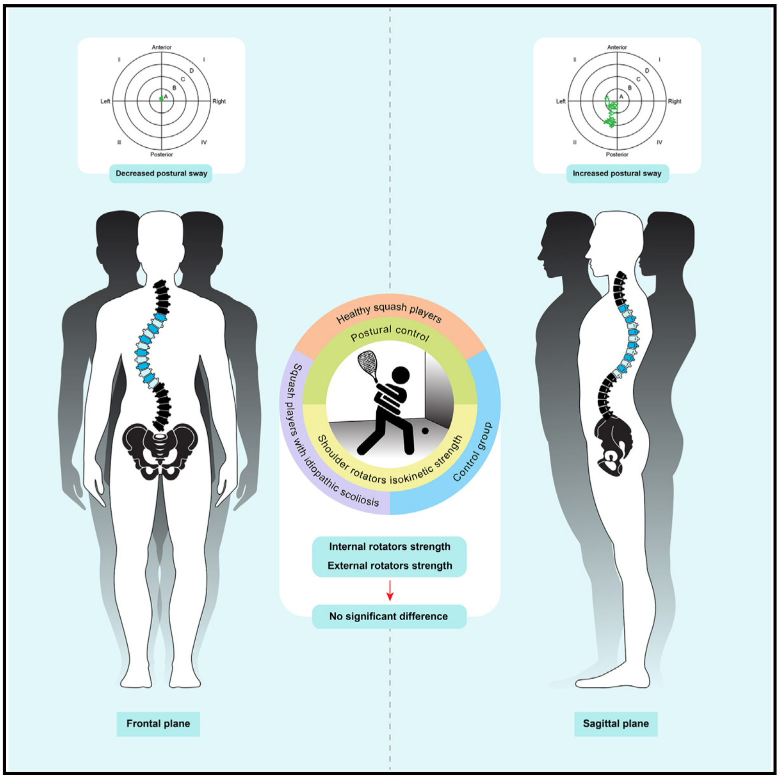
iScience

Article

Postural control and shoulder rotators isokinetic strength in squash players with and without idiopathic scoliosis

Graphical abstract



Authors

Leila Mousavi, Foad Seidi,
Hooman Minoonejad, Farshad Nikouei

Correspondence

foadseidi@ut.ac.ir

In brief

Kinesiology; Biomechanics

Highlights

- Balance function at anatomical planes varies in athletes with idiopathic scoliosis
- Postural sways increase in the frontal plane and decrease in the sagittal plane
- Squash athletes with scoliosis showed poor dynamic balance in the non-dominant leg
- Shoulder rotator strength does not change in athletes with idiopathic scoliosis

Mousavi et al., 2024, iScience *27*, 111353
December 20, 2024 © 2024 The Author(s). Published by Elsevier Inc.
https://doi.org/10.1016/j.isci.2024.111353

CellPress

CellPress
OPEN ACCESS

Article

Postural control and shoulder rotators isokinetic strength in squash players with and without idiopathic scoliosis

Leila Mousavi,[1] Foad Seidi,[1,3,*] Hooman Minoonejad,[1] and Farshad Nikouei[2]
[1]Sports Sciences and Health Faculty, University of Tehran, between 15th and 16th St., North Kargar St., Tehran, Iran
[2]Bone and Joint Reconstruction Research Center, Shafa Orthopedic Hospital, Iran University of Medical Sciences, Tehran, Iran
[3]Lead contact
*Correspondence: foadseidi@ut.ac.ir
https://doi.org/10.1016/j.isci.2024.111353

SUMMARY

Idiopathic scoliosis is a postural deformity of the spine that not only changes the shape of the spine but may also alter postural control and muscle strength. Although this deformity is more common in some sports, it is not known whether the scoliosis athlete's balance and strength are altered. Balance and strength are essential to perform complex technical movements and prevent injuries. This cross-sectional study compared postural control and isokinetic strength of shoulder rotator muscles in squash players with and without idiopathic scoliosis and the control group. We report a higher mediolateral stability index in the frontal plane in scoliosis athletes and this may be associated with increased variability in postural control in the frontal plane. Additionally, the peak torque of the shoulder rotators was not different between the groups. While the relationship between function and posture is complex, these results provide information for preventive health care interventions in scoliosis athletes.

INTRODUCTION

Idiopathic scoliosis is a multifactorial spine disorder that has been reported in about 27% of athletes in various sports.[1] Squash is an expanding sport that has been approved for the LA28 Olympic Games. Squash is a unilateral racket sport whose movement patterns include a variety of simultaneous fast and dynamic movements such as acceleration/deceleration in different directions, side-stepping motions, and repeated lunges. Shots require repetitive shoulder activity to hit the ball and score points.[2]

Serve, overhand smash and high forehand and backhand volley strokes put a lot of pressure on the shoulder and rotator cuff.[3] Following prolonged, repetitive unilateral activities, force that unilaterally twists the spine, or an exercise that involves rotational forces can lead to spinal deformity and abnormal posture.[4] Musculoskeletal adaptations as a result of repetitive dominant shoulder (DS) striking or throwing may cause bilateral skeletal asymmetry in some athletes.[1,5]

The lunge is often performed by squash players, and proper lunge technique is a key aspect of the game.[2] In squash games, the lunge allows the player to quickly stop the body's forward motion, establish a safe base for playing a shot, and step onto the court to prepare for the next shot.[6] Initial knee position has been reported to be positively related to racket speed and characteristics of more skilled players. The effects of the initial knee position are directly related to the movement of the center of mass.[7] The lunge involves high impact forces and it is prone to injury.[2] In the forward lunging, the trunk acts as the center of the functional kinetic chain and provides a stable base for lower extremity movements.[8] But it seems that the function of trunk muscles is changed in those with idiopathic scoliosis. Electromyographic (EMG) studies frequently reported a muscular overactivity on the convex side of the intrinsic spinae muscles. EMG changes in other trunk muscles have also been reported.[9] Since the dysfunction of a specific segment in the kinetic chain can lead to altered function or damage to the distal segment,[10] this deficit or breaks can lead to upper and lower extremity injury.

Effective postural control is essential in sports because reduces the risk of sports injuries and its negative consequences for the athlete's physical and professional status. It is also necessary for improving the control of voluntary movements in sports and thus increasing sports performance.[11] Injuries in squash athletes can occur in both the upper and lower extremities and the spine as a result of the speed and repetitive nature of squash.[12] Loss of balance during quick side-to-side movements can also lead to injury.[13]

Physical performance requires strength, endurance, power, and good balance along with sensorimotor integration and good neuromuscular control.[14] Squash athletes may need good dynamic and static postural control with shoulder rotator muscle strength to have a better chance of hitting a winning shot.

While a review and meta-analysis by Dufvenberg et al.,[15] a review by Paramento et al.[9] and other studies[15–21] reported significant evidence of impaired standing balance in patients with adolescent idiopathic scoliosis (AIS), there is a relative lack of studies on the effect of scoliosis and postural deformity on postural control in athletes of different disciplines. Nagornov et al.[22] reported that footballers with idiopathic scoliosis and flat feet had poor performance and a significant shift in the center of gravity compared to healthy footballers. Schoeman et al.[23] reported a relationship between squash player ratings and dynamic balance in the non-dominant leg (NDL) and suggested that it may be one of the important factors in the performance of squash athletes. Also, impaired postural control has been reported in dancers[24] with idiopathic scoliosis, but it is unclear whether squash players with idiopathic scoliosis have impaired postural control.

Altered kinematics and shoulder dysfunction have been reported in idiopathic scoliosis participants due to adaptation to abnormal spinal curvature.[25] But regarding the consequences of AIS, the main focus of researchers was on the paraspinal muscle due to its direct involvement with the spine and changes in shoulder girdle muscles related to idiopathic scoliosis have received less attention. A review by Chan et al.[26] showed that paraspinal muscles show consistent changes in the concavity of the curve, such as decreased type I fibers, decreased muscle activity, muscle atrophy, and altered muscle-related gene expression that may be the cause or result. Insufficient posterior tipping movement of the scapula and greater activity of the lower trapezius on the convex side and lower activity of the lower trapezius and serratus anterior on the concave side have also been reported.[25]

If the body moves in the order of trunk, shoulder, elbow, and wrist, the ball can fly at the highest speed.[27] The function of the kinetic chain is based on pre-programmed muscle activities that result in anticipatory postural adjustments, which position the body to endure perturbations caused by running, throwing, or kicking forces.[10]

Some shots, such as the drop shot, require a faster angular velocity for the trunk rotation, in other words, they tend to a precision stroke kinetic chain model rather than a power stroke model. Therefore, the parts of the upper limbs work more as a single unit and the rotation of the trunk has a greater effect on the speed of the racket during impact.[28] Tennis Service's mathematical analysis showed that a 20% reduction in kinetic energy generated by the trunk resulted in a need for 34% more arm speed or 80% more shoulder mass to deliver the same energy to the ball.[10] Despite these changes in muscle activity in the trunk and shoulder and dysfunction of the trunk kinetic chain in patients with idiopathic scoliosis, it is not known whether the shoulder rotation strength of the squash player with scoliosis is impaired or not.

