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ORIGINAL ARTICLE

Three-dimensional characteristics and sex-based differences in sprinting movements in adolescent athletes

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ABSTRACT

In this study, we aimed to use three-dimensional analysis to describe the characteristics and sex-based differences in sprinting movements during adolescence, with a specific focus on the upper limbs and trunk. A three-dimensional analysis of arm swing and trunk movement during sprinting was conducted in eight boys (aged 13–14 years) and eight girls (aged 13–14 years) belonging to a junior high school track and field club. The girls showed greater torsional movement of the trunk than the boys, and swung their arms laterally rather than longitudinally. These results indicate the existence of clear sex-based differences in adolescent sprinting movements. In addition, the large trunk rotation observed during sprinting in girls had a negative effect on pitch, suggesting that these movements are undesirable when attempting to improve sprinting performance.
Keywords: Performance analysis, Sprinting performance, Arm swing, Trunk movement.

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INTRODUCTION

Numerous reports have indicated that sex-based differences in humans significantly affect their motor ability and movement. Sex-based differences in performance are believed to stem from biological features, such as differences in segment length, muscle mass, and the distribution of muscle mass in males and females (Malina et al, 2004). Notably, in the case of running, sex-based differences in sprint times, and lower limb movement have been observed in children (Miyamaru, 2001). As development progresses, these differences expand, revealing distinct factors that influence arm swing movement, lower limb movement, and sprinting performance in men and women (Hiruma & Kariyama, 2019; Hiruma, 2022; Ito et al., 1998; Katoh & Miyamaru, 2006).

Research has also addressed the differences in coaching between boys and girls. Katoh and Miyamaru (2006) conducted a cross-sectional analysis of sprinting movements in high school students and pointed out differences in lower limb movements between the sexes. They suggested reducing ankle dorsiflexion during ground contact in male runners and minimizing knee and ankle dorsiflexion during ground contact in female runners.

Studies exploring sex-based differences in running movements using three-dimensional (3D) analysis have also been conducted. Xie et al. (2022) conducted a meta-analysis of the biomechanical differences between male and female runners. They found that female runners exhibited significantly larger hip flexion, adduction, and internal rotation angles during running, along with significantly smaller knee flexion angles than male runners. These differences may contribute to the higher prevalence of patellofemoral pain syndrome in female runners than in male runners. Studies investigating trunk movement have revealed that females exhibit greater trunk rotation and shoulder range of motion during running than males (Bruening et al., 2020; Pontzer et al., 2009). However, these studies have focused on running at lower speeds and may not be directly applicable to sprinting at maximum speeds.

Sex-based differences in sprinting ability increase after the age of 12 (Katoh et al., 1985), with sex-based differences in arm swing movements being observed in middle school and beyond; these movements are potentially linked to trunk movement (Hiruma & Kariyama, 2019). Therefore, the evaluation of sex-based differences in sprinting movement during adolescence could provide valuable insights for coaching in junior and youth age groups. Additionally, hamstring injuries are more prevalent in female high-school sprinters than in males (Matsuo et al., 2020). In middle school and female athletes, the proportion of quadriceps muscle injuries tends to be comparable to that of hamstring injuries (Kamada, 2023). Thus, the elucidation of sex-based differences in sprinting movements during adolescence may be useful for injury prevention. However, to our knowledge, no 3D analyses of the characteristics and sex-based differences in sprinting movements during adolescence have been published to date.

In this study, we aimed to use 3D analysis to describe the characteristics and sex-based differences in sprinting movements during adolescence, with a specific focus on the upper limbs and trunk.

MATERIAL AND METHODS

Participants

The participants consisted of eight boys (height: 165.6 ± 8.3 cm; weight: 51.6 ± 6.4 kg; age: 13–14 years) and eights girls (height: 157.9 ± 3.2 cm; weight: 45.1 ± 6.5 kg; age: 13–14 years) who were members of a middle school track and field club and were competing in short distance or jumping events. All procedures were approved by the ethics committees of the authors' institutional affiliations. Written informed consent was obtained from the guardians of all participants aged <19 years prior to the initiation of the study. All experiments were performed in accordance with the principles of the Declaration of Helsinki.

Experimental procedures

The participants participated in two 60-m sprints at maximum effort on an all-weather track after a thorough warm-up. Ample rest was provided between trials. The faster of the two sprints was selected for the analysis.

