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Article

Analysis of a difficulty movement of aerobic gymnasts based on biomechanics

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Abstract: Background: With the progress of technology, an increasing number of studies on biomechanics in sports are being conducted. **Objective:** Based on biomechanical methods, the characteristics of aerobic gymnasts at different skill levels performing the difficulty movement C715 were compared to provide a reference for teaching and training. **Methods:** Sixteen aerobic gymnasts were divided into two groups, A and B, according to their skill levels. Kinematic data and surface electromyography were collected using modern equipment, analyzed, and compared. **Results:** Group A spent 0.64 ± 0.03 s during the upright restoration stage, which was longer than that of group B ($p < 0.05$). In the pre-swing stage, the angle between the legs of group A at the moment of free leg landing was 46.52 ± 2.14°, which was significantly greater than that of group B. Muscle force was predominantly exerted on the right side, and there were obvious differences between group A and group B in the integral electromyogram (IEMG) of the right rectus abdominis, left and right gastrocnemius, and left rectus femoris ($p < 0.05$). During the phase when the free leg swings forward, no significant differences in kinematic characteristics were found between the two groups; however, there were significant differences in IEMG of muscle activity for the right rectus abdominis, left and right biceps femoris, right gastrocnemius, and left rectus femoris ($p < 0.05$). The right gastrocnemius force of group A reached 25.77 ± 3.64 μV·S, which was significantly higher. During the 360° leg-controlled rotation phase, the minimum angle of the right ankle in group A was significantly greater than group B ($p < 0.05$), and the muscle activity showed significant differences in IEMG of the left biceps femoris, right biceps femoris, left gastrocnemius, left rectus femoris, and right rectus femoris. In the upright stage, the knee and ankle angles of group A were larger, and there was a remarkable difference in gastrocnemius force ($p < 0.05$). Conclusion: There are biomechanical differences among aerobic gymnasts of varying levels when performing the difficulty movement C715.

Keywords: biomechanics; aerobics; difficulty movement; integral electromyography; C715

1. Introduction

Aerobics [1] requires gymnasts to complete a series of continuous and complex movements [2] with the accompaniment of music. Aerobics is limited by rhythm and time [3] and is characterized by health, strength, and beauty [4]. It has been included as an official sport in competitions by the International Gymnastics Federation [5]. Aerobics is highly competitive [6], and difficulty movements are the core technique of competitive aerobics [7]. Difficulty movements in aerobics are divided into ground difficulty, air difficulty, and standing difficulty according to different physical needs, and each group is further subdivided according to the characteristics of movements. In the competitive process, the gymnast must complete no less than five types of difficulty movements; therefore, the mastery of difficulty movements is the main embodiment of the technical level of the aerobic gymnast. The performance of difficulty movements directly affects the completion of the complete set of movements and then affects the result of the competition. With the increasing development of technical means, biomechanical means such as kinematics and surface electromyography (sEMG) have been applied more and more in various sports [8], providing reliable support for daily teaching and training [9]. As a relatively new sport, more research needs to be conducted on aerobics [1]. Kochanowicz et al. [10] analyzed the motor coordination abilities of 18 female gymnasts aged 7–9 years old and found significant correlations in various indices through Elipsis test, Flamingo balance test, and overall coordination level test. Sun et al. [11] examined the relationship between body type, professional competence, technical indicators, and performance scores of competitive aerobic gymnasts in China using gray relational technique. They discovered that artistic score was usually correlated with total score, followed by difficulty score and execution score. Tan et al. [12] analyzed the feasibility of incorporating yoga practice into the recovery training for competitive aerobics, and their experiment revealed that yoga practice holds significant importance in recovering from exercise fatigue. Wang [13] conducted a biomechanical analysis on difficulty elements of group C in competitive aerobics after dividing them into three stages: takeoff, flight, and landing, aiming to provide a theoretical foundation for coach training. At present, in the analysis of difficulty movements in aerobics, the kinematic analysis method based on high-speed camera has been applied in some applications, and there are also some sEMG analyses. However, there are few studies that have taken both into account. Therefore, through biomechanics, this paper compared and analyzed the kinematics and muscle activity characteristics of aerobic gymnasts at different levels by taking C715 (horizontal leg-control 1/1 standing turn) in group C-difficulty movement as an example, in order to help aerobic gymnasts, clarify the technical characteristics of the movement, better understand the force characteristics of muscles, and improve the mastery of the movement. It also provides some reference bases for coaches' daily guidance and training.

