Hip	Int/Ext Rot	0–94% ***	0–36% ***	3–87% ***	-	-	0.99
	C	Knee	Ab/Ad	0–43% ***	-	17–32% ***	-	-	0.86

Acronymous: Ipsilateral limb (I), Contralateral limb (C), Preferred side (P), Non-Preferred side (NP), Declared test (D), Undeclared test (ND), Abduction (Ab), Adduction (Ad), Internal (Int), External (Ext), Rotation (Rot), Flexion (Flex), Extension (Ext). Note: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

3.3.2. Continuous Relative Phase

SPM1D analysis revealed significant CRP alterations exclusively in the ipsilateral limb during Low Dive conditions ($p < 0.05$). Ankle-Hip CRP showed early (15–19%) and more extended mid-to-late differences (41–73%), complemented by P D vs. P ND differences (47–72%), as shown in Figure 4A. Ankle-Knee CRP differed across mid-movement (13–74%), with P D vs. P ND significance during late mid-stance to early push-off (41–69%), as shown in Figure 4B. Notably, NP side dives exhibited similar CRP trajectories between D and ND tests, while P side dives showed greater divergence between D vs. ND conditions. No significant differences were observed in contralateral CRP or High Dive values (see Table 6).

Table 6. SPM1D results summary for CRP during Low Dives. Only ipsilateral limb CRP variables showed significant ANOVA results (low dive only). Significant clusters are reported as time intervals (% movement cycle) with minimum *p*-value in parentheses.

CRP	ANOVA	P ND vs. NP ND	P D vs. NP D	P D vs. P ND	NP D vs. NP ND	Power
Ankle-Knee	13–74% ***	-	-	41–69% ***	-	0.87
Ankle-Hip	15–19% * 41–73% ***	-	-	47–72% ***	-	0.90

Acronymous: Preferred side (P), Non-Preferred side (NP), Declared test (D), Undeclared test (ND). Note: * $p < 0.05$, *** $p < 0.001$.

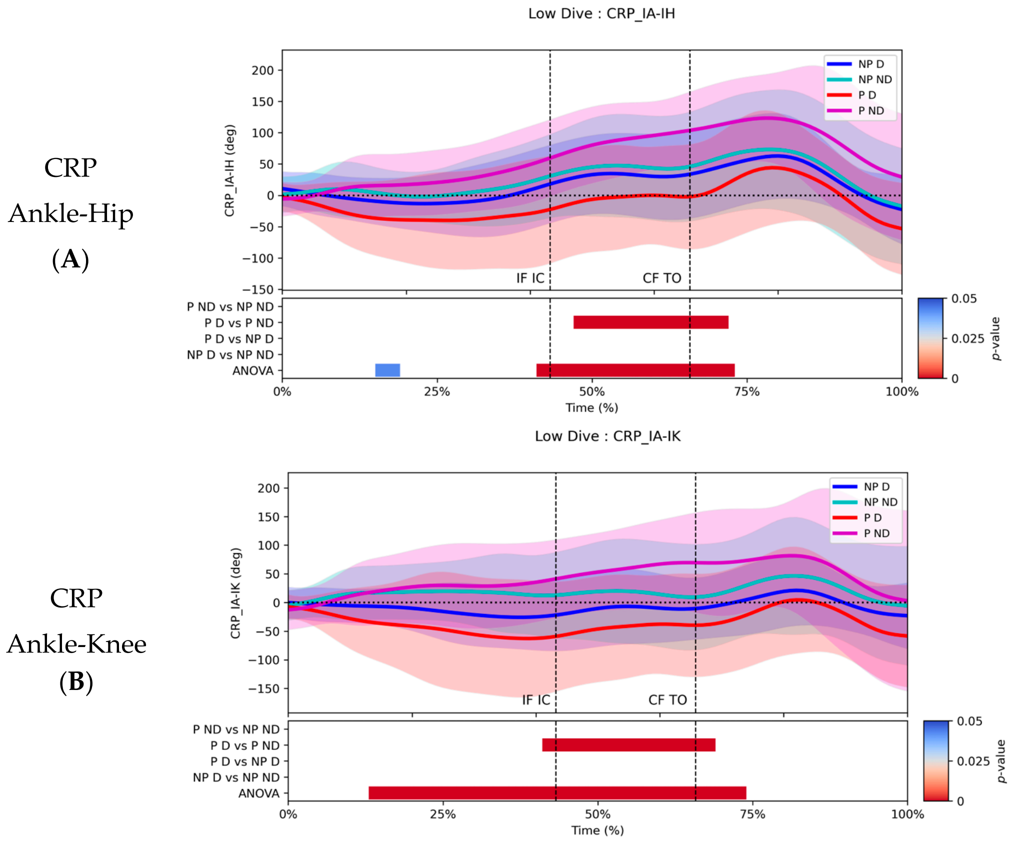


Figure 4. CRP time-series and SPM1D results. (**A**) CRP between the ipsilateral ankle (IA) and the ipsilateral knee (IK); (**B**) CRP between the ipsilateral ankle (IA) and the ipsilateral hip (IH). Shaded areas represent standard deviation (SD). Vertical lines indicate key events: Ipsilateral Foot-Initial Contact (IF-IC) and Contralateral Foot-Toe Off (CF-TO). Significant SPM1D ANOVA clusters ($p < 0.05$) are highlighted based on *p*-values from ANOVA and post hoc pairwise comparisons. Acronymous: Preferred side (P), Non-Preferred side (NP), Declared test (D), Undeclared test (ND).

4. Discussion

The main objective of the present study was to analyze the kinematic patterns in GK's diving saves in different conditions in terms of CRP. Our hypothesis, that ND conditions would exhibit greater CRP (larger absolute deviations from 0), was partially supported. Indeed, significant CRP differences emerged exclusively in the ipsilateral limb during low dives on the preferred side, reflecting less distal-proximal synchrony mid-stance to push-off. No contralateral or high-dive CRP effects were observed. These results showed laterality-driven differences in lower-limb kinematics during both high and low dives, in D and ND conditions, which may critically influence the ability to prevent goals in match scenarios.

4.1. Time Performance

Counterintuitive results emerged when examining movement timing. Despite having prior information about the ball direction, GKs showed longer movement initiation times in the D condition compared to the ND one. Rather than indicating poorer performance, this pattern may reflect a strategic modulation of movement execution. In the D condition, greater confidence in reaching the ball may enable a more pronounced initial ML weight shift toward the target side, prioritizing reach maximization over minimizing execution speed [39].

Importantly, movement initiation was defined as IF-TO, representing the first kinematic evidence of dive commitment based on an acceleration threshold. Total duration quantified only the mechanical phase from IF-TO to GKs ground impact, excluding perceptual processing and reaction time components.

Instead, the longer execution times observed in the D condition likely reflect task-specific motor strategy adaptations, whereby GKs reorganize preparatory posture and movement amplitude to optimize spatial coverage. All dives were performed under standardized conditions, with the ball shot from a calibrated cannon at consistent speed, height, and lateral placement, ensuring that observed differences in movement patterns, such as preferred-side dives or movement initiation duration, reflect strategy and coordination rather than variability in ball trajectory. However, the protocol of the present study did not assess dive success (i.e., saving the goal by touching the ball). Thus, it remains unclear how these kinematic patterns, such as preferred-side dives or movement initiation duration, relate to actual save performance.

4.2. Projection of the CoM on the BoS During Preparatory Posture

The preparatory posture adopted by GKs was analyzed through the projection of the CoM onto the BoS at the frame immediately preceding dive initiation. In dives with D shot direction, the CoM projection tended to shift laterally toward the side of the upcoming ball. This finding reflects GK's prior knowledge of the ball's direction, allowing an anticipatory weight transfer toward the target side as part of early movement preparation.

A distinct pattern emerged in the ND conditions, where GKs had no prior indication of dive direction. In this condition, the CoM projection was more oriented along the AP axis, shifting forward toward the toes, indicating a different preparatory stance associated with greater weight distribution toward the forefoot. These CoM adjustments may reflect structural postural anticipation strategies specific to informational constraints, consistent with larger displacements under unpredictable perturbations [40].

