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Hip strength ratios and trunk-pelvis coordination during the soccer inside kick: a 1D-SPM analysis

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Title: Hip strength ratios and trunk-pelvis coordination during the soccer inside kick: a 1D-SPM analysis

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Abstract

Background: The soccer inside kick requires coordinated trunk-pelvis and lower-limb motion across multiple planes. However, the relationship between velocity-specific hip strength imbalances and continuous kinematic patterns remains unclear.

Aims: To examine associations between multi-planar hip strength ratios and phase-specific trunk-pelvis and lower-limb kinematics during the inside kick.

Methods: Eighteen male soccer players performed maximal inside kicks following isokinetic hip strength assessment at 180°/s and 300°/s. Participant-averaged kinematic waveforms were analyzed using one-dimensional statistical parametric mapping (1D-SPM) linear regression. This study was exploratory, and no formal correction for multiple SPM models was applied.

Results: A higher stance-limb IR/ER ratio at 180°/s was associated with greater ipsilateral pelvic rotation velocity during early-to-mid swing (28.5–44.4% of the swing phase; $p = 0.0096$; $t = -3.740$; $r = -0.683$; $R^2 = 0.466$), followed by greater kicking-limb internal rotation acceleration (52.4–56.2% of the swing phase; $p = 0.0284$; $t = 3.749$; $r = 0.684$; $R^2 = 0.468$) and velocity (64.4–69.1% of the swing phase; $p = 0.0345$; $t = 3.586$; $r = 0.668$; $R^2 = 0.446$). A higher kicking-limb Ab/Ad ratio at 300°/s was associated with greater contralateral trunk lateral flexion during early swing (0.0–30.0% of the swing phase; $p = 0.0301$; $t = 3.380$; $r = 0.645$; $R^2 = 0.417$).

Conclusions: Hip strength imbalances were associated with distinct, phase-specific coordination patterns. These findings support the use of velocity-specific, multi-planar strength profiling combined with waveform analysis to better characterize movement strategies relevant to groin loading.

Keywords: Soccer kick; Kinematics; Statistical parametric mapping; Intersegmental coordination; Kinetic chain; Injury prevention

1. Introduction

In soccer, the inside kick is a highly dynamic movement that relies on a complex, multi-joint kinetic chain to transfer momentum from the proximal trunk and pelvis to the distal foot [1, 2]. Preserving the integrity of this kinetic chain is essential not only for optimizing performance but also for mitigating injury risk. Groin injuries are highly prevalent in soccer, representing a substantial proportion of all reported injuries, and frequently necessitate prolonged periods of absence from training and competition [3]. Adductor-related groin pain (AGP), a major subcategory of groin injuries, is strongly associated with soccer-specific actions that generate substantial mechanical demand and multi-directional shearing forces across the pelvic ring, such as kicking and sudden changes of direction [4]. Accordingly, identifying atypical movement strategies that may alter force transmission through the trunk-pelvis and lower-limb complex is clinically relevant, even in asymptomatic players, to understand the potential precursors of chronic overload.

A rigid-body mechanics perspective provides a robust framework for understanding how localized neuromuscular deficits may influence global movement behavior. By conceptualizing the body as a system of linked segments, reduced force capacity in one anatomical plane may require compensatory kinematic adjustments in upstream or downstream segments to preserve the trajectory and terminal velocity of the distal segment [2, 5]. While hip abduction-to-adduction (Ab/Ad) strength imbalances have traditionally been investigated in relation to hip and groin function and recovery status following injury [6, 7], contemporary biomechanical paradigms increasingly emphasize the critical role of transverse-plane control, particularly internal/external rotation (IR/ER) balance [8, 9].

During a soccer kick, the stance limb must function as a stable proximal anchor to withstand the substantial rotational torque generated by the swinging limb. Therefore, dynamic kinematic variations in the kicking limb may be associated with multi-planar stability deficits in the stance limb [10], particularly given that joint kinetics are sensitive to movement speed and task demands [11]. Furthermore, achieving optimal swing efficiency and safe load distribution likely involves precise intersegmental control of the trunk and pelvis [12], as trunk neuromuscular control has been linked to injury risk in dynamic athletic tasks [13].

