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Biomechanical and Neuromuscular Profiles of Competitive Adolescent Athletes From Different Sports Disciplines: A Cross-Sectional Study

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Abstract

Background

To investigate sport-specific differences in lower limb alignment, posture, muscular strength and neuromuscular performance of competitive adolescent athletes across different sports disciplines; and to explore potential associations with performance.

Methods

In this cross-sectional study, 62 competitive adolescent athletes from basketball (n = 20), football (n = 17), track and field (n = 13), and golf (n = 12) underwent standardized biomechanical and neuromuscular assessments including (1) static and dynamic leg alignment analysis, (2) rasterstereographic posture analysis, (3) isometric strength testing, (4) neuromuscular performance tests (Functional Movement Screen™-, Y-Balance- and Knee-to-Wall test), and (5) jump performance (countermovement jump, drop jump, reactive strength index). Analyses of variance, Kruskal-Wallis tests and Spearman's rank correlation were applied to assess significance across sports and relationships between variables, with additional post-hoc analysis being applied to investigate sport-specific clusters.

Results

Significant sport-specific distinctions were evident across multiple domains. Football players demonstrated greater static and dynamic knee varus alignment ($p = 0.010$ – < 0.001). Golfers showed increased static trunk inclination ($p = 0.038$). Track and field athletes exhibited the highest strength values, particularly in the leg extensors, hip abductors and adductors, and trunk rotators ($p = 0.003$ – < 0.001). Neuromuscular performance differed between groups, with higher Y-Balance scores being achieved in track and field athletes and golfers, and superior jump performance in football and track and field athletes (all $p < 0.001$). Moderate to strong associations were found between strength, performance, and knee alignment parameters ($r = 0.50$–0.87). No distinct sport-specific clusters were identified.

Conclusion

This cross-sectional investigation of adolescent competitive athletes demonstrates sport-specific differences in biomechanics and neuromuscular performance across sports. These exploratory findings may reflect discipline-specific mechanical loading patterns and could inform the development of sport-specific training and monitoring approaches in youth athletes.

1. Background

Participation in organized sports plays an important role in the physical and social development of children and adolescents (1). Repetitive, sport-specific loading imposes recurring forces on the developing musculoskeletal system and may lead to structural and functional adaptations (2–6). Children and adolescents are particularly susceptible due to the immature skeleton. These characteristics render the growing musculoskeletal system especially sensitive to repetitive high-volume loading, potentially contributing to sport-specific injury patterns and long-term musculoskeletal health consequences (7, 8). Sport specialization has been associated with an increased risk of overuse injuries compared with low specialization (9).

Previous studies have reported potential sport-specific characteristics in biomechanics and neuromuscular performance. For example, an increased prevalence of genu varum has been reported in football players, in whom varus alignment appears to develop during adolescent skeletal growth (10–12) and may persist into adulthood (13). Alterations in spinal curvature and trunk and pelvic asymmetries have similarly been described in adolescent basketball (14, 15) and volleyball players (6). In contrast, golfers are exposed to repetitive rotational loading of the spine (16, 17) and track and field athletes, particularly sprinters, to repetitive high-intensity symmetrical lower-limb loading associated with high rates of muscle force development (18). Early identification and characterization of these sport-specific adaptations may be essential for the development of targeted preventive strategies. However, previous studies have primarily focused on isolated parameters or single sports disciplines. A comprehensive, multidimensional comparison of postural alignment, lower limb biomechanics, muscle strength, and functional performance across different sports in adolescent competitive athletes is currently lacking. Therefore, the aim of the present study was to compare highly specialized youth athletes across different sports in order to investigate sport-specific static and dynamic biomechanical parameters as well as neuromuscular performance. We hypothesized that adolescent competitive athletes would demonstrate sport-specific differences across these domains and that these findings may allow the identification of sport-specific profiles.

2. Methods

Study Design and Participants

This study was a single-center cross-sectional investigation using non-invasive assessments. Athletes were recruited through existing collaborations with cooperating sports clubs, youth academies, and regional performance programmes in Northern Germany. Although recruitment was open to both sexes, no eligible female athletes volunteered to participate during the recruitment period. A total of 62 male adolescent athletes were included in the final analysis. According to the Participant Classification Framework proposed by McKay et al., all participants were classified as Tier 2 (Trained/Developmental) or Tier 3 (Highly Trained/National Level), as they completed structured sport-specific training at least four times per week and competed in national youth leagues or held regional or national squad status (19). The study adhered to the ethical principles of the 1964 Declaration of Helsinki, and written informed consent was obtained for each participant and their legal guardians following institutional review board

approval (Local Ethical Review Committee; study number: 2021-100686-BO-ff). Data collection was performed between 05/2022 and 12/2022.

Inclusion criteria required athletes to have a minimum of three years of sport-specific training experience, engage in organized training of at least four sessions per week (> 60 minutes per session), and be specialized in a single sport. Exclusion criteria included acute injuries or participation in multiple sports. Participants were aged 14 to 19 years. Four sport-specific groups were established: basketball (n = 20), football (n = 17), track and field (primarily sprint disciplines, n = 13), and golf (n = 12).

Assessments

The assessment protocol included collection of anthropometric data, questionnaires including history of sports participation, spinal and pelvic posture analysis, leg axis alignment, strength assessment and neuromuscular assessments. A structured questionnaire on sports participation was designed for this study; an English translation of the questionnaire is provided as a supplementary file. Basic data recorded prior to testing included body height, body weight, leg length (manual tape measurement), leg length difference (manual tape measurement), dominant side and shoe size. All assessments were performed in randomized order, following a standardized five-minute indoor cycling warm-up, with at least five minutes of rest between tests. A physical therapist supervised and guided all procedures. The test series consisted of a motion analysis system including static and dynamic (only knee axis) rasterstereography and leg axis analysis system, Functional Movement Screen (FMS™), Y-Balance Test (Y-BT), Jump Tests (Countermovement and Drop Jump), isometric strength measurements and the Knee-to-Wall-Test (KtW).

Rasterstereography

The video-rasterstereography system “Diers Formetric 4D” (Diers, Schlangenbad, Germany) is a non-invasive, radiation-free system used to analyze the spine, lower extremity alignment, and foot parameters. The examination was performed as previously described (20). Measurements were performed statically in neutral standing. Knee axis alignment was additionally assessed dynamically during walking at 5 km/h (21, 22). The following parameters were analyzed: torso length, dimple distance, trunk inclination, coronal imbalance, kyphotic and lordotic angles, surface rotation, apical deviation, pelvic inclination, pelvic torsion and rotation, foot rotation, knee angle, Achilles tendon angle, heel base angles, step lengths (single and double) and step width. For parameters describing rotations, inclinations, deviations or angles, higher absolute values indicate a greater magnitude of the respective biomechanical characteristic. Detailed definitions of all assessed parameters are presented in Table 1.