Each trial involved 3D recording of movements using two high-speed cameras (CASIO, EX-F1, 300 Hz) positioned on the right side and in front of the participants. The recorded videos were imported into a computer, and a motion analysis system, Frame DIAS V (Q'sfix, Tokyo, Japan), was used for digitization. This process provided 3D coordinates for the 23 body analysis points and 2D coordinates for the calibration poles. The DLT constants for each camera were computed using the 2D coordinates of the calibration poles, and the 3D coordinates of each body analysis point were calculated using the 3D direct linear transform (DLT) method (Abdel-Aziz and Karara, 1971). The 3D coordinate system was defined as a right-handed stationary coordinate system with the y-axis representing the sprinting direction, the x-axis orthogonal to it horizontally, and the z-axis vertically. The standard errors for each axis were: x-axis:, 0.009m; y-axis, 0.008m; and z-axis, 0.006m. The analysis interval was set to 42–50m. Figure 1 shows the camera setup and coordinate space during recording.

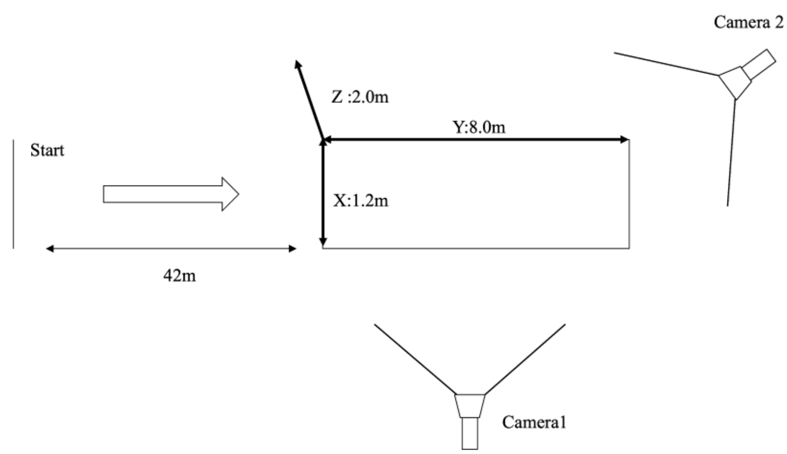

Figure 1. Experimental setup.

To eliminate digitization errors in the 3D coordinates of the various body parts, the optimal cutoff frequency determined by residual analysis (5.9–11.9 Hz) was used, and a fourth-order Butterworth digital filter without phase shift was applied for smoothing (Winter, 2004).

Computed parameters

Pitch, Stride, and Sprint Speed. Pitch was defined as the reciprocal of the time taken for one step, whereas stride represented the distance moved by the body's centre of mass in the sprinting direction (y-axis) during one step. The sprint speed was calculated as the product of pitch and stride.

Kinematics of the Upper Limbs, Trunk, and Lower Limbs. The upper limbs (arm swing) involved defining the forearm angle as the angle formed by the line segment connecting the elbow joint centre and hand joint centre after projecting it onto the X–Z plane. This angle is formed by the line segment connecting the elbow joint centre and hand joint centre and the line segment perpendicular to the ground (Figure 2). Left and right arm values were obtained, and the arm with the larger maximum value was used in the forearm angle analysis. The forearm and trunk angles described below were normalized for three phases of one cycle during sprinting (recovery late phase: from left foot contact to right foot contact, support phase: from right foot contact to right foot lift-off, recovery early phase: from right foot lift-off to left foot contact), with the support phase being 100%, and recovery early phase and late phase being 50% each (Figure 3) (Endo et al., 2008).

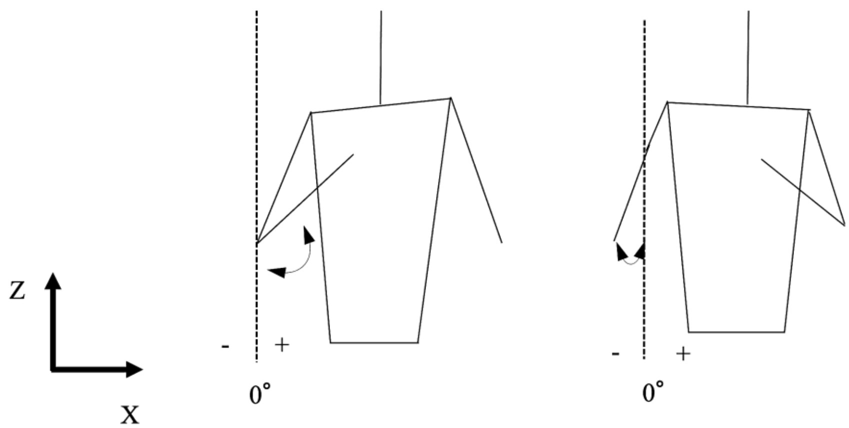

Figure 2. The definition of elbow joint angle and hand joint angle in X-Z plane.