Despite these theoretical considerations, it remains biomechanically unclear how static, multi-planar hip strength imbalances are associated with dynamic trunk-pelvis coordination during high-velocity kicking. Moreover, strength capabilities at higher contraction velocities (e.g., ≥300°/s) may reflect the functional demands of ballistic kicking more accurately than traditional lower-velocity assessments (e.g., 180°/s). A significant methodological limitation in

previous studies is the reliance on conventional zero-dimensional (0D) analyses, which extract only discrete, isolated kinematic points (e.g., peak values or values at ball impact). This discrete approach compresses the continuous temporal structure and risks missing or overstating functional kinematic features. One-dimensional statistical parametric mapping (1D-SPM) overcomes this barrier by allowing continuous statistical inference across entire time-series waveforms, permitting the identification of the exact temporal periods over which a specific relationship persists.

Building on prior work examining static hip strength and postural control, the present study utilized isokinetic testing across multiple planes and velocities, combined with 1D-SPM linear regression, to investigate how multi-planar hip strength ratios are associated with continuous trunk-pelvis and lower-limb kinematics during the inside kick. We hypothesized that a transverse-plane imbalance in the stance limb (relative external rotator weakness) would be associated with reduced proximal stability, manifesting as altered pelvic and kicking-leg rotational kinematics. Conversely, we hypothesized that a frontal-plane imbalance in the kicking limb (relative adductor weakness) would be associated with compensatory trunk-pelvis frontal-plane motion (e.g., excessive lateral flexion) during high-speed movements to facilitate leg swing.

2. Methods

2.1 Study Design and Participants

This cross-sectional experimental study was conducted in accordance with the STROBE guidelines for observational studies [14]. Eighteen healthy, right-leg dominant male soccer players from a regional first-division league participated in the study (age, 24.9 ± 3.5 years; height, 176.6 ± 6.3 cm; body mass, 70.3 ± 7.0 kg, soccer playing experience, 18.4 ± 3.3 years). To maintain sample homogeneity regarding pelvic anatomy (e.g., pelvic width and Q-angle)—variables that can significantly influence multi-planar hip and trunk kinematics during kicking—only male participants were included. Inclusion criteria required no history of recent (within the past 6 months) lower-limb or trunk injuries and no pain during strength testing or kicking tasks. The study was approved by the institutional ethics committee, and all participants provided written informed consent. All participants were right-leg dominant, and the left limb consistently served as the stance limb during the kicking trials. While this kinematic dataset is derived from a broader clinical cohort [15], the current study represents an independent, novel biomechanical analysis specifically utilizing 1D-SPM to explore continuous kinematic associations. An a priori sample size calculation was not

84 performed due to the lack of established effect size estimates for 1D-SPM linear regression; however, the sample
85 size (n = 18) is comparable to prior exploratory studies employing biomechanical waveform analyses [16]. This
86 study was exploratory and hypothesis-generating in nature.
87
88 **2.2 Hip Strength Assessment**
89 Isokinetic hip strength in the transverse plane (IR/ER) and frontal plane (Ab/Ad) was assessed using a Cybex-Norm
90 dynamometer. The IR/ER tests were performed in a seated position with the hip flexed to 90°, and the Ab/Ad tests
91 were performed in a side-lying position with the hip in neutral flexion/extension. The range of motion for each test
92 was set according to standard dynamometer guidelines to encompass the participant's maximum active range. To
93 minimize compensatory trunk and pelvic movements during maximal exertion, a therapist provided manual
94 stabilization of the pelvis. Following a standardized warm-up consisting of submaximal contractions, participants
95 performed 10 continuous maximal concentric contractions at angular velocities of 180°/s and 300°/s, with a 60-
96 second rest period between velocity conditions. The order of strength testing at 180°/s and 300°/s was randomized to
97 mitigate potential order effects. Peak torque values were first normalized to body mass (Nm/kg), and strength ratios
98 were subsequently calculated as the quotient of agonist to antagonist torque (IR/ER = internal rotation ÷ external
99 rotation; Ab/Ad = abduction ÷ adduction). A higher strength ratio indicates a relative deficit in the antagonist torque
100 compared with the agonist torque. This can arise from either elevated agonist torque, reduced antagonist torque, or a
101 combination thereof, and does not necessarily imply an absolute strength deficit.
102
103 **2.3 Motion Capture Procedures and Task**
104 Three-dimensional kinematics of the trunk-pelvis, and bilateral hip joints were captured at a sampling frequency of
105 250 Hz using a Vicon Nexus optical motion tracking system. Forty-one reflective markers were placed according to
106 the standard Plug-in Gait model, which utilizes Dempster's anthropometric body segment parameters to compute
107 continuous kinematic variables. Three-dimensional kinematics were calculated using a Cardan/Euler sequence (Y-
108 X-Z), representing flexion/extension, abduction/adduction, and internal/external rotation, respectively. Joint angles
109 were calculated relative to the local segment coordinate systems. Specifically, hip joint angles were defined as the
110 motion of the femur relative to the local pelvis coordinate system, whereas pelvis and trunk angles were expressed
111 relative to the global laboratory coordinate system.