Table 1
Definitions of rasterstereographic parameters using the DIERS Formetric 4D system

Parameter	Definition
Torso Length	Vertical distance between C7 and the pelvic dimples
Dimple Distance	Horizontal distance between the left and right pelvic dimples
Trunk Inclination	Forward or backward inclination of the trunk relative to the vertical axis
Coronal Imbalance	Lateral deviation of the trunk from the body midline in the frontal plane
Kyphotic Angle	Sagittal curvature angle of the thoracic spine
Lordotic Angle	Sagittal curvature angle of the lumbar spine
Surface Rotation	Axial rotation of the back surface relative to the body axis
Apical Deviation	Maximum lateral deviation of the spinal midline from the reference line
Pelvic Inclination	Vertical height difference between the left and right pelvic dimples
Pelvic Torsion	Relative anterior–posterior tilt difference between both sides of the pelvis
Pelvic Rotation	Rotation of the pelvis around the vertical axis
Foot Rotation	Angle between the foot axis and the direction of progression
Knee Angle	Frontal plane alignment angle of the knee joint
Achilles Tendon Angle	Angle of the Achilles tendon relative to the lower leg axis
Heel Base Angle	Angle describing the alignment of the rearfoot/heel
Single Step Length	Distance between consecutive foot contacts of opposite feet
Double Step Length	Distance between two consecutive contacts of the same foot
Step Width	Mediolateral distance between the feet during gait

Functional Movement Screen

The Functional Movement Screen (FMS™; Functional Movement Systems, Danville, VA, USA) is a standardized assessment of functional movement parameters, including mobility, stability and coordination and comprises seven bodyweight exercises. Each exercise is scored 0 to 3 (3 = correct execution without compensation, 0 = pain during movement). The maximum score is 21 points (22, 23).

Y-Balance Test

The Y-Balance Test (Y-BT) assesses dynamic balance, coordination, and functional symmetry and was performed for the lower body as previously described (23). Standing in a fixed foot position with hands placed on hips, the distance athletes reached maximally was measured in three directions: anterior (A),

posteromedial (PM) and posterolateral (PL). Each leg was tested three times, and the maximum reach distance was used for analysis. Trials were considered invalid if the hands left the hips, the stance foot moved, or the free leg touched the ground before returning to the starting position. A composite score (COMP) was calculated, which sets the maximum range in relation to the previously measured leg length (in %) (24, 25).

Countermovement Jump and Drop Jump

Jumping performance was assessed using the OptoJump system (Microgate, Bolzano, Italy) as previously described (26). The following jumps were performed: Countermovement Jump (CMJ) and Drop Jump (DJ) off a 30 cm elevation. The hands were placed on the hips for all jumps. In addition, the reactive strength index (RSI) was calculated during the DJ by dividing flight time by ground contact time, providing an indicator of reactive strength capacity (26, 27).

Whole-Body Strength Measurement

Isometric strength was assessed using the DIERS myoline system (Diers, Schlangenbad, Germany), which measures maximum force of individual muscle groups via strain gauge technology. Each contraction was held for a few seconds under standardized conditions, and each muscle group was tested three times, with the highest recorded values used for analysis (28). Isometric strength assessment using dynamometry has been shown to provide reliable and valid measurements in youth populations (29). Athletes were instructed and allowed to practice the contractions, with short self-paced rest intervals between tests. A total of 22 muscle groups were evaluated: four lower-limb muscles on each side (leg extensors, flexors, hip abductors, hip adductors), four upper-limb muscles on each side (shoulder internal/external rotation, arm flexors/extensors), and six trunk muscles (flexion, extension, lateral flexion to the left and right, trunk rotation to the left and right). In addition, the hamstring-to-quadriceps (H/Q) ratio was calculated as the ratio of isometric knee flexor to extensor strength for each limb.

Knee-to-Wall-Test

Ankle dorsiflexion range of motion was assessed using the Knee-to-Wall-Test (KtW). A tape measure was placed at a 90-degree angle to the wall, with the toes initially positioned at 10 cm. The test was conducted barefoot. Participants attempted to touch the wall with the knee while keeping the heel down. If successful, the foot was moved backward in 1 cm increments until reaching the maximal dorsiflexion without heel lift (30). Football players did not perform this test due to organizational constraints.

Statistical Analysis

The statistical analysis was carried out using SPSS (Version 29.0, IBM Corp., Armonk, New York, United States). The normality of the data distribution was assessed using Shapiro-Wilk test. To compare the specific sports groups, single-factor analyses of variance (ANOVA) were used for normally distributed variables, while Kruskal-Wallis Tests were applied for non-normally distributed variables. In case of

significance, appropriate post-hoc tests were used for multiple comparisons using the Dunn test following Kruskal-Wallis tests and the Tukey test (HSD) following ANOVAs. The statistically significant difference was set at $p < 0.05$. To quantify the magnitude of the observed group differences, effect sizes were calculated for all comparisons. Eta-squared ($\eta^2 = (F \cdot df_1)/(F \cdot df_1 + df_2)$) was computed for ANOVAs and Epsilon-squared ($\varepsilon^2 = H/(N - 1)$) for Kruskal-Wallis tests. Both measurements range from 0 to 1, with values of 0.01, 0.06 and 0.14 interpreted as small, medium and large effects (31). The Bonferroni correction was applied to adjust for multiple comparisons. Correlations between parameters were assessed using Spearman's rank correlation, coefficients of $|r| \geq 0.5$ were interpreted as indicating moderate to strong relationships. The values of the coefficient ranged between − 1 and 1. To evaluate whether athletes could be classified into specific sports profiles, a cluster analysis was performed using representative variables from each assessment domain (anthropometric, biomechanical, neuromuscular performance and strength). The analysis included the following predefined variables: body height, trunk length, leg axis alignment, step length, FMS score, Drop Jump performance, and Myoline-measured strength of the leg extensors and flexors. Initially, a two-step cluster analysis was performed to identify the optimal number of naturally occurring clusters. Subsequently, a K-means cluster analysis was performed, specifically constrained to four clusters to align with the four sports groups. This study was conducted and reported in accordance with the STROBE guidelines.

3. Results

Baseline Data and History of Sports Participation

Age was comparable across all sports groups, with no significant between-group differences ($p = 0.146$). Group differences were observed in anthropometry and training parameters. Basketball players were the tallest group (184.7 ± 9.0 cm), while football players were the shortest (178.6 ± 6.3 cm; $p = 0.038$; $\varepsilon^2 = 0.138$). Track and field athletes had the highest body weight (76.7 ± 6.1 kg), whereas golfers were the lightest (65.3 ± 6.3 kg; $p = 0.002$; $\varepsilon^2 = 0.249$) (Table 2). Training frequency did not differ significantly between groups ($p = 0.127$). However, training duration per session differed significantly ($p < 0.001$; $\eta^2 = 0.549$), with golfers reporting the longest sessions (181.0 ± 41.8 min) (Table 2).

