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RESEARCH

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High hamstring stiffness and flexibility with comparable spinopelvic morphometry in amateur footballers: a multimodal study

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Abstract

Background Football's repetitive lower-extremity biomechanics may drive functional adaptations in the hamstrings and spinopelvic alignment. We hypothesised that footballers would display greater hamstring stiffness and morphometric differences in SPPs, attributable to sport-specific loading, compared with non-athletes. This study therefore investigates the interrelationships among hamstring stiffness, flexibility, and spinopelvic alignment to clarify football-induced adaptations.

Methods This cross-sectional study included 50 licensed amateur male football players (Group A; mean age 21.74 ± 2.91 years) and 50 healthy males with no licensed sports participation (Group B; mean age 23.14 ± 2.98 years). Measurements comprised radiographic assessment of SPPs, Shear-Wave elastography (SWE) to quantify hamstring muscle stiffness, and clinical flexibility tests (CFTs) which consist of the Active Knee Extension (AKE) test, the Straight Leg Raise (SLR) test, and the Sit-and-Reach (SR) test.

Results No significant differences were detected between the groups in SPPs. All hamstring SWE values (except for the left Biceps Femoris, $p = 0.615$) and all CFT values were significantly higher in Group A ($p < 0.001$), indicating the 'high stiffness/high flexibility' paradox. Within Group A, SPPs were not associated with either SWE values or CFT values ($p > 0.05$). Likewise, no correlations were found between SWE values and CFT values in either group ($p > 0.05$).

Conclusions Footballers exhibited higher hamstring stiffness yet showed no spinopelvic morphometric differences compared with non-athletes. The absence of SWE–CFT correlations suggests that these methods assess distinct physiological properties. The observed "high stiffness/high flexibility" paradox in footballers indicates sport-specific functional adaptations. Future longitudinal studies are needed to clarify the long-term effects of this phenomenon.

Keywords Sports, Football, Adaptation, Sports biomechanics, Posture

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Introduction

The biomechanical balance between the spine, pelvis and lower extremity muscles is important for maintaining human posture and performing functional movements [1]. Lumbar lordosis (LL) is the physiological curvature of the spine and transfers the body weight to the pelvis and lower extremities in a balanced manner [2]. Lumbar curvature depends on the geometry of the pelvis and the balance between pelvic parameters such as sacral slope (SS), pelvic tilt (PT) and pelvic incidence (PI) in addition to the alignment of the vertebrae [3–5].

Football is a high-paced and multi-faceted sport that places high loads on the lower extremity muscles [6]. The hamstring muscles play a role in movement production and postural stability in football players through eccentric and concentric contractions [7]. Increased muscle strength requirements and postural balance demands can lead to increased muscle elasticity and stiffness in football players [8]. These structural adaptations can affect not only muscle functions but also lumbar spine and pelvic morphology [9, 10].

There are many studies examining the effects of sports on the musculoskeletal system, but most of them focus on performance, injury risk and muscle activation [6, 11–15]. The relationship between the flexibility and stiffness of the hamstring muscles and posture has been frequently examined in sports focused on the lower extremity [7, 8]. However, most studies are based only on clinical flexibility tests (CFTs) or focus on specific parts of the body [9, 10]. The number of studies that evaluate the spine, pelvis and muscle structure simultaneously with radiological and elastographic methods is limited. In the literature, there is no comprehensive study in which LL and pelvic alignment are evaluated with X-ray and hamstring stiffness is evaluated with SWE in a sport that involves repetitive loads such as football.

This study aims to compare spinopelvic parameters (SPPs), hamstring stiffness, and clinical flexibility between licensed amateur male football players and healthy male individuals who do not actively participate in licensed sports, and to investigate the relationships among these measures. SPPs were measured with X-ray, and hamstring stiffness was assessed using Shear-Wave elastography (SWE) and clinical flexibility was evaluated with the Active Knee Extension (AKE), Straight Leg Raise (SLR), Sit and Reach (SR) tests. The study design is summarized in Fig. 1.

The hypothesis is that hamstring stiffness will be higher in football players due to sports-related loads, and morphometric differences will occur in SPPs. It is predicted that these adaptations may lead to changes not only in muscle structure but also in postural alignment. This

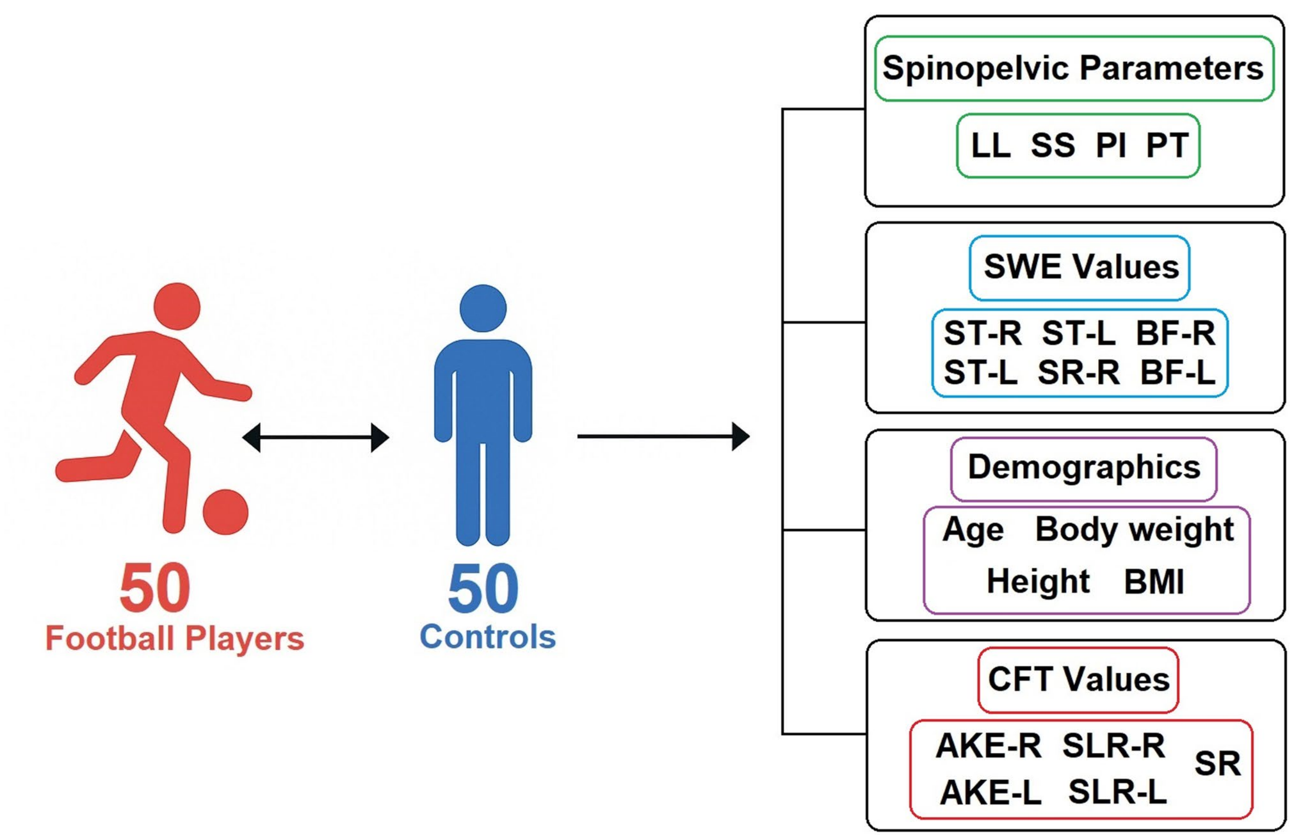

Fig. 1 Graphical abstract

study is expected to shed light on the football-specific interrelationships among hamstring stiffness, clinical flexibility, and spinopelvic alignment, thereby clarifying the musculoskeletal adaptations induced by the sport.