Stance configuration and CoM control are critical determinants of dive performance. Ibrahim et al. (2019) [2] reported that an optimal stance width of 75% leg length reduced CoM vertical countermovement. Moreover, knee angle adjustments alter movement time and CoM vertical trajectory, thereby indirectly influencing AP CoM projection during the preparatory-to-flight transition. Building on this, future studies may demonstrate that anterior foot positioning enhances dive performance by allowing GKs to initiate movement more effectively, resulting in faster and longer dives.

4.3. Lower Limb Kinematics

4.3.1. Joint Angle

The kinematic asymmetries observed during high and low dive maneuvers in youth elite GKs confirmed that the preferred side is a dominant variable influencing lower limb coordination patterns [28]. Ipsilateral hip internal/external rotation exhibited pronounced differences across the full movement cycle (high dive: 0–100%; low dive: 0–94%), characterized by sustained external rotation (~10°) on the non-preferred side, contrasting with initial internal rotation, neutral positioning at IF-TO, and slight external rotation (~5°) during push-off on the preferred side. Similar task-specific alterations emerged in ipsilateral knee and hip Abduction/Adduction (early loading: 0–18%; late push-off: 57–80%) and contralateral ankle Abduction/Adduction (prolonged from mid-stance to 100%, spanning IF-IC to final IF-TO). These patterns are similar to the findings by Di Paolo et al. [28], who reported preferential asymmetries in hip-trunk and knee kinematics among academy GKs, with greater ipsilateral hip internal rotation at dive initiation and contralateral external rotation/valgus, implicating the ipsilateral limb in directional control and the contralateral in propulsion.

The dominance of laterality observed in the present study aligns with broader evidence from athletic populations, although transferability must be interpreted in light of sport-specific task constraints. Kozinc and Šarabon [41] demonstrated superior dynamic balance on the preferred leg in highly trained tennis players, evidenced by reduced center-of-pressure velocity and amplitude during landing. Similarly, Leung et al. [42] observed task-specific outperformance of the self-selected dominant leg in youth hop tests, highlighting kinematic asymmetries in power output. Moreover, in Taekwondo athletes, Huang et al. [43] identified significant bilateral differences in hip/knee flexion moments, angular velocities, and foot velocity during sidekicks, confirming laterality's impact on sport-specific performance.

Despite these parallels, the mechanical demands underlying laterality differ substantially across sports. For example, in tennis, performance is characterized by rapid, short-distance adjustments, repeated deceleration–acceleration phases, and reactive postural control, with propulsion typically occurring over limited horizontal displacement [44]. In contrast, GK dives require explosive lateral push-off, substantial horizontal ground reaction force generation, and whole-body displacement toward the ball within a single high-intensity action [1].

From a task-constraint perspective, while laterality in Tennis and Taekwondo may primarily optimize precision, timing, and repeated reactive efficiency during complex, multi-trial movement patterns requiring rapid directional changes [41,43]. In GKs, it appears to influence inter-limb coordination strategies specifically for explosive lateral propulsion and whole-body displacement during single, high-intensity dive actions. Thus, although the underlying neuromuscular principle of limb dominance is common, the functional expression of asymmetry is sport-specific.

Collectively, the full-cycle hip rotation disparities (bilateral) and prolonged contralateral knee alterations (low dive: 0–43%) observed in our data reflect these small-to-medium effect sizes, with implications for optimizing training protocols and mitigating injury risk in asymmetrical sports tasks.

https://doi.org/10.3390/app16062879

4.3.2. Continuous Relative Phase

Analysis of differences between conditions showed the biggest changes in CRP metrics, with only small kinematic differences. This highlights how analytical choices can substantially influence performance interpretation, as different computational models may produce divergent outcomes even when applied to similar explosive lower-limb tasks [45]. Specifically, differences were observed between the ipsilateral ankle and hip, as well as the ipsilateral ankle and knee, when comparing D and ND conditions in low dives. No significant difference occurred in the high dive analysis. During the low dive on the preferred side, the ankle–hip and ankle–knee complexes exhibited an in-phase relationship, indicating tighter segmental coupling and reduced phase lag between joints. Consequently, GKs showed modified intersegmental coordination of these complexes, particularly between the instants of IF-IC and CF-TO. This pattern may represent a more constrained coordination strategy, potentially reducing degrees of freedom to stabilize movement during critical transition phases. This key event corresponds to the transition from the contralateral single-support phase to the ipsilateral stance phase and the subsequent take-off. Increased in-phase coupling may enhance stability but could simultaneously limit coordination flexibility, reflecting a trade-off between robustness and adaptability.

Our findings align with and extend the literature by demonstrating CRP's sensitivity to coordination deficits in GKs during similar dynamic transitions. In fact, Chardonnens et al. (2013) [46] used CRP to describe lower-limb coordination during ski jumping take-off, revealing that longer jumps featured greater shank leading relative to thighs and more symmetrical thigh–sacrum patterns. Similarly, Lukšys et al. (2021) [47] investigated coordination patterns across different gait phases in individuals with Parkinson's disease and healthy controls. The study found CRP more suitable for assessing disease severity than for distinguishing patients from healthy controls. As far as the authors are aware, this represents the first investigation employing wearable technology to analyze CRP during a complex, sport-specific movement.

4.4. Limitations and Future Research

The present study has several limitations. A primary constraint is the small sample size of 10 male participants, which, although consistent with existing literature [2,48,49], limits the generalizability of the results to female GKs. Using the Xsens MVN Awinda offers acceptable sagittal accuracy but may lead to errors in the frontal plane during dynamic dives, with moderate reliability. In addition, the relatively low sampling frequency (60 Hz) may be suboptimal for capturing the high-velocity and explosive characteristics of GK diving. Moreover, all participants were right-leg-dominant, limiting generalizability to other dominance profiles. This homogeneity constrains the interpretation of laterality effects, as preferred versus non-preferred differences may partly reflect structural dominance rather than sport-specific adaptations. Therefore, the observed asymmetries cannot be assumed to generalize to left-leg-dominant GKs or represent universal coordination strategies. The ball cannon setup, although standardized, fails to replicate factors such as different types of shots, fatigue, and pitch conditions encountered during real matches, thereby reducing ecological validity.

Future research could explore several directions. It could incorporate plantar pressure insoles to assess weight distribution and center-of-pressure variations. Analyses could extend to full-body kinematics and electromyography for muscle activation patterns. Machine learning could predict dive success under D versus ND conditions. Sample sizes could expand to include left-footed participants, females, and athletes across diverse ages and competitive categories.

5. Conclusions

In conclusion, this study identifies dive height, side preference, and shot uncertainty as key variables influencing GK dive kinematics. Distinct coordination strategies emerged between D and ND conditions in both high and low dives, influencing lower-limb kinematic symmetry and preparatory CoM position. Laterality effects in lower-limb coordination, along with CRP inter-segmental changes observed during low dives on the preferred side, suggest the presence of side-specific biomechanical strategies. However, given the limited sample size and the absence of direct performance outcomes, these findings should be interpreted as descriptive of coordination patterns rather than indicative of functional advantages or deficits.

Author Contributions: Conceptualization, S.P., R.Z. and L.B.; methodology, S.P.; software, S.P.; validation, R.Z. and L.R.; data curation, S.P.; writing—original draft preparation, S.P. and L.R.; writing—review and editing, G.S., M.S.M. and L.B.; visualization, S.P.; supervision, L.B.; project administration, L.B. All authors have read and agreed to the published version of the manuscript.

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 Ethics Committee of the University of Bologna Bioethics Committee (protocol No. 0025861) for studies involving humans.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study. Since the study participants were minors, the consent form was signed by their parents or legal guardians.

Data Availability Statement: The data are available upon reasonable request.

Acknowledgments: The authors would like to thank Alessandro Colombo and Daniele Airoldi for their contribution to the study.