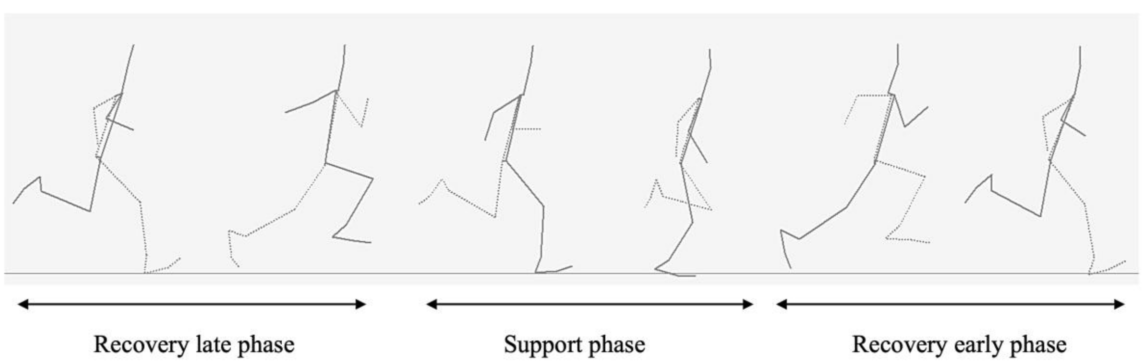

Figure 3. The definition of the normalizing of one cycle during sprinting.

The trunk angles, including the pelvic segment angle (pelvic angle), shoulder segment angle (shoulder angle), and trunk rotation angle (rotation angle), were calculated according to the procedure described by Arellano and Kram (2011). The angles were defined by projecting the vectors from the right greater trochanter to the left greater trochanter and from the right shoulder joint to the left shoulder joint onto the x-y plane of the stationary coordinate system. The angles between each vector and the x-axis were defined as the pelvic and shoulder angles, respectively, and the difference between them was defined as the rotation angle (Figure 4).

Regarding lower limb movement, as in previous studies (Ito et al., 1998), the analysis was conducted separately for the swing and support legs (Figure 5), using the maximum values for each phase. For the swing leg, parameters included thigh elevation angle (θ1): angle between the thigh (line connecting the greater trochanter and knee joint centre) and the horizontal line during thigh elevation, thigh elevation angular velocity (ω1): maximum angular velocity of the angle between the horizontal line and the thigh, minimum knee flexion angle (θ2): minimum angle of the knee joint angle (angle formed by the line connecting the greater trochanter and the knee joint centre and the line connecting the lateral malleolus and the knee joint centre) after liftoff, and swing angular velocity (ω2): angular velocity of the entire leg (line connecting the greater trochanter and the ankle joint centre) just before ground contact. For the support leg, maximum extension angular velocities of the hip (ω3), knee (ω4), and ankle (ω5) joints during ground contact, and the maximum swing speed of the entire leg (ω6) were determined. All angular and angular velocity values for the lower limbs were based on the analysis of the right leg, and the values projected onto the y-z plane were used.

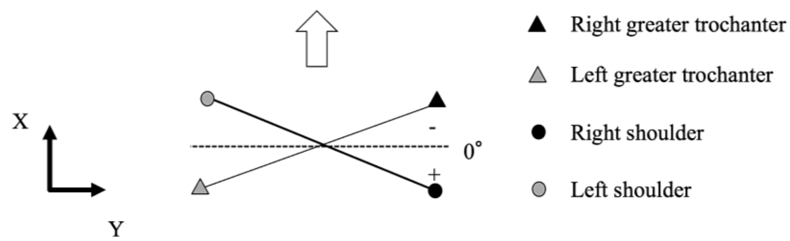

Figure 4. The definition of pelvic angle and shoulder angle in X-Y plane.

