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ORIGINAL ARTICLE

Sex differences regarding the effects of arm swing on ground reaction force and trunk movements between track and field athletes: Focusing on the difference in the direction of arm swing

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ABSTRACT

The purpose of this study was to clarify the sex difference in the effects of arm swing movements of track and field athletes on ground reaction force and trunk movement. Seven male and nine female athletes belonging to a university track and field team were asked to perform arm swings for 10 seconds each under three different conditions (longitudinal, lateral, and original) while in the standing position. Three-dimensional coordinate data for each experimental trial was collected using an automatic optical motion analyser, and ground reaction forces were measured using a force plate. Under the longitudinal condition, the mean acceleration force was greater for males than for females ($p < .05$), and the operating range of trunk twist angle was significantly greater for females than for males ($p < .05$). However, under the original condition, there were no significant differences between the sexes in mean acceleration force, but there were significant differences in maximum twist angle and minimum and maximum shoulder abduction angles ($p < .05$). These results indicate that there are sex differences in trunk movement and ground reaction force depending on the direction of arm swing.

Keywords: Performance analysis of sport, Sprint running, Coaching, Twist angle.

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INTRODUCTION

It is important to increase the maximum sprinting speed for superior performance in sprint running (Volkov and Lapin, 1979). Therefore, the most crucial priority to improve sprinting performance is to improve the ability to accelerate sprinting until maximum speed is reached (Doolittle & Tellez, 1984).

Biomechanical studies have revealed characteristics of athletes with high sprinting performance from various perspectives, providing useful knowledge for training. For example, with regard to lower limb movements, the following measures were taken: increasing the extension of the supporting leg hip joint and the swing speed of the thigh backward (Mann & Herman 1985), shortening the horizontal distance between both knee joints during ground contact (Bushnell & Hunter 2007), and decrease the knee joint angle at take-off (Mann & Hermann 1985). In reference to trunk movement, it has been shown that small thoracic obliquity and twisting the trunk are associated with higher running speed (Nagahara et al., 2017). Data on ground reaction force using force plates have also shown that it is important to exert a large horizontal backward force at each step throughout the acceleration phase and that athletes with the highest running speeds can exert greater acceleration forces against the ground (Brughelli et al., 2011 ; Nagahara et al., 2021 ; Rabita et al., 2015).

Thus, while much research has been conducted on findings related to the lower limbs and trunk, relatively little research has been conducted on the upper limbs, and there are still many unknowns. Previous studies on the upper extremities have primarily examined the role of arm swing, specifically, in improving balance by counteracting the angular momentum produced when swinging the leg about the vertical axis, reducing the side-to-side motion of the centre of mass (Hinrichs, 1987), preventing trunk rotation, reducing energy metabolism (Arellano and Kram, 2014), and increasing stride and ground reaction forces (Sayers, 2000).

These studies compared arm swing with no arm swing, and there is significant evidence that suggests that arm swing is better than no arm swing during sprinting. However, in the actual evaluation and instruction of arm swing during sprinting, the magnitude of arm swing (shoulder joint angle), elbow joint flex-ion/extension angle, angular velocity, and direction of arm swing (longitudinal, lateral, or diagonal) are addressed (Hiruma and Kariyama, 2019 ; Mann and Herman, 1985), rather than comparing "*swing*" or "*no swing*", and these may influence sprint performance. For example, Mann and Herman (1985) analysed the biomechanics of sprinting movements and reported that superior sprinters had a greater range of motion in shoulder and elbow joint angles and a greater shoulder joint angular velocity. In addition, Hiruma and Kariyama (2019) examined the direction of arm swing of general elementary school-age to top adult sprinters using observational evaluation methods. The percentage of "*longitudinal swing*" was high among males throughout all generations; alternatively, the percentage of "*lateral swing*" was high among females from junior high school age onward the authors also reported that the percentage of "*lateral swing*" was high among top sprinters in Japan who have relatively high sprinting speeds. Generally, the arm swing motion in sprinting should be a vertical swing without it crossing in front of the chest (Tellez et al., 2020). However, the results for females in a previous study (Hiruma and Kariyama, 2019) were different from generalizations (Tellez et al., 2020) such as "*arms should swing longitudinally*”.