Injuries have an adverse effect on team and individual sports success. A review by Drew et al.[29] found that there is strong evidence that pre-competition and intra-competition injuries are associated with increased risk of failure and also increased availability of team members/athletes decreases the risk of failure. The rate of shoulder injury in overhead sports has been reported between 0.2/1000 and 1.8/1000 h.[30] The main squash injuries occur in the upper limb around the arm 0.51%, shoulder 3.72%, and forearm 0.17%.[31] A review by Asker et al.[30] showed that external workload is a risk factor for shoulder injury in overhead sports. It is worth noting that idiopathic scoliosis also increases the possibility of some injuries in athletes.[32,33] The main goal of athletes, coaches, and physiotherapists is to improve performance, while injury leads to reduced load capacity, which directly and negatively affects sports performance.

We hypothesized that squash players with idiopathic scoliosis have poor static and dynamic postural control compared to healthy players and the control group. Also, we hypothesized that squash players with idiopathic scoliosis would have lower peak torque (PT) in isokinetic shoulder internal and external rotators than healthy squash players and controls. Considering the above, our aim was to compare static and dynamic postural control and isokinetic shoulder rotational strength of squash players with and without idiopathic scoliosis and controls.

RESULTS

The mean ± SD of the major Cobb angle, kyphosis, and lordosis for scoliosis athletes were 23.8 ± 19°, 44 ± 12°, and 62.5 ± 11.1°, respectively (more information about the participants is shown in Table 1).

Postural control test results

The comparison of the groups revealed significant differences in static postural stability test, mediolateral direction ($F = 5.07$, mean square for between group = 1.00, mean square for within group = 0.19 and $p = 0.01$, $p < 0.05$), non-dominant leg (NDL) dynamic athletic single leg test, anteroposterior direction ($F = 4.83$, mean square for between group = 2.21, mean square for within group = 0.45 and $p = 0.01$, $p < 0.05$) and dominant leg (DL) static athletic single leg test, anteroposterior direction ($F = 3.65$, mean square for between group = 2.13, mean square for within group = 0.58 and $p = 0.04$, $p < 0.05$). No significant difference was observed between the groups in other postural control variables (Table 2).

The post hoc test (Table 3) showed that in athletes with IS ($p = 0.01$) and the control group ($p = 0.01$), static MLSI was significantly higher than in healthy athletes. The static anteroposterior stability index (APSI) in the DL in athletes with idiopathic scoliosis was significantly lower than the control group ($p = 0.02$). APSI of dynamic balance in the NDL in athletes with idiopathic scoliosis was significantly lower than in healthy athletes ($p = 0.03$) and controls ($p = 0.01$).

The Kruskal-Wallis H test did not show a statistically significant difference between the groups in the static MLSI of the DL static athletic single leg test ($H(2) = 0.11$, $p = 0.94$, $\eta^2 = 0.003$, $p < 0.05$).

Isokinetic shoulder strength test results

The one-way analysis of variance (ANOVA) test showed a significant difference between groups in all tests except internal rotators (IR) strength at 90°, non-dominant shoulder (NDS) ($F = 2.43$, mean square for between group = 376.7, mean square for within group = 154.5 and $p = 0.10$, $p < 0.05$) (Table 4). Based on the post hoc test, the comparison of scoliosis athletes with healthy athletes did not show a significant difference in the isokinetic normalized peak torques of the evaluated shoulder muscles ($p < 0.05$) (Table 5). There was no significant difference between squash players with idiopathic scoliosis and the control group in

CellPress
OPEN ACCESS

Table 1. Participant information

	Athletes with IS (*n* = 8)	Healthy athletes (*n* = 8)	Control group (*n* = 13)	*p* value
Age (years)	29.7 ± 8.6	25.7 ± 6	29.6 ± 5.4	0.38
Body weight (kg)	53 (51–66)[a]	64.4 ± 10.5	61.9 ± 14.5	0.63
Height (cm)	168.7 ± 9.3	165 (163–184)[a]	164 (160–167)[a]	0.34
Body mass index (kg/m2)	20.4 ± 2.2	23 ± 3.1	21.6 ± 3.1	0.24

Values other than number of participants are expressed as mean ± SD except where the data were non-normally distributed where these data are presented as median and IQR.
[a]Non normally distributed data. The ANOVA was used for between groups comparison ($p < 0.05$).

the PT of external rotators (ER) of the NDS at 90° (mean difference = 5.33, $p = 0.06$) and the mean values of the rest of the tests were significantly greater in squash players with idiopathic scoliosis than the control group ($p < 0.05$). Also, healthy athletes showed significantly greater isokinetic strength than controls, except for the PT of the ER muscle of the NDS at 45°, which did not show a significant difference (mean difference = 8.38, $p = 0.06$, $p < 0.05$).

The Kruskal-Wallis H test showed a statistically significant difference between groups in the normalized peak torques of the IR at a 45° in the NDS (H (2) = 7.04, $p = 0.02$, $\eta^2 = 0.25$). Pairwise comparisons using Dunn's test indicated that control group scores were significantly lower than healthy athletes ($p = 0.03$) and IS athletes ($p = 0.02$) and there was no significant difference between scoliosis athletes and healthy athletes. There was no missing data in the tests of this study.

A common way to assess effect size, especially in sports science, is the partial eta square. In the context of ANOVA, this criterion evaluates the strength of the effect of an independent variable on a dependent variable.[34] Effect sizes for each of the outcome measures in this study are shown in Tables 2 and 4. Small, medium, and large effects are reflected in partial values of partial η^2 equal to 0.01, 0.06, and 0.14 respectively.[34,35] In this study, the smallest and largest effect sizes for postural control were partial $\eta^2 = 0.28$ and $\eta^2 = 0.77$, respectively. Also, the smallest and largest effect sizes for the isokinetic strength of shoulder rotators were $\eta^2 = 0.90$ and $\eta^2 = 1.0$, respectively.

DISCUSSION

Postural control

Squash requires a stable base of support to execute a strong and accurate shot on the squash court.[23] The results of the postural stability test showed that squash players with idiopathic scoliosis and the control group had higher static MLSI than healthy players. Also, the DL showed a lower static APSI in squash players with idiopathic scoliosis than control group in the athletic single leg test. As well the NDL showed lower dynamic APSI in squash players with idiopathic scoliosis than in healthy squash players and controls. There was no difference between the three groups in the rest of the postural control variables (Table 3).

Previous studies on postural control have shown different results in idiopathic scoliosis participants. Some studies have reported greater sway in scoliosis participants compared to controls.[15–17,36–39] Other studies have shown no difference between idiopathic scoliosis and controls.[18,40–43] Findings of this study were supported by the study of Steinberg et al.[24] and Nagornov et al.[22] Both of these studies reported postural control problems in athletes with idiopathic scoliosis. Steinberg reported that dancers with scoliosis had poor dynamic postural control. Nagornov stated that as a result of balance and coordination problems footballers with scoliosis changed their kick speed sharply. When comparing our results with other studies, it should be considered that most studies used different protocols (open and closed eyes,[16,42] three trials were collected for 10 s each, and only the final 7 s were used for analysis; [17] three trials of 64 s with 2 min rest between each trial with eyes open; [38] participants stood for 2 min with eyes open and 2 min with eyes closed[40]), assessment tools (force platform (Stabiliometer),[16,17,37,38,40,42,43] motion analyzer[18]) and participants (sports other than squash,[22,24] non-athletic adolescents; [17,37,39,40] participants had single or double curves with right or left primary curves,[43] all participants had double curves[41]).

Postural control and idiopathic scoliosis

In most of the literature, greater postural sway and higher scores on the BSS are interpreted as poor balance.[44] In this study squash players with idiopathic scoliosis and controls showed higher static MLSI than healthy athletes. Postural control requires the integration of proprioceptive, vestibular, and visual senses as well as appropriate sensorimotor control to produce motor commands.[45] Patients with idiopathic scoliosis have disorders in the proprioceptive and vestibular systems[18,19,37] and this sensorimotor dysfunction in patients with idiopathic scoliosis has been shown to cause them to give more weight to vestibular information and the variability of the vestibular system is six to ten times greater than that of the proprioceptive system.[45] This reweighting in favor of the vestibular system and remaining sensory system is problematic. In this case, vestibular sensory information must be combined with other remaining sensory information to adjust postural control commands to the gravitational torque.[46] Relying on vestibular information, which is less accurate than visual and proprioceptive information, may have caused poor postural control in squash players with idiopathic scoliosis.

One of the two main mechanisms for postural control of the frontal plane is foot tilt[47] and the center of pressure (COP) position in patients with AIS is shifted posteriorly in the sagittal plane.[15] This condition may have affected postural control in athletes with scoliosis. The posterior displacement of the COP causes patients with scoliosis to stand on their heels. This condition impairs horizontal standing balance and therefore more torsional control will be required.[48] When the COP is displaced posteriorly, the efficiency of the foot tilt is reduced, therefore, a

Table 2. Comparison of postural control between groups

	Index	F	*p* value	Partial η^2
Dynamic postural stability	OSI[a]	0.57	0.57	0.53
Dynamic postural stability	APSI[b]	0.21	0.80	0.43
Dynamic postural stability	MLSI[c]	2.14	0.13	0.39
Static postural stability	OSI	1.76	0.19	0.30
Static postural stability	APSI	1.00	0.38	0.39
Static postural stability	MLSI	5.07	0.01[f]	0.34
Dynamic athletic single leg (DL)[d]	OSI	0.44	0.64	0.65
Dynamic athletic single leg (DL)	APSI	0.94	0.40	0.43
Dynamic athletic single leg (DL)	MLSI	0.29	0.74	0.28
Dynamic athletic single leg (NDL)[e]	OSI	1.40	0.26	0.58
Dynamic athletic single leg (NDL)	APSI	4.83	0.01[f]	0.77
Dynamic athletic single leg (NDL)	MLSI	2.10	0.14	0.53
Static athletic single leg (DL)	OSI	0.71	0.50	0.49
Static athletic single leg (DL)	APSI	3.65	0.04[f]	0.44
Static athletic single leg (NDL)	OSI	1.45	0.25	0.56
Static athletic single leg (NDL)	APSI	0.68	0.51	0.50
Static athletic single leg (NDL)	MLSI	0.86	0.43	0.55

[a]Overall stability index.
[b]Anteroposterior stability index.
[c]Mediolateral stability index.
[d]Dominant leg.
[e]Non-dominant leg.
[f]Statistically significant $p < 0.05$.

larger and faster foot tilt movement is required.[47] Therefore, poor postural control in the frontal plane in squash players with idiopathic scoliosis may be due to poor foot tilt function.