Materials and methods

Participant selection and collection of demographic data

This study was performed in accordance with the principles of the Declaration of Helsinki. The study was approved by the Bezmialem Vakıf University Ethics Committee (decision number: 2024/251), and institutional permissions were also obtained from the Kahramanmaraş Provincial Health Directorate of the Republic of Turkey Ministry of Health and Necip Fazıl City Hospital. The purpose and process of the study were explained to the participants, and written informed consent was obtained from all participants.

This cross-sectional study was conducted with a total of 100 healthy male individuals aged between 18 and 30 years. Two independently designed groups were included in the study. Group A comprised 50 male amateur football players who had at least three years of licensed experience and were actively playing in the amateur football leagues of Kahramanmaraş province during the 2024–2025 season. Group B comprised 50 healthy male individuals with no history of licensed football participation, who were not actively engaged in either professional or amateur sports, and who had no chronic musculoskeletal disorders. Participants in Group B were selected based on age- and sex-matching and voluntary participation, without the use of any specific tests or questionnaires. For all participants, age, height, weight, body mass index (BMI) were recorded; in Group A, license year data were additionally collected. Exclusion criteria included musculoskeletal disease, neurological disorder, history of lower extremity or lumbar spine surgery, or presence of acute pain. Individuals with a history of hamstring injury within the past six months, clinical low back pain within the past year, a BMI $\geq$ 30, or chronic systemic diseases such as diabetes, hypertension, cardiovascular, rheumatic, or respiratory conditions were also excluded.

Radiological measurement of spinopelvic parameters

The lumbar spine and pelvis were evaluated radiologically with standing lateral radiographs. During imaging, participants were positioned in a natural posture, with knees extended and feet shoulder-width apart. The upper extremities were extended forward. Rotation of the pelvis was prevented. All images were taken digitally and measured by the same radiologist. The LL angle was determined as the angle between the T12 lower plane and the S1 upper plane using the Cobb method. This angle was used to evaluate the physiological curvature and sagittal alignment of the lumbar region [16, 17]. Pelvic parameters were evaluated as SS, PT and PI angles. SS, the angle between the upper endplate of the sacrum and the horizontal plane; PT, the angle between the line between the femoral head and the upper midpoint of the sacrum and the vertical axis; PI was measured as the angle between the line between the upper midpoint of the sacrum and the femoral head and the tangent line to the sacrum surface [16–18].

Hamstring muscle stiffness assessment with SWE

The SWE method was used to quantitatively assess the passive stiffness of the hamstring muscles. All measurements were performed by a radiologist with at least 5 years of experience using the Mindray Resona R9 device. Participants were positioned in the prone position, with the hips neutral and the knees extended; a roll was placed under the ankle and measurements were made only at rest. Both lower extremities were evaluated separately; semitendinosus (ST), semimembranosus (SM) and the long head of the biceps femoris (BF) were examined. Measurements were made only from the mid-belly (trunk) region of each muscle and standardized according to anatomical reference points specific to the muscles. Measurements were taken 10–15 cm distal from the ischial tuberosity for ST and SM, and 5–7 cm distal from the gluteal crease for BF. The probe was placed parallel to the muscle fiber direction; Three measurements were made for each muscle and the mean value was used in the analyses [19, 20]. Stiffness measurements were made in the elastography mode of the device within circular and automatically defined region on interest (ROI) areas, only the shear elastic modulus (Young's modulus) was taken into account and recorded in kilopascals (kPa). The device's 'propagation mode' was activated in the measurements and smooth propagation lines were sought. All procedures were performed with the same operator and fixed protocol, ensuring measurement consistency.

Clinical flexibility tests

Flexibility was assessed with three CFTs: AKE and SLR tested hamstring flexibility, whereas SR tested both hamstring and lumbopelvic flexibility. Although these tests are not football-specific performance determinants, they were selected because they are standardized, non-invasive and repeatable methods widely used in clinical and sports science research to evaluate passive muscle stiffness and flexibility, which are important in revealing musculoskeletal adaptations; independent of neuromuscular performance variability. All tests were performed by the same orthopedics and traumatology specialist, under fixed conditions and in accordance with the standard protocol. The test order was kept constant; each test was applied three times for the right and left legs, and the highest value was used in the analyses. A three-minute rest period was given between the tests.

Active knee extension test

The participant was in the supine position, the tested hip was fixed and placed at 90° flexion, and the opposite leg was stabilized in a straight position to prevent pelvic movement. The participant was asked to extend the knee and the maximum angle reached was measured with a goniometer. The center of the goniometer was placed on the lateral epicondyle of the femur; the fixed arm was aligned to the greater trochanter and the mobile arm was aligned to the lateral malleolus [21, 22]. The knee extension reached by the hip at 90° flexion was calculated by subtracting 90° from the measured angle. A third person provided support to maintain the hip position. This test is intended to evaluate the flexibility of the hamstring muscles under active contraction. The AKE measurements were analyzed by subtracting 90° in order to make them comparable with the SLR on a common measurement scale (Fig. 2).