Previous studies have indicated that factors affecting sprinting performance differ between male and female sprinters (Gleadhill and Nagahara, 2021). In addition, running movements (Takabayashi et al., 2017), lower limb movements in one-legged squat and landing movements (Jacobs et al., 2007 ; McBride and Nimphius, 2020 ； Russel et al., 2006 ； Zeller et al., 2003), and upper limb movements in throwing (Liue et al., 2010) all differ between males and females. These studies imply that males and females have different mechanisms in body response when performing similar exercises, and they suggest that different approaches may be needed for males and females to prevent injury and improve athletic performance.

Based on the given information, it is possible that differences in kinematics and kinetics data between males and females may be observed in arm swing movements when performed under the same conditions (e.g., longitudinal or lateral). If these findings can be clarified, it will provide useful information for coaching arm swing movements that take sex differences into account.

Therefore, the purpose of this study was to clarify the sex difference in the effects of arm swing movements of athletes on ground reaction force and trunk movement. To this end, we address the following hypothesis: when the conditions for arm swing are same conditions between male and female athletes, there are sex differences in ground reaction force and trunk movement. In light of previous research (Hiruma and Kariyama, 2019), it is expected that males may be positively affected when arms are swung longitudinally and females may be positively affected when arms are swung laterally.

MATERIAL AND METHODS

Participants

The participants were seven male amateurs track and field sprinters and jumpers (body height, 173.6 ± 6.6 cm; body mass, 66.1 ± 6.9 kg) and nine female amateurs track and field sprinters and jumpers (body height, 164.4 ± 3.1 cm; body mass, 54.7 ± 4.4 kg). After obtaining approval from the ethics committee of the affiliated institution, all participants were fully informed of the purpose, methods, and safety of the experiment, and their consent was obtained to participate in the experiment.

Experimental procedures

Since arm swing movements in the standing position are also incorporated as part of sprint training (Tellez et al., 2020), in this study, arm swing movements were performed in a standing position, without sprinting, in order to examine the effects of arm swing movements alone and to facilitate control of the arm swing direction. The arm swing in the standing position was performed for 10 seconds under the three conditions of "*longitudinal*", "*lateral*", and "*original*". One examiner provided an oral explanation of the trial to the participant along with a demonstration. Under the "*longitudinal*" condition, the participants were in-structed to "*swing straight, longitudinally*", and as a guide, the left and right forearms were supposed to be roughly parallel to the sagittal plane on swinging (Figure 1-A). Under the "*lateral*" condition, the participants were instructed to "*swing laterally*" and as a guide, when they swung their arms forward, the left and right hands had to reach reflex markers attached to the upper border of the sternum (as described below) (Figure 1-B). Under the "*original*" condition, no specific instruction was given regarding the direction of the arm swing, and only the verbal instruction was given to perform the arm swing motion peculiar to the participant. An examiner, positioned in front of the participants, checked the movements during the pre-trial practice and during the measured trials. In all conditions, the speed and magnitude of the arm swing was set to 120 BPM (Beats Per Minute) using a metronome (metronome: Tempo Lite) in order to keep the speed and magnitude of the arm swing as close as possible among the participants. All participants were verbally instructed to swing their arms to the metronome tempo. To eliminate in-fluence of the order of trials, the order of trials in each condition was randomly assigned to each participant.

Data analysis

Referring to previous studies (Kariyama et al., 2017), kinematic and kinetic data were calculated using the data by a motion capture system and force platforms. Reflective markers were affixed to the participants on eighteen points of the body : the end of the third metacarpal (left), ulnar eminence (left), radial eminence (left), lateral humeral epicondyle (left), medial humeral epicondyle (left), anterior scapulohumeral joint (left and right), posterior scapulohumeral joint (left and right), acromion (left and right), superior sternal border, greater trochanter (left and right), superior anterior iliac spine (left and right), and superior posterior iliac spine (left and right).