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

Abbreviations

The following abbreviations are used in this manuscript:

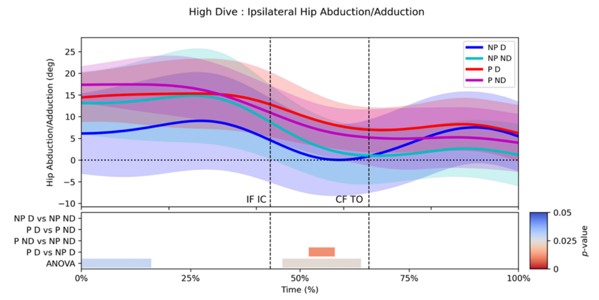
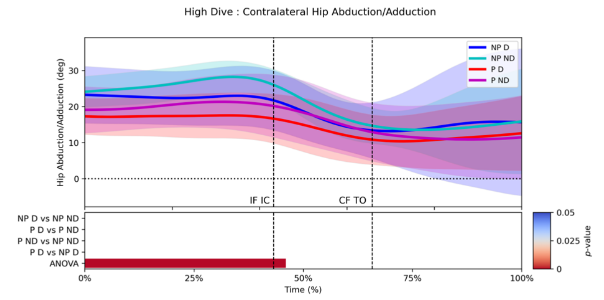
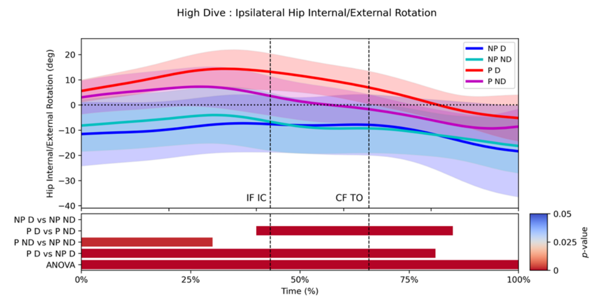
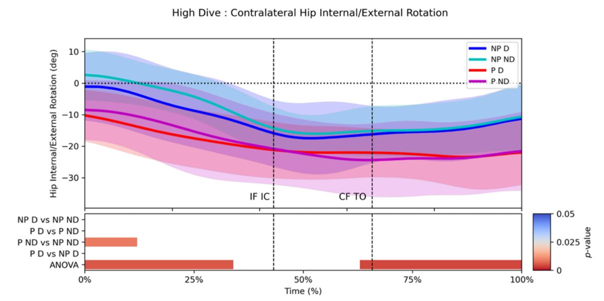
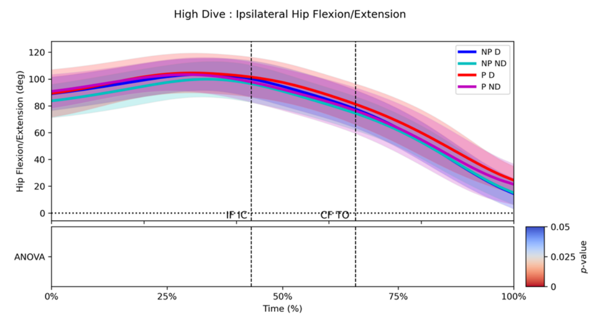
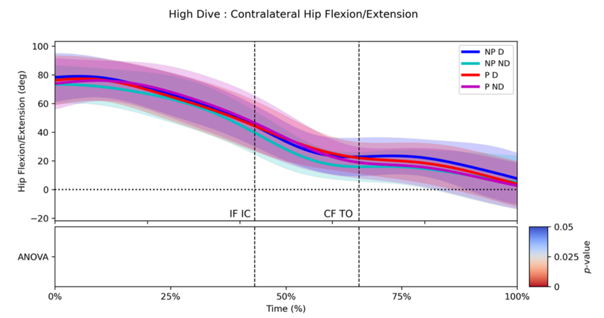
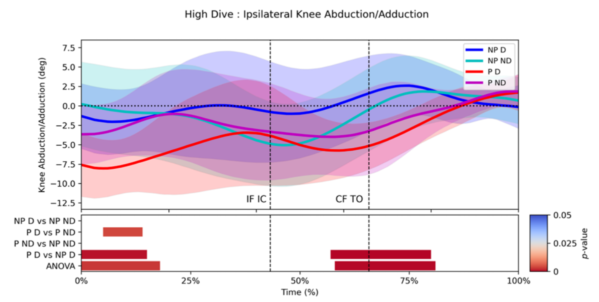
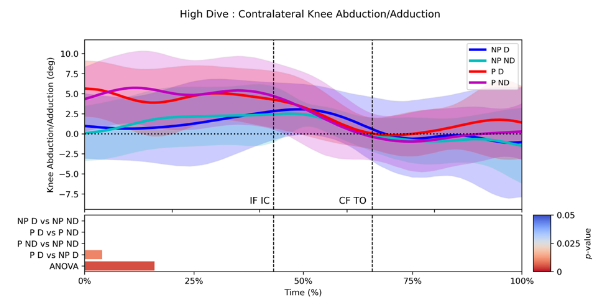
GK	Goalkeeper
CoM	Center of Mass
CRP	Continuous Relative Phase
D	Declared
ND	Undeclared
P	Preferred side
NP	Non-preferred side
IF	Ipsilateral Foot
TO	Toe-Off
IC	Initial Contact
CF	Contralateral Foot
BoS	Base of Support
ML	Mediolateral
AP	Anteroposterior
SPM1D	Statistical Parametric Mapping 1D

Appendix A

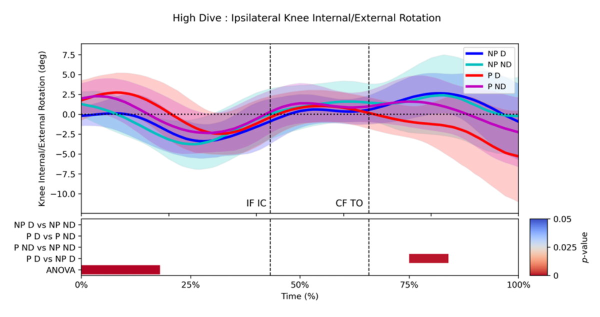
Appendix A.1. High Dive SPM1D Comparison Kinematics

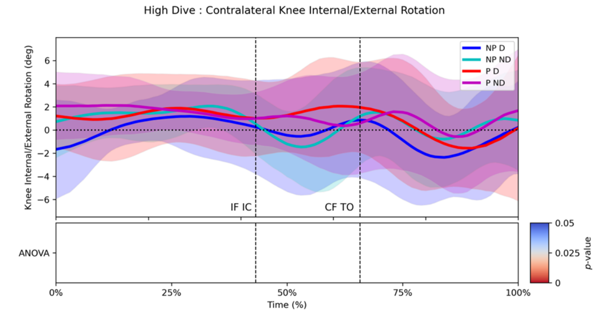
Comprehensive SPM1D analysis of kinematics time-series for all lower-limb joint angles during high dives.

The following abbreviations are used: Ab/Ad = Abduction/Adduction, Flex/Ext = Flexion/Extension, Int/Ext = Internal/External rotation. Positive values indicate abduction, flexion, or internal rotation movements, whereas negative values correspond to adduction, extension, or external rotation. A value of zero represents the neutral anatomical position. SPM1D ANOVA clusters ($p < 0.05$) are highlighted, with p-values derived from ANOVA and Bonferroni-corrected post hoc t-tests indicating specific temporal differences. Acronymous: Preferred side (P), Non-Preferred side (NP), Declared test (D), Undeclared test (ND).