Regarding the kinematic polarities for our variables of interest: for hip rotation, positive values indicated internal rotation and negative values indicated external rotation; for pelvic rotation in the transverse plane, negative values indicated ipsilateral (rightward) rotation; and for trunk lateral flexion in the frontal plane, positive values indicated contralateral (leftward) flexion. Participants wore standardized indoor soccer shoes and performed maximal-effort inside kicks toward a target 4.0 m away using a self-selected approach angle (typically 20°–45°) and run-up distance (1.5–2.0 m). Five successful trials—defined as clean ball contact striking the target area—were analyzed per participant.

The swing phase was defined as the interval from toe-off of the kicking limb to ball impact, consistent with commonly adopted definitions in soccer kicking biomechanics [17]. A critical methodological consideration in impact sports biomechanics is the application of signal filtering. Conventional zero-lag low-pass (Butterworth) filtering, while effective for reducing gait noise, tends to over-smooth kinematic waveforms at the moment of ball impact, leading to a significant attenuation of peak angular velocity and acceleration values [18]. Therefore, to maximize the fidelity of high-frequency temporal features during the rapid ball-striking phase, we employed a Savitzky–Golay polynomial filter (third-order, 36-ms window). A 36-ms window was selected to balance noise reduction with the preservation of high-frequency temporal features inherent to ballistic soccer kicking, as previously validated [18]. This method is specifically advantageous in ballistic sports research as it maintains local waveform morphology and temporal precision better than standard low-pass approaches, ensuring that the rapid changes in pelvic and hip rotation critical to our analysis were preserved for 1D-SPM. The kinematic waveforms of the swing phase were then time-normalized to 101 points (0–100%). Finally, waveforms from the five successful trials were averaged to generate one representative ensemble-averaged waveform per participant. Statistical analyses were therefore rigorously performed at the participant level (n = 18) to maintain statistical independence of observations, a recommended practice in biomechanical waveform analyses.

2.4 Statistical Analysis

1D-SPM linear regression analyses were conducted using the spm1d library (version 0.4) in Python [19]. Statistical inference was based on random field theory (RFT) as implemented in spm1d. The associations between hip strength ratios and time-normalized continuous kinematic waveforms were evaluated using an alpha level of 0.05. No formal

correction for multiple comparisons across the eight separate 1D-SPM linear regression models was applied, as the analyses were hypothesis-driven and exploratory in nature. However, the 1D-SPM framework inherently controls the family-wise error rate across the time continuum using RFT. Additionally, to evaluate the relationship between the evaluated multi-planar hip strength ratios and terminal ball speed, Spearman's rank correlation coefficients ρ were calculated. This non-parametric approach was selected to ensure statistical robustness given the modest sample size. Statistical significance for these discrete (0D) analyses was also set at an alpha level of 0.05.

3. Results

Analyses were based on participant-averaged waveforms (n = 18). The mean ball speed attained during the maximum-effort kicks was 23.7 ± 1.7 m/s. To evaluate whether the hypothesized compensatory mechanisms effectively preserved terminal kicking performance, we calculated Spearman's rank correlation coefficients (ρ) and their 95% confidence intervals (CIs). Participant hip strength profiles (peak torque and strength ratios), which assist in differentiating relative imbalance from absolute strength levels, are detailed in **Table 1**.