Table 2
Baseline characteristics and training variables across sports.

Variable	Football (n = 17)	Track and Field (n = 13)	Golf (n = 12)	Basketball (n = 20)	Test statistic	p-value	Effect size (η^2/ε^2)
Age (years)	16.8 (0.6)	16.5 (0.8)	16.2 (1.6)	16.2 (0.9)	H = 5.38	0.146	0.088
Height (cm)	178.6 (6.3)	184.5 (5.1)	179.4 (4.9)	184.7 (9.0)	H = 8.40	0.038	0.138
Weight (kg)	71.9 (5.5)	76.7 (6.1) [3]	65.3 (6.3) [2]	73.3 (13.0)	H = 15.20	0.002	0.249
Training frequency (days/month)	17.6 (3.2)	20.1 (3.0)	19.2 (2.4)	17.8 (3.5)	F = 1.98	0.127	0.093
Training frequency (days/week)	4.4 (0.8)	5.0 (0.8)	4.8 (0.6)	4.4 (0.9)	F = 1.98	0.127	0.093
Duration (min)	120.0 (0.0)[3]	122.5 (8.6)[3]	181.0 (41.8)[124]	127.5 (16.5)[3]	F = 23.53	< 0.001	0.549
Training history (years)	10.0 (2.8)[24]	6.58 (3.2)[1]	8.4 (1.8)	6.2 (3.4)[1]	F = 5.83	0.002	0.232

Values are mean (standard deviation). H = Kruskal-Wallis, F = ANOVA. Superscripts indicate pairwise differences ($p < 0.05$), compared with [1]Football, [2]Track and Field, [3]Golf, and [4]Basketball. Effect sizes are reported as ε^2 (Kruskal–Wallis) and η^2 (ANOVA); values of 0.01, 0.06 and 0.14 indicate small, medium and large effects, respectively.

Spinal and Pelvic Posture

Analysis of spinal and pelvic posture revealed few sports-specific differences. The lordotic angle differed significantly between groups ($p = 0.024$; $\varepsilon^2 = 0.154$), with football players showing the highest values (36.6 ± 6.9°) and track and field athletes the lowest (30.3 ± 3.9°). Mean thoracic kyphosis exceeded 40° in all groups without significant inter-sport differences ($p = 0.129$). Golfers showed a significantly greater trunk inclination compared to track and field athletes (golf: 4.6 ± 1.8°, track and field: 2.4 ± 2.3°, $p = 0.038$; $\varepsilon^2 = 0.137$). Coronal imbalance also differed between groups ($p = 0.032$; $\varepsilon^2 = 0.140$), with golfers demonstrating higher values compared with basketball players. No significant sport-specific differences were observed for pelvic parameters, including pelvic inclination, torsion, and rotation (all $p > 0.05$) (Table 3).

Table 3
Static postural parameters across sports.

Variable	Football (n = 17)	Track and Field (n = 13)	Golf (n = 12)	Basketball (n = 20)	Test statistic	p-value	Effect size (η^2/ ε^2)
Torso length (mm)	452.6 (24.1)	463.9 (24.5)	450.0 (24.9)	481.1 (51.7)	H = 4.13	0.208	0.075
Dimple distance (mm)	94.9 (13.5)	97.8 (11.5)	88.7 (15.1)	87.7 (19.8)	H = 5.59	0.134	0.092
Trunk inclination (°)	3.5 (1.9)	2.4 (2.3)[3]	4.6 (1.8)[2]	4.0 (2.5)	H = 8.35	0.038	0.137
Coronal imbalance (°)	-0.5 (1.4)	0.0 (1.1)	0.4 (0.8)[4]	-0.9 (1.3)[3]	F = 3.15	0.032	0.140
Kyphotic angle (°)	45.8 (6.5)	40.0 (3.1)	41.4 (7.6)	42.6 (8.1)	F = 1.97	0.129	0.092
Lordotic angle (°)	36.6 (6.9)[2]	30.3 (3.9)[1]	32.3 (5.3)	30.3 (7.0)	H = 9.42	0.024	0.154
Surface rotation (rms, °)	2.8 (1.5)	2.2 (0.8)	4.7 (5.6)	2.6 (1.9)	H = 1.58	0.663	0.026
Apical deviation (rms)	4.5 (4.0)	3.2 (2.1)	4.2 (1.6)	3.3 (1.6)	H = 2.89	0.408	0.047
Pelvic inclination (°)	-1.2 (6.4)	-0.5 (1.1)	1.1 (12.6)	-1.7 (6.4)	H = 0.02	0.999	0.000
Pelvic torsion (°)	1.5 (3.1)	1.9 (1.5)	-0.5 (3.2)	2.9 (6.0)	H = 5.31	0.150	0.087
Pelvic rotation (°)	0.5 (3.4)	-0.7 (1.7)	-0.8 (4.6)	3.6 (9.4)	H = 3.05	0.384	0.050

Values are mean (standard deviation). H = Kruskal-Wallis, F = ANOVA. Superscripts indicate pairwise differences ($p < 0.05$), compared with [1]Football, [2]Track and Field, [3]Golf, and [4]Basketball. Effect sizes are reported as ε^2 (Kruskal–Wallis) and η^2 (ANOVA); values of 0.01, 0.06 and 0.14 indicate small, medium and large effects, respectively.

Leg Axis Alignment and Foot Rotation

Lower limb alignment and gait parameters differed between the sports groups for several variables. For static knee alignment, significant differences were found for both the left ($p = 0.010$; $\eta^2 = 0.176$) and right knee ($p < 0.001$; $\eta^2 = 0.330$). Football players demonstrated higher varus angles on the left side (4.6 ±

4.1°) compared with golfers (1.0 ± 2.8°, p = 0.026) and basketball players (1.4 ± 2.5°, p = 0.020), and on the right side compared with all other groups (5.5 ± 3.1°, p < 0.001) (Table 4, Fig. 1).

During dynamic assessment, only the right knee varus angle showed significant differences between sports (p < 0.001; η^2 = 0.480), with football players exhibiting the highest values (5.5 ± 3.7°), whereas no significant differences were observed for the left side (p = 0.300) (Table 4).

Static Achilles tendon angle of the left side differed significantly between groups (p < 0.001; η^2 = 0.266), with basketball players presenting the largest values (7.9 ± 3.7°). Static foot rotation of the right foot also differed significantly (p < 0.001; ε^2 = 0.137), with track and field athletes demonstrating lower angles (4.3 ± 2.2°) compared to football players (8.9 ± 4.2°, p = 0.016), and basketball players (11.5 ± 5.6°, p < 0.001) (Table 4).