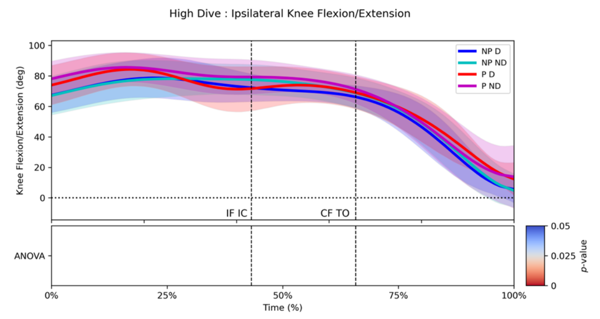
	Ipsilateral	Contralateral
Hip Ab/Ad		
Hip Int/ext		
Hip flex/ext		
Knee Ab/Ad		

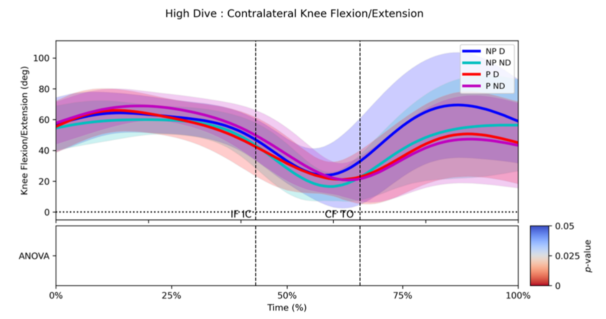
Knee Int/ext



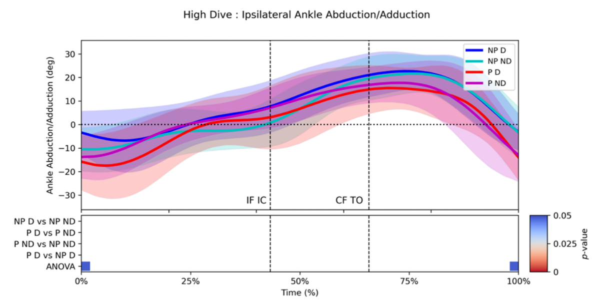


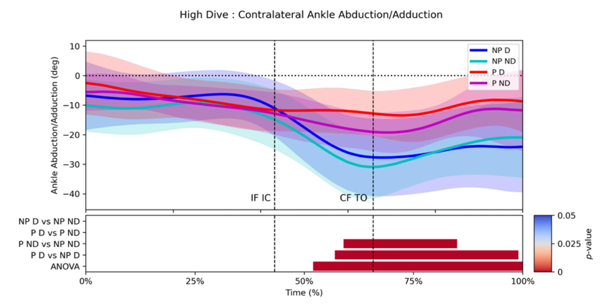
Knee flex/ext



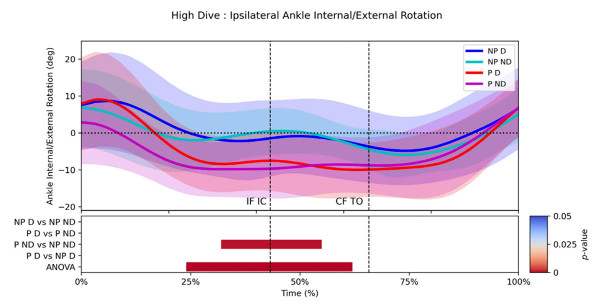


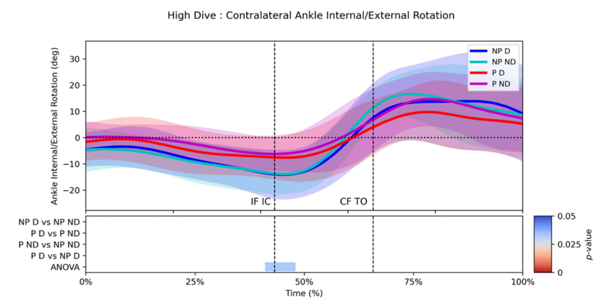
Ankle Ab/Ad



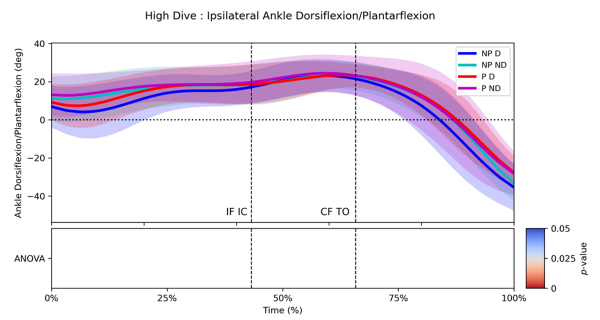


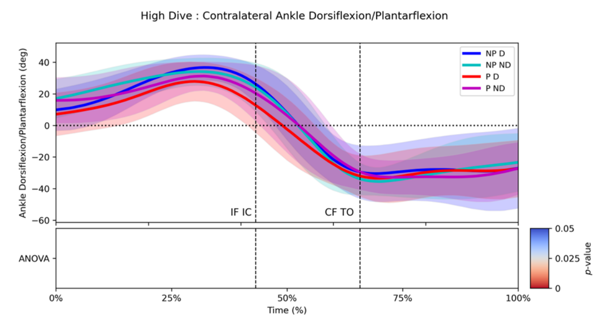
Ankle Int/ext





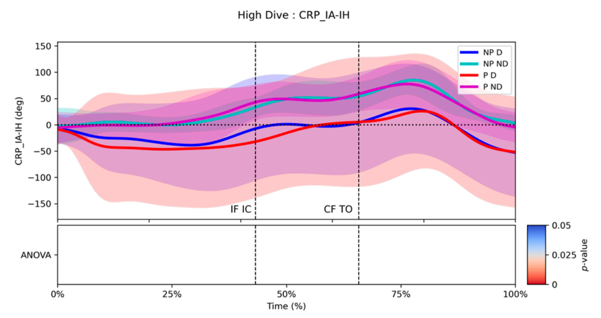
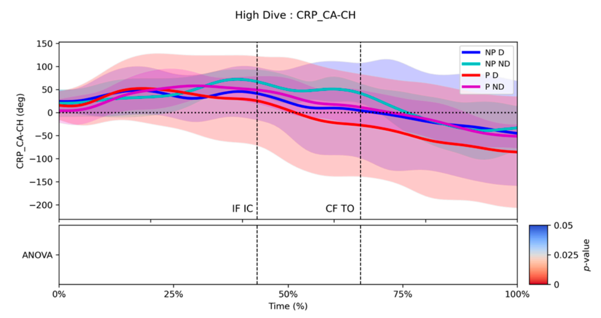
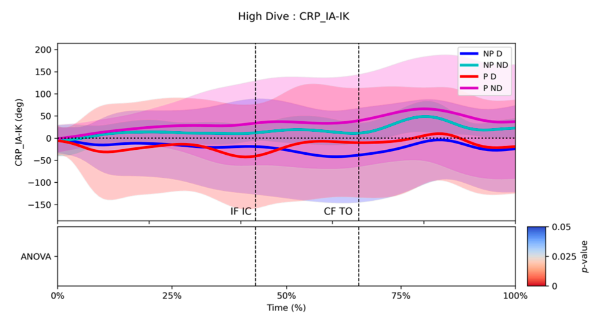
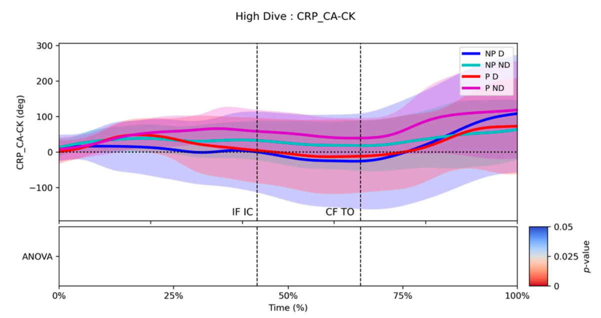
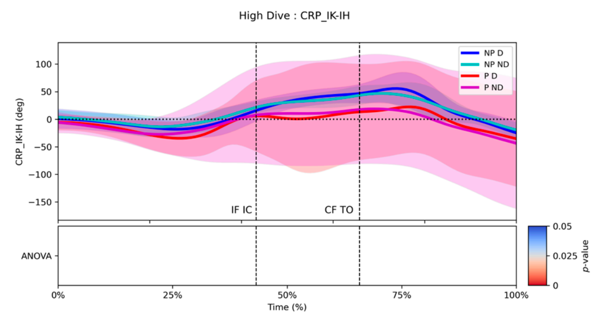
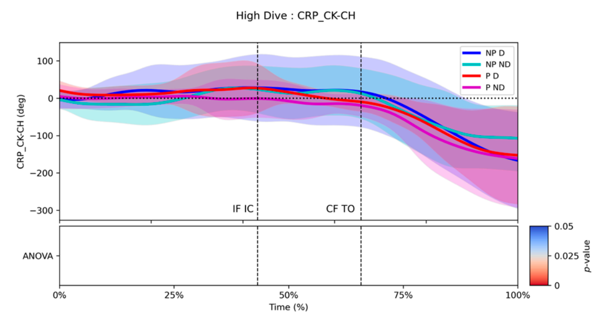
Ankle flex/ext