Table 1. Hip strength profiles of the participants (n = 18)

Variable	Kicking Leg (180°/s)	Stance Leg (180°/s)	Kicking Leg (300°/s)	Stance Leg (300°/s)
Peak Torque (Nm/kg)				
Abduction	1.44 ± 0.36	1.44 ± 0.35	1.33 ± 0.40	1.93 ± 0.49
Adduction	1.10 ± 0.39	1.10 ± 0.33	0.89 ± 0.40	0.99 ± 0.37
Internal Rotation	1.26 ± 0.42	1.32 ± 0.46	1.40 ± 0.42	1.45 ± 0.47
External Rotation	0.98 ± 0.18	0.96 ± 0.20	1.03 ± 0.20	1.02 ± 0.20
Strength Ratio				
Ab/Ad Ratio	1.49 ± 0.67	1.52 ± 0.91	1.71 ± 0.72	2.34 ± 1.30
IR/ER Ratio	1.29 ± 0.34	1.39 ± 0.43	1.35 ± 0.29	1.43 ± 0.37

Note: Values are presented as mean (standard deviation). Ab/Ad = Abduction/Adduction, IR/ER = Internal/External Rotation. A higher strength ratio indicates a relative torque deficit in the antagonist muscle group (i.e., external rotators or adductors) compared to the agonist. These ratios should be interpreted alongside the provided absolute normalized peak torque values to differentiate between relative strength imbalances and absolute weakness.

Crucially, neither the stance-limb IR/ER ratio at 180°/s (ρ = -0.045, 95% CI [-0.515, 0.445], p = 0.863) nor the kicking-limb Ab/Ad ratio at 300°/s (ρ = -0.374, 95% CI [-0.725, 0.130], p = 0.139)—the two primary imbalances driving the phase-specific kinematic alterations—were significantly correlated with ball speed. Interestingly, the kicking-limb Ab/Ad ratio at the lower velocity of 180°/s demonstrated a significant negative correlation with ball speed (ρ = -0.521, 95% CI [-0.801, -0.054], p = 0.032). During the swing phase, peak hip extension and peak knee flexion of the kicking limb occurred at 45.4 ± 4.3% and 75.1 ± 1.8% of the normalized cycle, respectively. Participant hip strength profiles (peak torque and strength ratios) are detailed in Table 1.

Association with Stance-Limb Transverse Plane (IR/ER) Strength Ratio (180°/s)

A higher stance-limb IR/ER ratio at 180°/s (reflecting relative weakness of the external rotators) was significantly associated with greater ipsilateral (rightward) pelvic rotation angular velocity during early-to-mid swing (28.5–44.4% of the swing phase; p = 0.0096; t = -3.740; r = -0.683; R^2 = 0.466). The same transverse-plane strength imbalance was also associated with greater internal rotation angular acceleration (52.4–56.2% of the swing phase; p = 0.0284; t = 3.749; r = 0.684; R^2 = 0.468) and internal rotation angular velocity (64.4–69.1% of the swing phase; p = 0.0345; t = 3.586; r = 0.668; R^2 = 0.446) of the kicking hip during mid-to-late swing **(Fig. 1a–c)**.

Association with Kicking Leg Transverse Plane (IR/ER) Strength Ratio (300°/s)

A higher kicking-limb IR/ER ratio at 300°/s was significantly associated with greater internal rotation angle of the kicking limb near ball impact (80.6–100.0% of the swing phase; p = 0.0285; t = 3.690; r = 0.678; R^2 = 0.460).

Association with Kicking Leg Frontal Plane (Ab/Ad) Strength Ratio (300°/s)

A higher kicking-limb Ab/Ad ratio at 300°/s (reflecting relative adductor weakness at high speeds) was significantly associated with greater contralateral (leftward) trunk lateral flexion angle during early swing (0.0–30.0% of the swing phase; p = 0.0301; t = 3.380; r = 0.645; R^2 = 0.417) **(Fig. 1d)**.