Almost every sport has an optimistic non-specific effect on postural regulation, and these positive effects on postural regulation components lead to better postural stability.[11] The increase in COP sway in the control group compared to healthy athletes could be due to lack of physical activity.

A combination of deficits in sensorimotor mechanisms associated with scaling balance control commands and biomechanical factors worsen AIS body sway.[46] If the spine cannot be accurately tracked, the information used by the central nervous system (CNS) will be noisy and the control exerted on the spine will not be accurate.[49] In the presence of idiopathic scoliosis, abnormal impulses sent from proprioceptive receptors in the spine attack the brainstem, causing dysfunction and the release of more abnormal impulses.[36] When sensory information is retrieved in patients with scoliosis, they have problems in dynamically regulating the weights of different sensory inputs to regulate postural control commands with a mechanical context.[50]

The trunk is the center of the functional kinetic chain in lunge movement[8] but in the trunk with a scoliotic spine this kinetic chain cannot provide a firm base for the squash player's lower extremity as the trunk's muscles EMG have been shown to be changed in idiopathic scoliosis.[9] Thus deficit in the trunk functional kinetic chain, the posterior displacement of the COP[15] plus sensorimotor dysfunction[18,19,37] and deficiency in foot tilt as mechanisms for postural control of the frontal plane[47] seem to effect these squash player's postural control. The lunge creates a high compressive contact force on the ankle,[51] and therefore poor postural control combined with this high force can lead to ankle injury.

We considered reduced COP sway in the sagittal plane as a weak postural control in squash players with idiopathic scoliosis compared to healthy athletes and controls. Reduced postural sway may indicate resistance to movement as patients with scoliosis are more likely to reach the limits of stability and thus lose postural control.[17] The reduction of COP sway in the sagittal plane in athletes with idiopathic scoliosis can be due to adaptation to a different control strategy to control the scoliotic spine. Any change in body posture is impossible without affecting muscle activity patterns and changes in movement patterns because there is a direct relationship and interaction between these three factors.[49]

An inaccurate perception of the gravitational vertical[52] and morphological changes of the trunk in right thoracic scoliosis causes more weight to be carried on the DL, thus, stepping with the right limb has been reported to be more challenging than stepping with the NDL.[53] This is consistent with our finding of poor dynamic balance in the NDL. There is a relationship between the ranking of healthy squash players and dynamic balance in the NDL and this may be one of the most important factors in the performance of squash athletes.[23] This factor was impaired in squash players with scoliosis.

Balance helps limit the mediolateral displacement and loading of the knee during dynamic activities.[54] Studies have shown that squash players[55] and female athletes[56] are more likely to injure the anterior cruciate ligament in their NDL. We suggest that poor dynamic balance of the NDL in scoliosis squash athletes can put them at risk of injury.

The present study provides evidence that athletes with scoliosis in both static and dynamic single leg tests have poor balance only in the sagittal plane. There is a relationship between sagittal alignment and postural instability. Also, one of the key factors for pain and progression in adult scoliosis is the sagittal balance.[39] It can be concluded that these results are due to the loss of natural curvature in squash players with scoliosis in the sagittal plane.

No significant difference was observed between the groups in other static and dynamic postural control variables. The reason may be that all tests were performed with eyes open, so athletes with idiopathic scoliosis could improve balance with the help of visual feedback. The organization of a structural unit in the body is such that if one component causes an error in the output, the other components change their contribution to reduce the original error, so there is no need for corrective action from the

Table 3. The result of the post hoc test comparing the posture control of three groups

	Athletes with IS[a]-healthy athletes		Athletes with IS- controls		Healthy athletes-controls	
	p value	Mean difference (95% CI[b] s)	*p* value	Mean difference (95% CIs)	*p* value	Mean difference (95% CIs)
Static postural stability/MLSI[c]	0.01[g]	0.63 (0.15–1.10)	0.91	0.02 (−0.38 to 0.43)	0.01[g]	−0.60 (−1.03 to −0.18)
Dynamic athletic single leg (NDL)[d]/APSI[e]	0.03[g]	−0.76 (−1.48 to −0.04)	0.01[g]	−0.97 (−1.62 to −0.32)	0.49	−0.21 (−0.83 to 0.41)
Static athletic single leg (DL)[f]/APSI	0.55	−0.23 (−1.05 to 0.57)	0.02[g]	−0.88 (−1.62 to −0.15)	0.06	−0.65 (−1.35 to 0.05)

[a]Idiopathic scoliosis.
[b]Confidence interval.
[c]Mediolateral stability index.
[d]Non-dominant leg.
[e]Anteroposterior stability index.
[f]Dominant leg.
[g]Statistically significant $p < 0.05$.

controller.[57] Visual input is important in maintaining postural balance. Information from the visual system can be more sensitive than proprioception and more accurate than the vestibular system.[16] patients with idiopathic scoliosis compensate for the deficit in the estimation of gravitational vertical using vision.[58] A greater COP sway in the eyes closed condition has been reported in scoliosis participants.[42,50] Compensatory strategies may have emerged in patients with idiopathic scoliosis to overcome balance control challenges. Lanthier et al.[40] reported no balance control difference but reported a higher alpha peak frequency in patients with AIS compared to healthy controls. They suggested that AIS may require increased cortical processing to maintain postural control in normal standing, and this may be a compensatory strategy to manage postural control challenges.

Complexity and variability in postural control

Higher MLSI in the frontal plane in athletes with idiopathic scoliosis may be associated with increased complexity and variability in postural control, and lower APSI in the sagittal plane may be associated with decreased complexity and variability in postural control in athletes with idiopathic scoliosis. There is an optimal variability state with a chaotic structure in healthy and functional movement.[59] In cases such as unhealthy pathological conditions where biological systems are less adaptive to perturbation, the systems are either excessively inflexible or noisy and unstable.[60] It has been suggested that diseases are related to loss of variability and complexity.[61] In dynamic systems and under certain conditions, when variability increases and reaches a critical and unstable point, the system changes to a new and more stable movement pattern that has less variability.[60]

It can be concluded that the reduction of proprioceptive ability in athletes with idiopathic scoliosis[24] may change the complexity of postural control. The number of system elements and functional interactions among them is defined as complexity. The change in complexity depends on the dimension of the intrinsic dynamic of the physiological or behavioral system. With age and disease, complexity increases in systems with oscillatory dynamics. In contrast, the complexity is reduced in systems with fixed-point dynamics.[62] In squash athletes with idiopathic scoliosis, postural control strategies operate differently in the frontal and sagittal planes. We propose that the complexity and variability may operate differently in athletes with idiopathic scoliosis in the frontal and sagittal planes. Gruber et al.[17] suggested that the two planes of COP motion should be investigated independently to provide more insight into the postural needs of patients with scoliosis. We suggest that increased complexity may be related to oscillatory dynamics in the frontal plane and decreased complexity may be related to fixed point dynamics in the sagittal plane.

The postural control of athletes with idiopathic scoliosis was not impaired in most indexes, perhaps visual feedback compensates for proprioceptive and vestibular impairments in these athletes. Also, postural control functions differently in frontal and sagittal planes in squash athletes with idiopathic scoliosis. Our findings suggest that researchers should consider both the sagittal and frontal planes when assessing postural control.

Table 4. ANOVA test results

Test		Index	F	*p* value	Partial η^2
IR[a]/90°	$60°s^{-1}$	DS[b]	6.27	0.00[e]	1.0
IR/45°	$60°s^{-1}$	DS	7.71	0.00[e]	1.0
IR/90°	$60°s^{-1}$	NDS[c]	2.43	0.10	0.97
ER[d]/90°	$60°s^{-1}$	DS	6.47	0.00[e]	0.90
ER/45°	$60°s^{-1}$	DS	8.46	0.00[e]	1.0
ER/90°	$60°s^{-1}$	NDS	3.70	0.03[e]	0.97
ER/45°	$60°s^{-1}$	NDS	3.99	0.03[e]	1.0

[a]Internal rotators.
[b]Dominant shoulder.
[c]Non-dominant shoulder.
[d]External rotators, Normalized PT (N.m) for the ER and the IR in two testing positions.
[e]Statistically significant $p < 0.05$.