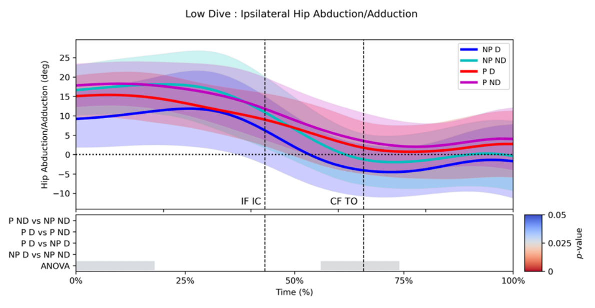
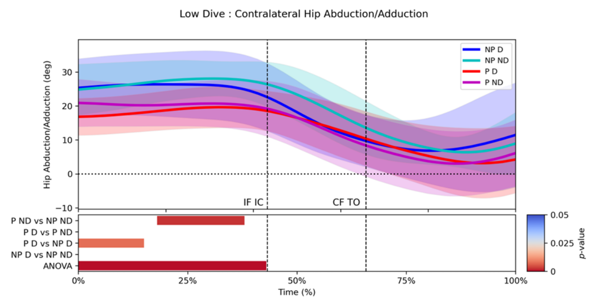
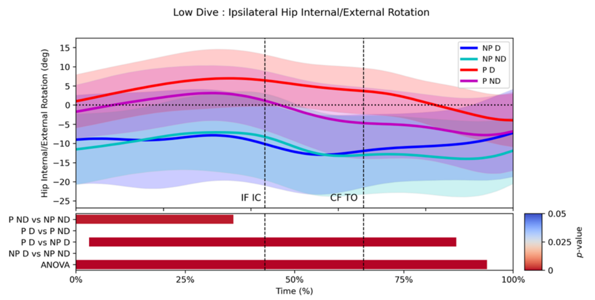
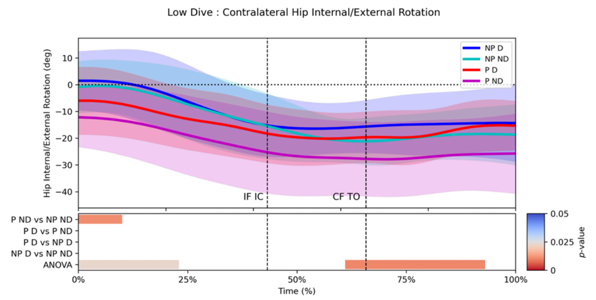
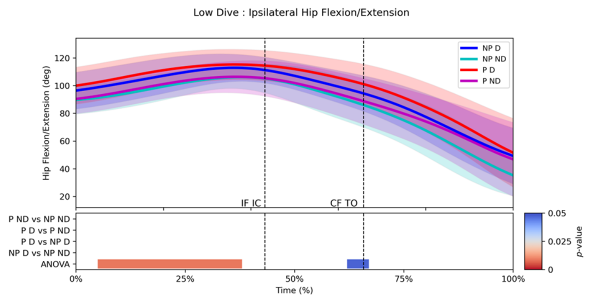
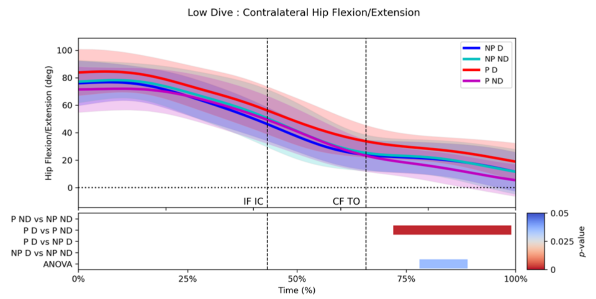
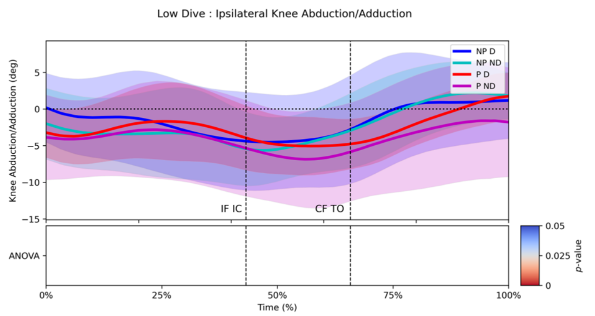
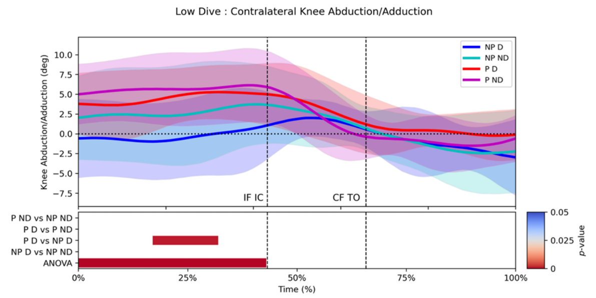
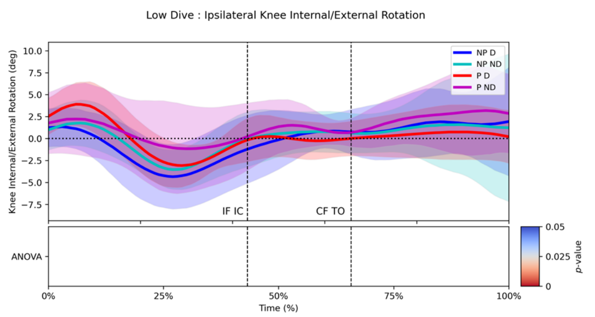
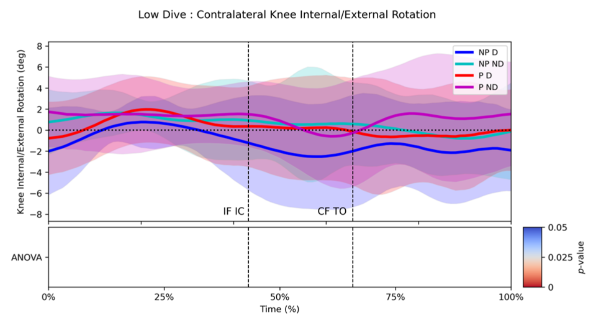
Appendix A.2. High Dive SPM1D Comparison CRP