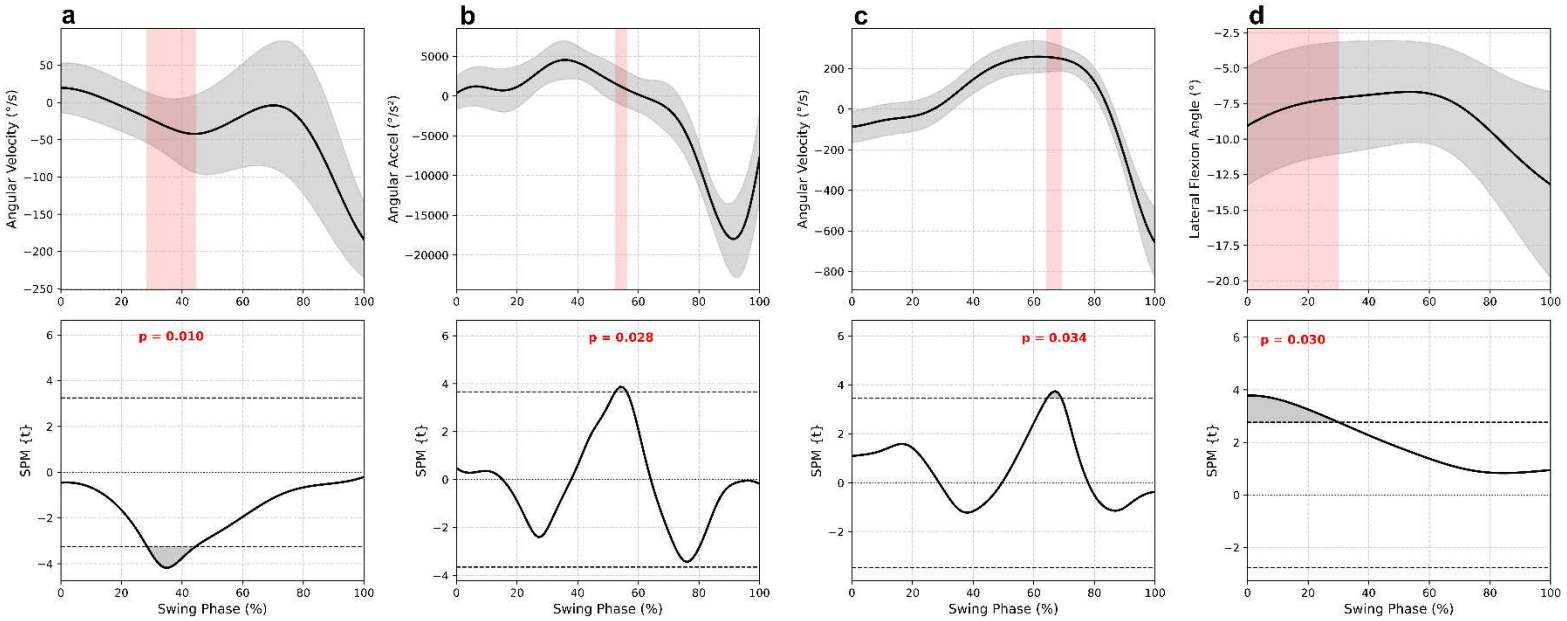


Fig. 1 One-dimensional statistical parametric mapping (1D-SPM) linear regression analysis evaluating the relationship between multi-planar hip strength ratios and continuous kicking kinematics during the soccer inside kick in male players (n = 18).

a Correlation between the stance leg IR/ER ratio (180°/s) and pelvic rotation angular velocity.

b Correlation between the stance leg IR/ER ratio (180°/s) and kicking leg hip rotation angular acceleration.

c Correlation between the stance leg IR/ER ratio (180°/s) and kicking leg hip rotation angular velocity.

d Correlation between the kicking leg Ab/Ad ratio (300°/s) and trunk lateral flexion angle.

The top panels illustrate the mean kinematic waveforms (solid lines) ± 1 standard deviation (light shaded bands), while the bottom panels display the corresponding SPM{t} profile. Red shaded areas indicate significant temporal clusters ($p < 0.05$). Kinematic polarities: negative values indicate ipsilateral pelvic rotation and external hip rotation; positive values indicate internal hip rotation and contralateral trunk lateral flexion. Abbreviations: IR/ER, internal/external rotation; Ab/Ad, abduction/adduction.

4. Discussion

This study utilized 1D-SPM to systematically examine the relationships between multi-planar hip strength ratios and continuous kinematic patterns during the ballistic soccer inside kick. The primary finding was that specific, isolated static strength imbalances are significantly associated with distinct, phase-specific trunk-pelvis and lower-limb coordination strategies. These findings underscore the premise that localized muscular deficits may influence how players organize global movement during high-velocity tasks **(Fig. 2)**.