Isokinetic shoulder strength

The angular and linear movements of the athlete's trunk and upper extremities serve a crucial function in effective shots by controlling racket speed, position at impact, and trajectory.[28] This study showed that the isokinetic PT of the IR and ER muscles

Table 5. The result of the post hoc test comparing the shoulder rotators strength of three groups

	Athletes with IS[a]- healthy athletes		Athletes with IS- controls		Healthy athletes-controls	
	p value	Mean difference (95% CI[b] s)	*p* value	Mean difference (95% CIs)	*p* value	Mean difference (95% CIs)
IR[c]/90°/DS[d]	0.98	−0.08 (−12.8 to 12.6)	0.00[g]	16.0 (4.94–27.0)	0.00[g]	16.1 (4.55–27.6)
IR/45°/DS	0.42	−5.35 (−18.8 to 8.18)	0.01[g]	15.9 (4.23–27.7)	0.00[g]	21.3 (9.08–33.6)
ER[e]/90°/DS	0.93	−0.32 (−8.47 to 7.82)	0.00[g]	10.4 (3.16–17.8)	0.00[g]	10.8 (3.48–18.1)
ER/45°/NDS[f]	0.58	2.64 (−7.29 to 12.5)	0.01[g]	11.0 (2.40–19.6)	0.06	8.38 (−61.0 to 17.3)
ER/90°/NDS	0.61	−1.55 (−7.83 to 4.73)	0.06	5.33 (−0.31 to 10.9)	0.01[g]	6.88 (1.23–12.5)
ER/45°/DS	0.93	−0.36 (−9.74 to 9.01)	0.00[g]	13.5 (5.40–21.6)	0.00[g]	13.9 (5.41–22.4)

[a]Idiopathic scoliosis.
[b]Confidence interval.
[c]Internal rotators.
[d]Dominant shoulder.
[e]External rotators.
[f]Non-dominant shoulder.
[g]Statistically significant $p < 0.05$.

of the shoulder is not significantly different between squash players with idiopathic scoliosis and healthy squash players. Comparing the results (athletes with scoliosis and control group) showed that except for the PT of the ER muscle of the NDS at 90°, which did not show a difference, other tests showed higher values in athletes with idiopathic scoliosis than the control group. Also, comparing the results (healthy athletes and control group) showed that except for the PT of the ER muscle of the NDS at 45°, which did not show a difference, other tests showed higher values in healthy athletes than the control group.

A healthy spinal posture is essential for physical performance in overhead athletes because it acts as a transmission link for the upper extremity through the spinal kinematic chain. Since the arm, scapula, and thoracic spine are links in the kinematic sequence of upper quadrant movements, any dysfunction is related to other links.[25]

Although changes in paraspinal and scapular muscles have been reported in patients with AIS ,[63] the results of the present study did not show a difference between the normalized PT of the internal and external shoulder rotators of the DS and NDS in 90- and 45-degree shoulder abduction in squash players with and without idiopathic scoliosis. Few studies have examined the relationship between posture and strength. Yagci et al.[64] found that upper extremity function was influenced by curve patterns. Their results do not support the findings of this study. Given that they assessed bilateral handgrip strengths and participants were all non-athletes, comparisons of results should be cautious. The study of Sari et al.[65] and Reyhani et al.[66] showed the same result as our study. Sari et al.[65] reported that scapular asymmetry did not affect muscle strength in subjects with AIS. Although they examined shoulder flexion and abduction strength in subjects with AIS and not shoulder rotators. Reyhani et al.[66] compared shoulder proprioception in asymptomatic athletes with and without scapular dyskinesia and reported that while athletes with scapular dyskinesia had significantly less active shoulder joint position sense in internal and external rotation, they did not have significant differences in hand grip strength. Considering the previously stated, we suggest that muscle strength in participants with idiopathic scoliosis may be affected only in the proximal (spinal) part of the trunk and not in the distal (shoulder girdle) part.

Our findings may be influenced by the level of sports activity because the sports activity level of athletes was competitive and elite. Although we excluded athletes with idiopathic scoliosis and previous history of brace use or physical therapy to reduce the effect of treatment, they may have compensated shoulder rotation weakness with strength training during sports activity.

There are several ways to record muscle function such as measuring strength, muscle latency, activity, and endurance. The purpose of the present study was to investigate the isokinetic strength of the shoulder rotator muscles, so we did not evaluate the participants' shoulder rotator muscle endurance. It has been hypothesized that muscular endurance may be more important than muscular strength in maintaining posture because postural muscle contractions should last for a long time and posture is maintained by tonic muscle contraction.[67] Insufficiencies in type I fibers and dysfunction of calcium pumps in muscles have been identified in those with idiopathic scoliosis[68] and therefore these may affect the ability of those muscles to sustain correct posture. Therefore, it appears that strength is less related to postural misalignments.[69] Some studies have shown a relationship between posture and muscle endurance.[70–73] The association between passive sitting postures and reduced back muscle endurance in participants with low back pain was suggested by O'Sullivan et al.[72] Mulhearn et al.[71] also reported that there is evidence of a relationship between posture and postural muscular endurance in gymnasts. Postural muscular endurance was reduced in gymnasts with lordotic posture and low back pain. This suggests that other factors such as muscular endurance rather than absolute shoulder rotator muscle strength may be more important in the shoulder complex of athletes with scoliosis.

Furthermore, fatigue of the shoulder rotator muscles could be a factor that might have an effect on the difference between the strength of the squash players with scoliosis and healthy athletes. This difference may show itself when the muscles are fatigued during a long game of squash. In squash, the average match time was reported to be 49 min.[74] Chan et al.'s[75] study found that the trunk extensors of participants with AIS are

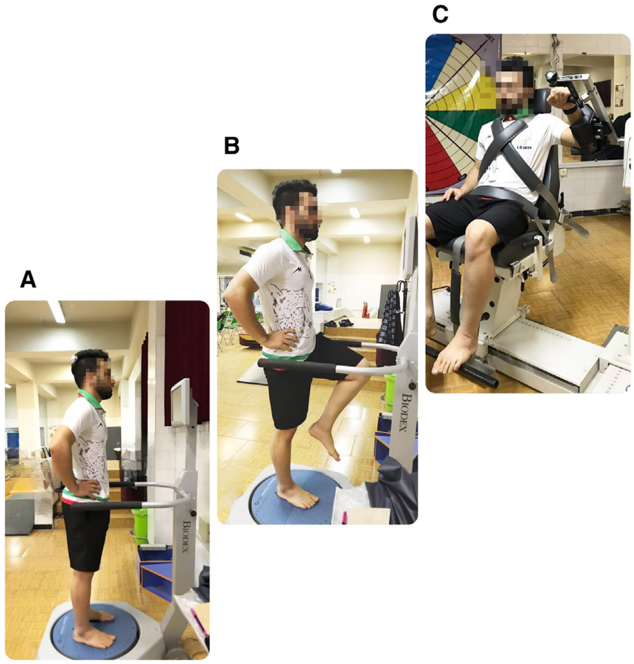


Figure 1. Postural control test and Isokinetic strength test
(A) Postural stability test (B) Athletic single leg test (C) Shoulder rotators isokinetic strength test.

affected by trunk extensor fatigue more than the corresponding muscles in healthy participants.

Our findings showed that the normalized PT of the control group was significantly lower than athletes with scoliosis and healthy athletes in post hoc tests (Table 5). This could be explained by considering that the control group was non-athletes who had no regular physical activity for more than 1 year.

Control participants had healthy spine posture but showed lower normalized PT compared to scoliosis athletes. As we mentioned before, this can be explained by the level of sports activity and strength training of athletes with scoliosis.

Anwajler et al.[76] showed that the force-velocity parameters of trunk flexors and extensors are influenced by the shape of the scoliotic spine. However, it is unclear whether these parameters are changed in the shoulder rotator muscles of squash players with idiopathic scoliosis. It is believed that force and speed are important factors that enable proper muscle activity and are also key indicators of physical performance. The muscle's ability to produce concentric force is greater at slow isokinetic speeds and decreases at high speeds. We suggest that future studies focus on functional parameters of shoulder muscles in athletes with idiopathic scoliosis as well as muscular endurance.

Scoliosis should not be considered only as a trunk pathology.[64] This study examined squash players with three curve scoliosis patterns, although the posture of the shoulder girdle was changed in these athletes, but the results of the present study showed that there is no difference between the normalized PT of the internal and external shoulder rotators of the DOM and NDOM shoulder in squash players with and without idiopathic scoliosis. Furthermore, we conclude that muscle strength may be less important for shoulder posture in squash players with idiopathic scoliosis.

We investigated postural control and shoulder rotation strength in adult squash athletes with and without idiopathic scoliosis, and to the authors' knowledge, most studies have focused on adolescent non-athletes with idiopathic scoliosis. The study used the EOS system instead of conventional X-rays; therefore, athletes were exposed to less radiation. In order to comprehensively investigate postural control in idiopathic scoliosis athletes, we evaluated static and dynamic balance with two tests in double leg and single leg standing positions. Also, to comprehensively investigate rotator strength in idiopathic scoliosis athletes, we evaluated the isokinetic strength of the DOM and NDOM shoulder in 90- and 45-degree shoulder abduction. This study also considered the effect of time of day and circadian rhythm on isokinetic strength in the data collection process.

Conclusion

Although the relationship between postural control and strength with form and posture is complex, changes in form may follow functional impairments and vice versa. Squash athletes with idiopathic scoliosis showed higher MLSI in the frontal plane and lower APSI in the sagittal plane. Our suggestion is to evaluate both planes in the study of postural control in order to have a comprehensive and accurate study. This study found no significant difference between shoulder rotator muscle strength in squash athletes with and without idiopathic scoliosis. We suggest that idiopathic scoliosis may not affect shoulder rotation strength.