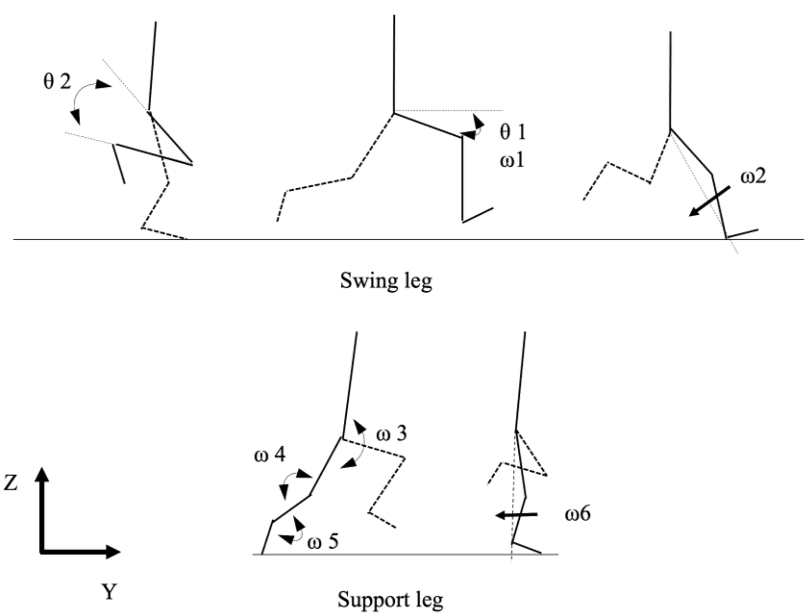

Figure 5. The definition of leg angle in Y-Z plane.

Statistical analysis

All computed parameters were presented as mean ± standard deviation. The Mann–Whitney U test was used to assess differences between the average values for boys and girls. Statistical significance was set at a risk level of <5%.

RESULTS

Table 1 presents the sprint speed, pitch, stride, and stride length-to-height ratios of the boys and girls. Significant differences were observed between the sexes in sprint speed, pitch, and stride length-to-height ratio, with boys exhibiting a significantly higher sprint speed and pitch, and girls having a significantly larger stride length-to-height ratio.

Table 1. Comparison of sprint speed, pitch, stride, and stride length-to-height ratio.

	Boys	Girls
Sprint speed (m/s)	8.13 ± 0.60	7.16 ± 0.26*
Step frequency (Hz)	4.40 ± 0.37	3.92 ± 0.22*
Step length (m)	1.85 ± 0.09	1.83 ± 0.07
Step length / body height	1.11 ± 0.04	1.15 ± 0.04*

*Note. Significantly different to boys: * p < .05.*

Table 2 compares the results of the lower limb movement analysis for boys and girls. In the swing leg, a significant difference was observed in the minimum knee flexion angle, with females exhibiting significantly smaller angles (greater flexion) than those observed in boys. For the supporting leg, significant differences were observed in the maximum knee extension angular velocity, maximum ankle extension angular velocity, and overall leg swing velocity, with girls having significantly higher knee extension and ankle extension angular velocities than boys; boys demonstrated significantly higher overall leg swing velocity.

Table 2. Comparison of lower limb movement analysis.

	Boys	Girls
Swing leg		
Thigh lift angle (deg)	154.2 ± 4.4	151.1 ± 3.9
Minimum Knee angle (deg)	40.1 ± 8.9	34.3 ± 4.4*
Thigh lift angular velocity (deg/s)	699.0 ± 44.3	689.6 ± 37.5
Leg touch down angular velocity (deg/s)	307.6 ± 44.3	284.1 ± 38.3
Support leg		
Hip joint extension velocity (deg/s)	515.2 ± 65.0	468.2 ± 58.5
Knee joint extension velocity (deg/s)	143.4 ± 46.5	254.1 ± 80.3*
Ankle joint extension velocity (deg/s)	521.5 ± 59.5	593.1 ± 90.4*
Leg swing velocity (deg/s)	548.3 ± 40.4	503.9 ± 24.5*

*Note. Significantly different to boys: * p < .05.*

Figure 6 shows the time-series data for the forearm angle. Significant differences were observed between the data for boys and girls during the early recovery phase (23–45%), with girls showing significantly smaller angles than those for boys.