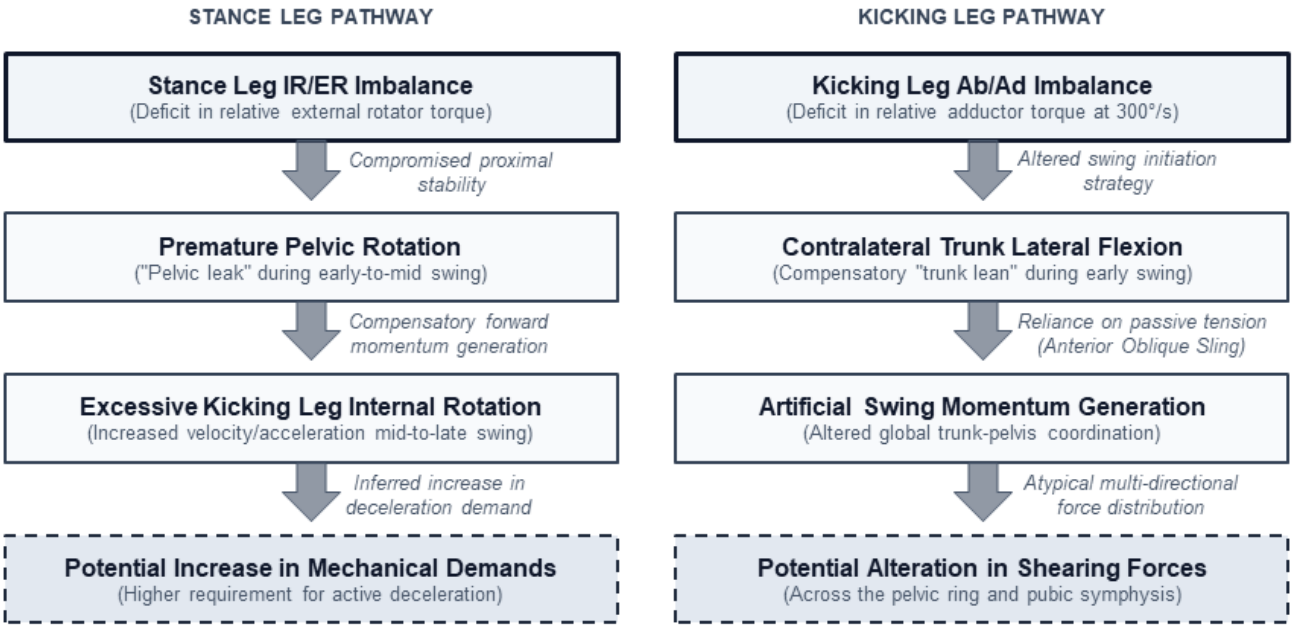


Fig. 2 Schematic representation of the hypothesized compensatory mechanisms and kinetic chain disruptions associated with multi-planar hip strength imbalances during the soccer inside kick (n = 18).
The flowchart illustrates two distinct biomechanical pathways identified via one-dimensional statistical parametric mapping (1D-SPM) continuous kinematic analysis. (Left) Stance Leg Pathway: Hypothesized consequences of a relative deficit in stance leg external rotator torque (high IR/ER ratio at 180°/s). (Right) Kicking Leg Pathway: Hypothesized consequences of a relative deficit in kicking leg adductor torque during high-speed movements (high Ab/Ad ratio at 300°/s).

Stance-Limb Transverse Plane Imbalance and Pelvic Control

The present findings indicate that a higher stance-limb IR/ER ratio at 180°/s—reflecting relatively lower external rotator torque—was significantly associated with greater ipsilateral pelvic rotation velocity during the early-to-mid swing phase. From a biomechanical perspective, the stance limb acts as a crucial proximal anchor during the kick.

The early leg-cocking phase serves as a vital "wind-up" period, requiring the stance leg external rotators to provide eccentric counter-torque against the substantial rotational forces of the swinging limb [10, 11]. This finding suggests that when the stance limb lacks sufficient transverse-plane control, it may fail to maintain this stable proximal anchor, a pattern consistent with a premature ipsilateral pelvic rotation, hereafter referred to as a "pelvic leak" as a descriptive shorthand. Furthermore, as indicated in Table 1, this higher IR/ER ratio was primarily driven by lower absolute external rotator torque rather than excessively high internal rotator torque, supporting the notion of relative weakness compromising the proximal anchor.