Limitations of the study

Although vision plays an important role in postural control, it has been reported that elite athletes in various sports disciplines rely less on vision to control postural balance and visually pay attention to their sports activities.[77] We did not assess postural control with eyes closed (Figure 1). Therefore, future studies should aim to comprehensively assess postural control in both eyes-closed and eyes-open conditions.

RESOURCE AVAILABILITY

Lead contact

Further information and requests for resources should be directed to and will be fulfilled by the lead contact, Foad Seidi (foadseidi@ut.ac.ir).

Materials availability

This study did not generate new unique reagents.

Data and code availability

- Anonymized data have been provided in the Supplemental file (S1).
- This article does not report the original code.
- Any additional information required to reanalyze the data reported in this article is available from the lead contact upon request.

ACKNOWLEDGMENTS

The authors express their sincere respect to the squash players and staff of Dibaji and Enghelab sports complex for their help in this program.

Funding The authors have not declared a specific grant for this research from any funding agency in the public, commercial, or not-for- profit sectors.

AUTHOR CONTRIBUTIONS

L.M. and F.S. designed the experiment. L.M. and F.N. conducted the experiment. L.M. analyzed the data and wrote the article. F.S., H.M., and F.N. provided feedback on the article. All authors read and approved the current version of the article.

DECLARATION OF INTERESTS

The authors declare no competing interests.

STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

- KEY RESOURCES TABLE
- EXPERIMENTAL MODEL AND STUDY PARTICIPANT DETAILS
  - Study design and subjects
  - Participants, inclusion and exclusion criteria
- METHOD DETAILS
  - Equipment
  - Procedure and testing
  - Postural control test
  - Isokinetic strength test
- QUANTIFICATION AND STATISTICAL ANALYSIS

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.isci.2024.111353.

Received: April 14, 2024
Revised: August 29, 2024
Accepted: November 6, 2024
Published: November 9, 2024

REFERENCES

1. Mousavi, L., Seidi, F., Minoonejad, H., and Nikouei, F. (2022). Prevalence of idiopathic scoliosis in athletes: a systematic review and meta-analysis. BMJ Open Sport Exerc. Med. *8*, e001312. https://doi.org/10.1136/bmjsem-2022-001312.
2. Horobeanu, C., Johnson, A., and Pullinger, S.A. (2019). The prevalence of musculoskeletal injuries in junior elite squash players. Asian J. Sports Med. *10*, e84495. https://doi.org/10.5812/asjsm.84495.
3. Wörner, E.A. (2022). Safran MR. Racquet Sports: Tennis, Badminton, Racquetball, Squash. Specific Sports-Related Injuries (Springer), pp. 431–446.
4. Jeon, K., and Kim, S. (2016). Effect of unilateral exercise on spinal and pelvic deformities, and isokinetic trunk muscle strength. J. Phys. Ther. Sci. *28*, 844–849. https://doi.org/10.1589/jpts.28.844.
5. Bussey, M.D. (2010). Does the demand for asymmetric functional lower body postures in lateral sports relate to structural asymmetry of the pelvis? J. Sci. Med. Sport *13*, 360–364. https://doi.org/10.1016/j.jsams.2009.02.010.
6. Kim, D.-W., Ryue, J.-J., Lee, J.-H., Lee, K.-K., Kim, Y.-W., and Yi, J.-H. (2012). The Biomechanical Comparison of Close and Open Stance during the Forehand Squash Drive in Elite Squash Players. Off. J. Korean Acad. Kinesiol. *14*, 9–19. https://doi.org/10.15758/jkak.2012.14.1.9.
7. Nesbit, S.M., Serrano, M., and Elzinga, M. (2008). The role of knee positioning and range-of-motion on the closed-stance forehand tennis swing. J. Sports Sci. Med. *7*, 114–124.
8. Huang, M.-T., Lee, H.-H., Lin, C.-F., Tsai, Y.-J., and Liao, J.-C. (2014). How does knee pain affect trunk and knee motion during badminton forehand lunges? J. Sports Sci. *32*, 690–700. https://doi.org/10.1080/02640414.2013.848998.
9. Paramento, M., Passarotto, E., Maccarone, M.C., Agostini, M., Contessa, P., Rubega, M., Formaggio, E., and Masiero, S. (2024). Neurophysiological, balance and motion evidence in adolescent idiopathic scoliosis: A systematic review. PLoS One *19*, e0303086. https://doi.org/10.1371/journal.pone.0303086.
10. Sciascia, A., Thigpen, C., Namdari, S., and Baldwin, K. (2012). Kinetic chain abnormalities in the athletic shoulder. Sports Med. Arthrosc. Rev. *20*, 16–21. https://doi.org/10.1097/JSA.0b013e31823a021f.
11. Andreeva, A., Melnikov, A., Skvortsov, D., Akhmerova, K., Vavaev, A., Golov, A., Draugelite, V., Nikolaev, R., Chechelnickaia, S., Zhuk, D., et al. (2021). Postural stability in athletes: The role of sport direction. Gait Posture *89*, 120–125. https://doi.org/10.1016/j.gaitpost.2021.07.005.
12. Sinclair, J., Bottoms, L., Taylor, P.J., and Mahmood, K. (2017). Effects of shoes on kinetics and kinematics of the squash forward lunge in male players. Kinesiology *49*, 178–184. https://doi.org/10.26582/k.49.2.9.
13. Zemková, E. (2011). Assessment of balance in sport: sience and reality. Serbian J. Sports Sci. (SJSS) *5*, 127–139.
14. Guirelli, A.R., Dos Santos, J.M., Cabral, E.M.G., Pinto, J.P.C., De Lima, G.A., and Felicio, L.R. (2021). Relationship between upper limb physical performance tests and muscle strength of scapular, shoulder and spine stabilizers: A cross-sectional study. J. Bodyw. Mov. Ther. *27*, 612–619. https://doi.org/10.1016/j.jbmt.2021.05.014.
15. Dufvenberg, M., Adeyemi, F., Rajendran, I., Öberg, B., and Abbott, A. (2018). Does postural stability differ between adolescents with idiopathic scoliosis and typically developed? A systematic literature review and meta-analysis. Scoliosis Spinal Disord. *13*, 19. https://doi.org/10.1186/s13013-018-0163-1.
16. Sahlstrand, T., Örtengren, R., and Nachemson, A. (1978). Postural equilibrium in adolescent idiopathic scoliosis. Acta Orthop. Scand. *49*, 354–365. https://doi.org/10.3109/17453677809050088.
17. Gruber, A.H., Busa, M.A., Gorton Iii, G.E., Van Emmerik, R.E.A., Masso, P.D., and Hamill, J. (2011). Time-to-contact and multiscale entropy identify differences in postural control in adolescent idiopathic scoliosis. Gait Posture *34*, 13–18. https://doi.org/10.1016/j.gaitpost.2011.02.015.
18. Assaiante, C., Mallau, S., Jouve, J.-L., Bollini, G., and Vaugoyeau, M. (2012). Do adolescent idiopathic scoliosis (AIS) neglect proprioceptive information in sensory integration of postural control? PLoS One *7*, e40646. https://doi.org/10.1371/journal.pone.0040646.
19. Dąbrowska, A., Olszewska-Karaban, M.A., Permoda-Białozorczyk, A.K., and Szalewska, D.A. (2020). The postural control indexes during unipodal support in patients with idiopathic scoliosis. BioMed Res. Int. *2020*, 7936095. https://doi.org/10.1155/2020/7936095.
20. Herman, R., Mixon, J., Fisher, A., Maulucci, R., and Stuyck, J. (1985). Idiopathic scoliosis and the central nervous system: a motor control problem. The Harrington lecture, 1983. Scoliosis Research Society. Spine *10*, 1–14.
21. Cristancho, D.C.G., Trujillo, G.J., Manrique, I.F., Rodríguez, J.C.P., Orduz, R.C.D., and Calderón, M.E.B. (2022). Neurological Mechanisms Involved in Idiopathic Scoliosis. Systematic Review of the Literature, English Edition (Neurocirugía). https://doi.org/10.1016/j.neucie.2022.02.009.
22. Nagornov, M., Davlet'yarova, K., Il'in, A., and Kapilevich, L. (2015). Physiological features of shot technique of football players with musculoskeletal disorders. Theory Pract. Phys. Cult. *7*, 3. https://doi.org/10.15293/2226-3365.1601.11.
23. Schoeman, H., Coetzer, E., Watkin, S., Shaw, B.S., Lombard, A.J., and Shaw, I. (2014). Role of physical fitness parameters in squash performance. Afr. J. Phys. Health Educ. Recreat. Dance (AJPHERD) *20*, 55–962. https://hdl.handle.net/10520/EJC162470.
24. Steinberg, N., Tenenbaum, S., Zeev, A., Pantanowitz, M., Waddington, G., Dar, G., and Siev-Ner, I. (2021). Generalized joint hypermobility, scoliosis, patellofemoral pain, and physical abilities in young dancers. BMC Musculoskelet. Disord. *22*, 161. https://doi.org/10.1186/s12891-021-04023-z.