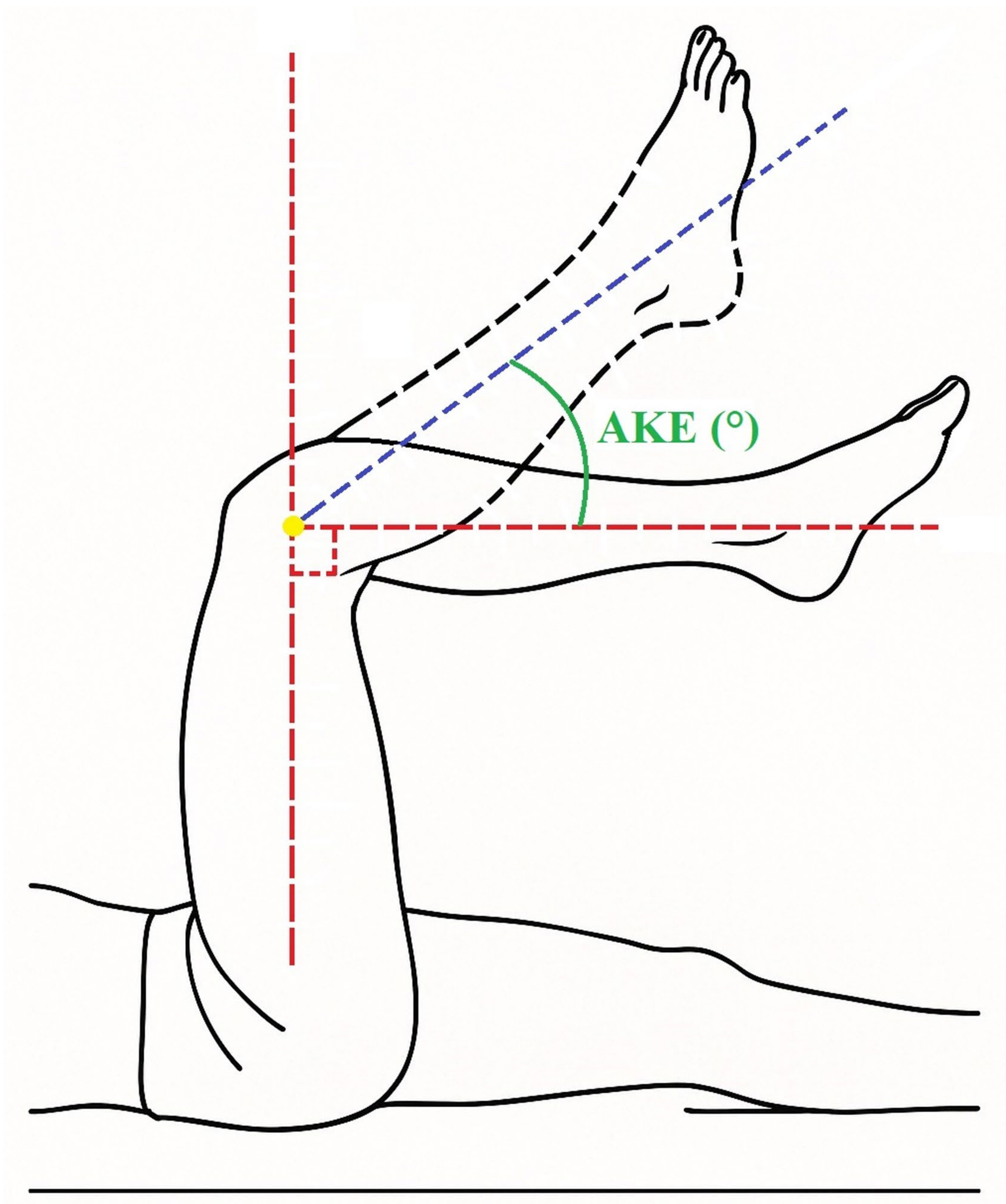

Fig. 2 Active Knee Extension Test Measurement Method

Straight leg raise test

The participant was in the supine position, the hip was passively flexed with the tested leg in knee extension. The goniometer was placed centered on the greater trochanter, the fixed arm was aligned along the trunk axis, and the mobile arm was aligned to the lateral femoral condyle [23]. Support was provided to prevent posterior pelvic rotation, and the opposite leg was kept straight. The movement was applied at a constant speed, smoothly, and without compensatory movements. This test was preferred to evaluate the passive flexibility level of the hamstring muscles (Fig. 3).

Sit and reach test

Participants were seated on the floor with their knees extended and the soles of their feet touching a box at a height of 35 cm. The hands were extended in front, maximum forward bending was achieved, and the distance reached by the fingertips was measured with a ruler [21]. During the test, the knees were not bent, the trunk was symmetrically bent and the heels did not leave the box. This test was applied to evaluate both hamstring and lumbopelvic flexibility (Fig. 4).

Statistical analysis

Statistical analyses in this study were performed using Python (version 3.12.7). The normality distribution of continuous variables was assessed using the Shapiro-Wilk test; variables with $p < 0.05$ were considered to be non-normally distributed. Parametric tests were applied to variables with normal distribution, and non-parametric tests were applied to those without.