2. Research subjects and method

2.1. Research subjects

Sixteen aerobic gymnasts from the School of Physical Education of South-Central Minzu University for Nationalities were selected as subjects, and their exercise level was determined by their score reduction when they completed C715. Each gymnast repeated the C715 movement three times, and two national judges scored their performance. Those with a score reduction of less than 0.1 were regarded as high-level ones and recorded as group A; those with a score reduction of > 0.1 were regarded as average ones and recorded as group B. The comparison of general data between the two groups is shown in **Table 1**, and they had no significant differences.

Table 1. General data of subjects.

		Group A (*n* = 8)	**Group B (*n* = 8)**	***p***
Gender	Male	4	4	0.987
	Female	4	4	0.987
Age/year		23.12 ± 1.45	22.76 ± 1.05	0.942
Height/cm		174.39 ± 2.36	173.67 ± 3.64	0.854
Weight/kg		61.26 ± 8.72	62.37 ± 7.87	0.658
Training time/years		5.64 ± 1.17	4.86 ± 1.29	0.746

2.2. Research methods

2.2.1. Experimental procedure

The subjects were determined. The groups were divided according to the different exercise levels. The basic information of the two groups was collected.

The experiment site was arranged. The kinematic data was collected using the 12-lens Vicon motion capture system [14], and the sEMG data was collected using the Noraxon sEMG acquisition system [15]. The electromyography system was connected to the Vicon system through a synchronization line. During data collection, the Vicon system output a pulse signal to trigger the acquisition of electromyographic signals, thereby achieving synchronized data collection.

Table 2. Plug-in-gait pasting scheme.

Position	**Name**	**Location**
Head (4)	LFHD, RFHD	Left and right front head
	LBHD, RBHD	Left and right back head
Torso (5)	C7	The 7th cervical vertebra
	T10	The 10th lumbar vertebra
	CLAV	The upper end of manubrium sternum
	STRN	The lower end of manubrium sternum
	RBAK	Middle of the right shoulder blade
Pelvis (4)	LASI, RASI	Left and right anterior superior iliac spine
	LPSI, RPSI	Left and right posterior superior iliac spine
Upper limbs (14)	LSHO, RSHO	Left and right shoulder peak
	LUPA, RUPA	Left and right upper arm
	LELB, RELB	Left and right elbow joint
	LFRA, RFRA	Left and right forearm
	LWRA, RWRA	The inner side of left and right wrist joint
	LWRB, RWRB	The outer side of left and right wrist joint
	LFIN, RFIN	Left and right first finger joint
Lower limbs (12)	LKNE, RKNE	Left and right knee joint
	LTHI, RTHI	Left and right thigh
	LTIB, RTIB	Left and right tibia
	LANK, RANK	Left and right ankle joint
	LTOE, RTOE	Left and right toe
	LHEE, RHEE	Left and right heel

After the gymnasts arrived at the experimental site, they warmed up by 10-min jogging, and the heart rate during the warm-up was 50%–60% of the maximum exercise heart rate [16]. Then, the same experimentist pasted the reflective markers and electrodes on the bodies of the subjects. Before pasting, the hair and skin at the pasting sites were treated. The skin surface was wiped with 75% medical alcohol. Reference was made to the Plug-in-gait model [17] for the pasting scheme. There was a total of 39 points, as shown in **Table 2**. The method for the electrode pasting is shown in **Table 3**.

Table 3. The paste positions of the sEMG electrodes.