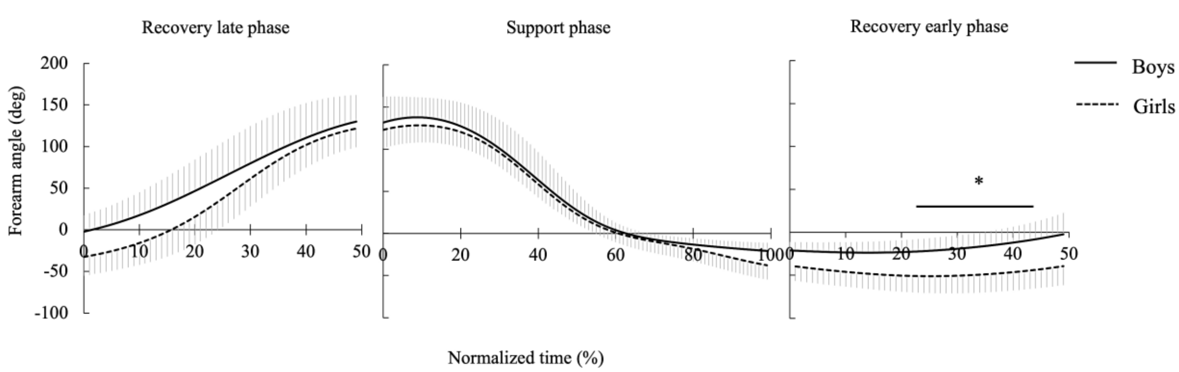

Figure 6. Comparison of time series data of forearm angles.

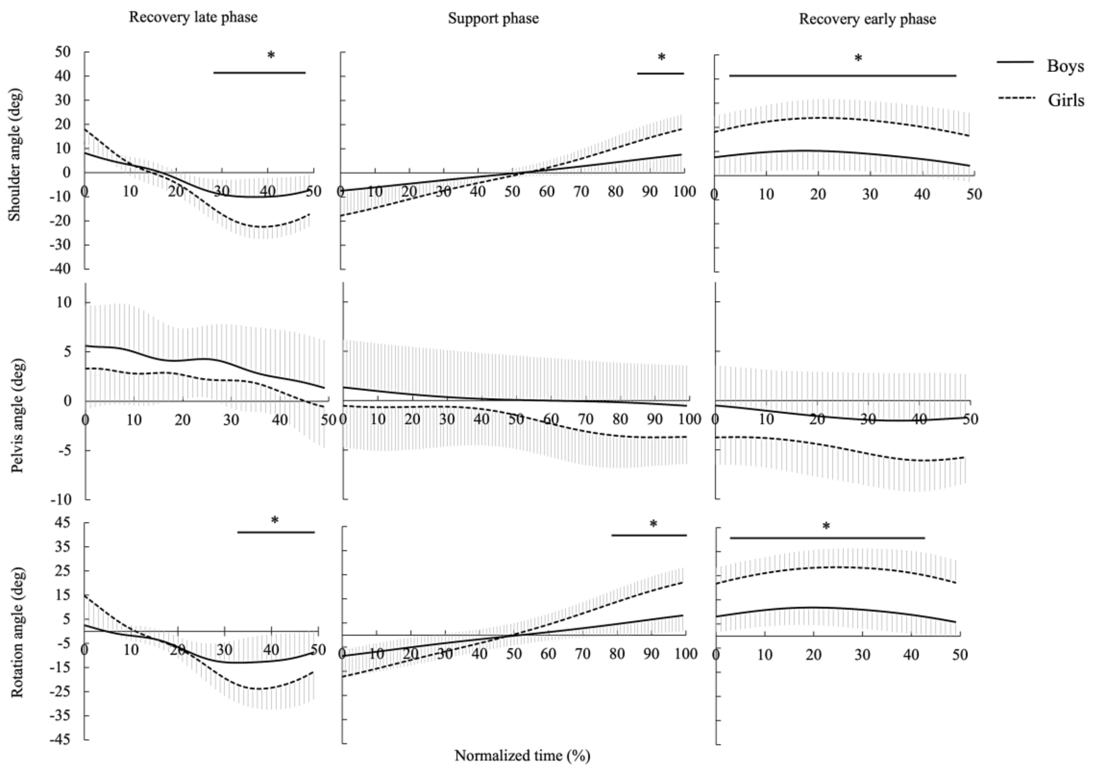

Figure 7. Comparison of time series data of shoulder angle, pelvic angle, and rotation angle.