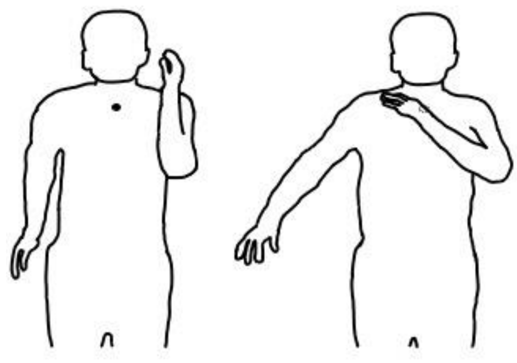

Figure 1. Examples of longitudinal and lateral swings.

Three-dimensional coordinate data for each experimental trial were collected using an automatic optical motion analyser (Vicon Motion Systems, 250 Hz) that included ten infrared cameras. The static coordinate system was defined as a right-hand coordinate system with the Y-axis in front of the participant at the start of the trial, the X-axis orthogonal to the Y-axis, and the Z-axis pointing vertically upward. The obtained coordinate values for each body part were smoothed using the Butterworth Low-Pass Digital Filter after determining the optimal cutoff frequency (7.5-15.0 Hz) for each coordinate com-ponent based on the method of Wells and Winter (1980). Ground reaction forces were measured using a force platform (Kistler, 9287C) placed under the left leg, converted at a sampling frequency of 1,000 Hz, and then captured into a personal computer.

Analysis range

One cycle consisted of swinging the left arm forward from the most posterior position of the elbow joint centre (the midpoint of the markers attached to the lateral humeral epicondyle and medial humeral epicondyle) during arm swing in the XZ plane to the most posterior position of the elbow joint centre again. The analysis range for the calculated items was 2 cycles, 5 seconds after the start of the test.

Study variables

Based on the data obtained from the motion capture and force platform described above, the following data were calculated. Referring to previous studies (Arellano and Kram, 2014 ; Kariyama et al., 2018), the following procedures were used to calculate the pelvic segment angle (hereafter, pelvic angle), both shoulder segment angles (here after, shoulder angle), trunk twist angle (hereafter, twist angle), and shoulder joint abduction angle.

Vectors from the right hip joint centre to the left hip joint centre and from the right shoulder joint centre to the left shoulder joint centre were projected onto the XY plane of the stationary coordinate system. The angle of each vector with the X axis was defined as the pelvic angle and shoulder angle, and the difference between them was defined as the twist angle. The hip joint centre was determined with reference to a previous study, and the shoulder joint centre was the midpoint of the markers attached to the anterior and posterior scapulohumeral joints. The range of motion (ROM) was then calculated after determining the maximum and minimum angles within the analysis range. The shoulder joint abduction angle was defined as the angle between the vector from the midpoint of both shoulders (midpoint of the vector from the centre of the right shoulder joint to the centre of the left shoulder joint) to the midpoint of the hip joint (midpoint of the vector from the centre of the right hip joint to the centre of the left hip joint) in the YZ plane of the stationary coordinate system and the vector from the shoulder joint to the elbow joint. The maximum and minimum angles within the analysis range were then determined. The left arm was used as the target for the shoulder joint abduction angle.

In addition, referring to previous studies (Brughelli et al., 2011 ; Nagahara et al., 2021; Rabita et al., 2015), of the ground reaction forces obtained with the force plate the average of the positive values of the horizontal component, which is closely related to sprinting ability ("*acceleration average force*"), was calculated. The data from the force plate placed under the left leg were used, and the average of two consecutive cycles at 5 seconds after the start of the trial was used as the acceleration average force for each participant.

In addition, shoulder width and pelvic width (Tanner, 1951), which are physical characteristics of males and females, were determined as follows. Shoulder width was the horizontal distance between markers attached to the left and right acromion in a stationary upright posture, and pelvic width was the horizontal distance between markers attached to the left and right superior anterior iliac spine.