Name	**Location**
Left and right rectus abdominis (LA, RA)	The superior spine of the ilium beside the rectus abdominis
Left and right biceps femoris (LBF, RBF)	50% between the ischiatic tuberositas and the lateral malleolus of the tibia
Left and right gastrocnemius (LG, RG)	The hump of the belly of the inner shallow muscle at the back of the calf
Left and right rectus femoris (LRF, RRF)	The center of the front of the thigh

The pre-experiment was carried out after the pasting was completed. The formal experiment started after ensuring that the movements would not be affected by the pasted markers and the device could collect data simultaneously. After the experimenter gave the command, each gymnast successively completed the C715 movement (**Figure 1**) three times in the test area. C715 belongs to category 7 of Group C-standing difficulty, with a score of 0.5. The requirements for this movement include standing on one leg, fully extending the free leg, and horizontally raising the free leg forward, and ending in standing position after completing a 360° standing turn. In the experiment, all the subjects took their right leg as their free leg. In the subsequent research, the stages of movement were divided as follows:

1) Pre-swing: the toe of the supporting leg was off the ground, and the free leg started to swing from the retreating position.
2) The free leg swinging to the front: the free leg swung from the beginning and then to the front of the body.
3) Leg-control 1/1 turn: the free leg swung to the front and then turned 360°, and it swung again to the front of the body.
4) Upright restoration: After the free leg swung to the front again, the heel landed and got close to the supporting leg, and the subject stood with two feet.
5) The movement of each gymnast was scored by two national judges, and the one with the least point reduction was selected for subsequent analysis.

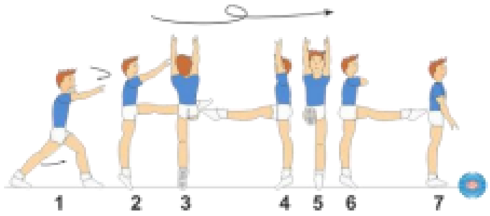

Figure 1. C715 (AER CoP 2022-2024 Page 112/126).

2.2.2. Mathematical and statistical methods

The kinematic data was analyzed using the Nexus 1.7.1 software of Vicon [18]. After smoothing processing on the data, joint angle, velocity, and other data were obtained. The sEMG data was analyzed using the supporting software of Noraxon to obtain integral electromyography (IEMG) [19]. After preliminary sorting of the original data, statistical analysis was performed in SPSS 25.0 [20]. All data were expressed as mean ± standard deviation. According to the Shapiro-Wilk test, it was found that all variables met the normal distribution [21], therefore an independent samples t-test was conducted [22]. The significance level was set at 0.05.

3. Research results

From **Figure 2**, it can be found that, except for the upright restoration stage, there was no significant difference in the time of other stages between the two groups ($p > 0.05$). In the upright restoration stage, the time consumed by group A was 0.64 ± 0.03 s, and that of group B was 0.16 ± 0.02 s ($p < 0.05$), indicating that the time consumed by high-level gymnasts in the upright restoration stage was significantly longer than that of average gymnasts.

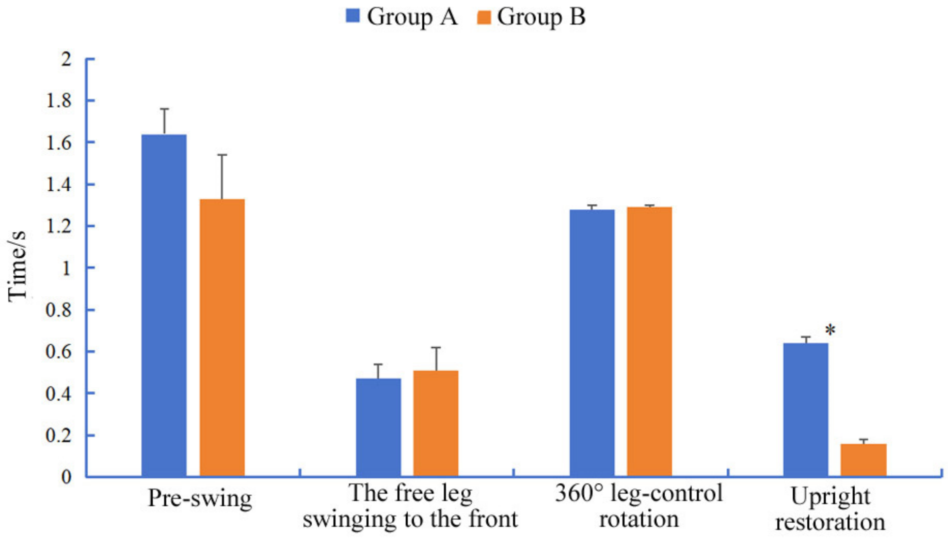

Figure 2. Comparison of time for different stages.

*: compared with group B, $p < 0.05$.