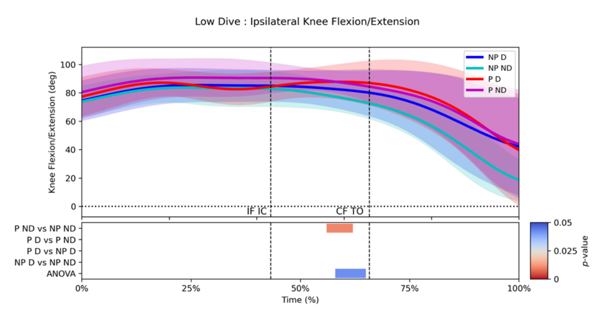
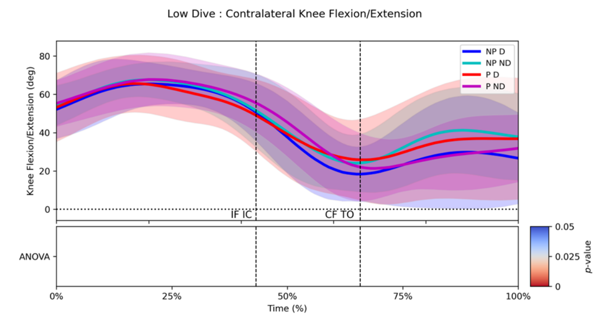
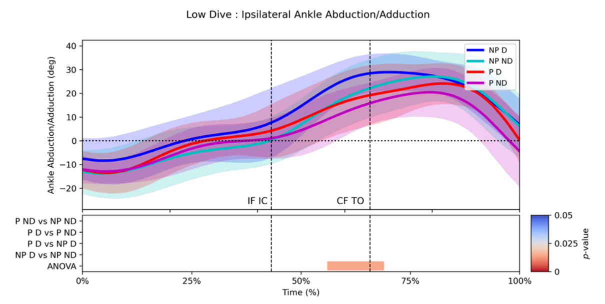
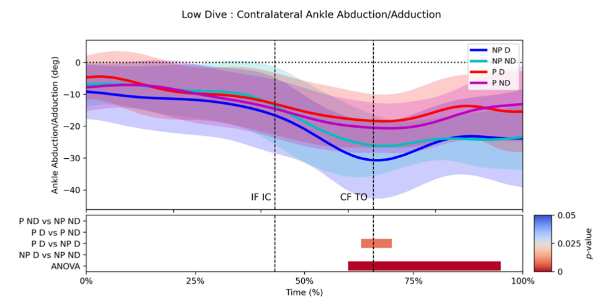
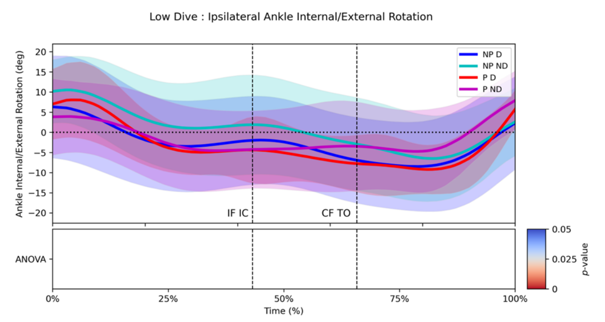
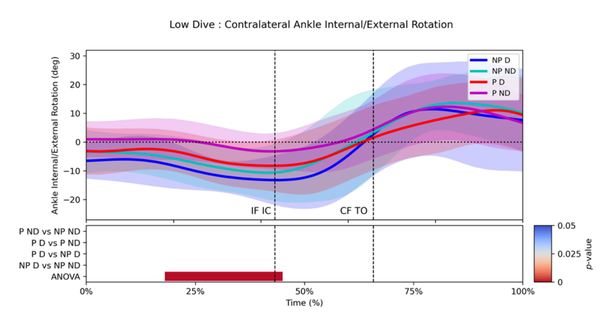
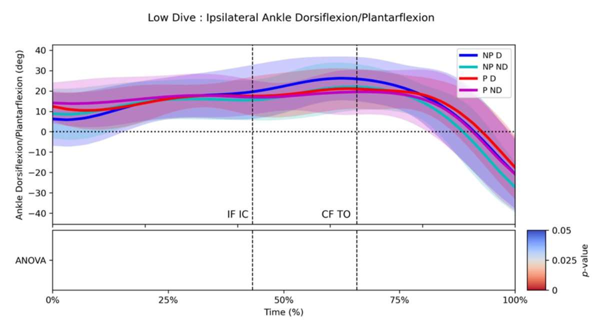
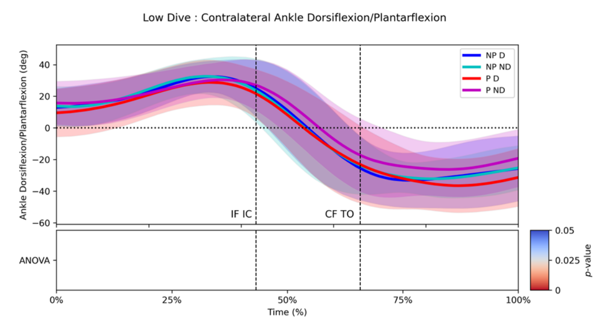
Comprehensive SPM1D analysis of CRP time-series for all lower-limb joint coupling angles during high dives. Significant SPM1D ANOVA clusters ($p < 0.05$) are highlighted, with *p*-values derived from ANOVA and Bonferroni-corrected post hoc *t*-tests indicating specific temporal differences. Acronymous: Preferred side (P), Non-Preferred side (NP), Declared test (D), Undeclared test (ND).

	Ipsilateral	Contralateral
CRP Ankle-Hip		
CRP Ankle-Knee		
CRP Knee-Hip		

Appendix A.3. Low Dive SPM1D Comparison Kinematics

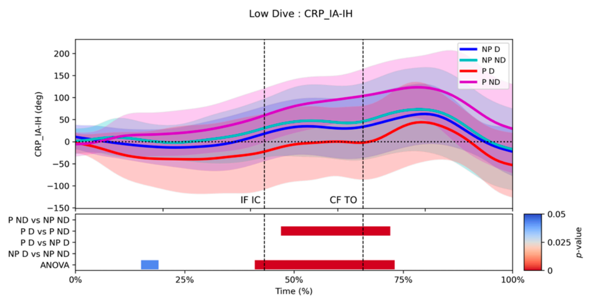
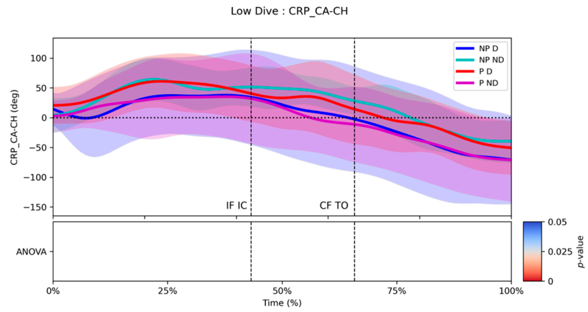
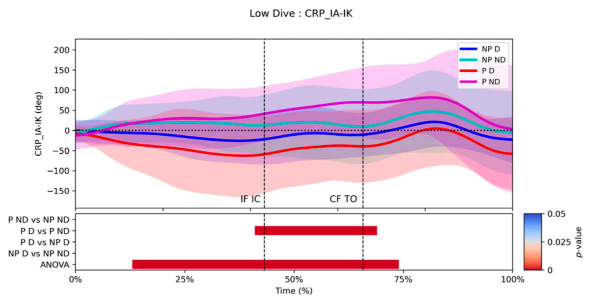
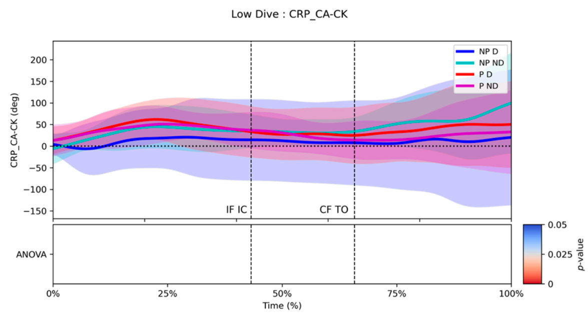
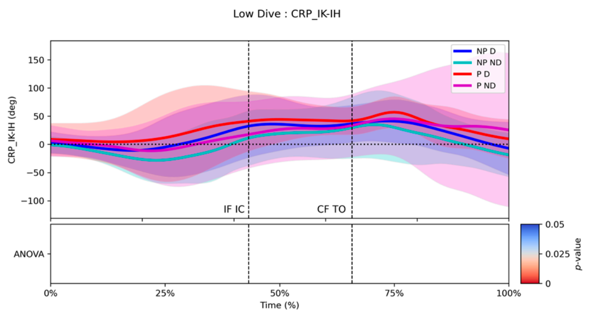
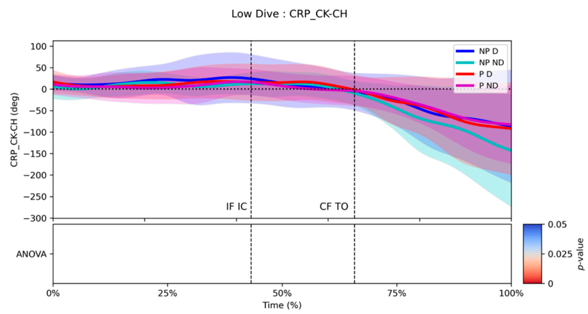
Comprehensive SPM1D analysis of kinematics time-series for all lower-limb joint angles during low dives. The following abbreviations are used: Ab/Ad = Abduction/Adduction, Flex/Ext = Flexion/Extension, Int/Ext = Internal/External rotation. Positive values indicate abduction, flexion, or internal rotation movements, whereas negative values correspond to adduction, extension, or external rotation. A value of zero represents the neutral anatomical position. Significant SPM1D ANOVA clusters ($p < 0.05$) are highlighted, with p-values derived from ANOVA and Bonferroni-corrected post hoc t-tests indicating specific temporal differences. Acronymous: Preferred side (P), Non-Preferred side (NP), Declared test (D), Undeclared test (ND).