Statistical analysis

Descriptive statistics are presented as mean values ± standard deviation. Statistical processing software (SPSS ver. 25, IBM, Armonk, NY, USA) was used for all statistical processing. The Shapiro-Wilks test was used to confirm normality for each variable; when normality was confirmed, an uncorrelated t-test was used to assess differences in the variables between the two groups. If a deviation from normality was determined, Mann-Whitney's test was used to test the difference in variables between the two groups. In addition, Pearson's product-rate correlation analysis was used to calculate correlation coefficients between items when normality was confirmed, and Spearman's rank correlation coefficient was used when deviation from normality was determined. The significance level was set at 5%.

RESULTS

Physical characteristics of the participants (Table 1) showed sex differences in all items except pelvic width, which was significantly greater in males than in females ($p < .05$), and the shoulder abduction angle (Figure 2) showed a sex difference only under the original condition, with females having a significantly larger angle than males ($p < .05$).

Table 1. Characteristics of the participants.

	Male	Female
Height (cm)	173.6 ± 6.6	164.4 ± 3.1*
Weight (kg)	66.1 ± 6.9	57.4 ± 4.4*
Breadth of shoulder (cm)	39.7 ± 0.1	34.5 ± 0.1*
Breadth of pelvis (cm)	26.8 ± 0.1	26.7 ± 0.1

*Note: * Significant difference between the male and female, p < .05.*

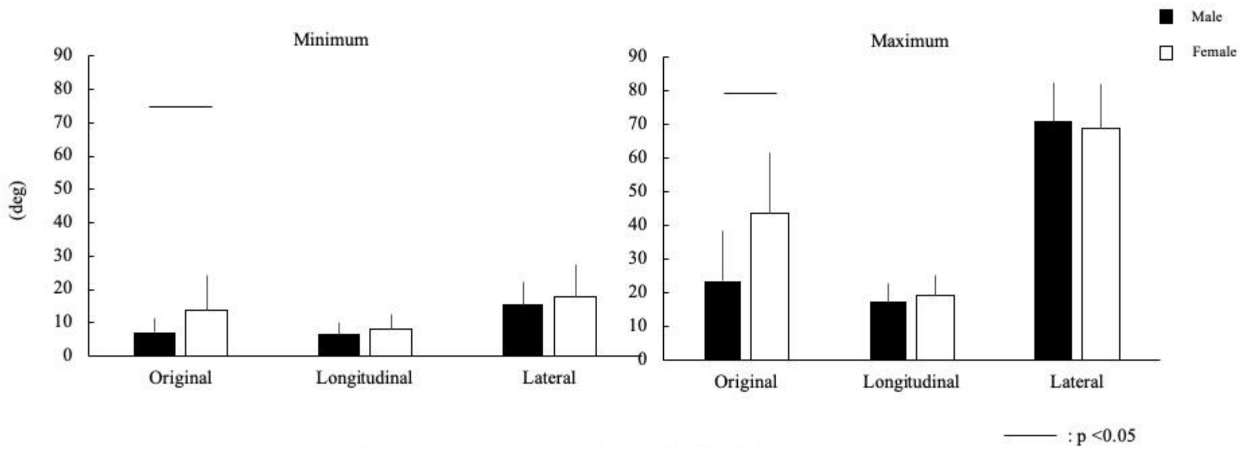

Figure 2. Comparison of shoulder joint abduction angles.

Table 2 shows the mean acceleration forces for each condition by sex. There was a sex difference under the longitudinal condition, with males being significantly larger than females (*p* < .05).

Table 2. Average propulsive force under each condition.

		Original	Longitudinal	Lateral
Average force (N/kg)	Male	0.33 ± 0.19	0.46[a] ± 0.20*	0.44 ± 0.21
	Female	0.23 ± 0.15	0.32 ± 0.10	0.39 ± 0.09

*Note: All data were normal and tested via two-tailed paired t-test except for those indicated by the superscript a, which were not normally distributed and were tested using the Wilcoxon test. *Significant difference between Male and Female, p < .05.*

Table 3. Comparison of minimum, maximum and ROM of pelvis angle, shoulder angles and twist angle.