As can be seen from **Figure 3**, the maximum value of the shoulder-hip torsion angle in group A was 37.12 ± 2.31°, while that in group B was only 28.36 ± 7.76°. The maximum value of the shoulder-hip torsion angle in group A was slightly larger than that in group B, but $p > 0.05$. Then, in terms of the angle between the two legs at the landing moment of the free leg, group A was larger than group B (46.52 ± 2.14° vs. 36.12 ± 3.35°) ($p < 0.05$).

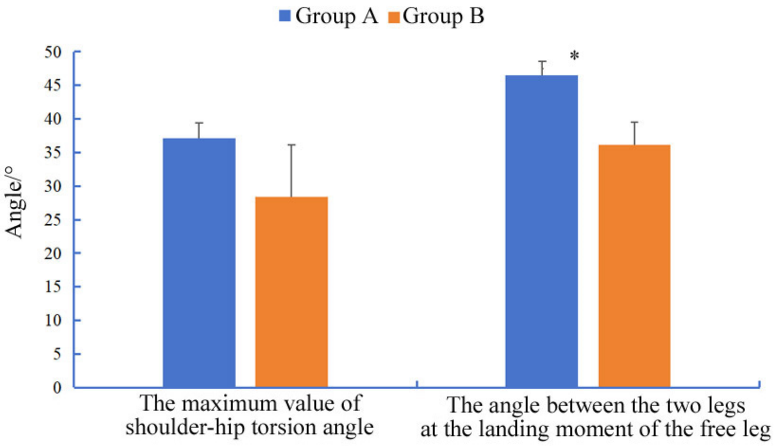

Figure 3. Comparison of kinematic characteristics in the pre-swing stage.
*: compared with group B, $p < 0.05$.

In the pre-swing stage, the body was mainly manifested as rotation to the right. As shown in **Figure 4**, the rectus abdominis and rectus femoris exerted less force in this stage, and the force of gastrocnemius was mainly manifested, and the force of the right side of the muscles was greater than that of the left side. The two groups had remarkable differences in IEMG of RA, LG, RG, and LRF ($p < 0.05$).

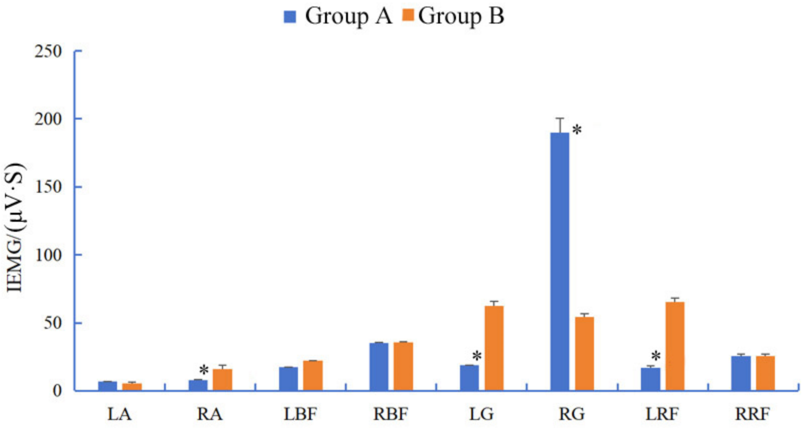

Figure 4. Comparison of muscle activity characteristics in the pre-swing stage.
*: compared with group B, $p < 0.05$.

As indicated in **Table 4**, the difference in the kinematic characteristics between the two groups was insignificant at this stage ($p > 0.05$).

Table 4. Comparison of kinematic characteristics in the stage where the free leg swings to the front.

		Group A (*n* = 8)	**Group B (*n* = 8)**	***p***
The degree of ankle joint angle variation/°		40.75 ± 2.16	37.64 ± 2.33	0.162
Maximum ankle joint speed (m/s)		6.96 ± 0.03	6.72 ± 0.04	0.124
Maximum elbow joint speed (m/s)	Left	3.32 ± 0.01	3.33 ± 0.02	0.985
	Right	3.07 ± 0.02	2.88 ± 0.03	0.665
Maximum wrist joint speed (m/s)	Left	5.55 ± 0.04	5.87 ± 0.03	0.625
	Right	4.83 ± 0.03	4.45 ± 0.02	0.524

As seen from **Figure 5**, the IEMG in this stage was mainly activated by the gastrocnemius muscle. There were significant differences in IEMG of RA, LBF, RBF, RG, and LRF between the two groups ($p < 0.05$). Specifically, the IEMG value of RG in group A was higher, reaching 25.77 ± 3.64 μV·S, while that in group B was 8.77 ± 1.23 μV·S. The larger force of the right gastrocnemius muscle indicated that the gymnasts in group A had better control over the ankle joint.