Significant group differences were also observed for gait parameters, including step length (left: p = 0.006; ε^2 = 0.207, right: p = 0.002; ε^2 = 0.244), double step length (p = 0.006), and step width (p = 0.007). Football and track and field athletes demonstrated longer step lengths (football: 68.0 ± 3.4 cm; track and field: 67.1 ± 9.9 cm), whereas basketball players exhibited the greatest step width (12.8 ± 3.3 cm) (Table 4).

Table 4
Lower limb alignment and gait parameters across sports.

Variable	Football (n = 17)	Track and Field (n = 13)	Golf (n = 12)	Basketball (n = 20)	Test statistic	p-value	Effect size (η^2/ ε^2)
Static foot rotation right (°)	8.9 (4.2)[2]	4.3 (2.2)[14]	8.5 (5.0)	11.5 (5.6)[2]	H = 17.99	< 0.001	0.295
Static foot rotation left (°)	6.7 (7.8)	9.6 (9.3)	7.8 (4.2)	10.8 (7.9)	H = 2.53	0.470	0.041
Static knee left (°)	4.6 (4.1)[34]	2.2 (3.2)	1.0 (2.8)[1]	1.4 (2.5)[1]	F = 4.13	0.010	0.176
Static knee right (°)	5.5 (3.1)[234]	2.5 (3.2)[1]	1.5 (2.2)[1]	0.6 (2.9)[1]	F = 9.53	< 0.001	0.330
Static Achilles tendon left (°)	3.7 (3.6)[4]	3.9 (2.7)[4]	6.6 (2.4)	7.9 (3.7)[12]	F = 7.00	< 0.001	0.266
Static Achilles tendon right (°)	5.5 (3.4)	3.2 (2.9)	6.0 (3.2)	4.4 (3.4)	H = 4.47	0.215	0.073
Static heel base left (°)	-0.6 (3.4)	0.2 (2.9)	-0.7 (5.6)	-0.9 (5.6)	H = 0.55	0.908	0.009
Static heel base right (°)	0.8 (3.7)	-0.5 (3.4)	2.2 (5.8)	-0.1 (3.0)	F = 1.18	0.324	0.058
Dynamic knee left (°)	2.3 (3.5)	1.1 (2.1)	0.8 (2.0)	0.8 (3.0)	H = 3.66	0.300	0.060
Dynamic knee right (°)	5.5 (2.7)[234]	0.8 (2.1)[1]	-0.4 (2.7)[1]	-0.6 (3.2)[1]	F = 17.88	< 0.001	0.480
Single step length left (cm)	68.0 (3.4)[4]	67.1 (9.9)	61.6 (2.7)	61.1 (8.0)[1]	H = 12.60	0.006	0.207
Single step length right (cm)	68.5 (3.6)[24]	66.4 (8.8)	59.0 (5.3)[1]	60.7 (8.0)[1]	H = 14.90	0.002	0.244
Double step length (cm)	112.4 (3.6)[3]	107.7 (12.5)	96.9 (3.7)[1]	102.8 (18.1)	H = 12.40	0.006	0.203
Step width (cm)	9.0 (2.4)[4]	9.7 (2.8)	11.1 (4.0)	12.8 (3.3)[1]	H = 11.98	0.007	0.196

Values are mean (standard deviation). H = Kruskal-Wallis, F = ANOVA. Superscripts indicate pairwise differences ($p < 0.05$), compared with ¹Football, ²Track and Field, ³Golf, and ⁴Basketball. Effect sizes are reported as ε^2 (Kruskal–Wallis) and η^2 (ANOVA); values of 0.01, 0.06 and 0.14 indicate small, medium and large effects, respectively.

Strength Assessment

Isometric strength parameters differed significantly between the sports groups for several muscle groups of the lower extremity, upper extremity, and trunk.

In the lower extremities, significant group differences were observed for leg extensor strength (left: $p = 0.003$; $\varepsilon^2 = 0.223$, right: $p < 0.001$; $\varepsilon^2 = 0.267$) as well as hip abduction and adduction (all $p < 0.001$; $\varepsilon^2 = 0.327–0.351$), with track and field athletes consistently demonstrating the highest strength values, whereas golfers showed lower values (e.g., hip adduction right in golf: 1,263.4 ± 522.8 N vs. track and field: 2,285.9 ± 285.0 N, Supplementary Table 1). The H/Q ratio ranged between approximately 0.26 and 0.35 across groups, with football players showing the lowest ratios. Side-to-side comparisons between dominant and non-dominant extremities revealed significant differences in leg extensor strength in football ($p = 0.005$), track and field ($p = 0.031$), and golf athletes ($p = 0.004$), whereas no differences were observed in basketball players ($p = 0.313$). No side-to-side differences were found for leg flexor strength (all $p > 0.05$) (Table 5).

In the upper extremities, significant differences were found for shoulder internal rotation (left: $p < 0.001$, $\varepsilon^2 = 0.406$; right: $p < 0.001$, $\varepsilon^2 = 0.514$) and forearm flexor (left: $p < 0.001$, $\varepsilon^2 = 0.356$, right: $p < 0.001$, $\varepsilon^2 = 0.351$) and extensor strength (left: $p < 0.001$, $\varepsilon^2 = 0.303$, right: $p = 0.003$, $\varepsilon^2 = 0.235$), with greater strength values in football and track and field athletes compared with golfers and basketball players (e.g., shoulder internal rotation right in track and field: 860.5 ± 235.8 N vs. golf: 477.3 ± 140.3 N). Trunk strength also differed significantly between groups, including flexion ($p = 0.008$; $\varepsilon^2 = 0.195$), extension ($p = 0.007$; $\varepsilon^2 = 0.201$), trunk rotation (left: $p = 0.001$, $\varepsilon^2 = 0.254$; right: $p < 0.001$, $\varepsilon^2 = 0.286$), and lateral flexion (left: $p < 0.001$, $\varepsilon^2 = 0.290$; right: $p < 0.001$, $\varepsilon^2 = 0.239$). Track and field athletes demonstrated the highest trunk rotation strength (e.g., left: 454.3 ± 149.3 N), whereas football players showed higher trunk flexion and extension strength compared with basketball players (e.g., trunk flexion in football: 320.7 ± 100.7 N vs. basketball: 208.6 ± 75.8 N) (Supplementary Table 1).

Table 5
Dominant vs. non-dominant lower limb strength across sports.