25. Lin, J.-J., Chen, W.-H., Chen, P.-Q., and Tsauo, J.-Y. (2010). Alteration in shoulder kinematics and associated muscle activity in people with idiopathic scoliosis. Spine *35*, 1151–1157. https://doi.org/10.1097/BRS.0b013e3181cd5923.
26. Chan, W.W.Y., Fu, S.-N., Chong, T.-F., Singh, G., Tsai, D.S.J., Wong, M.C.Y., Zheng, Y.-P., Parent, E.C., Cheung, J.P.Y., and Wong, A.Y.L. (2024). Associations between paraspinal muscle characteristics and spinal curvature in conservatively treated adolescent idiopathic scoliosis: a systematic review. Spine J. *24*, 692–720. https://doi.org/10.1016/j.spinee.2023.11.008.
27. An, Y.-H., Ryu, J.-S., Ryu, H.-Y., and Lim, Y.-T. (2007). The kinematic analysis of the upper extremity during backhand stroke in squash. Korean J. Sport Biomech. *17*, 145–156. https://doi.org/10.5103/KJSB.2007.17.2.145.
28. Williams, B.K., Sanders, R.H., Ryu, J.H., Graham-Smith, P., and Sinclair, P.J. (2020). The kinematic differences between skill levels in the squash forehand drive, volley and drop strokes. J. Sports Sci. *38*, 1550–1559. https://doi.org/10.1080/02640414.2020.1747828.
29. Drew, M.K., Raysmith, B.P., and Charlton, P.C. (2017). Injuries impair the chance of successful performance by sportspeople: a systematic review. Br. J. Sports Med. *51*, 1209–1214. https://doi.org/10.1136/bjsports-2016-096731.
30. Asker, M., Brooke, H.L., Waldén, M., Tranaeus, U., Johansson, F., Skillgate, E., and Holm, L.W. (2018). Risk factors for, and prevention of, shoulder injuries in overhead sports: a systematic review with best-evidence synthesis. Br. J. Sports Med. *52*, 1312–1319. https://doi.org/10.1136/bjsports-2017-098254.
31. O'Donnell, V., and Leeder, J. (2020). The epidemiology of injuries in English professional squash; A retrospective analysis between 2004 and 2015. Phys. Ther. Sport *46*, 1–6. https://doi.org/10.1016/j.ptsp.2020.07.009.
32. Supartono, B., Gamma, R., Wiyono, S., and Yuli, S. (2015). The influence of scoliosis towards secondary osteoarthritis of the knee joint in athletes. Indonesian J. Sport Sci. *1*, 1.
33. Wong, A.Y.L., Chan, C., Hiller, C., Yung, P.S.H., Lau, K.K.L., Samartzis, D., and Surgenor, B. (2022). Is Scoliosis Associated with Dance Injury in Young Recreational Dancers? A Large-Scale Cross-Sectional Epidemiological Study. J. Dance Med. Sci. *26*, 41–49. https://doi.org/10.12678/1089-313X.031522f.
34. Yagin, F.H., Pinar, A., and de Sousa Fernandes, M.S. (2024). Statistical Effect Sizes in Sports Science. J. Ex. Sci. Phys. Act. Rev. *2*, 164–171. https://doi.org/10.5281/zenodo.12601138.
35. Richardson, J.T. (2011). Eta squared and partial eta squared as measures of effect size in educational research. Educ. Res. Rev. *6*, 135–147. https://doi.org/10.1016/j.edurev.2010.12.001.
36. Yamada, K., Ikata, T., Yamamoto, H., Tezuka, A., Hinoki, M., Hine, S., Okada, S., Niki, H., Fukui, K., Ishida, Y., and Ushio, N. (1967). 194. Equilibrium Function in Abnormal Varieties of Posture, Especially in Scoliosis. Med.-Chir. *9*, 234. https://doi.org/10.2176/nmc.9.234.
37. Gauchard, G.C., Lascombes, P., Kuhnast, M., and Perrin, P.P. (2001). Influence of different types of progressive idiopathic scoliosis on static and dynamic postural control. Spine *26*, 1052–1058. https://doi.org/10.1097/00007632-200105010-00014.
38. Beaulieu, M., Toulotte, C., Gatto, L., Rivard, C.H., Teasdale, N., Simoneau, M., and Allard, P. (2009). Postural imbalance in non-treated adolescent idiopathic scoliosis at different periods of progression. Eur. Spine J. *18*, 38–44. https://doi.org/10.1007/s00586-008-0831-6.
39. Şahin, F., Urak, Ö., and Akkaya, N. (2019). Evaluation of balance in young adults with idiopathic scoliosis. Turk. J. Phys. Med. Rehabil. *65*, 236–243. https://doi.org/10.5606/tftrd.2019.2825.
40. Lanthier, J., Simoneau, M., Knoth, I.S., Lippé, S., Bluteau, C., and Fortin, C. (2020). Increased EEG alpha peak frequency in adolescents with idiopathic scoliosis during balance control in normal upright standing. Neurosci. Lett. *722*, 134836. https://doi.org/10.1016/j.neulet.2020.134836.
41. Kuo, F.-C., Wang, N.-H., and Hong, C.-Z. (2010). Impact of visual and somatosensory deprivation on dynamic balance in adolescent idiopathic scoliosis. Spine *35*, 2084–2090. https://doi.org/10.1097/BRS.0b013e3181cc8108.
42. Byl, N.N., and Gray, J.M. (1993). Complex balance reactions in different sensory conditions: adolescents with and without idiopathic scoliosis. J. Orthop. Res. *11*, 215–227. https://doi.org/10.1002/jor.1100110209.
43. Wiernicka, M., Kotwicki, T., Kamińska, E., Łochyński, D., Kozinoga, M., Lewandowski, J., and Kocur, P. (2019). Postural stability in adolescent girls with progressive idiopathic scoliosis. BioMed Res. Int. *2019*, 7103546. https://doi.org/10.1155/2019/7103546.
44. Schmitz, R., and Arnold, B. (1998). Intertester and intratester reliability of a dynamic balance protocol using the Biodex Stability System. J. Sport Rehabil. *7*, 95–101. https://doi.org/10.1123/jsr.7.2.95.
45. Pialasse, J.-P., Mercier, P., Descarreaux, M., and Simoneau, M. (2016). Sensorimotor control impairment in young adults with idiopathic scoliosis compared with healthy controls. J. Manip. Physiol. Ther. *39*, 473–479. https://doi.org/10.1016/j.jmpt.2016.06.001.
46. Simoneau, M., Richer, N., Mercier, P., Allard, P., and Teasdale, N. (2006). Sensory deprivation and balance control in idiopathic scoliosis adolescent. Exp. Brain Res. *170*, 576–582. https://doi.org/10.1007/s00221-005-0246-0.
47. Hoogvliet, P., van Duyl, W.A., de Bakker, J.V., Mulder, P.G., and Stam, H.J. (1997). Variations in foot breadth: effect on aspects of postural control during one-leg stance. Arch. Phys. Med. Rehabil. *78*, 284–289. https://doi.org/10.1016/S0003-9993(97)90035-6.
48. Stylianides, G.A., Dalleau, G., Begon, M., Rivard, C.-H., and Allard, P. (2013). Pelvic morphology, body posture and standing balance characteristics of adolescent able-bodied and idiopathic scoliosis girls. PLoS One *8*, e70205. https://doi.org/10.1371/journal.pone.0070205.
49. Hodges, P.W., Cholewicki, J., and Van Dieën, J.H. (2013). Spinal control: the rehabilitation of back pain: state of the art and science. https://doi.org/10.3138/ptc.67.4.rev1.
50. Simoneau, M., Mercier, P., Blouin, J., Allard, P., and Teasdale, N. (2006). Altered sensory-weighting mechanisms is observed in adolescents with idiopathic scoliosis. BMC Neurosci. *7*, 68. https://doi.org/10.1186/1471-2202-7-68.
51. Chen, T.L.-W., Wang, Y., Wong, D.W.-C., Lam, W.-K., and Zhang, M. (2022). Joint contact force and movement deceleration among badminton forward lunges: a musculoskeletal modelling study. Sports BioMech. *21*, 1249–1261. https://doi.org/10.1080/14763141.2020.1749720.
52. Le Berre, M., Pradeau, C., Brouillard, A., Coget, M., Massot, C., and Catanzariti, J.-F. (2019). Do adolescents with idiopathic scoliosis have an erroneous perception of the gravitational vertical? Spine Deform. *7*, 71–79. https://doi.org/10.1016/j.jspd.2018.05.004.
53. Bruyneel, A.-V., Chavet, P., Bollini, G., Allard, P., Berton, E., and Mesure, S. (2009). Dynamical asymmetries in idiopathic scoliosis during forward and lateral initiation step. Eur. Spine J. *18*, 188–195. https://doi.org/10.1007/s00586-008-0864-x.
54. Steffen, K., Nilstad, A., Krosshaug, T., Pasanen, K., Killingmo, A., and Bahr, R. (2017). No association between static and dynamic postural control and ACL injury risk among female elite handball and football players: a prospective study of 838 players. Br. J. Sports Med. *51*, 253–259. https://doi.org/10.1136/bjsports-2016-097068.
55. Seyedi, M., Shirzad, E., Mirkarimpour, S.H., and Rezvankhah Golsefidi, N. (2014). The Comparison of High-Risk Patterns of ACL Injury in Dominant and Non-Dominant Legs of Males and Females during Cutting Maneuver. J. Ex. Sci. Med. *5*, 23–37. https://sshr.ut.ac.ir/article_36540_06971c637b67eb6d7894cb2f98205d13.pdf.
56. Brophy, R., Silvers, H.J., Gonzales, T., and Mandelbaum, B.R. (2010). Gender influences: the role of leg dominance in ACL injury among soccer players. Br. J. Sports Med. *44*, 694–697. https://doi.org/10.1136/bjsm.2008.051243.

57. Latash, M.L., Scholz, J.P., and Schöner, G. (2002). Motor control strategies revealed in the structure of motor variability. Exerc. Sport Sci. Rev. *30*, 26–31. https://doi.org/10.1097/00003677-200201000-00006.