	Ipsilateral	Contralateral
Hip Ab/Ad		
Hip Int/ext		
Hip flex/ext		
Knee Ab/Ad		
Knee Int/ext		

<table>
<tr><td>Knee flex/ext</td><td>
</td><td>
</td></tr>
<tr><td>Ankle Ab/Ad</td><td>
</td><td>
</td></tr>
<tr><td>Ankle Int/ext</td><td>
</td><td>
</td></tr>
<tr><td>Ankle flex/ext</td><td>
</td><td>
</td></tr>
</table>

Appendix A.4. Low Dive SPM1D Comparison CRP

Comprehensive SPM1D analysis of CRP time-series for all lower-limb joint coupling angles during high dives. Significant SPM1D ANOVA clusters ($p < 0.05$) are highlighted, with p-values derived from ANOVA and Bonferroni-corrected post-hoc t-tests indicating specific temporal differences. Acronymous: Preferred side (P), Non-Preferred side (NP), Declared test (D), Undeclared test (ND).

	Ipsilateral	Contralateral
CRP Ankle-Hip		
CRP Ankle-Knee		
CRP Knee-Hip		

References

1. Ibrahim, R.; Kingma, I.; de Boode, V.A.; Faber, G.S.; van Dieën, J.H. Kinematic and Kinetic Analysis of the Goalkeeper's Diving Save in Football. *J. Sports Sci.* **2019**, *37*, 313–321. [CrossRef]
2. Ibrahim, R.; Kingma, I.; de Boode, V.; Faber, G.S.; van Dieën, J.H. The Effect of Preparatory Posture on Goalkeeper's Diving Save Performance in Football. *Front. Sports Act. Living* **2019**, *1*, 466921. [CrossRef]
3. Ibrahim, R.; de Boode, V.; Kingma, I.; van Dieën, J.H. Data-Driven Strength and Conditioning, and Technical Training Programs for Goalkeeper's Diving Save in Football. *Sports Biomech.* **2025**, *24*, 2871–2883. [CrossRef]
4. Matsukura, K.; Asai, T.; Sakamoto, K. Characteristics of Movement and Force Exerted by Soccer Goalkeepers During Diving Motion. *Procedia Eng.* **2014**, *72*, 44–49. [CrossRef]
5. Bouisset, S.; Zattara, M. Biomechanical Study of the Programming of Anticipatory Postural Adjustments Associated with Voluntary Movement. *J. Biomech.* **1987**, *20*, 735–742. [CrossRef] [PubMed]
6. Cavallari, P.; Bolzoni, F.; Bruttini, C.; Esposti, R. The Organization and Control of Intra-Limb Anticipatory Postural Adjustments and Their Role in Movement Performance. *Front. Hum. Neurosci.* **2016**, *10*, 525. [CrossRef]
7. Berg, W.P. Advances in the Study of Anticipatory Postural Adjustments. *Brain Sci.* **2024**, *14*, 1219. [CrossRef] [PubMed]
8. Hayashi, H.; Tomita, H.; Ogawa, Y.; Kawamata, N.; Motomura, S.; Kanai, A. Anticipatory Postural Adjustments during Multidirectional Gait Initiation with Body Turning among Healthy Young Men. *Gait Posture* **2026**, *123*, 110003. [CrossRef]
9. Kingma, I.; Toussaint, H.M.; Commissaris, D.A.C.M.; Hoozemans, M.J.M.; Ober, M.J. Optimizing the Determination of the Body Center of Mass. *J. Biomech.* **1995**, *28*, 1137–1142. [CrossRef]
10. Mornieux, G.; Gehring, D.; Fürst, P.; Gollhofer, A. Anticipatory Postural Adjustments during Cutting Manoeuvres in Football and Their Consequences for Knee Injury Risk. *J. Sports Sci.* **2014**, *32*, 1255–1262. [CrossRef] [PubMed]
11. Moriyama, M.; Kouzaki, M.; Hagio, S. Anticipatory Postural Control in Adaptation of Goal-Directed Lower Extremity Movements. *Sci. Rep.* **2024**, *14*, 4142. [CrossRef] [PubMed]