Variable	Side	Football (n = 17)	Track and Field (n = 13)	Golf (n = 12)	Basketball (n = 20)
Leg flexor (N)	Dominant	123.2 (37.1)	156.8 (72.4)	137.8 (69.1)	118.0 (50.8)
	Non-dominant	130.0 (46.3)	168.1 (70.0)	135.8 (45.9)	120.4 (42.4)
	p-value	0.341	0.807	0.894	0.721
Leg extensor (N)	Dominant	483.1 (123.5)[1]	507.5 (144.9)[1]	465.3 (113.6)[1]	340.8 (101.3)
	Non-dominant	443.8 (95.4)[1]	497.0 (133.5)[1]	417.4 (136.4)[1]	353.1 (118.8)
	p-value	0.005	0.031	0.004	0.313

Values are mean (SD). P-values represent within-group comparisons between dominant and non-dominant side. Superscripts indicate a significant difference between the dominant and non-dominant side within the respective sport ($p < 0.05$).

Functional Assessment

Balance performance, expressed as the Y-BT composite score, differed significantly between groups for both legs (left: $p < 0.001$, $\varepsilon^2 = 0.337$; right: $p < 0.001$, $\varepsilon^2 = 0.403$). Track and field athletes and golfers demonstrated higher values (e.g., right side, track and field: 115.6 ± 12.9%, golf: 119.2 ± 10.4%) compared with football (left: 104.3 ± 10.8%) and basketball players (left: 101.4 ± 13.8%) (Table 6). In addition, golfers achieved the highest scores in the FMS (18.1 ± 1.4), significantly higher than football and track and field athletes (football: 14.9 ± 2.0, track and field: 15.9 ± 1.4, $p < 0.001$; $\varepsilon^2 = 0.363$). Jump performance differed significantly between sports for CMJ ($p < 0.001$, $\varepsilon^2 = 0.675$), DJ ($p < 0.001$, $\varepsilon^2 = 0.306$), and RSI ($p < 0.001$, $\varepsilon^2 = 0.592$). Football and track and field athletes demonstrated higher values compared with golfers and basketball players (e.g., CMJ in football: 46.0 ± 4.1 cm, track and field: 42.8 ± 5.4 cm, golf: 27.7 ± 4.5 cm, basketball: 28.7 ± 6.4 cm; RSI in football: 1.9 ± 0.45, track and field: 1.7 ± 0.4, golf: 1.1 ± 0.3, basketball: 1.1 ± 0.3) (Table 6). No significant differences were observed for ankle dorsiflexion range of motion assessed by the KtW test (left: $p = 0.677$; right: $p = 0.104$) (Table 6).

Table 6
Functional performance parameters across sports.

Variable	Football (n = 17)	Track and Field (n = 13)	Golf (n = 12)	Basketball (n = 20)	Test statistic	p-value	Effect size (η^2/ε^2)
Y-BT composite score left (%)	104.3 (10.8)	114.8 (14.0)[4]	117.7 (11.0)[4]	101.4 (13.8)[23]	H = 20.55	< 0.001	0.337
Y-BT composite score right (%)	103.6 (9.1)	115.6 (12.9)[4]	119.2 (10.4)[4]	101.3 (12.2)[23]	H = 24.60	< 0.001	0.403
FMS (score)	14.9 (2.0)[3]	15.9 (1.4)[3]	18.1 (1.4)[12]	16.6 (1.5)	H = 22.13	< 0.001	0.363
CMJ (cm)	46.0 (4.1)[34]	42.8 (5.4)[34]	27.7 (4.5)[12]	28.7 (6.4)[12]	H = 41.17	< 0.001	0.675
DJ (cm)	39.2 (4.8)[34]	37.0 (8.7)[3]	26.1 (7.6)[12]	32.2 (9.0)[1]	H = 18.65	< 0.001	0.306
RSI	1.9 (0.4)[34]	1.7 (0.4)[34]	1.1 (0.3)[12]	1.1 (0.3)[12]	H = 36.13	< 0.001	0.592
KtW test left (cm)	—	12.8 (2.2)	14.0 (4.0)	12.7 (2.6)	H = 0.78	0.677	0.018
KtW test right (cm)	—	12.5 (3.3)	15.0 (4.7)	12.0 (2.1)	H = 4.53	0.104	0.103

Values are mean (SD). H = Kruskal-Wallis, F = ANOVA. Superscripts indicate pairwise differences ($p < 0.05$), compared with [1]Football, [2]Track and Field, [3]Golf, and [4]Basketball. Effect sizes are reported as ε^2 (Kruskal–Wallis) and η^2 (ANOVA); values of 0.01, 0.06 and 0.14 indicate small, medium and large effects, respectively.

Abbreviations: CMJ, countermovement jump; DJ, drop jump; RSI, reactive strength index; FMS, Functional Movement Screen; KtW, knee-to-wall test; Y-BT, Y-Balance-Test.

Correlation and Cluster Analysis

Correlation analysis across the overall dataset and sport-specific subsamples resulted in a total of 14,260 calculated correlations. Of these, 1,283 correlations exceeded the predefined threshold of $|r| \geq 0.5$. Given the exploratory nature and the large number of calculated correlations, only moderate to strong associations that remained statistically significant after correction are reported. Table 7 summarizes significant correlations in the overall dataset between performance tests and other variables. Strong positive correlations were observed between sport motor tests themselves. Notably, a strong positive correlation was found between RSI and CMJ ($r = 0.807$, $p < 0.001$), as well as between CMJ and DJ height ($r = 0.723$, $p < 0.001$) (Table 7).

Balance performance was significantly associated with strength parameters, particularly in the upper and lower extremities (e.g., Y-BT composite score and arm flexor strength: $r = 0.636$, $p < 0.001$). In addition, hip adduction and abduction strength were positively associated with jump performance (e.g., CMJ and hip adduction: $r = 0.579$, $p < 0.001$). Both static and dynamic knee alignment showed significant positive associations with performance measures. Dynamic knee alignment correlated with RSI ($r = 0.562$, $p < 0.001$) and CMJ ($r = 0.552$, $p < 0.001$), while static knee alignment was also associated with performance parameters (e.g., CMJ: $r = 0.531$, $p < 0.001$). In contrast, trunk inclination showed a negative correlation to RSI ($r = -0.531$, $p < 0.001$) (Table 7).

Table 7. Selected significant correlations between sport-motor performance tests and biomechanical parameters in the overall cohort.