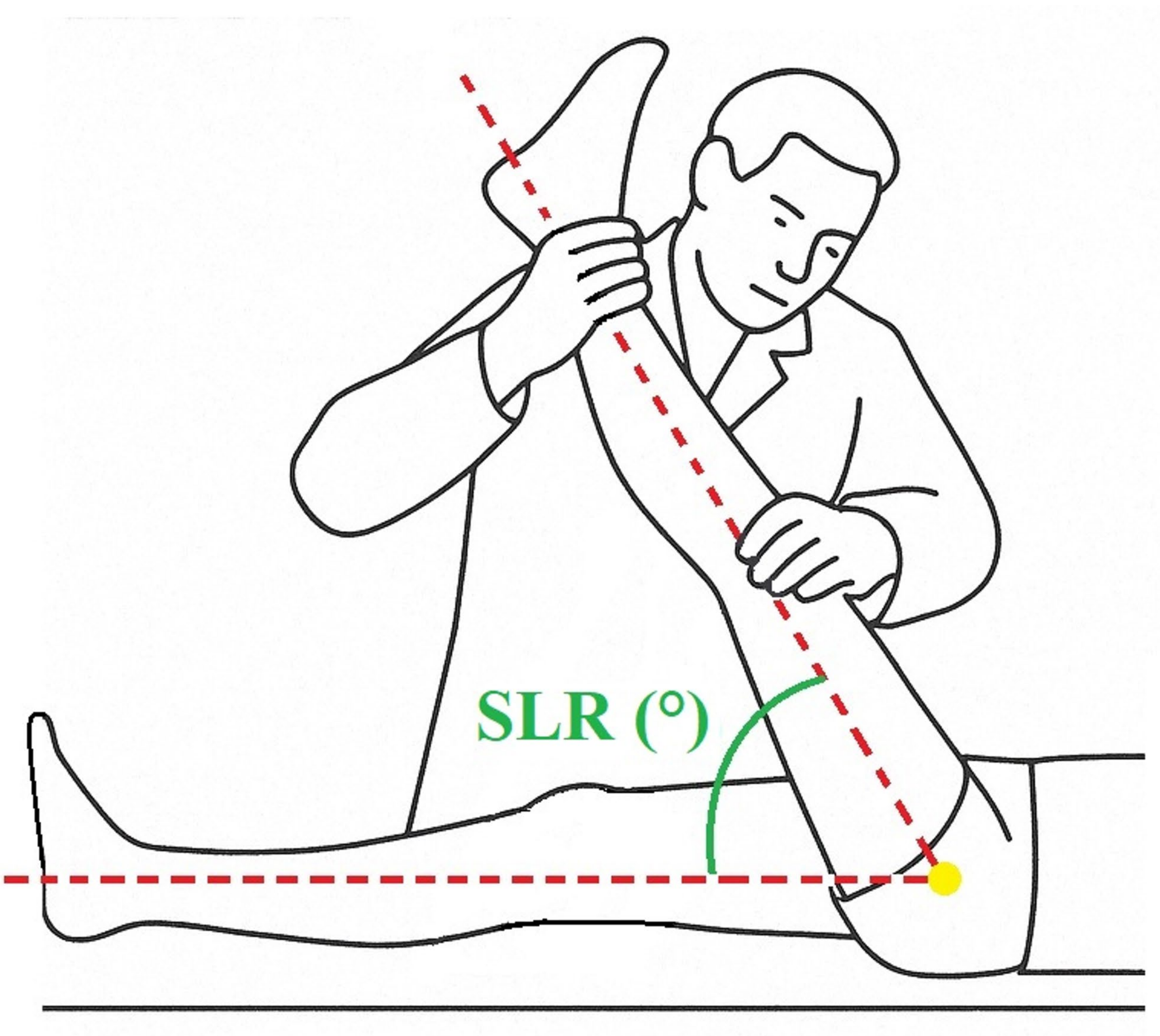

Fig. 3 Straight Leg Raise Test Measurement Method

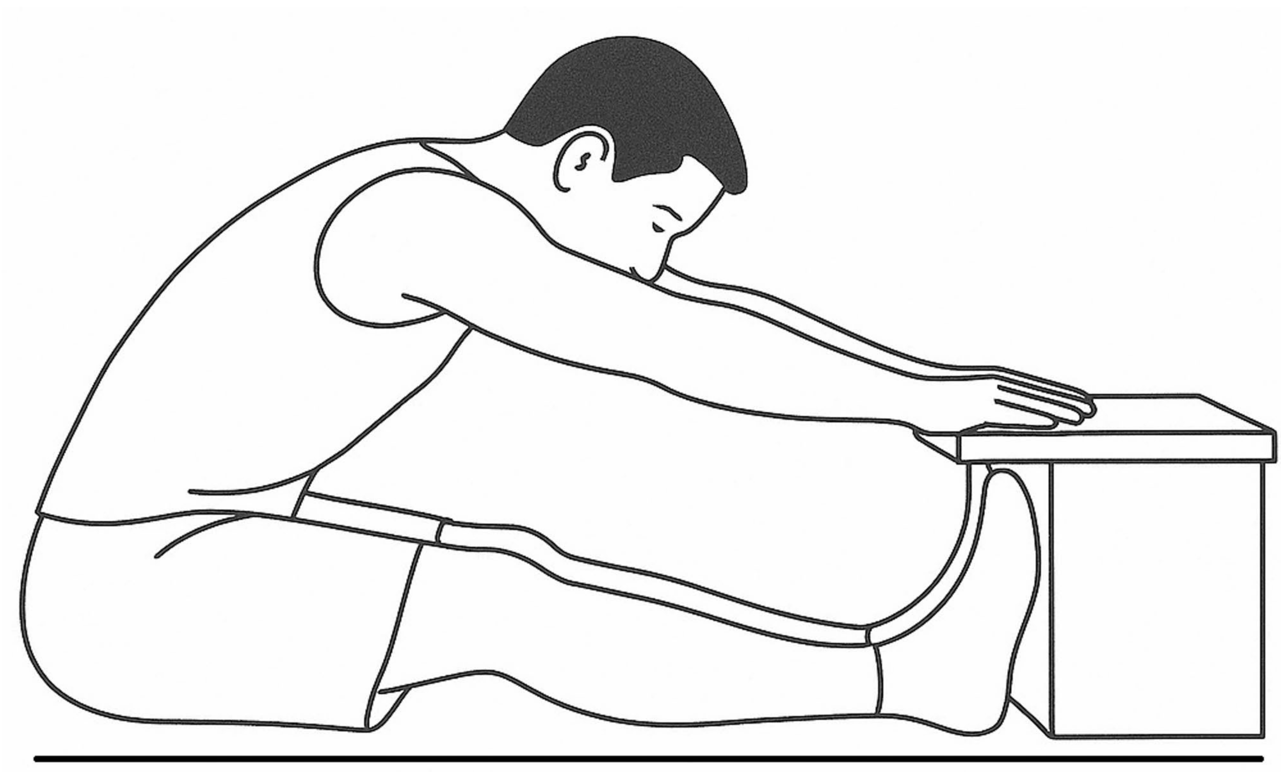

Fig. 4 Sit and Reach Test

An a priori power analysis was conducted using GPower version 3.1.9.2 (Heinrich Heine University Düsseldorf, Germany). Assuming a medium effect size (f = 0.25), α = 0.05, and power = 0.80, the required total sample size was 88 participants (44 per group). The final sample included 100 participants (50 per group), which exceeds the minimum requirement and strengthens statistical reliability.

In comparisons between groups A and B, appropriate tests were selected according to distribution properties. In variables with normal distribution, variance homogeneity was assessed using Levene's test; if variances were equal, Independent Samples T-Test was used, if not, Welch's corrected T-Test was used. Mann-Whitney U test was applied for variables with non-normal distribution.

Relationships between continuous variables were assessed using Pearson or Spearman correlation analyses depending on distribution properties. Correlation strength was determined according to Cohen's classification as|r| = 0.10–0.29 was interpreted as weak, 0.30–0.49 as moderate and ≥ 0.50 as strong. Cohen's d was used for parametric tests, and eta squared (η^2) effect size was used for nonparametric tests. For Cohen's d, ≥ 0.2 was considered small, ≥ 0.5 as moderate, ≥ 0.8 as large; for η^2, ≥ 0.01 was considered small, ≥ 0.06 as moderate and ≥ 0.14 as large.

In all analyses, statistical significance was defined at the α = 0.05 level, and significance was evaluated using exact *p*-values. Extremely small *p*-values (e.g., $p < 0.001$) were reported using threshold notation for brevity, while all other *p*-values were presented with two to three decimal precision to ensure clarity and transparency.

Results

Comparison of descriptive statistics between groups

No statistically significant differences were observed between groups in spinopelvic parameter (SPP) comparisons (all $p > 0.05$) (Fig. 5; Table 1). Group A showed significantly higher SWE values than Group B in all measurements ($p < 0.001$), except for the left BF ($p = 0.615$) (Fig. 6; Table 1). All CFTs showed significantly higher values in Group A than in Group B (all $p < 0.001$) (Fig. 7; Table 1). Age, body weight, and BMI were significantly lower in Group A than in Group B ($p = 0.018$, $p = 0.021$, $p = 0.005$, respectively), and license years were recorded only in Group A with a mean of 7.82 ± 3.11 years (Table 1).

Correlation analysis within the data categories

Significant SPP correlations were observed across groups. The LL-SS correlation was strongly positive in Group A ($r = 0.646$, $p < 0.001$) and moderately positive in Group B ($r = 0.515$, $p < 0.001$). The LL-PT correlation was

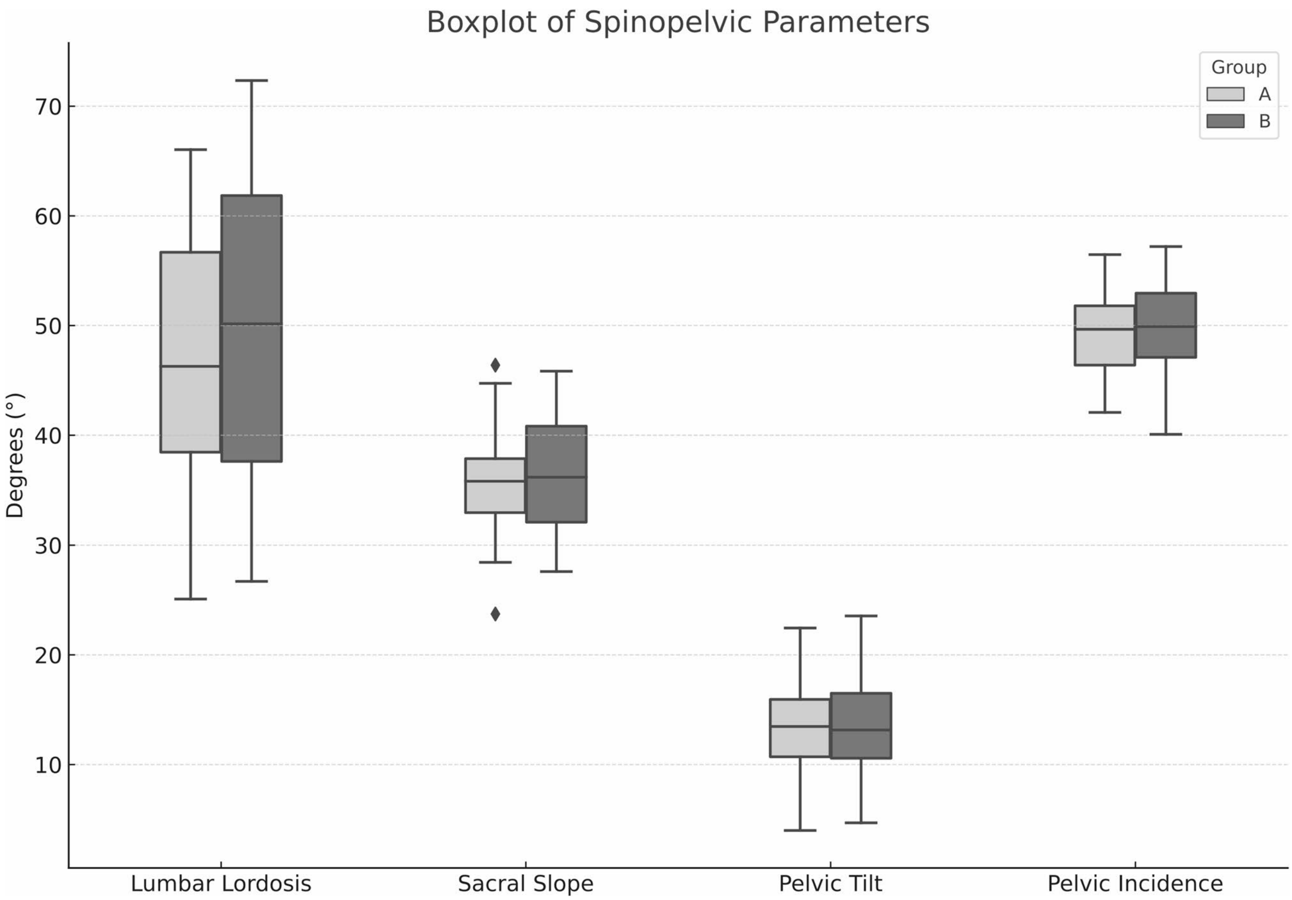

Fig. 5 Spinopelvic Parameters by Group

moderately negative in Group A (r = -0.355, $p = 0.011$) and not significant in Group B (r = -0.154, $p = 0.292$). The LL-PI correlation was moderately positive in both Group A ($r = 0.382$, $p = 0.006$) and Group B ($r = 0.429$, $p = 0.002$). The SS-PT correlation was strongly negative in Group A (r = -0.598, $p < 0.001$) and Group B (r = -0.629, $p < 0.001$). The SS-PI correlation was moderately positive in Group A ($r = 0.542$, $p < 0.001$) and strongly positive in Group B ($r = 0.626$, $p < 0.001$). The PT-PI correlation was moderately positive in Group A ($r = 0.350$, $p = 0.013$) and not significant in Group B ($r = 0.262$, $p = 0.066$) (Table 2).