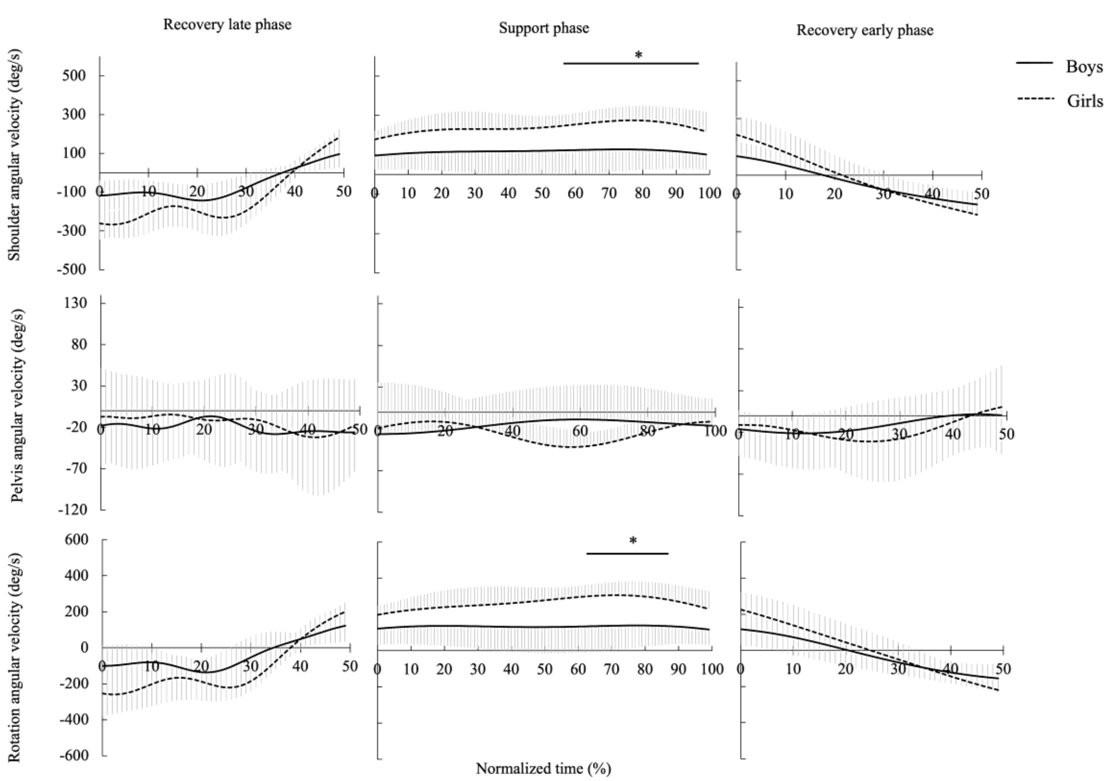

Figure 8. Comparison of time series data of shoulder angular velocity, pelvic angular velocity, and rotation angular velocity.

Figure 7 displays the time-series data for the shoulder, pelvic, and rotation angles. Significant differences between boys and girls were observed for shoulder angle in the late recovery phase (28–50%), shoulder angle in the support phase (84–100%), and rotation angle in the early recovery phase (6–48%).

Figure 8 shows the time-series data for shoulder, pelvic, and rotation angular velocity. Significant differences between the results for boys and girls were detected in the support phase (56–100%) for shoulder angular velocity and in the support phase (61–89%) for rotation angular velocity.

DISCUSSION

In this study we used 3D analysis to describe characteristics and sex-based differences in sprinting movements during adolescence, with a specific focus on the upper limbs and trunk. A notable sex-based difference in lower limb movement was observed, as girls exhibited significantly higher knee and ankle extension angular velocities and significantly lower overall leg swing velocity than boys. This result aligns with those of previous studies on adult short-distance runners (Ito et al., 1998) and general high school students (Katoh & Miyamaru, 2006) that examined sex-based differences in sprinting movements.