Consistent with the principles of proximal-to-distal intersegmental sequencing within the kinetic chain [5, 20], this early proximal behavior was associated with subsequent downstream kinematic adjustments. Specifically, the "pelvic leak" was associated with significantly greater internal rotation acceleration and velocity of the kicking hip later in the swing phase. While causality cannot be definitively established in a cross-sectional study, this temporal sequence may suggest a plausible biomechanical interpretation: potentially limiting effective elastic energy storage during the wind-up phase, the athlete might adopt a compensatory strategy involving rapid, active internal rotation of the kicking leg to drive the limb toward the ball. This altered coordination pattern may have relevant clinical implications. Decelerating a highly internally rotated segment post-impact may place substantial active deceleration demands on the proximal hip musculature [21]. Repeated reliance on such compensatory rotation could potentially increase multi-directional shearing forces and eccentric load across the pubic symphysis and adductor insertions, which have been proposed as mechanical contributors to the development of AGP [4, 22].

Kicking-Limb Frontal Plane Imbalance and Compensatory Trunk Lean

A higher kicking-limb Ab/Ad ratio at 300°/s, indicating relatively weaker adductor torque at high contraction velocities, was associated with greater contralateral trunk lateral flexion ("trunk lean") during the early swing phase. This suggests that when high-velocity concentric adductor capacity is insufficient to independently accelerate the leg, players might utilize a whole-body compensatory strategy involving extensive trunk-pelvis motion to facilitate swing initiation. This interpretation aligns with biomechanical models emphasizing the contribution of trunk motion to force generation in dynamic tasks [12, 13]. By laterally flexing the trunk away from the kicking limb, the athlete elevates the ipsilateral pelvis (hip hiking), mechanically placing the hip into relative abduction.

We postulate that this altered strategy may contribute to increased loading across trunk-pelvis myofascial structures,

conceptually consistent with the anterior oblique sling model [23]. In essence, athletes with relative adductor weakness may rely more heavily on the passive elastic tension of the anterior oblique sling (AOS) and the stretch-shortening cycle (SSC) to generate swing momentum [2, 13]. While this myofascial compensation might temporarily preserve distal kick velocity, repeated exposure to these extreme trunk movements could theoretically redistribute loading across the anterior trunk-pelvis complex, which is commonly involved in imaging findings of athletic pubalgia [24]. Over time, this reliance on passive structures may be associated with structural overloading of the abdominal-adductor aponeurosis.

Notably, the velocity-specific manifestation of this association (observed at 300°/s but not 180°/s) underscores the utility of testing at higher angular velocities to capture functionally relevant strength deficits in ballistic athletes. This interpretation is further supported by our correlation analysis. While relative adductor weakness at the lower velocity (180°/s) was directly associated with reduced ball speed, the lack of such correlation at the high velocity (300°/s) suggests that the whole-body trunk-lean strategy effectively preserves terminal kicking performance, albeit at the potential cost of altered proximal loading. While these compensatory kinematics might plausibly alter force distribution across the pelvic ring, it is important to emphasize that our interpretations regarding groin loading are speculative. Although such mechanical demands are biomechanically consistent with previous AGP models [4, 21, 22], our study did not measure joint moments, tissue-level strain, or prospective injury outcomes. Therefore, these findings should be viewed as providing a biomechanical foundation for future clinical investigation rather than direct evidence of injury causation.

Methodological Significance

An important methodological contribution of this study is the application of 1D-SPM to evaluate time-specific associations across the entire continuous movement cycle. Traditional discrete 0D analyses, which rely on isolated peak values, not only risk compressing the temporal structure and missing functional features that occur away from local extrema [25], but may also increase the likelihood of false positive findings when analyzing continuous 1D trajectories [26, 27]. By keeping the analysis in the original time domain, 1D-SPM provides a more rigorous statistical framework that mitigates these biases, allowing for the identification of temporal periods over which strength–kinematic relationships persist [28, 29]. This temporal resolution is valuable for analyzing highly ballistic, phased actions like soccer kicking, where the timing of intersegmental coordination is as critical as the magnitude of

the movement. For practitioners, these results demonstrate that velocity-specific, multi-planar strength screening provides a more comprehensive picture of underlying movement strategies and potential injury risk profiles than conventional, single-plane assessments.