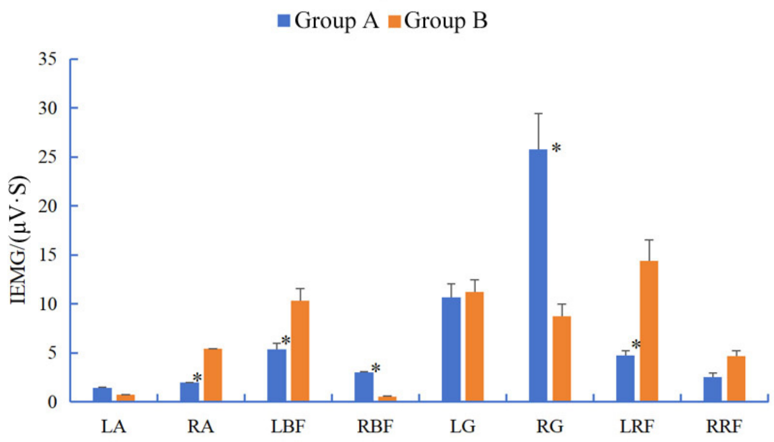

Figure 5. Comparison of muscle activity characteristics in the stage where the free leg swings to the forward.

*: compared with group B, $p < 0.05$.

As can be seen from **Table 5**, there was no remarkable difference between the two groups in the angle of the knee joint ($p > 0.05$). In terms of ankle joint angle, the minimum angle of the right ankle joint was significantly larger in group A than that in group B ($p < 0.05$). This result indicated that group A had better control over the knee and ankle joints.

Table 5. Comparison of kinematic characteristics in the 360° leg-control rotation stage.

		Group A ($n = 8$)	**Group B ($n = 8$)**	***p***
Maximum knee joint angle	Left	173.75 ± 2.64	168.64 ± 2.51	0.251
	Right	176.64 ± 2.15	176.92 ± 1.83	0.845
Minimum knee joint angle	Left	156.85 ± 1.64	156.67 ± 1.56	0.715
	Right	170.36 ± 1.21	164.25 ± 1.33	0.062
Maximum ankle joint angle	Left	101.21 ± 1.36	106.34 ± 1.55	0.845
	Right	135.15 ± 2.12	134.56 ± 2.31	0.762
Minimum ankle joint angle	Left	90.77 ± 1.24	86.45 ± 1.23	0.258
	Right	$126.87 \pm 3.21^*$	112.66 ± 2.67	0.021

*: compared with group B, $p < 0.05$.1

As can be seen from **Figure 6**, in this stage, the IEMG in this stage was mainly activated by the lower extremity muscles. Compared with the previous stage, the left muscles exerted more force in this stage, because the left supporting leg bore the whole body weight in this stage. In addition to the supporting leg, the force of the free leg was mainly exerted by the rectus femoris muscle. In comparison, the two groups showed obvious differences in IEMG of LBF, RBF, LG, LRF, and RRF. The RRF force of group B was small, indicating that group B had weak control over the free leg at this moment.

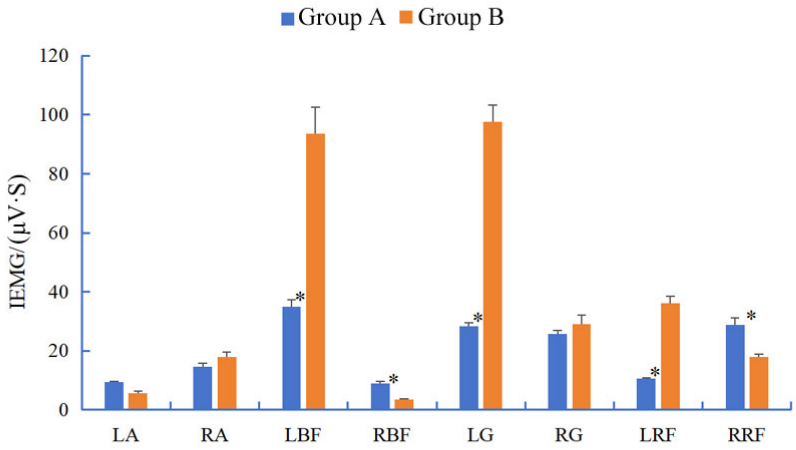

Figure 6. Comparison of muscle activity characteristics in the 360° leg-control rotation stag.e.