			Original	Longitudinal	Lateral
Pelvis	Maximum angle (deg)	Male	8.08 ± 3.32	11.56 ± 5.09	10.61 ± 5.13
		Female	11.69 [a] ± 7.85	9.60 ± 3.97	10.46 ± 2.97
	Minimum angle (deg)	Male	-8.03 ± 6.76	-4.92 ± 2.70	-7.10 ± 5.94
		Female	-6.80 ± 5.93	-6.45 ± 4.17	-7.22 ± 2.84
	ROM (deg)	Male	16.96 ± 6.09	17.71 ± 6.46	17.71 ± 7.85
		Female	19.29 [a] ± 11.80	17.68 ± 6.87	17.68 ± 4.18
Shoulder	Maximum angle (deg)	Male	8.63 ± 2.73	12.21 ± 3.64	8.59 ± 3.03
		Female	7.46 ± 2.52	12.92 ± 4.32	9.63 ± 3.36
	Minimum angle (deg)	Male	-3.05 ± 3.16	-3.89 ± 3.39	-6.15 ± 3.18
		Female	-5.47 ± 2.58	-5.13 ± 4.00	-5.45[a] ± 4.25
	ROM (deg)	Male	12.21 ± 4.63	13.40 ± 5.31	14.74 ± 4.91
		Female	12.92 ± 3.22	15.18 ± 1.84	15.17 ± 3.50
Twist	Maximum angle (deg)	Male	6.35* ± 3.16	9.05 ± 3.22	11.92[a] ± 5.57
		Female	10.77[a] ± 5.95	11.00 ± 4.75	9.62 ± 6.13
	Minimum angle (deg)	Male	-12.87 ± 9.20	-8.34 ± 3.95	-15.08 ± 8.42
		Female	-12.12 ± 4.72	-13.43 ± 9.16	-11.00 ± 5.73
	ROM (deg)	Male	19.22 ± 10.57	17.39* ± 5.02	27.01 ± 11.18
		Female	22.90 ± 8.56	24.43 ± 8.77	20.61 ± 8.30

*Note: All data were normal and tested via two-tailed paired t-test except for those indicated by the superscript a, which were not normally distributed and were tested using the Wilcoxon test. *Significant difference between Male and Female, p < .05.*

Table 3 shows the minimum and maximum values of twist angle, and ROM for each condition by sex. Sex differences were observed in the maximum twist angle under the original condition and twist ROM under the longitudinal condition, both of which were significantly greater in females than in males ($p < .05$).

The relationship between the minimum and maximum values of pelvic angle, shoulder angle and twist angle, ROM, and acceleration mean force under each condition were examined (Table 4), and a significant negative correlation (r = -0.606, $p < .05$) was found between twist ROM and acceleration mean force in females under the original condition. Under the longitudinal condition, a significant negative correlation (male: r = -0.668, female: r = -0.604, $p < .05$) was found between twist ROM and acceleration mean force for both males and females, and a significant positive correlation (r = 0.691, $p < .05$) was found between minimum twist angle and acceleration mean force for males. Under the lateral condition, significant correlations were found only in females, and significant positive correlations were found between bilateral shoulder ROM, maximum twist angle, and twist ROM and acceleration average force.

Table 4. Correlation coefficient between kinematics data and average propulsive force.

		Original		Longitudinal		Lateral	
		Male	Female	Male	Female	Male	Female
Pelvis	Maximum angle	-0.463	-0.353	-0.073	-0.080	-0.139	0.201
	Minimum angle	0.085	0.453	0.231	0.452	0.031	-0.153
	RoM	-0.391	-0.438	-0.154	-0.321	-0.114	0.246
Shoulder	Maximum angle	-0.187	0.177	-0.290	-0.327	-0.337	0.059
	Minimum angle	-0.033	-0.430	-0.091	-0.289	0.136	-0.600
	RoM	-0.116	0.489	-0.140	-0.052	-0.296	0.760**
Twist	Maximum angle	-0.493	-0.399	-0.055	-0.027	0.328	0.676*
	Minimum angle	0.290	0.587	0.691*	0.527	0.229	-0.303
	RoM	-0.400	-0.606*	-0.668*	-0.604*	-0.009	0.708*