Significant SWE correlations were observed in both groups. In Group A, the right ST–right BF correlation was moderately positive ($r = 0.333$, $p = 0.018$); the right SM–right BF correlation was also moderately positive ($r = 0.308$, $p = 0.030$); the right–left ST correlation was weakly positive ($r = 0.296$, $p = 0.037$); and the left SM–left BF correlation was moderately positive ($r = 0.338$, $p = 0.021$). In Group B, the left ST–left SM correlation was moderately positive ($r = 0.366$, $p = 0.004$), whereas the right–left SM correlation was weakly positive and not statistically significant ($r = 0.254$, $p = 0.075$) (Table 3).

All CFTs were significantly correlated in both groups (all $p < 0.001$). In Group A, ipsilateral AKE and SLR demonstrated very strong positive correlations ($r = 0.867–0.898$), whereas the remaining test pairings showed strong positive correlations ($r = 0.566–0.709$). In Group B, ipsilateral AKE and SLR again exhibited very strong positive correlations ($r = 0.904–0.917$), and the SR test correlated strongly to very strongly with all other measures ($r = 0.756–0.879$) (Table 4). Significant correlations with demographic variables were also observed in both groups (see Supplementary Table 8).

Correlation analysis between the data categories

No significant relationships were identified between LL or pelvic angles and SWE values in either group, except for a moderate positive correlation between the left BF SWE and PT in Group B ($r = 0.302$, $p = 0.031$) (see Supplementary Table 9).

No significant correlation was found between LL and CFTs in Group A. In Group B, moderate negative correlations were found between LL and right AKE (r = −0.366, $p = 0.009$), left AKE (r = −0.365, $p = 0.009$), right SLR (r = −0.390, $p = 0.005$), and left SLR (r = −0.380, $p = 0.007$). There was a weak negative but not statistically significant correlation between LL and the SR Test in this group (r = −0.245, $p = 0.086$). No significant correlation

Table 1 Group-wise comparison of radiological, elastographic, demographic, and flexibility parameters

Parameter	Group A Mean ± SD (Min- Max)	Group B Mean ± SD (Min- Max)	Test statistic	Effect size	*p* value
Lumbar Lordosis (°)	46.34 ± 10.66 (25.09–66.04)	50.05 ± 13.48 (26.7–72.34)	U = 1064 ‡	0.016	0.201
Sacral Slope (°)	35.87 ± 4.46 (23.73–46.39)	36.42 ± 5.08 (27.6–45.84)	U = 1212.5 ‡	0.001	0.799
Pelvic Tilt (°)	13.11 ± 4.0 (3.99–22.45)	13.34 ± 4.27 (4.69–23.55)	t = -0.267 †	-0.053	0.790
Pelvic Incidence (°)	48.99 ± 3.82 (42.08–56.47)	49.75 ± 4.1 (40.08–57.2)	t = -0.967 †	-0.193	0.336
ST-R (kPa)	28.91 ± 2.98 (24.1–34.1)	25.15 ± 2.59 (19.95–31.92)	U = 2074 ‡	0.323	$p < 0.001$
SM-R (kPa)	34.6 ± 2.73 (26.21–38.79)	32.45 ± 1.96 (29.8–39.27)	U = 1863 ‡	0.178	$p < 0.001$
BF-R (kPa)	24.78 ± 3.06 (19.17–29.61)	22.96 ± 1.25 (19.96–27.65)	U = 1747.5 ‡	0.117	$p < 0.001$
ST-L (kPa)	29.41 ± 2.45 (25.05–33.32)	26.24 ± 1.58 (23.83–31.01)	U = 2131 ‡	0.368	$p < 0.001$
SM-L (kPa)	33.74 ± 2.79 (28.79–38.66)	30.89 ± 2.97 (25.7–37.66)	t = 4.952 †	0.99	$p < 0.001$
BF-L (kPa)	24.33 ± 2.7 (19.38–29.21)	24.13 ± 2.5 (18.96–27.3)	U = 1323.5 ‡	0.003	0.615
Age	21.74 ± 2.91 (18–27)	23.14 ± 2.98 (18–29)	U = 908.5 ‡	0.056	**0.018**
Body weight (kg)	70.94 ± 7.61 (53–85)	74.72 ± 8.44 (61–95)	t = -2.351 †	-0.47	**0.021**
Height (cm)	176.28 ± 5.64 (163–187)	175.4 ± 5.77 (160–189)	t = 0.771 †	0.154	0.442
BMI (kg/m^2)	22.81 ± 2.08 (18.78–26.7)	24.26 ± 2.24 (21.07–29.41)	U = 846.5 ‡	0.077	**0.005**
License Year	7.82 ± 3.11 (3–13)	N/A	N/A	N/A	N/A
AKE-R (°)	64.08 ± 4.5 (52–73)	59.8 ± 4.6 (52–69)	U = 1866.5 ‡	0.181	$p < 0.001$
AKE-L (°)	63.28 ± 4.14 (54–72)	59.3 ± 5.25 (51–70)	U = 1809 ‡	0.149	$p < 0.001$
SLR-R (°)	75.74 ± 3.82 (67–87)	72.02 ± 3.68 (64–79)	t = 4.956 †	0.991	$p < 0.001$
SLR-L (°)	75.06 ± 3.43 (67–84)	71.64 ± 4.29 (63–81)	t = 4.406 †	0.881	$p < 0.001$
SR (cm)	9.52 ± 2.38 (3–15)	3.5 ± 4.48 (-5–12)	t = 8.391 §	1.678	$p < 0.001$

SD: Standard deviation, min: minimum, max: maximum, kPa: Kilopascal

ST: Semitendinosus, SM: Semimembranosus, BF: Biceps Femoris, R: Right leg, L: Left leg

AKE: Active Knee Extension Test, SLR: Straight Leg Raise Test, SR: Sit and Reach Test, BMI: Body Mass Index

†: Independent Samples T-Test (t value), ‡: Mann-Whitney U Test (U value), §: Welch-Corrected T-Test (t value)

*Effect size is reported as Cohen's d for T-tests and eta squared (η²) for the Mann-Whitney U test

N/A: Not applicable, as License Year is exclusive to Group A

was found between pelvic angle parameters and CFTs in either group (Table 5).

Significant spinopelvic-demographic correlations were observed in both groups (see Supplementary Table 10). No significant relationship was found between SWE values and demographic variables in both groups (all $p > 0.05$) (see Supplementary Table 11). No significant relationship was found between SWE values and CFTs in both groups (all $p > 0.05$) (see Supplementary Table 12). Significant correlations observed between demographic variables and CFTs in both groups (see Supplementary Table 13).