Variable 1	Variable 2	r	p-value
Composite score right	Composite score left	0.869	<0.001
Reactive Strength Index	Countermovement Jump	0.807	<0.001
Knee to Wall test right	Knee to Wall test left	0.761	<0.001
Reactive Strength Index	Drop Jump	0.740	<0.001
Drop Jump	Countermovement Jump	0.723	<0.001
Countermovement Jump	Shoulder internal rotation right	0.663	<0.001
Composite score right	Arm flexor right	0.636	<0.001
Composite score right	Arm flexor left	0.635	<0.001
Reactive Strength Index	Shoulder internal rotation right	0.606	<0.001
Countermovement Jump	Hip adduction left	0.579	<0.001
Countermovement Jump	Shoulder internal rotation left	0.578	<0.001
Reactive Strength Index	Hip adduction right	0.576	<0.001
Reactive Strength Index	Hip abduction right	0.572	<0.001
Countermovement Jump	Hip adduction right	0.571	<0.001
Reactive Strength Index	Hip adduction left	0.570	<0.001
Drop Jump	Hip adduction left	0.569	<0.001
Reactive Strength Index	Dynamic knee right	0.562	<0.001
Countermovement Jump	Dynamic knee right	0.552	<0.001
Reactive Strength Index	Hip abduction left	0.543	<0.001
Hip abduction right	Hip adduction right	0.539	<0.001
Countermovement Jump	Hip abduction right	0.534	<0.001
Countermovement Jump	Hip abduction left	0.530	<0.001
Reactive Strength Index	Static knee right	0.530	<0.001
Countermovement Jump	Static knee right	0.519	<0.001
Reactive Strength Index	Trunk inclination	-0.503	<0.001

Spearman correlation coefficients (r) for the overall cohort. To highlight associations of interest, correlations between sport-motor performance tests and other assessed parameters are shown, with $|r| \geq 0.5$ and $p < 0.001$.

Sport-specific correlation analyses revealed additional findings. In golfers, a significant negative correlation was observed between RSI and the kyphotic angle ($r = -0.657$, $p = 0.020$). Further results between sport motor tests and other variables are presented in Supplementary Table 2.

The two-step cluster analysis resulted in a single-cluster solution with medium cluster quality, indicating a lack of distinct natural groupings within the data. When a four-cluster solution was forced using K-means analysis, the variables failed to provide a clear and significant differentiation between the sports disciplines (Figure 2).

4. Discussion

This study demonstrates that competitive adolescent athletes exhibit significant sport-specific differences in biomechanical parameters and neuromuscular performance. Significant differences were observed in spinal posture, leg axis alignment, foot rotation, muscle strength, jump performance and balance tasks. Correlation analyses indicated associations between strength, alignment, and performance, whereas cluster analysis did not reveal distinct sport-specific profiles.

Spinal and Pelvic Posture

In the present study, all athletes, regardless of sport type, exhibited thoracic kyphosis angles above 40° and exceeded commonly reported reference values of 20–40° (17,32). Similar findings were reported in adolescent athletes, linking higher training loads to increased thoracic kyphosis and lumbar lordosis (33). Elevated kyphotic angles have also been documented in adolescent athletes from various sports, suggesting that repetitive axial loading and growth-related factors may contribute to altered spinal curvature (34,35). Despite these alterations, no differences between disciplines were observed, which may suggest that increased thoracic kyphosis reflects a more general characteristic of adolescent competitive athletes rather than a discipline-specific finding. Findings from this study do not allow for further interpretation on whether changes in spinal posture are physiological adaptations to repetitive training loads or could support pathologies such as spondylolysis. Our analysis further revealed that trunk inclination was the highest in golf and the lowest in track and field athletes. This finding is consistent with the characteristic forward-flexed posture and unilateral loading patterns during the golf swing, which are known to influence spinal biomechanics (36). Despite these observations, the absence of significant differences in pelvic parameters across groups suggests that pelvic alignment remains relatively stable and less susceptible to sport-specific adaptations, particularly in young athletes.

Leg Axis Alignment and Foot Rotation

The pronounced genu varum observed in football players clearly supports previous reports suggesting that football-specific movement patterns, such as repetitive asymmetric loading during kicking and cutting, may be associated with structural characteristics of the lower limb (11,37,38). These differences were among the most pronounced biomechanical findings in the present study (static right knee $\eta^2 = 0.330$; dynamic right knee $\eta^2 = 0.480$). These mechanical stresses most likely lead to tibiofemoral bone

adaptations and can explain the higher prevalence of varus angles among football players (37,38). Such adaptations are thought to develop during adolescence, when mechanical loading interacts with skeletal growth, and may persist into adulthood, as described by Steffen et al. and Colyn et al. (10,11). In contrast, basketball and track and field athletes demonstrated more neutral or slightly valgus leg axes, consistent with the predominantly symmetrical, vertical-loading and kicking-free patterns of their sports. While such alignment characteristics have been discussed in relation to injury and degenerative joint disease occurrence, particularly anterior cruciate ligament injuries and medial-sided osteoarthritis of the knee, the present study did not assess pathology outcomes. Therefore, these findings should be interpreted as descriptive rather than predictive with regard to injury risk (39). Golfers displayed the least deviation from neutral, likely reflecting the relatively low-impact and the absence of high-velocity cutting or contact situations of the sport (40).

Basketball players exhibited a significantly increased Achilles tendon angle on the left side. This unilateral difference may reflect sport-specific loading patterns, as repetitive jump–landing maneuvers are often performed with side-dominant strategies. As described for bone stress injuries, repetitive mechanical loading can induce structural adaptations of musculoskeletal tissues in response to accumulated loading demands (41, 42). The observed differences may represent sport-specific adaptations or loading demands; however, it remains unclear whether this reflects functional optimization or increased mechanical stress exposure.

Strength and Functional Assessment

The high strength levels observed in track and field (sprinting) athletes are consistent with previous reports that explosiveness-oriented sports elicit greater peak torque and explosive strength as compared to endurance or team sports (43). These differences likely reflect sport-specific training adaptations, with repetitive high-force and high-velocity movements promoting enhanced neuromuscular development. In contrast, athletes in team sports may prioritize coordination, endurance, and sport-specific technical and tactical skills rather than maximal strength. A similar tendency was observed in the Y-BT, where track and field athletes and golfers achieved higher composite scores than basketball players and showed slightly higher values compared with football players, suggesting better dynamic balance and lower-limb control.

The H/Q ratio was consistently below 0.5 across all groups, aligning with previously reported values in athletic populations (44). While this may reflect quadriceps-dominant adaptations associated with repetitive sprinting, jumping, and rapid deceleration, adequate hamstring strength remains essential for dynamic knee stabilization and force transmission during high-demand movements such as cutting and braking (45).

Athletes across all sports exhibited relatively low trunk flexion and extension strength, although the typical pattern of stronger extensors compared with flexors was preserved. One possible explanation is that sport-specific training programs emphasize lower-limb power and sport-specific skills, while targeted core stabilization and trunk strength training may receive less attention (46). Reduced trunk

muscle strength has been associated with an increased risk of low back pain (47) and may contribute to suboptimal load distribution during repetitive sagittal and rotational movements in sports.