*Note. **: p < .01, *: p < .05.*

DISCUSSION

We found no significant difference in shoulder joint abduction angle between the sexes under the longitudinal condition; however, acceleration mean force was greater in males than in females (Table 2), while twist ROM was significantly greater in females than in males (Table 3). These results support our hypothesis that a male arm swinging longitudinally has a more positive effect on ground reaction force and trunk movements than a female arm swinging longitudinally. In the lateral condition, however, there were no significant differences between the sexes in mean acceleration force, pelvis angle, shoulder angle, twist angle, or shoulder abduction angle. This result was in contrast with our hypothesis that swinging the arms laterally would positively affect ground reaction force and trunk movements, which are known to affect females than males in sprinting.

Several studies have found sex differences in trunk movements during exercise, and a study examining walking movements (Bruening, et al., 2015) found that the pattern of pelvic and torso angle changes during one cycle differed between males and females and that torso ROM was greater in females than that in males. The results of this study (Bruening, et al., 2015) suggests that males and females use different control strategies during walking. In our study, sex differences were observed in twist ROM under the longitudinal condition (Table 3). It has also been reported that the ROM of the torso during running was significantly greater for females than for males (Bruening, et al., 2020). In sprinting, it has been noted that a trunk twist greater than necessary negatively affects sprinting performance (Nagahara et al., 2017) ; thus, this is considered an action to avoid. In the present study, the correlation coefficient between twist ROM and average acceleration force in the longitudinal condition showed a significant negative correlation for both males and females (Table 4), and the acceleration force ap-plied to the ground was greater for those with less twisting of the trunk. According to Kreighbaum and Barthels (1985) stated that the role of the trunk is to be a source of energy due to the presence of large muscles and also support energy transfer due to its large mass and moment of inertia. If priority is given to the function energy transfer of the trunk, it is conceivable that the less the distortion of the trunk segment, the more efficient is the energy transfer. In other words, it is thought that energy transfer efficiency can be improved by reducing the phase shift between the pelvis and shoulders in trunk movements and by preventing twist from occurring.

As shown in Table 1, there were differences between males and females in terms of height, weight, and shoulder width; however, pelvic width was similar. However, considering the significant differences in height and weight between males and females, it is assumed that the relative pelvic width was greater among females. In other words, shoulder width was larger in males and pelvic width was larger in females; these are the body shapes typical of these sexes even in the general population (Tanner, 1951). There were no significant differences in either the maximum or minimum shoulder joint abduction angles between the sexes under the longitudinal condition. Further-more, although muscle mass was not measured in this study, it has been shown that when physical characteristics are taken into account, there are sex differences in the muscle cross-sectional area of the upper limbs and trunk, with males having a larger muscle cross-sectional area than females (Abe et al., 2003). Therefore, when both males and females perform arm swings under the same conditions (longitudinal), the moment of inertia around the long axis of the body is smaller for females than for males because females have smaller shoulder width relative to pelvic width and less muscle mass in the upper limbs and trunk than males. Therefore, the upper body is expected to rotate more easily. Consequently, females are more likely to have a greater phase shift between the pelvis and shoulders than males, and the twist may result in less efficient energy transfer. This could be the explanation for sex difference in mean acceleration force.

In contrast, under the lateral condition, there were no significant differences between the sexes in mean acceleration force, pelvis angle, shoulder angle, and twist angle, as well as shoulder abduction angle. A significant negative correlation was found between mean acceleration force and twist ROM under the longitudinal and original conditions, but no such trend was observed under the lateral condition (Table 4). Considering the positive effects of suppressing trunk twisting on acceleration and sprinting performance under the original and longitudinal conditions, as well as during sprinting, it is assumed that the arm swinging motion under the lateral condition was very different from the actual arm swinging motion in sprinting. In fact, the maximum shoulder joint abduction angle under the lateral condition was greater than that under the other conditions for both males and females. Therefore, it is reasonable to assume that both males and females may have been unfamiliar with the movement. As a result, no sex differences in acceleration and trunk movement were observed. Therefore, it may be necessary to reconsider the condition setting of the lateral swing in future investigations.