*: compared with group B, $p < 0.05$.

As indicated in **Table 6**, there was a minimal disparity in the left and right knee joint between the two groups. The maximum and minimum angles of the left and right knee joints of group A were greater than those of group B, and the difference in the maximum angle was obvious ($p < 0.05$). In terms of ankle angle, the right ankle joint angle of both groups was slightly greater than that of the left ankle jont, and the maximum and minimum angles of the left and right ankle joints of group A were slightly greater than those of group B, in which the maximum angle of the right ankle exhibited a significant difference ($p < 0.05$). This result also proved the ability of group A to control the joint.

Table 6. Comparison of kinematic characteristics in the upright restoration stage.

		Group A (*n* = 8)	**Group B (*n* = 8)**	***p***
Maximum knee joint angle	Left	175.12 ± 1.46*	167.33 ± 1.16	0.016
	Right	176.14 ± 1.21*	171.08 ± 1.32	0.012
Minimum knee joint angle	Left	168.94 ± 1.26	161.22 ± 1.07	0.061
	Right	166.12 ± 1.25	161.37 ± 1.15	0.215
Maximum ankle joint angle	Left	98.84 ± 1.13	94.12 ± 1.12	0.125
	Right	128.68 ± 2.33*	110.23 ± 2.37	0.013
Minimum ankle joint angle	Left	91.45 ± 1.32	88.64 ± 2.12	0.458
	Right	97.84 ± 1.26	95.31 ± 1.52	0.215

*: compared with group B, $p < 0.05$.2

As indicated in **Table 7**, the two groups showed significant differences in the forces of gastrocnemius ($p < 0.05$). The IEMG value of LG in group A was lower, and the IEMG value of RG was higher, indicating that group A had better control over the free leg at this stage.

Table 7. Comparison of IEMG in the upright restoration stage.

	Group A (*n* = 8)	**Group B (*n* =8)**	***p***
LA	6.87 ± 1.12	5.66 ± 1.21	0.258
RA	5.08 ± 0.64	7.43 ± 1.07	0.128
LBF	41.26 ± 1.26	58.64 ± 2.87	0.251
RBF	22.36 ± 1.08	16.77 ± 1.26	0.133
LG	18.97 ± 0.87*	56.33 ± 5.68	0.001
RG	88.64 ± 5.69*	38.12 ± 3.55	0.001
LRF	8.88 ± 1.25	17.64 ± 2.21	0.715
RRF	42.36 ± 5.26	18.99 ± 2.08	0.064

*: compared with group B, $p < 0.05$; unit: μV·S.3

4. Discussion

According to the research findings, it can be observed that aerobic gymnasts of different levels exhibit some biomechanical differences when performing the C715 movement, and high-level gymnasts demonstrated stronger control over their limbs. These results confirm the applicability of biomechanical techniques in aerobics research and provides some references for further investigation into the C715 movement.

The analysis of the time consumed in different stages demonstrated that compared with group B, group A took longer time in the pre-swing and upright restoration stage, and the difference in the upright restoration stage was significant. When performing the movement, group A provided a better initial speed for the subsequent rotation by a full pre-swing and then enhanced the completion quality of the movement by briefly controlling the leg and then restoring to an upright position.

In the pre-swing stage, the aerobic gymnasts need to withdraw their free legs from the ground to prepare for the subsequent rotation. The torsion of the shoulders and hips is very important, and the proper torsion of the body can provide a good initial speed for the subsequent rotation. From the comparison of the two groups, the torsion angle of the shoulders and hips and the angle between the legs in group A were larger, and the angle between the legs was significantly higher than that in group B ($p < 0.05$). In the pre-swing stage, group A obtained greater inertia force through more sufficient shoulder and hip torsion, which promoted the rotation to be smoother, and also obtained better stability when the free leg withdrew. From the point of view of muscle activity characteristics, aerobic gymnasts at this stage turned right, so the IEMG of the right muscles was larger than that of the left side. The comparison found that the two groups had significant differences in the IEMG of some muscles. Therefore, in exercises, the training of lower limb muscles should be strengthened to improve the explosive power of lower limbs [23].