Limitations

Several limitations should be acknowledged:

- **Study Design:** The cross-sectional design precludes any definitive causal inferences regarding the relationship between strength imbalances and kinematic alterations; our findings support biomechanical associations rather than direct causation.
- **Sample Size and Statistical Approach:** Given the modest and homogeneous sample size (n = 18 male, right-leg dominant players from a regional league), these findings may have limited external validity for female athletes, elite professionals, or left-leg dominant players. Furthermore, while 1D-SPM controls for family-wise error across the time continuum, we did not apply a global correction for the multiple separate regression models tested (i.e., various ratios, limbs, and velocities), which may inflate the risk of false positives.
- **Kinematic Variability:** Averaging five trials per participant was necessary to ensure statistical independence, but this approach removes intra-individual trial-to-trial movement variability, which could provide additional insights into coordination stability. Future studies employing trial-level analyses or mixed-effects models are warranted to complement these findings and explore how strength deficits influence within-subject coordination stability.
- **Ecological Factors:** While the approach angle and run-up distance were standardized within established ranges, individual-specific variations were not recorded, which may introduce uncontrolled variability in kicking mechanics.
- **Injury Inference:** Our discussion linking the observed kinematics to specific groin injury risks (e.g., pubic symphysis loading) remains speculative, as we did not prospectively measure injury history, tissue stress, joint moments, or muscle activation.

Practical Applications

From a practical perspective, identifying individualized multi-planar strength deficits through isokinetic testing

provides critical diagnostic information that may not be fully captured by conventional field-based asymmetry tests. Recent football studies have emphasized that targeted strength and conditioning programs implemented during the transition or off-season periods can successfully preserve or enhance selected physical qualities [30, 31]. Therefore, the present findings highlight the clinical relevance of designing individualized, high-velocity, multi-planar hip-strength interventions during these periods. Such targeted off-season training may help optimize kicking mechanics, correct compensatory trunk-pelvis coordination, and potentially mitigate the risk of abnormal groin loading [32, 33].

Future Research Directions

While the current findings highlight the biomechanical relevance of multi-planar hip strength profiling, future research should employ prospective longitudinal designs to determine whether the observed compensatory kinematic strategies directly increase the risk of adductor-related groin pain or other clinical injuries. Additionally, incorporating trial-level analyses to examine within-subject movement variability could provide deeper insights into how localized strength deficits affect overall coordination stability in ballistic tasks.

5. Conclusion

Multi-planar hip strength imbalances were significantly associated with distinct, phase-specific trunk-pelvis and lower-limb kinematic coordination patterns during the soccer inside kick. In particular, transverse-plane imbalances in the stance limb were associated with reduced proximal stability and subsequent compensatory, high-velocity internal rotation of the kicking limb, whereas frontal-plane imbalances in the kicking limb were associated with compensatory contralateral trunk lateral flexion. While these associations may provide a mechanical basis for understanding intersegmental coordination during kicking, they do not establish direct causation or injury prediction. Future longitudinal and prospective studies are required to determine whether these kinematic strategies directly influence clinical outcomes and groin injury risk. Comprehensive, velocity-specific strength profiling across multiple planes is vital for understanding movement strategies that may influence mechanical loading in soccer players. Practically, targeted off-season or transition-period interventions addressing these specific multi-planar deficits may help optimize kicking coordination and potentially mitigate atypical groin loading.

Declaration of Interest

· **Funding:** This study was supported by the Japan Society for the Promotion of Science under Grant No. 17K18312.

· **Competing interests:** The authors have no competing interests to declare that are relevant to the content of this article.

· **Ethics approval:** This study was performed in line with the principles of the Declaration of Helsinki. Approval was granted by the Ethics Committee of Nittazuka Medical Welfare Center (Approval No. 29-108).

· **Consent to participate:** Informed consent was obtained from all individual participants included in the study.

· **Consent to publish:** The authors affirm that human research participants provided informed consent for publication of their data.

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

· **Author contributions:**

· **Conceptualization:** Tomonari Sugano, Ryo Kuboshita; **Methodology:** Tomonari Sugano, Ryo Kuboshita; **Software:** Tomonari Sugano, Toru Tanabe; **Formal analysis and investigation:** Tomonari Sugano (including 1D-SPM analysis, isokinetic dynamometry and motion capture data collection); **Writing - original draft preparation:** Tomonari Sugano; **Writing - review and editing:** Ryo Kuboshita, Seigaku Hayashi, Toru Tanabe, Nobuhide Azuma, Masahito Hitosugi; **Funding acquisition:** Tomonari Sugano; **Supervision:** Masahito Hitosugi. All authors have read and agreed to the published version of the manuscript

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