Jump performance was highest in football players and track and field athletes, suggesting sport-specific neuromuscular adaptations in explosive lower-limb power. These differences corresponded to large effect sizes for the countermovement jump ($\varepsilon^2 = 0.675$) and reactive strength index ($\varepsilon^2 = 0.592$). Previous studies reported comparable jump performance across team sports, indicating that the observed differences may be related to training emphasis, competitive level, or maturation status rather than sport discipline alone (48).

Anthropometric characteristics may further contribute to the comparatively lower values, particularly in the basketball group. Greater body mass and limb length can influence force–velocity characteristics and jump mechanics, reducing relative jump output (49-51).

Correlation and Cluster Analysis

Correlation analysis across all sports disciplines revealed that greater muscular strength in both upper and lower extremities was associated with superior jump performance. This is consistent with previous research, as Wisløff et al. (52) linked maximal lower-body strength to vertical jump height. In addition, Diker et al. (53) reported an association between upper-body strength and sprint performance in young football athletes. Given the shared neuromuscular demands of sprinting and jumping, upper-body strength may also contribute to effective force transmission during vertical jumping.

Of note, greater varus alignment of the knee joint was positively correlated with jump performance. This may reflect altered load distribution or sport-specific mechanical adaptations influencing force generation during take-off. While frontal plane knee alignment is known to affect joint mechanics and muscle activation (54), this finding should be interpreted cautiously, as direct evidence linking static varus alignment to jump performance is currently lacking.

In contrast, increased anterior trunk inclination was negatively associated with jump performance. A more pronounced forward trunk posture may alter the distribution of joint moments during the take-off phase and reduce the contribution of the knee extensors to vertical force production. Experimental data have shown that forward trunk inclination can significantly modify joint power output during vertical jumping (55).

Notably, no substantial correlations were observed across the entire cohort of athletes between jump performance or mobility test outcomes and sagittal spinal parameters, such as kyphosis or lordosis angles. However, within the golf subgroup, increased kyphosis was negatively correlated with RSI and DJ performance. This finding is in line with previous research by Theodorou et al. (56). Nevertheless, the small sample size of this subgroup limits the generalizability of these results.

The cluster analysis conducted to identify sport-specific profiles based on the biomechanical and functional parameters did not reveal distinct groupings according to sport disciplines, indicating

substantial overlap between athletes across sports. This suggests that sport-specific differences in individual parameters do not necessarily translate into clearly separable multidimensional profiles at the individual level. This may be explained by several factors. First, the relatively small sample size within each sport group may have limited the ability to detect robust multidimensional profiles, as cluster-based approaches typically require large datasets. Second, the participants were adolescents undergoing substantial biological maturation (2-6). During this phase, growth-related changes and individual variability may mask sport-specific adaptations. In addition, many of the assessed parameters, such as strength, jump performance, or balance, represent general athletic capacities shared across sports, potentially limiting the emergence of distinct clusters. Future studies with larger samples, longitudinal designs, and more sport-specific variables may provide further insights into potential clustering patterns across sports disciplines.

The limitations of this study include the comparatively small sample size which is due to a limited availability of Tier 2-3 athletes. Therefore, generalizability is limited. Biological maturation status of the athletes was not assessed and may have influenced the observed differences. Furthermore, due to the cross-sectional nature of the study, causal conclusions cannot be drawn. It must be considered that inter-individual variability may reflect not only sport-specific adaptations but also inherent characteristics that predispose athletes to excel in a given sport. Readers should also note that this study included competitive adolescent athletes from four selected sport disciplines; therefore, findings may not be generalizable to other sports.

5. Conclusion

In conclusion, competitive adolescent athletes exhibited sport-specific differences in static and dynamic biomechanical parameters, muscle strength, and neuromuscular performance. These differences were particularly evident in spinal posture, lower limb alignment, strength, and motor performance tests. Although no distinct sport-specific cluster profiles were identified, the findings suggest that sport-specific characteristics can be detected at the group level but do not clearly separate athletes at the individual profile level. These exploratory findings may inform the development of sport-specific screening approaches and future injury prevention strategies. Longitudinal studies are required to determine their relevance for injury risk and athlete development.

Declarations

Patient and public involvement:

Patients and the public were not involved in the design, conduct, reporting, or dissemination of this study. All participants and their legal guardians received written information about the study procedures prior to participation.

Ethics approval and consent to participate:

The study was conducted in accordance with the Declaration of Helsinki. Ethical approval was obtained

from the Ethics Committee of the Medical Association of Hamburg (reference number: 2021-100686-BO-ff). Written informed consent was obtained from all participants and their legal guardians prior to participation.

Consent for publication:
Not applicable.

Consent to publish:

Not applicable.

Availability of data and materials:
The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

Competing interests:
The authors declare that they have no competing interests. KH is Editor for the German Journal of Sports Medicine, Associate Editor for BMJ Open Sports and Exercise Medicine and Chief Medical Officer of the German Athletics Federation.

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Authors' contributions:
DD conceived and designed the study and supervised the project. VS, GW and DD contributed to participant recruitment and data collection. AS and VS performed the statistical analyses. All authors contributed to data interpretation. VS drafted the first version of the manuscript. All authors critically revised the manuscript for important intellectual content, approved the final version of the manuscript, and agree to be accountable for all aspects of the work.