Regarding trunk movement, clear sex-based differences were observed in shoulder angle, angular velocity, torsion angle, and angular velocity, with girls having greater trunk torsion (Tellez et al., 2020) than boys, which is detrimental to sprinting ability. This trend is similar to that observed in previous studies (Bruening et al., 2020; Pontzer et al., 2009), but such sex-based differences have not previously been confirmed in adolescence. Morphological differences between the sexes have been cited as a major reason for the range of motion and torsion angle of the shoulder during sprinting. The most obvious structural sex-based difference is a wider pelvis and wider opening around the pelvis in women (Lewis et al., 2017); this is thought to influence the greater movement of the torso in the horizontal plane during running (Bruening et al., 2020). We did not have data on the morphological characteristics, such as the pelvic width, of the participants in this study. However, considering that the participants were adolescent athletes in whom morphological sex-based differences were recognized and that clear sex-based differences in height and weight were observed, morphological sex-based differences may have influenced the differences in trunk movement, as demonstrated in previous studies.

In addition, girls had smaller pitch and larger stride length-to-height ratios than boys. In this context, correlation coefficients were computed for pitch, stride length-to-height ratio, and trunk kinematic data. A significant negative correlation ($r = -0.709$, $p < .05$) was observed between pitch and maximum rotation angle in girls. A significant positive correlation ($r = 0.739$, $p < .05$) was also observed between the stride length-to-height ratio and the maximum angle of rotation. This suggests that the pronounced trunk rotation observed in girls contributes to an increase in the stride-to-height ratio, but results in a decrease in pitch. When rotating the trunk during a sprint, it is necessary to subsequently rotate it in the opposite direction, which makes it challenging to bring the support leg forward quickly (Ogiso, 2001). Therefore, substantial trunk rotation is believed to cause a decrease in pitch, negatively impacting sprinting speed.

Observational movement evaluations have revealed sex-based differences in arm swing movements beginning in adolescence, with boys swinging their forearms longitudinally and females swinging them laterally (Hiruma and Kariyama, 2019). The biomechanical section of this study also revealed that the boys' forearms were close to perpendicular to the ground when they swung backward, whereas the girls' forearms were closer to parallel (Figure 9).

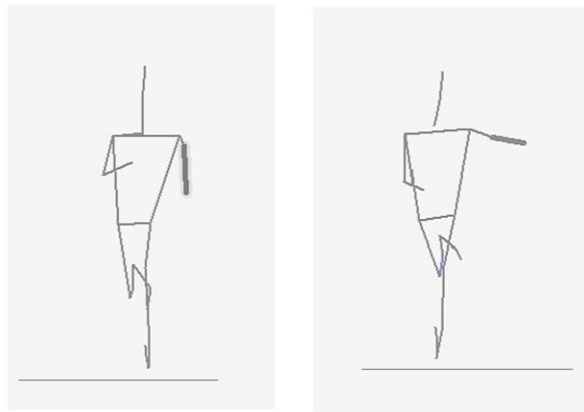

Figure 9. Typical example of arm swing movement.

Hiruma and Kariyama (2019) suggested that females, whose upper body mass is relatively smaller than that of males, may swing their arms in the lateral direction to increase the moment of inertia of their upper body and compensate for the angular momentum generated by their lower body, thereby preventing unnecessary trunk rotation and maintaining balance. If the suggestions of the previous study are supported, there should be sex-based differences in arm swing movement but no sex-based differences in trunk movement. However, in the present study, sex-based differences were observed for both movements, with girls swinging their arms laterally rather than longitudinally, with greater trunk rotation than that observed in boys. As Hiruma and Kariyama (2019) pointed out, whether it is performed consciously or unconsciously, swinging of the arms in the lateral direction increases the moment of inertia of the upper body and prevents unnecessary rotation of the trunk; however, even so, the trunk rotation may have been greater. It is also possible that the arms swing laterally because of trunk rotation, or vice versa; however, this could not be determined from the data collected in this study. Nevertheless, sprinting movements with laterally swinging arms and greater trunk rotation were characteristic of adolescent girls and had a negative impact on their sprinting performance.

CONCLUSIONS

In this study, we investigated the characteristics and sex-based differences in adolescent sprinting movements, focusing on the upper limbs and trunk, using 3D analysis. The results showed that girls had greater torsional movement of the trunk and swung their arms more laterally than boys. These results indicate clear sex-based differences in adolescent sprinting movements. In addition, large trunk rotation movements during sprinting in girls have a negative effect on pitch, suggesting that these movements are detrimental to sprinting performance.

SUPPORTING AGENCIES

No funding agencies were reported by the author.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the author.

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