58. Antoniadou, N., Hatzitaki, V., Stavridis, S.I., and Samoladas, E. (2018). Verticality perception reveals a vestibular deficit in adolescents with idiopathic scoliosis. Exp. Brain Res. *236*, 1725–1734. https://doi.org/10.1007/s00221-018-5256-9.

59. Davids, K., Shuttleworth, R., Button, C., Renshaw, I., and Glazier, P. (2004). "Essential noise"–enhancing variability of informational constraints benefits movement control: a comment on Waddington and Adams (2003). Br. J. Sports Med. *38*, 601–605. https://doi.org/10.1136/bjsm.2003.007427.

60. Stergiou, N., and Decker, L.M. (2011). Human movement variability, nonlinear dynamics, and pathology: is there a connection? Hum. Mov. Sci. *30*, 869–888. https://doi.org/10.1016/j.humov.2011.06.002.

61. van Emmerik, R.E.A., and van Wegen, E.E.H. (2002). On the functional aspects of variability in postural control. Exerc. Sport Sci. Rev. *30*, 177–183. https://doi.org/10.1097/00003677-200210000-00007.

62. Vaillancourt, D.E., and Newell, K.M. (2002). Changing complexity in human behavior and physiology through aging and disease. Neurobiol. Aging *23*, 1–11. https://doi.org/10.1016/S0197-4580(01)00247-0.

63. Alves, D.P.L., and Araújo, B. (2016). Muscle disorders in adolescent idiopathic scoliosis: literature review. Coluna/Columna *15*, 73–77. https://doi.org/10.1590/S1808-185120161501151839.

64. Yagci, G., Aydin Ozcan, D., Ayhan, C., Demirkiran, G., Yakut, Y., and Yazici, M. (2020). Evaluation of upper extremity function and its relation to curve pattern in female adolescents with idiopathic scoliosis: a pilot study. Spine Deform. *8*, 1175–1183. https://doi.org/10.1007/s43390-020-00148-8.

65. Sarı, M., Bütün, M., and Bek, N. (2024). Does scapular asymmetry affect shoulder joint position sense and muscle strength in adolescent idiopathic scoliosis? A pilot study. J. Ortho. Res. Rehabil. *2*, 49–54. https://doi.org/10.51271/JORR-0033.

66. Reyhani, F., Meftahi, N., and Rojhani-Shirazi, Z. (2024). Comparing shoulder proprioception, upper extremity dynamic stability, and hand grip strength in overhead athletes with and without scapular dyskinesis. J. Bodyw. Mov. Ther. *39*, 304–310. https://doi.org/10.1016/j.jbmt.2024.03.001.

67. Young, M., and Michael, L. (2002). A review on postural realignment and its muscular and neural components. Br. J. Sports Med. *9*, 51–76.

68. Mannion, A.F., Meier, M., Grob, D., and Müntener, M. (1998). Paraspinal muscle fibre type alterations associated with scoliosis: an old problem revisited with new evidence. Eur. Spine J. *7*, 289–293. https://doi.org/10.1007/s005860050077.

69. Forte, P., Gouveia, J., and Coelho, E. (2020). The Postural Alignment Determinants: What is Known And Further Research. J Ergon. *10*, 266. https://doi.org/10.35248/2165-7556.20.10.266.

70. Dejanovic, A., Cambridge, E.D.J., and McGill, S. (2013). Does spine posture affect isometric torso muscle endurance profiles in adolescent children? Adv. Phys. Educ. *03*, 111–115. https://doi.org/10.4236/ape.2013.33019.

71. Mulhearn, S., and George, K. (1999). Abdominal muscle endurance and its association with posture and low back pain: An initial investigation in male and female elite gymnasts. Physiotherapy *85*, 210–216. https://doi.org/10.1016/S0031-9406(05)65666-0.

72. O'Sullivan, P.B., Mitchell, T., Bulich, P., Waller, R., and Holte, J. (2006). The relationship beween posture and back muscle endurance in industrial workers with flexion-related low back pain. Man. Ther. *11*, 264–271. https://doi.org/10.1016/j.math.2005.04.004.

73. Oliveira, A.C., and Silva, A.G. (2016). Neck muscle endurance and head posture: a comparison between adolescents with and without neck pain. Man. Ther. *22*, 62–67. https://doi.org/10.1016/j.math.2015.10.002.

74. Jones, T.W., Williams, B.K., Kilgallen, C., Horobeanu, C., Shillabeer, B.C., Murray, A., and Cardinale, M. (2018). A review of the performance requirements of squash. Int. J. Sports Sci. Coach. *13*, 1223–1232. https://doi.org/10.1177/1747954118792492.

75. Chan, R.Y.H., Ma, A.C.F., Cheung, T.S.K., Chan, J.C.L., Kwok, R.W.Y., Fu, A.C.L., and Tsang, S.M.H. (2023). Effect of muscle fatigue of the thoracic erector spinae on neuromuscular control when performing the upper extremity functional tasks in people with adolescent idiopathic scoliosis. PLoS One *18*, e0281001. https://doi.org/10.1371/journal.pone.0281001.

76. Anwajler, J., Skrzek, A., Mraz, M., Skolimowski, T., and Woźniewski, M. (2006). The size of physiological spinal curvatures and functional parameters of trunk muscles in children with idiopathic scoliosis. Isokinet. Exerc. Sci. *14*, 251–259. https://doi.org/10.3233/IES-2006-0234.

77. Onofrei, R.R., and Amaricai, E. (2022). Postural balance in relation with vision and physical activity in healthy young adults. Int. J. Environ. Res. Public Health *19*, 5021. https://doi.org/10.3390/ijerph1909502.

78. Cobley, S., Baker, J., Wattie, N., and McKenna, J. (2009). Annual age-grouping and athlete development. Sports Med. *39*, 235–256. https://doi.org/10.2165/00007256-200939030-00005.

79. Huang, S.-C. (1997). Cut-off point of the Scoliometer in school scoliosis screening. Spine *22*, 1985–1989. https://doi.org/10.1097/00007632-199709010-00007.

80. Cassar-Pullicino, V.N., and Eisenstein, S.M. (2002). Imaging in scoliosis: what, why and how? Clin. Radiol. *57*, 543–562. https://doi.org/10.1053/card.2001.0909.

81. Ponkilainen, V., Kuitunen, I., Liukkonen, R., Vaajala, M., Reito, A., and Uimonen, M. (2022). The incidence of musculoskeletal injuries: a systematic review and meta-analysis. Bone Joint Res. *11*, 814–825. https://doi.org/10.1302/2046-3758.1111.BJR-2022-0181.R1.

82. van Melick, N., Meddeler, B.M., Hoogeboom, T.J., Nijhuis-van der Sanden, M.W.G., and van Cingel, R.E.H. (2017). How to determine leg dominance: The agreement between self-reported and observed performance in healthy adults. PLoS One *12*, e0189876. https://doi.org/10.1371/journal.pone.0189876.

83. Deschênes, S., Charron, G., Beaudoin, G., Labelle, H., Josée, D., Miron, M.C., and Parent, S. (2010). Diagnostic imaging of spinal deformities: reducing patients radiation dose with a new slot-scanning X-ray imager. Spine *35*, 989–994. https://doi.org/10.1097/BRS.0b013e3181bdcaa4.

84. Paterno, M.V., Myer, G.D., Ford, K.R., and Hewett, T.E. (2004). Neuromuscular training improves single-limb stability in young female athletes. J. Orthop. Sports Phys. Ther. *34*, 305–316. https://doi.org/10.2519/jospt.2004.34.6.305.

85. Edouard, P., Codine, P., Samozino, P., Bernard, P.-L., Hérisson, C., and Gremeaux, V. (2013). Reliability of shoulder rotators isokinetic strength imbalance measured using the Biodex dynamometer. J. Sci. Med. Sport *16*, 162–165. https://doi.org/10.3233/IES-2012-0470.

86. Izadi, M., Thomas, E., Thomas, A.C., and Bellafiore, M. (2022). The effect of time-of-day and sleep deprivation on postural control: A systematic review. Gait Posture *97*, 94–103. https://doi.org/10.1016/j.gaitpost.2022.07.245.

87. Ejnisman, B., Barbosa, G., Andreoli, C.V., de Castro Pochini, A., Lobo, T., Zogaib, R., Cohen, M., Bizzini, M., and Dvorak, J. (2016). Shoulder injuries in soccer goalkeepers: review and development of a FIFA 11+ shoulder injury prevention program. Open Access J. Sports Med. *7*, 75–80. https://doi.org/10.2147/OAJSM.S97917.

88. Forthomme, B., Dvir, Z., Crielaard, J.-M., and Croisier, J.-L. (2011). Isokinetic assessment of the shoulder rotators: a study of optimal test position. Clin. Physiol. Funct. Imaging *31*, 227–232. https://doi.org/10.1111/j.1475-097X.2010.01005.x.

STAR★METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Deposited data		
Analyzed data	This paper	Data S1
Software and algorithms		
Biodex Stability System	BSS, Shirley, NY, USA	https://biodexrehab.com/products/balance-system-sd/
Biodex System 4 Pro	Biodex Medical System Inc, Shirley, NY, USA	https://biodexrehab.com/products/system-4-pro/
SPSS 26.0	IBM Corporation, USA	https://www.ibm.com/products/spss-statistics

EXPERIMENTAL MODEL AND STUDY PARTICIPANT DETAILS

Study design and subjects

Twenty-nine participants (24 female and five male) participated in this study. Eight squash athletes with idiopathic scoliosis, eight healthy squash athletes and 13 control participants voluntarily participated in this study (Table 1). As shown in Table 1, there was no significant difference between the groups in terms of age, sex, body weight, height, body mass index (BMI). Written informed consent was obtained from each participant before data collection.