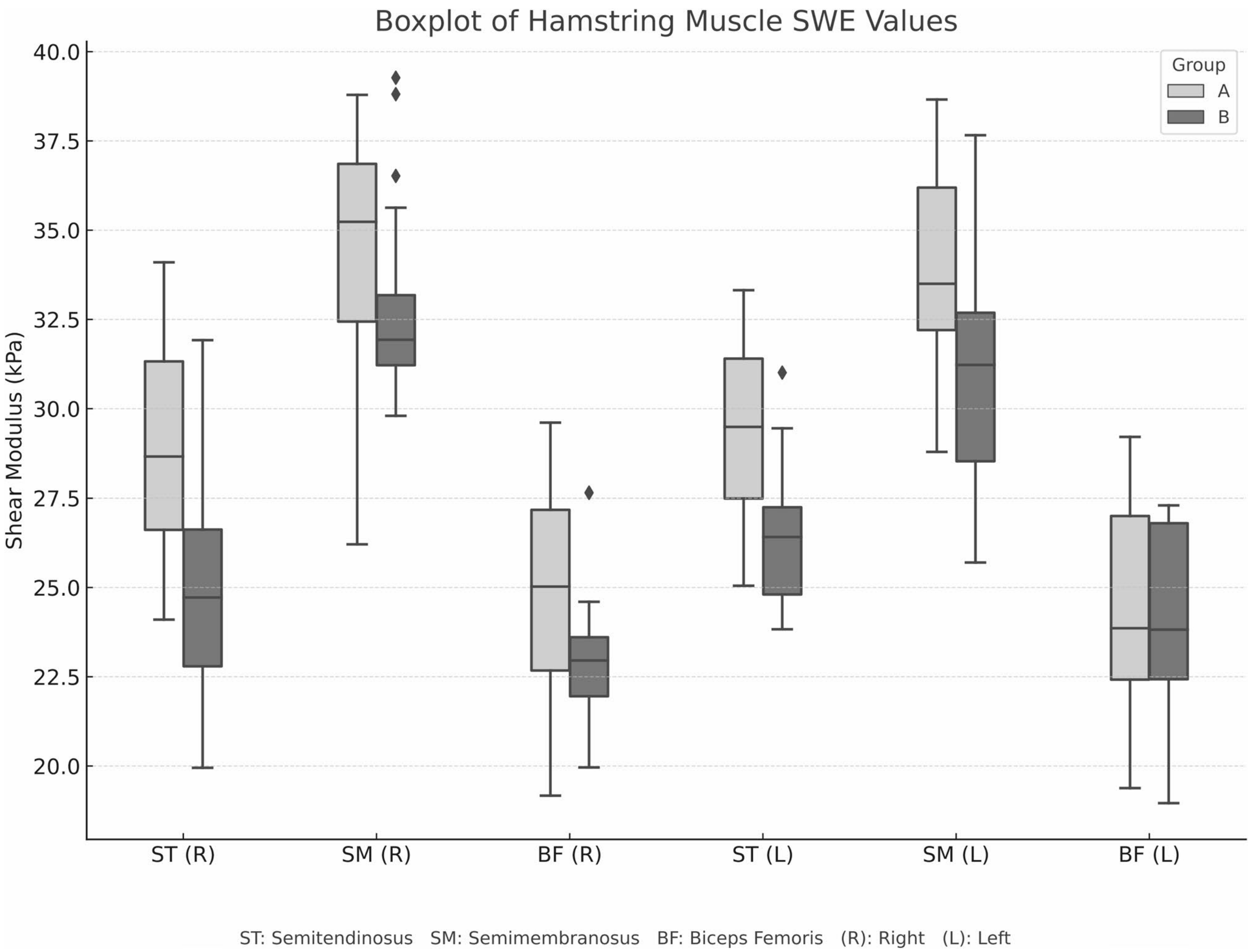

Fig. 6 Shear-Wave Elastography Values by Group

Discussion

No significant difference in SPPs was detected between the two groups. In the literature, findings from studies comparing football players' SPPs with those of individuals in similar age groups vary. Among French footballers, the mean PI and SS are significantly higher, while the mean LL is higher in footballers but not to a significant degree [24]. Reports on professional Brazilian footballers state that the mean PT is significantly lower, the mean PI is similar [25], and the mean LL is similar [26]. Cruz et al. [27], when comparing the SPPs of Brazilian footballers with the data from those studies, reported findings such as SS being similar, PI and PT lower, and LL higher [24]; PT and SS lower [25]; and no difference in LL [26]. The authors attributed these morphometric differences to factors such as muscular effects arising during skeletal muscle development in athletes, biotype differences between populations, the type of training applied, and the age at which sport participation begins [24–27]. The absence of a significant difference in SPPs in our study is therefore not merely a neutral finding but also shows that these parameters may remain morphologically stable despite intense physical activity such as football.

The structural relationships among SPPs are well established and have been examined in detail in the literature [28]; our study likewise identified comparable associations. For example, Mi et al. [29] reported a positive correlation between PI and LL in a cohort of 324 healthy Asian adults (115 men, 209 women; mean age 55 ± 13 years). Although correlations among SPPs generally reflect an underlying morphometric relationship, the mean values of these parameters may vary by ethnicity [30, 31]. In our study, the fact that all participants were of Turkish descent allowed assessment within an ethnically homogeneous sample; however, because the cohort consisted solely of men, a sex-based evaluation of SPPs could not be performed.

The relationship between SPPs and demographic variables is well documented in the literature. In our study, LL correlated with age, body weight, and BMI in both groups, while PI correlated with body weight and height. These findings are consistent with earlier reports

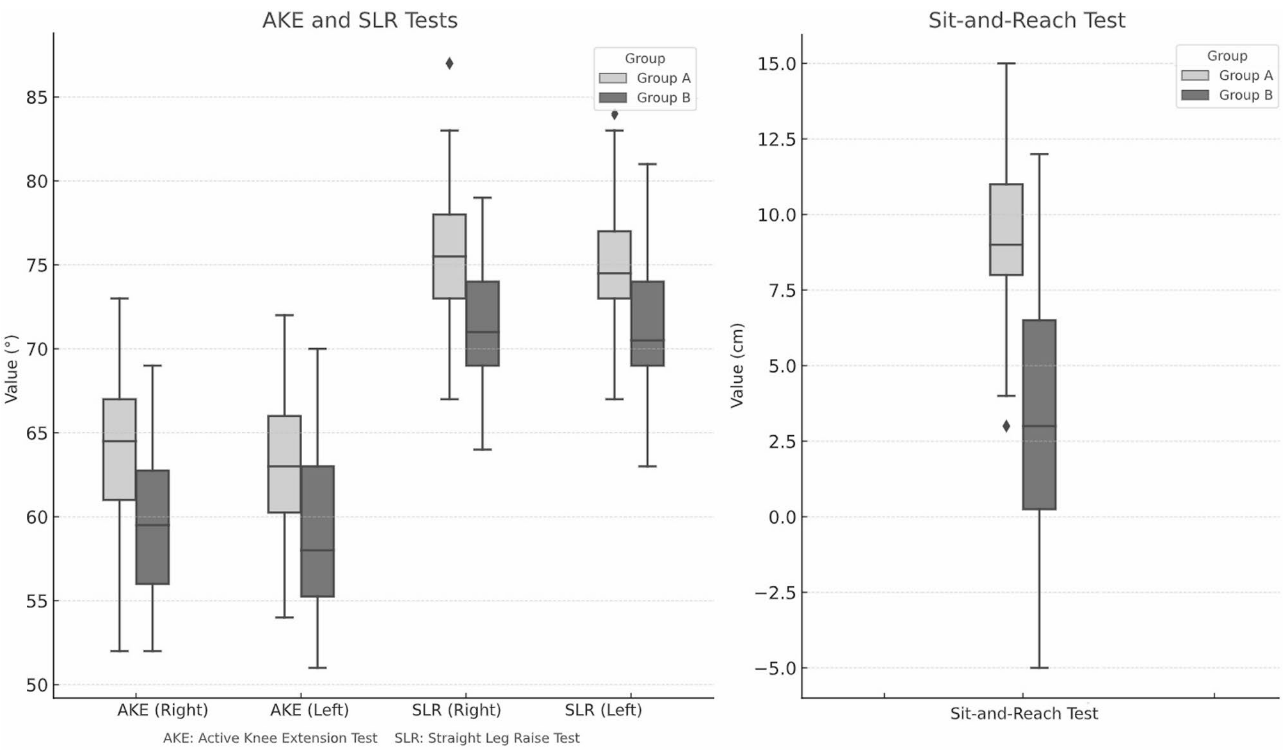

Fig. 7 Clinical Flexibility Test Values by Group

Table 2 Correlation analysis within spinopelvic parameters

Parameter		Group A		Group B	
Parameter 1	Parameter 2	*r* value	*p* value	*r* value	*p* value
Lumbar Lordosis	Sacral Slope	0.646 ‡	*p* < 0.001	0.515 †	*p* < 0.001
Lumbar Lordosis	Pelvic Tilt	-0.355 ‡	**0.011**	-0.229 †	0.11
Lumbar Lordosis	Pelvic Incidence	0.382 ‡	**0.006**	0.429 †	**0.002**
Sacral Slope	Pelvic Tilt	-0.598 ‡	*p* < 0.001	-0.629 †	*p* < 0.001
Sacral Slope	Pelvic Incidence	0.542 ‡	*p* < 0.001	0.626 †	*p* < 0.001
Pelvic Tilt	Pelvic Incidence	0.350 ‡	**0.013**	0.262 ‡	0.066