12. Ji, Q.; Zhou, C.; Wang, Y. Influence of Conflicting Prior Information on Action Anticipation in Soccer Players: An ERP Study. *Front. Behav. Neurosci.* **2023**, *17*, 1320900. [CrossRef]
13. Nakagawa, K. Specialized Perceptual-Cognitive Skills in Soccer Goalkeepers. *J. Phys. Educ. Sports* **2025**, *25*, 2389–2394. [CrossRef]
14. Hu, M.; Kobayashi, T.; Zhou, J.; Lam, W.-K. Current Application of Continuous Relative Phase in Running and Jumping Studies: A Systematic Review. *Gait Posture* **2021**, *90*, 215–233. [CrossRef]
15. Lamb, P.F.; Stöckl, M. On the Use of Continuous Relative Phase: Review of Current Approaches and Outline for a New Standard. *Clin. Biomech.* **2014**, *29*, 484–493. [CrossRef]
16. Dubois, O.; Roby-Brami, A.; Parry, R.; Jarrassé, N. JcvPCA and JsvCRP: A Set of Metrics to Evaluate Changes in Joint Coordination Strategies. *PLoS ONE* **2025**, *20*, e0325792. [CrossRef]
17. Kelso, J.A.S. Multistability and Metastability: Understanding Dynamic Coordination in the Brain. *Philos. Trans. R. Soc. Lond. B Biol. Sci.* **2012**, *367*, 906–918. [CrossRef] [PubMed]
18. Stergiou, N.; Decker, L.M. Human Movement Variability, Nonlinear Dynamics, and Pathology: Is There a Connection? *Hum. Mov. Sci.* **2011**, *30*, 869–888. [CrossRef] [PubMed]
19. Cowin, J.; Nimphius, S.; Fell, J.; Culhane, P.; Schmidt, M. A Proposed Framework to Describe Movement Variability within Sporting Tasks: A Scoping Review. *Sports Med. Open* **2022**, *8*, 85. [CrossRef]
20. Gheller, R.G.; Dal Pupo, J.; Ache-Dias, J.; Detanico, D.; Padulo, J.; dos Santos, S.G. Effect of Different Knee Starting Angles on Intersegmental Coordination and Performance in Vertical Jumps. *Hum. Mov. Sci.* **2015**, *42*, 71–80. [CrossRef]
21. Ibrahim, R.; Kingma, I.; de Boode, V.; Faber, G.S.; van Dieën, J.H. Angular Velocity, Moment, and Power Analysis of the Ankle, Knee, and Hip Joints in the Goalkeeper's Diving Save in Football. *Front. Sports Act. Living* **2020**, *2*, 13. [CrossRef]
22. Pinelli, S.; Zinno, R.; Senesi, G.; Massini, M.S.; Pinelli, E.; Bragonzoni, L. Enhancing Soccer Athletes' Performance: A Kinematic Analysis of Agility Training. *J. Mech. Med. Biol.* **2025**, 2540053. [CrossRef]
23. Pinelli, S.; Zinno, R.; Jòdar-Portas, A.; Prats-Puig, A.; Font-Lladó, R.; Bragonzoni, L. Automated Detection of Change of Direction in Basketball Players Using Xsens Motion Tracking. *Sensors* **2025**, *25*, 942. [CrossRef]
24. Dal Pupo, J.; Dias, J.A.; Gheller, R.G.; Detanico, D.; Santos, S.G.D. Stiffness, Intralimb Coordination, and Joint Modulation during a Continuous Vertical Jump Test. *Sports Biomech.* **2013**, *12*, 259–271. [CrossRef]
25. Kurz, M.J.; Stergiou, N.; Buzzi, U.H.; Georgoulis, A.D. The Effect of Anterior Cruciate Ligament Reconstruction on Lower Extremity Relative Phase Dynamics during Walking and Running. *Knee Surg. Sports Traumatol. Arthrosc.* **2005**, *13*, 107–115. [CrossRef]
26. Nijmeijer, E.M.; Heuvelmans, P.; Bolt, R.; Gokeler, A.; Otten, E.; Benjaminse, A. Concurrent Validation of the Xsens IMU System of Lower-Body Kinematics in Jump-Landing and Change-of-Direction Tasks. *J. Biomech.* **2023**, *154*, 111637. [CrossRef] [PubMed]
27. di Paolo, S.D.; Lopomo, N.F.; Villa, F.D.; Paolini, G.; Figari, G.; Bragonzoni, L.; Grassi, A.; Zaffagnini, S. Rehabilitation and Return to Sport Assessment after Anterior Cruciate Ligament Injury: Quantifying Joint Kinematics during Complex High-Speed Tasks through Wearable Sensors. *Sensors* **2021**, *21*, 2331. [CrossRef] [PubMed]
28. di Paolo, S.D.; Santillozzi, F.; Zinno, R.; Barone, G.; Bragonzoni, L. On-Field Biomechanical Assessment of High and Low Dive in Competitive 16-Year-Old Goalkeepers through Wearable Sensors and Principal Component Analysis. *Sensors* **2022**, *22*, 7519. [CrossRef]
29. Gryszczenko, H.B.; Barreira, J.; Sandoval, G.O.; Mercadante, L.A. An Analysis of the Efficiency of Preparatory Posture and Anticipation Actions Performed by Goalkeepers in the 2018 FIFA World Cup. *Retos* **2024**, *57*, 725–730. [CrossRef]
30. Hamill, J.; van Emmerik, R.E.A.; Heiderscheit, B.C.; Li, L. A Dynamical Systems Approach to Lower Extremity Running Injuries. *Clin. Biomech.* **1999**, *14*, 297–308. [CrossRef]
31. Guo, L.; Xiong, S. Accuracy of Base of Support Using an Inertial Sensor Based Motion Capture System. *Sensors* **2017**, *17*, 2091. [CrossRef]
32. LaHuis, D.M.; Hartman, M.J.; Hakoyama, S.; Clark, P.C. Explained Variance Measures for Multilevel Models. *Organ. Res. Methods* **2014**, *17*, 433–451. [CrossRef]
33. von Diecken, C.; Riedl, M.; Willwacher, S.; Ueberschär, O. Runners with Lower Dynamic Stability Exhibit Better Running Economy. *Sci. Rep.* **2025**, *15*, 38117. [CrossRef]
34. Cohen, J. *Statistical Power Analysis for the Behavioral Sciences*; Erlbaum: Hillsdale, MI, USA, 1977; ISBN 978-0-12-179060-8.
35. Pataky, T.C. One-Dimensional Statistical Parametric Mapping in Python. *Comput. Methods Biomech. Biomed. Engin.* **2012**, *15*, 295–301. [CrossRef]
36. Overview of Random Effects Analysis—Spm1d 0.4 Documentation. Available online: https://spm1d.org/doc/RandomEffects.html (accessed on 26 February 2026).
37. Pataky, T.C.; Vanrenterghem, J.; Robinson, M.A. Zero- vs. One-Dimensional, Parametric vs. Non-Parametric, and Confidence Interval vs. Hypothesis Testing Procedures in One-Dimensional Biomechanical Trajectory Analysis. *J. Biomech.* **2015**, *48*, 1277–1285. [CrossRef]

38. Pataky, T.C. Power1D: A Python Toolbox for Numerical Power Estimates in Experiments Involving One-Dimensional Continua. *PeerJ Comput. Sci.* **2017**, *3*, e125. [CrossRef]
39. Valkanidis, T.C.; Craig, C.M.; Cummins, A.; Dessing, J.C. A Goalkeeper's Performance in Stopping Free Kicks Reduces When the Defensive Wall Blocks Their Initial View of the Ball. *PLoS ONE* **2020**, *15*, e0243287. [CrossRef] [PubMed]
40. Santos, M.J.; Kanekar, N.; Aruin, A.S. The Role of Anticipatory Postural Adjustments in Compensatory Control of Posture: 2. Biomechanical Analysis. *J. Electromyogr. Kinesiol.* **2010**, *20*, 398–405. [CrossRef]
41. Kozinc, Ž.; Šarabon, N. The Effects of Leg Preference and Leg Dominance on Static and Dynamic Balance Performance in Highly-Trained Tennis Players. *PLoS ONE* **2021**, *16*, e0259854. [CrossRef] [PubMed]
42. Leung, A.; Dyke, J.; Zarzycki, R.; Lawrence, J.T.; Ganley, T.; Greenberg, E. Rethinking Lower Extremity Limb Dominance: A Comparison of Performance-Based and Self-Selected Measures. *Sports Health* **2025**, 19417381251343085. [CrossRef]
43. Huang, R.; Ma, Y.; Lin, S.; Zheng, W.; Liu, L.; Jia, M. Research on the Biomechanical Laterality of Athletes' Lower Limbs during Side Kick in the Competitive Taekwondo. *Sci. Rep.* **2025**, *15*, 10180. [CrossRef]
44. Ferrauti, A.; Fernandez-Fernandez, J.; Klapsing, G.M.; Ulbricht, A.; Rosenkranz, D. Diagnostic of Footwork Characteristics and Running Speed Demands in Tennis on Different Ground Surfaces. *Sport-Orthop. Sport-Traumatol. Sports Orthop. Traumatol.* **2013**, *29*, 172–179. [CrossRef]
45. Geantă, V.A.; de Hillerin, P.J.; Iacobini, A.R.; Camenidis, C.M.; Ionescu, A. Differences in Average Power Output Values from Computational Models of Repeated Vertical Jump Tests: A Single-Group Quasi Experimental Approach. *J. Funct. Morphol. Kinesiol.* **2025**, *10*, 397. [CrossRef]
46. Chardonnens, J.; Favre, J.; Cuendet, F.; Gremion, G.; Aminian, K. Characterization of Lower-Limbs Inter-Segment Coordination during the Take-off Extension in Ski Jumping. *Hum. Mov. Sci.* **2013**, *32*, 741–752. [CrossRef]
47. Lukšys, D.; Jatužis, D.; Jonaitis, G.; Griškevičius, J. Application of Continuous Relative Phase Analysis for Differentiation of Gait in Neurodegenerative Disease. *Biomed. Signal Process. Control* **2021**, *67*, 102558. [CrossRef]
48. Spratford, W.; Mellifont, R.; Burkett, B. The Influence of Dive Direction on the Movement Characteristics for Elite Football Goalkeepers. *Sports Biomech.* **2009**, *8*, 235–244. [CrossRef] [PubMed]
49. Monteiro, R.L.M.; dos Santos, C.C.A.; Blauberger, P.; Link, D.; Russomanno, T.G.; Tahara, A.K.; Chinaglia, A.G.; Santiago, P.R.P. Enhancing Soccer Goalkeepers Penalty Dive Kinematics with Instructional Video and Laterality Insights in Field Conditions. *Sci. Rep.* **2024**, *14*, 10225. [CrossRef] [PubMed]