This cross-sectional study was approved by the Research Ethics Committee of Tehran University (IR.UT.SPORT.REC.1398.055). All methods were performed in accordance with the relevant guidelines and regulations. The influence of gender on the data was not specifically tested in this study.

Participants, inclusion and exclusion criteria

Athletes were selected among 70 squash players at the sports complexes of Dibaji and Enghelab. The sports activity level of athletes was competitive and elite.[78] The standing posture of all participants was assessed by observing from anterior, posterior and lateral views and looking for any abnormal shape or symmetry. The presence of scoliosis was assessed using Adam's forward bending test. If trunk rotation was present, a scoliometer was used to assess the angle of trunk rotation for referral for radiography.[79] All the participants were screened by the same examiner. An orthopedic surgeon examined 22 athletes who were referred to him based on trunk rotation ≥ 7.[1,79] Eight athletes met the inclusion and exclusion criteria. Healthy athletes were squash players without previous injury or postural abnormalities and were recruited from the same place as athletes with idiopathic scoliosis. Control group (healthy non-athletes without postural abnormalities and history of musculoskeletal injury) were recruited by sending online invitation messages using social networking sites. The control group was sedentary participants who had no regular physical activity for more than one year.

Inclusion criteria

Three-curve idiopathic scoliosis pattern with major curvature in the thoracic or thoracolumbar region (cobb angle ≥ 10),[80] all three groups: adults aged ≥ 18 years, active at competitive or elite level (An athlete who trains and/or competes in local competitions is considered a competitive athlete and an athlete who trains and/or competes at the national or international level is considered an elite athlete),[1] and all three groups: no recent (<3 month) history of musculoskeletal injury (injuries were defined as all fractures or tears of the corresponding anatomical region).[81]

Exclusion criteria

Having postural abnormalities (considered for healthy squash players and controls), congenital scoliosis, spina bifida, neurological scoliosis, neuromuscular scoliosis, spondylolisthesis, leg-length discrepancy greater than two cm, history of bracing or/and physiotherapy (<1 year). Leg dominance was determined by the leg used to kick the ball.[82] Hand dominance was defined as the one preferred for daily activities. All participants except one control participant were right-handed and right foot dominant. The mean ± standard deviation of the training experience and weekly training hours of squash players with idiopathic scoliosis and healthy squash players was 7.06±6.08 and 12.87±4.01 years, and 8.8±5.8 and 10.7±3.6 hours, respectively. Also, in this research, each sports group included two elite athletes and six competitive athletes.

METHOD DETAILS

Equipment

We used the EOS system (gold standard) to take radiographs with very low radiation exposur.[83] The Biodex Stability System (BSS, Shirley, NY, USA) was used to assess postural control. The BSS was shown to be reliable (ICCs ranged from 0.82 to 0.42 for OSI, APSI, and MLSI).[44] This device consists of a movable circular platform that can be tilted 20 degrees from horizontal in all directions. It measures the deviation of the COP in static conditions and the degree of tilt in dynamic conditions. The platform allows different difficulty levels of stability testing, from level 1 (least stable) to level 8 (most stable).[84]

Isokinetic strength of the shoulder was assessed using the Biodex System 4 Pro (Biodex Medical System Inc, Shirley, NY, USA) which is a valid and reliable tool.[85] The Biodex software program recorded the PT. The isokinetic dynamometer was calibrated using a certified weight prior to data collection.

Procedure and testing

All data were collected between 12:00 and 15:00 PM to account for the influence of circadian rhythm and time of day on postural control and muscle strength.[86] The warm-up protocol took approximately 10 minutes and consisted of jogging, jumping, and a series of shoulder warm-up exercises. We used the second part (1 A to 10 A) of the FIFA 11+S warm-up exercise in one set of 15 repetitions.[87] In the test session, the participants got acquainted with the test equipment and procedures.

Postural control test

Participants were wearing shorts, no shoes or socks. The measurements for each subject took 30 min. Postural control was measured using postural stability test and athletic single leg test in two conditions (dynamic and static) with eyes open. Postural control was evaluated by overall stability index (OSI), APSI and MLSI. All tests consisted of three trials that lasted 20 seconds with a 10-second rest period between each trial. The mean score was calculated from three trials. The difficulty level of the test in dynamic conditions were four.

Participants were instructed to stand on the locked platform of the BSS and adjust the supporting feet to achieve a comfortable standing position that allowed them to maintain balance. Then the position of the participants' feet was recorded. The position of the participants' feet remained constant in all tests. Participants were instructed to keep their hands on the iliac crests and were allowed to grab the handrailing if they lost their balance (any body movements in relation to the test position that forced the participants to grab a handrail to maintain balance was considered a loss of balance). One subject in the idiopathic scoliosis group lost her balance; the test canceled and repeated again. The subject was then instructed to keep the platform as stable as possible. Participants were instructed to look straight ahead and focus on a point on the wall approximately 0.5 m away. The control screen was covered during the test, so they did not receive any visual feedback about their test. Also, they did not receive any verbal feedback.[84] Participants had two practice tests before each test. Postural stability test was performed while standing on two legs. The athletic single leg test was performed in a single-leg standing position on the right and left leg, and the non-load-bearing leg was at 30° of hip and knee flexion (Figure 1).

The participants performed the tests in this order: 1- Dynamic postural stability, 2- Static postural stability, 3- Dynamic athletic single leg on the DL, 4- Dynamic athletic single leg on the NDL, 5- Static athletic single leg on the DL, 6- Static athletic single leg on the NDL.

Isokinetic strength test

Participants were assessed in a seated position while secured with pelvic and diagonal straps to stabilize the trunk. It took 30 minutes to collect isokinetic data from each participant. The isokinetic strength of shoulder ER and IR of the DS and NDS were evaluated randomly with the arm at 45° and 90° shoulder abduction in the scapular plane in the concentric/concentric mode. The elbow was bent 90° in all tests. The axis of the device coincided with the longitudinal axis of the humerus and the center of the glenohumeral joint. Gravity correction was performed with the arm relaxed in shoulder abduction (90° or 45° depending on the test) and the elbow in 90° flexion, and the forearm was in neutral pronation/supination.

Before each test, 10 submaximal concentric repetitions at $120^{\circ}s^{-1}$ and three preliminary submaximal repetitions at $60^{\circ}s^{-1}$ were used to get familiar with the test. Then the participants performed the test with three repetitions at $60^{\circ}s^{-1}$ concentric exertion. The range of motion (ROM) was 45° in IR and 55° in ER. There was a one-minute rest interval between all sections.[88] Isokinetic PT was determined and normalized by individual body weight (PT/body weight). Participants were verbally supported and were not allowed to see the displayed curves.

QUANTIFICATION AND STATISTICAL ANALYSIS

Before using the ANOVA, we checked the assumptions of normality (Shapiro-Wilk test) and homogeneity of variance (Levene's test). Normal distribution was not observed in some data, so inverse normal transformation method was used for them. After transformation, the assumption of normal distribution and homogeneity of data variance was obtained, except for the MLSI of the DL static athletic single leg test and the ER strength of the NDS at 45°. The results of the Shapiro-Wilk test to evaluate normality showed that in the dynamic postural stability test, MLSI had a normal distribution (p=0.14). The Shapiro-Wilk test also showed that in the dynamic postural stability test, OSI, APSI had a non-normal distribution (p=0.01 and p= 0.01, respectively). The Shapiro-Wilk test showed that in the static postural stability test, OSI, APSI and MLSI had a non-normal distribution (p=0.01, p=0.01 and p= 0.01, respectively).

The normality test showed that in the dynamic athletic single leg test, OSI, APSI and MLSI of DL had a non-normal distribution (p=0.01, p=0.01 and p= 0.01, respectively). The normality test showed that in the dynamic athletic single leg test, OSI, APSI and MLSI of NDL had a non-normal distribution (p=0.01, p=0.01 and p= 0.01, respectively).

The normality test showed that in the static athletic single leg test, OSI, APSI and MLSI of DL had a non-normal distribution (p=0.01, p=0.01 and p= 0.01, respectively). The normality test showed that in the static athletic single leg test, OSI, APSI and MLSI of NDL had a non-normal distribution (p=0.01, p=0.01 and p= 0.02, respectively).

The results of the Shapiro-Wilk test to evaluate normality showed that the normalized PT of ER strength of the DS at 90°, ER strength of the NDS at 90°, IR strength of the DS at 45° and ER strength of the NDS at 45° had a normal distribution (p=0.27 and p=0.44, p=0.05 and p=0.64, respectively).

The normality test also showed that the normalized PT of IR strength of the DS at 90°, ER strength of the DS at 45°, IR strength of the NDS at 90° and IR strength of the NDS at 45° had a non-normal distribution (p=0.01, p=0.03, p=0.01 and p=0.01, respectively). The ANOVA test and then post hoc analysis with Fisher's test (LSD) were used for normally distributed data. The Kruskal-Wallis test and then Dunn-Bonferroni post hoc method was used for non-normal data. A probability level of $P<0.05$ was selected for all tests. Statistical analysis of all tests was conducted in IBM SPSS Statistics Version 26.