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Figures

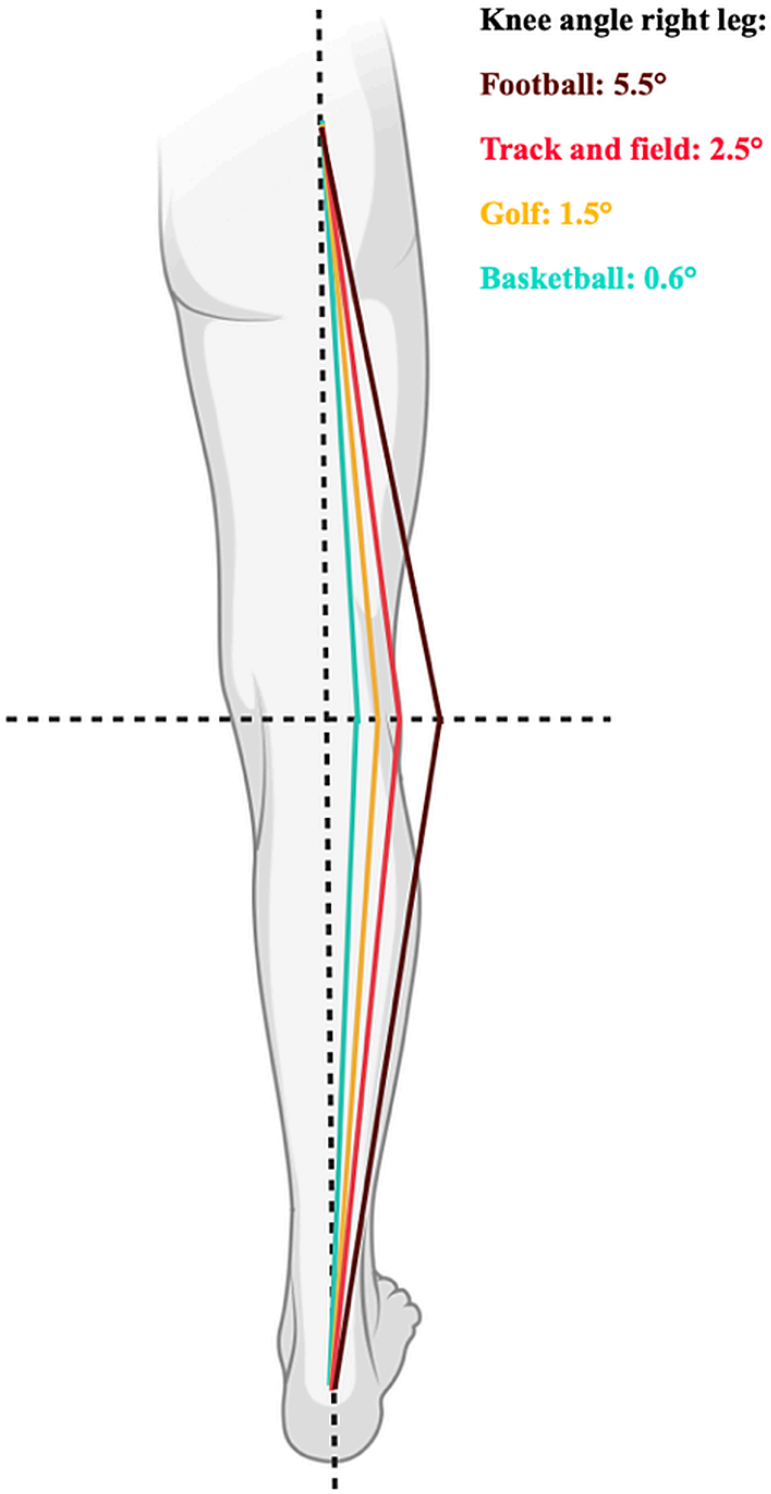


Figure 1

Schematic illustration of the static knee alignment of the right leg across sport disciplines. Sport disciplines are highlighted in different colors (football = dark red, track and field = light red, golf = yellow,

basketball = turquoise). (Created in BioRender. Stoll, V., https://BioRender.com/dbdcteb , is licensed under CC BY 4.0.)

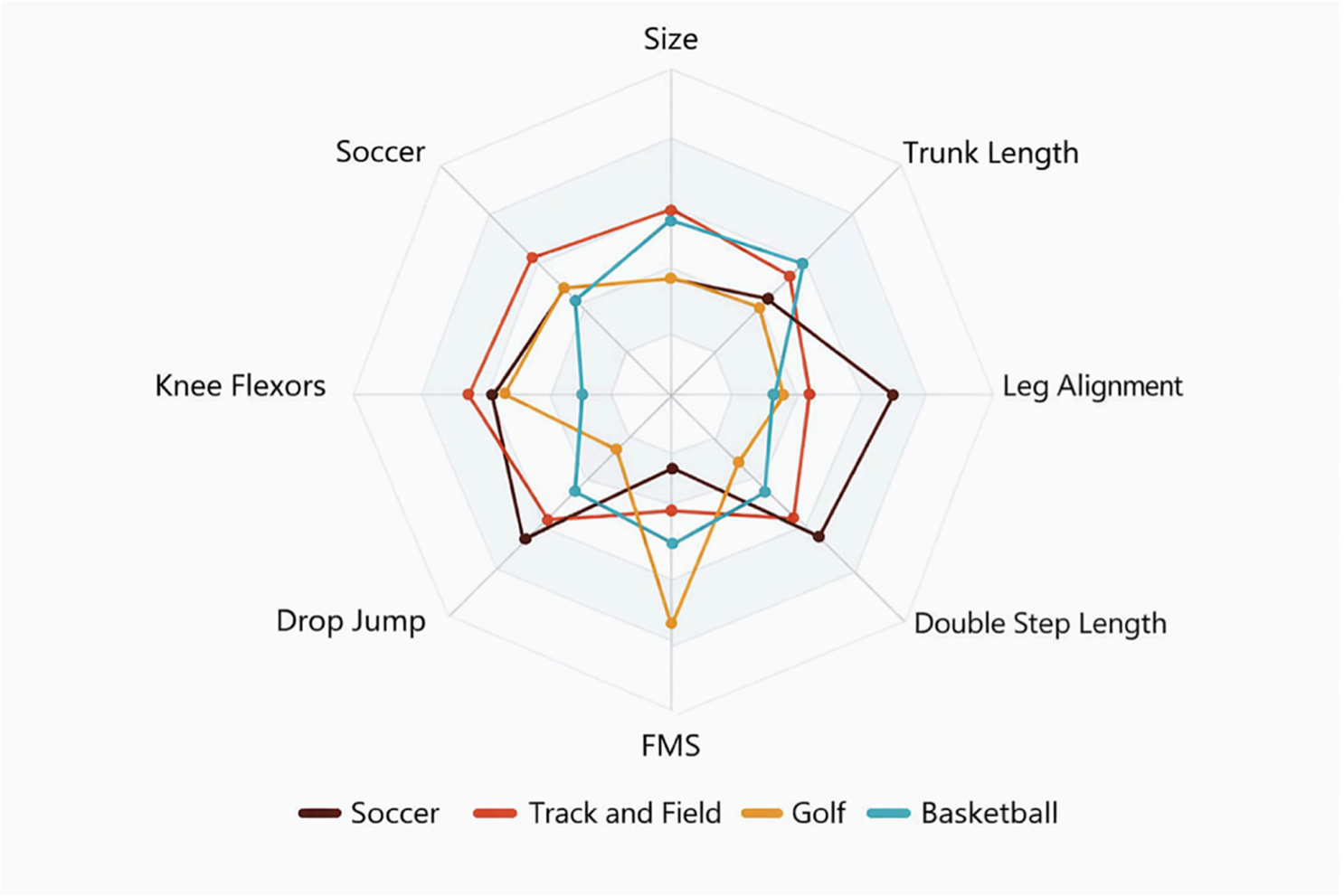


Figure 2

Radar plot illustrating the cluster profiles of the different sports based on selected anthropometric, postural, performance, and strength parameters. Values represent group-level mean percentile ranks derived from z-standardized scores. Raw scores were first z-standardized within each variable and then converted into percentile ranks to facilitate comparison across variables with different original scales. Higher values indicate higher relative standing within the respective variable distribution. Sport disciplines are highlighted in different colors (football = dark red, track and field = light red, golf = yellow, basketball = turquoise).

Supplementary Files

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