†: Spearman test, ‡: Pearson test

Table 3 Correlation analysis within hamstring muscle SWE values

Parameter		Group A		Group B	
Parameter 1	Parameter 2	*r* value	*p* value	*r* value	*p* value
ST-R	SM-R	0.252 †	0.078	0.058 †	0.691
ST-R	BF-R	0.333 †	**0.018**	0.091 †	0.528
SM-R	BF-R	0.308 †	**0.030**	-0.167 †	0.246
ST-L	SM-L	0.274 †	0.054	0.366 †	**0.004**
ST-L	BF-L	0.098 †	0.500	-0.008 †	0.957
SM-L	BF-L	0.338 †	**0.021**	-0.075 †	0.604
ST-R	ST-L	0.296 †	**0.037**	0.188 †	0.190
SM-R	SM-L	0.168 †	0.242	0.254 †	0.075
BF-R	BF-L	0.225 †	0.116	0.187 †	0.195

†: Spearman test

ST: Semitendinosus, SM: Semimembranosus, BF: Biceps Femoris, R: Right leg, L: Left leg

Table 4 Correlation analysis within clinical flexibility test values

Parameter		Group A		Group B	
Parameter 1	Parameter 2	*r* value	*p* value	*r* value	*p* value
AKE-R	SLR-R	0.898 ‡	*p* < 0.001	0.904 †	*p* < 0.001
AKE-L	SLR-L	0.867 ‡	*p* < 0.001	0.917 †	*p* < 0.001
AKE-R	AKE-L	0.709 ‡	*p* < 0.001	0.879 †	*p* < 0.001
SLR-R	SLR-L	0.566 ‡	*p* < 0.001	0.808 ‡	*p* < 0.001
AKE-R	SR	0.673 ‡	*p* < 0.001	0.776 †	*p* < 0.001
AKE-L	SR	0.690 ‡	*p* < 0.001	0.756 †	*p* < 0.001
SLR-R	SR	0.683 ‡	*p* < 0.001	0.790 ‡	*p* < 0.001
SLR-L	SR	0.636 ‡	*p* < 0.001	0.802 ‡	*p* < 0.001

†: Spearman test, ‡: Pearson test

AKE: Active Knee Extension Test, SLR: Straight Leg Raise Test, SR: Sit and Reach Test,

R: Right leg, L: Left leg

Table 5 Correlation analysis between spinopelvic parameters and clinical flexibility tests

Parameter		Group A		Group B	
Parameter 1	Parameter 2	*r* value	*p* value	*r* value	*p* value
Lumbar Lordosis	AKE-R	-0.117 ‡	0.417	-0.366 †	**0.009**
Lumbar Lordosis	AKE-L	0.087 ‡	0.546	-0.365 †	**0.009**
Lumbar Lordosis	SLR-R	-0.172 ‡	0.232	-0.390 †	**0.005**
Lumbar Lordosis	SLR-L	0.058 ‡	0.687	-0.380 †	**0.007**
Lumbar Lordosis	SR	-0.111 ‡	0.442	-0.245 †	0.086
Sacral Slope	AKE-R	-0.117 ‡	0.420	0.053 †	0.716
Sacral Slope	AKE-L	-0.044 ‡	0.764	-0.145 †	0.316
Sacral Slope	SLR-R	-0.163 ‡	0.258	-0.070 †	0.630
Sacral Slope	SLR-L	-0.049 ‡	0.737	-0.164 †	0.255
Sacral Slope	SR	-0.024 ‡	0.867	-0.029 †	0.843
Pelvic Tilt	AKE-R	0.218 ‡	0.128	0.058 †	0.691
Pelvic Tilt	AKE-L	0.199 ‡	0.167	0.249 †	0.081
Pelvic Tilt	SLR-R	0.146 ‡	0.313	0.060 ‡	0.678
Pelvic Tilt	SLR-L	0.128 ‡	0.374	0.085 ‡	0.555
Pelvic Tilt	SR	0.118 ‡	0.414	0.101 ‡	0.485
Pelvic Incidence	AKE-R	0.092 ‡	0.523	0.112 †	0.441
Pelvic Incidence	AKE-L	0.157 ‡	0.275	0.042 †	0.775
Pelvic Incidence	SLR-R	-0.038 ‡	0.795	0.033 ‡	0.821
Pelvic Incidence	SLR-L	0.078 ‡	0.592	0.016 ‡	0.913
Pelvic Incidence	SR	0.095 ‡	0.510	0.155 ‡	0.284

†: Spearman test, ‡: Pearson test

AKE: Active Knee Extension Test, SLR: Straight Leg Raise Test, SR: Sit and Reach Test,

R: Right leg, L: Left leg

indicating that higher BMI is associated with greater PI and LL [32, 33].

All hamstring SWE values (except for the left BF) and all CFT values were significantly higher in Group A, indicating greater muscular stiffness and enhanced flexibility compared with Group B. Although the greater muscle stiffness observed in Group A would ordinarily be expected to reduce flexibility, this group in fact recorded higher values than Group B on all CFTs. The 'high stiffness/high flexibility' paradox seen in Group A may reflect sport-specific adaptive mechanisms and represents a key finding of our study. One possible mechanism is the stretch-based training routinely performed by football players; however, a single causal explanation should be avoided, as sport-specific adaptations are likely shaped by multiple factors. A limitation of our work is that we did not track the dynamic interplay between stretching and muscle stiffness over time in either group; future studies could incorporate such longitudinal assessments into their methodology.

Satkunskiene et al. [34] investigated the changes in hamstring passive stiffness in 11 professional male football players during the preseason and in-season and the relationship between these changes and training/match loads. They stated that regular training and match load increased hamstring passive stiffness within 10 weeks, but this increase occurred without a change in knee joint range of motion (ROM); a decrease in hamstring eccentric strength was observed throughout the season, and this may increase the risk of injury. Apparently, increased muscle stiffness may not be related to increased muscle strength. Stretching is defined as a movement applied with an internal or external force in order to increase muscle flexibility and improve ROM [35]. The fact that group A showed higher values in CFTs compared to group B can be explained by the wide ROM effect provided by increased muscle flexibility through stretching, based on the assumption that this group performed more stretching exercises [36]. At this point, the 'paradoxical relationship between increased hamstring stiffness and increased functional flexibility' detected in Group A in our study can be supported by information that increased hamstring stiffness in football players throughout the season occurs without any limitation in ROM [34] and that this situation is also explained by improved stretch tolerance [37]. The sample of our study consists of amateur football players, and the finding of increased hamstring stiffness was obtained by comparing with the control group, not with changes during the season. In this sense, our study's finding that football increases hamstring stiffness is supported by the observation that football also increases hamstring stiffness during the season in professional players. In this context, it is clear that the amateur football player sample is a limitation in revealing the relationships and that studies should be conducted on a larger professional football player population to reveal the relationship between hamstring stiffness and functional flexibility more clearly. However, there are some theories that can explain this paradoxical adaptation at the cellular and tissue level: decrease in fast-glycolytic fibers and increase in hybrid fibers in individuals who do high-intensity activities such as football players; optimization of α-motor neuron activation and improvement of simultaneous contraction-relaxation dynamics of muscle fibers with regular exercise; and increase in lateral force transmission of the muscle by the nonlinear network structure of sarcomeres [38]. However, we must emphasize that it was not possible to verify these tissue level adaptations in the context of our study.