When the free leg swung to the front, the ankle joint angle of group A changed more widely and the speed was faster, indicating that high-level aerobic gymnasts had better control over the ankle joint and can accelerate the free leg swing through greater speed to enhance the fluency of the C715 movement. At this stage, the aerobic gymnast expanded the left arm and swung to the upper left side with the right arm to drive the torso to rotate. The comparison of the maximum speed of the left elbow and wrist joints suggested that the speed of the left elbow and wrist joints was greater, because their displacements were larger in this process. The speed of the right elbow and wrist joints in group A at this stage was higher, showing small differences with the speed of the left elbow and wrist joints, and it indicated that the stability of the center of gravity in group A was better. From the perspective of muscle activity characteristics, the IEMG of the RG of group A was significantly higher than that of group B ($p < 0.05$), which also proved the control ability of group A on the ankle joint. In the training process, aerobic gymnasts should strengthen the exercise of some muscles to enhance the stability of joint control.

In the 360° leg-control rotation stage, aerobic gymnasts were required to keep both legs straight, i.e., the knee joint angle should be larger, and the free leg ankle joint was required to maintain dorsiflexion, so the angle was also large. The comparison of the maximum and minimum angles of the knee and ankle joints suggested that the completion degree of the movement in group A was better, the control of the knee and ankle joints was better, and the joints were more flexible. From the perspective of muscle activity characteristics, to bear the whole weight and maintain good stability by the supporting leg (left leg), the muscle force was mainly on the left side. The right femoris rectus muscle of group A was larger than group B, indicating that group A had stronger control over the free leg. For the exercises of C715, attention should be paid to the horizontal position of the free leg during the process of rotation, and the training of thigh muscle strength should be strengthened to obtain a better movement appreciation.

In the upright restoration stage, aerobic gymnasts in group A had a larger knee joint angle than those in group B, indicating that group A had a better joint posture. In terms of ankle joint angle, group A was also larger, which also proved the superiority of group A in joint control ability. In terms of muscle activity characteristics, the free-leg gastrocnemius force of group A was significantly greater than that of group B, which proved the control ability of group A over the free leg. This result showed that aerobic gymnasts can better maintain the stability of the body at the end of the movement by strengthening the exercises of joint flexibility and control and improving the exercises of free-leg muscle strength.

Based on the comprehensive research results, high-level aerobic gymnasts demonstrate superior performance in limb stability and joint flexibility compared to the general gymnasts, which confirms the reliability of biomechanical methods in aerobic gymnastics research and provides some useful references for further studying difficult movements in aerobic gymnastics. However, this study also has some limitations such as subjective grouping methods and a small sample size. In future work, more objective grouping methods will be employed for further research, and the scope of experiments will be expanded to validate the findings using a larger sample size.

5. Conclusion

Based on biomechanical methods, this article analyzed the kinematic and sEMG data of aerobic gymnasts at different levels performing the difficulty movement C715, demonstrating the biomechanical differences among these gymnasts, such as differences in joint angles and muscles. This article provides some guidance for aerobic gymnasts to perform the C715 movement in practice.

The research in this article further demonstrates the importance of biomechanical methods in the field of sports, providing theoretical references for the further application and exploration of techniques such as kinematics, dynamics, and EMG in aerobic gymnastics research. The findings can also be applied to teaching and learning aerobic gymnastics, assisting coaches in developing training plans more effectively and promoting the improvement of athletes' performance levels.

Author contributions: Conceptualization, ZY and HL; methodology, ZY; software, HL; validation, ZY and HL; formal analysis, ZY; investigation, HL; resources, ZY; data curation, HL; writing—original draft preparation, ZY; writing—review and editing, HL; visualization, ZY; supervision, HL; project administration, ZY; funding acquisition, HL. All authors have read and agreed to the published version of the manuscript.

Ethical approval: All participants signed the informed consent in this study.

Conflict of interest: The authors declare no conflict of interest.

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