Under the original condition, there was no difference in mean acceleration force between males and females, but there were significant differences in maximum twist angle and minimum and maximum shoulder abduction angles. The relationship between pelvis angle, shoulder angle, and twist angle and acceleration average force (Table 4) also showed different trends between males and females, with a significant negative correlation between twist ROM and mean acceleration force for females; however, no significant correlation was noted for males. The significant difference between the sexes in shoulder joint abduction angle indicates that arm swing movements differ between the sexes. This result is consistent with that of a previous study on running movements (Hiruma and Kariyama, 2019) in which females tended to swing arms more lateral. This may be related to the difference in correlation coefficients between males and females in relation to the pelvis angle, shoulder angle, twist angle and mean acceleration force. In other words, it is possible that females who were able to control their trunk twisting to some extents were able to increase their mean acceleration force, even though more of them swung their arms lateral than males. It has been mentioned previously that swinging the arms lateral is an undesirable action in sprinting (Tellez et al., 2020) ; however, it is possible that females, due to their body shape and muscle mass, prioritized preventing trunk twisting by swinging their arms lateral more than male, although it is unclear whether this was consciously or unconsciously. Therefore, it is necessary to evaluate the arm swinging motion in sprinting in relation to the trunk twisting motion, rather than simply negatively considering the arm swinging to the lateral.

Finally, there are certain factors that must be acknowledged when interpreting the results of the current study. Since this study investigated the effects of only arm swing movements in a stationary state, the results cannot be generalized to those obtained during actual running movements. Therefore, it is necessary to collect data in an experimental setting that more closely resembles sprinting in the future. Finally, there are certain factors that must be acknowledged when interpreting the results of the current study. Since this study investigated the effects of only arm swing movements in a stationary state, the results cannot be generalized to those obtained during actual running movements. Therefore, it is necessary to collect data in an experimental setting that more closely resembles sprinting in the future. And, as far as the measurement is concerned, it was performed during the winter season (from December to February) when the athletes are not taking part in athletics competitions and are in process of recovering physical and mental stress or injury. As matter of fact, the latter made it difficult to recruit a larger number of participants. Furthermore, it should be noted that this study result is limited to college students sprint and jump athletes who are amateurs in the sense that they have practiced this modality as students but have been receiving specialized coaching in track and field in order to compete in official events. Therefore, the results obtained in this study may not apply to top athletes, athletes of other disciplines, or other age groups. These points were limitations of this study.

However, the fact that sex differences were observed in mean acceleration force and trunk motion when arm swinging was performed the same experimental and measurement conditions is interesting and is an important finding to consider during training and motion instruction so that sex differences are also taken into account.

CONCLUSIONS

Under the longitudinal arm swing condition, females showed greater twist ROM and lower mean acceleration force compared to males. One of the factors that may have contributed to this is the difference in body shape between males and females. Therefore, when females aim for longitudinal swinging, these factors should be taken into consideration in their decision-making. In addition, the comparison under the original conditions suggests that if females can control the twist ROM, even if they swing their arms more laterally than males, they may be able to obtain the same mean acceleration force as males. Therefore, it may not be necessary to consider the female lateral swing as a negative factor.

AUTHOR CONTRIBUTIONS

Conceptualization, K.H. and Y.K.; investigation, K.H. and Y.K.; methodology, K.H. and Y.K.; formal analysis K.H.; writing—original draft preparation K.H.; writing—review and editing K.H. and Y.K.; visualization; K.H.

project administration K.H. and Y.K.; funding acquisition, K.H. All authors have read and agreed to the published version of the manuscript.

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DISCLOSURE STATEMENT

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