In SWE values, four significant intermuscular correlations were found in Group A (BF-R with ST-R; BF-R with SM-R; BF-L with SM-L; ST-R with ST-L), while only one was detected in Group B (ST-L with SM-L). These findings indicate that football provides a more balanced stiffness adaptation between ipsilateral and contralateral hamstring muscle groups.

In terms of CFTs, the positive correlation of right-left leg measurements of AKE and SLR and SR test with both AKE and SLR in both groups demonstrates that these tests are related to each other and is consistent with the literature recommending the use of more than one test in clinical flexibility measurement since each one evaluates different anatomical components of the hamstring-lumbopelvic complex [39–41]. The unique contribution of our study is that it presents the methodology that quantitatively reveals the hamstring stiffness-flexibility paradox by integrating SWE measurements with these CFTs.

No significant associations emerged between SPPs and hamstring SWE values in either group, except for a positive correlation between the left BF and PT in Group B, suggesting that hamstring stiffness is generally unrelated to pelvic morphometry. One limitation of our study is that hamstring stiffness was assessed only in a static position, without incorporating dynamic postures or contraction modalities. Furthermore, the limited number of comparable studies underscores the need for additional research in this area.

In both groups, no significant associations were found between hamstring SWE values and demographic variables. Likewise, a study that measured BF stiffness with SWE in a cohort of basketball players reported no significant relationship between age and hamstring stiffness [42]. Consequently, further research is needed to investigate hamstring muscle stiffness in diverse demographic groups.

No statistically significant correlation was found between hamstring SWE values and CFT values in either group. This finding indicates that muscle stiffness assessed via SWE and flexibility evaluated through CFTs are distinct concepts. In contrast to this finding from our study, research involving a sample of sports science students (98 participants: 76 male, 22 female; mean age ~ 21 years) detected weak but significant correlations between SWE values and SLR/SR tests [43]. However, it should be noted that male-specific findings were not separately reported in the aforementioned study.

In the analysis of relationships between demographic variables and CFTs, high BMI was associated with lower CFT values in both groups. While this association was limited to SR and right AKE in Group A, Group B showed stronger negative correlations with all AKE, SLR, and SR tests. Additionally, in Group A, height demonstrated a moderate positive correlation with the SR test ($r = 0.467$, $p < 0.001$). The literature includes reports of negative correlations between BMI and SR test values, and positive correlations between trunk-to-height ratio and SR test values [44]. Conversely, other studies report no significant correlation between SR test values and anthropometric variables such as height, leg length, or trunk length [45]. Therefore, given that these isolated correlations may be influenced by multiple factors, further research is clearly warranted.

As stated in the introduction, one of our study's motivations was to 'shed light on the football-specific interrelationships among clinical flexibility and spinopelvic alignment.' In our study, while no correlation was detected between SPPs and CFTs in Group A, Group B exhibited moderate negative correlations between LL and both AKE and SLR. A similar trend was observed in the relationship between LL and SR, though it did not reach statistical significance. The differential relationships between LL and CFTs across the two groups may reflect sport-specific neuromuscular adaptations; however, our study design cannot elucidate the mechanisms underlying these adaptations. López-Miñarro et al. [23] evaluated lumbar curvature (inclinometer) and hamstring flexibility (SLR test) in male skiers, male canoeists, and non-athlete male students, finding no significant relationship between lumbar curvature and hamstring flexibility. Similarly, Allam et al. [46] detected no statistically significant correlation between LL (flexi-curve method) and hamstring flexibility measurements (AKE and SLR tests) in sedentary individuals. The absence of correlations between SPPs and CFTs in Group A aligns with this literature. Nevertheless, conflicting reports exist: Cejudo et al. [15] reported positive correlations between hamstring flexibility (hip flexion-knee extension test) and spinal alignment parameters (PT and LL measured via Spinal Mouse® device) in young male athletes actively participating in team sports. Discrepancies across studies may arise from heterogeneity in sample groups, methodological variations in spinopelvic tilt measurement, and use of diverse clinical tests. Consequently, our study employed radiographic measurements as a more objective and standardized method for SPP assessment, while comprehensively evaluating hamstring-trunk flexibility through three distinct CFTs.

This study has several noteworthy limitations. The exclusive inclusion of male participants precluded gender-based analysis. Another limitation is the relatively broad age range (18–30 years), which may introduce physiological variability in flexibility outcomes and affect internal sample homogeneity, despite statistically comparable group means. Although Group B participants were matched to football players by age and sex, they were not screened for activity levels, daily movement behaviors, or habitual flexibility routines, and the broad inclusion criterion (not being licensed athletes) may have introduced heterogeneity in physical activity patterns. The cross-sectional design restricts causal inferences. For instance, despite observing both higher hamstring stiffness and higher CFT values in Group A, the absence of dynamic longitudinal data regarding training routines, particularly stretching regimens, prevents definitive conclusions about the origin of this 'high stiffness/high flexibility' paradox. Furthermore, SWE assessments were performed only in the resting prone position; the impact of active contraction or different pelvic postures on stiffness measurements was not evaluated. Another limitation is the lack of sport-specific functional tests such as sprint or agility assessments, which might have provided additional context regarding dynamic performance adaptations. CFTs may have been influenced by individual variations in pain tolerance and assessor technique. Additionally, intra-rater reliability was not assessed for any measurement modality (radiographic evaluation, SWE, or CFTs), creating potential measurement bias due to intra-observer variability and constituting a significant methodological limitation. Conversely, to highlight the study's strength, the research design facilitates multidimensional correlations among morphometric (radiographic), biomechanical (SWE), and functional (clinical) variables. This integrated approach provides a comprehensive perspective on hamstring characteristics and spinopelvic alignment, while the comparison between amateur football players and healthy male controls contributes to revealing sport-specific adaptations.

Conclusion

In conclusion, our study confirmed that 'hamstring stiffness is higher in football players due to sports-related loads', while rejecting the hypothesis that 'morphometric differences occur in SPPs'. Nevertheless, the study yielded significant findings beyond hypothesis validation. SPPs showed no intergroup differences, indicating football does not alter lumbar-pelvic morphology. The absence of correlations between SPPs and hamstring stiffness or flexibility in footballers suggests distinct regulatory mechanisms. Crucially, the lack of SWE-CFT correlations in both groups implies these methods capture different physiological properties. Football players exhibited higher SWE values (except fot the left BF) and superior CFT values compared with controls, revealing a 'high stiffness/high flexibility' paradox indicative of sport-specific functional adaptations. Future longitudinal studies could help clarify the long-term effects of this phenomenon.

Abbreviations

AKE	Active knee extension test
BF	Biceps femoris
BMI	Body mass index
CFT	Clinical flexibility test
kPa	Kilopascal
LL	Lumbar lordosis
PI	Pelvic incidence
PT	Pelvic tilt
ROI	Region of interest
ROM	Range of motion
SLR	Straight leg raise test
SM	Semimembranosus
SPP	Spinopelvic parameter
SR	Sit and reach test
SS	Sacral slope
ST	Semitendinosus
SWE	Shear-wave elastography

Supplementary Information

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Supplementary Material 1

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Author contributions

Conceptualization, N.M. and N.E; methodology, N.M., S.Ç. and N.E.; software, N.M. and S.Ç.; validation, N.E., K.B., and İ.T.; formal analysis, N.E. and K.B.; investigation, N.M. and N.E.; resources, N.M. and S.Ç.; data curation, N.M, N.E., and İ.T.; writing—original draft preparation, N.M. and N.E.; writing—review and editing, K.B. and İ.T.; visualization, N.M. and S.Ç.; supervision, N.E., K.B. and İ.T.; project administration, N.M. and N.E. All authors have read and agreed to the published version of the manuscript.

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Data availability

The datasets analyzed during this study are available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate

This study was performed in accordance with the principles of the Declaration of Helsinki. Approval was granted by the Bezmialem Vakıf University Ethics Committee (Decision No: 2024/251). Institutional permissions were obtained from the Kahramanmaraş Provincial Health Directorate (Republic of Turkey Ministry of Health) and Necip Fazıl City Hospital. All participants provided written informed consent after detailed explanation of the study purpose and procedures.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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