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Original Research

Gender Effects on Lower Limb Biomechanics of Novice Runners before and after a 5 km Run

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Abstract

Background: Gender has been considered as an influencing factor in the incidence of sports injuries. But few studies have discussed whether gender differences change after long-distance running. This study aimed at investigating whether the kinematic and ground reaction forces (GRFs) differences between males and females were altered by a 5 km run. **Methods**: Thirty novice runners (15 males and 15 females) with heel strikes were recruited for this study. In the test before and after the 5 km run, the participants were asked to run through the force plate with their right foot at a speed of 3.3 m/s ± 5%. Kinematics data and GRFs were collected synchronously. Each participant completed five successful running trials for further analysis of data. **Results**: Gender differences existed in ankle sagittal peak angle (pre: p = 0.059; post: p = 0.013), knee frontal peak angle (pre: p = 0.345; post: p = 0.014), knee horizontal nadir angle (pre: p = 0.056; post: p = 0.005), hip frontal nadir angle (pre: p = 0.103; post: p = 0.001) and peak lateral force (pre: p = 0.564; post: p = 0.001) after a 5 km run, but there were no gender differences before a 5 km run. Gender differences in the knee and hip movement in the frontal plane and horizontal plane and anterior-posterior GRFs changed obviously in the stance phase before and after a 5 km run. **Conclusions**: The gender difference in lower limb biomechanics during running is not constant. Differences change in peak angle, peak lateral force, knee and hip movement in the frontal plane and horizontal plane, and anterior-posterior GRFs between males and females were associated with the different incidence of running-related injuries, such as patellofemoral joint injuries, anterior cruciate ligament injury and iliotibial band syndrome, etc. These changes can give some concrete details to explore the different incidence rates of lower limb sports injuries between genders.

Keywords: gender difference; biomechanics; lower limbs; long-distance running

1. Introduction

Running is a health-beneficial physical activity that is easily accessible and increasingly popular worldwide [1,2]. However, there is also a high incidence of running-related sports injuries, especially for novice runners. Previous research has shown that more than 25% of novice runners have suffered sports injuries during running training, and 40% of these runners cannot continue training due to injuries [3].

Compared to males, females have a lower incidence of certain running-related diseases. Taunton counted 2002 runners with sports injuries and found that females were 62% more likely than males to have patellofemoral pain syndrome and iliotibial band friction syndrome, and females were 76% more likely to suffer from gluteus medius injuries than males who were 24% [4]. Boling found that females had 2.23 times the incidence of patellofemoral pain syndrome compared with males [5]. Macintyre J found that male marathon and recreational runners were less likely than females to suffer from patellofemoral pain [6]. The reasons for these differences in the incidence of injury are not completely clear, and gender differences in lower limb biomechanics have been considered an influencing factor [7,8]. For instance, research has shown that males showed lower peak angles of hip rotation and adduction, as well as lower peak knee abduction in the stance phase [9]. This difference in non-sagittal motion is thought to be one of the causes of various running-related injuries, such as iliotibial band syndrome and patellofemoral pain [10]. Previous studies have found that gender differences also exist in hip movement during walking, suggesting that this phenomenon is not specific to running gaits [11].

For novice runners, 5 km running often results in changes in lower limb kinematics. Previous research has revealed that runners' ankle eversion angle and knee abduction angle increase, knee and ankle frontal range of motion increases, and peak angular velocity of ankle dorsiflexion and hip inter-rotation increases in the terminal phase of 5 km treadmill running [12]. Kinematic measurements after a 5 km run showed that knee adduction angle increased significantly at 81–91%, and internal rotation angle increased significantly at 13–27%. At the hip joint after a 5 km run, the flexion angle decreases at 0–56%, the adduction angle decreases at 0–14%, and the internal rotation angle decreases at 56–100% [13]. Ground reaction forces (GRFs) are considered to be the potential cause of several running-related injuries, these injuries are related to the state of body movement, tissue stress, and limb load rate [14]. Several studies have shown that the maximal GRFs and the peak vertical GRFs decrease after long-distance running and the impact loading rate was similar before and after long-distance running [15]. Whether gender differences in GRFs existed in males and females were not consistent during the running stance phase. Sinclair and Willson found that there was no difference between the parameters of the ground reaction forces between males and females [16,17]; While sang-Kyoon found that regardless of the running speed, the impact load rate of females is greater than that of males. Increasing running speed may lead to a higher rate of running injuries [18].

This information indicated that the kinematics of the lower limbs were not constant during running. However, the majority of the participants were males. There are anatomical differences between males and females. It remains unclear whether female runners undergo similar changes in lower limb kinematics and GRFs as male runners before and after long-distance running. The difference in changes can cause alterations in lower limb kinematics and GRFs differences between males and females. Alterations in lower limb kinematics and GRFs in males and females may provide new explanations indirectly for the different incidences of running-related injuries from a biomechanical perspective.

So we took an equal number of males and females participants and experimented to learn more about the differences in biomechanical changes of lower limbs between gender and provide a reference to explain the existence of gender differences in running-related injuries from a biomechanical standpoint. To compare the lower limb kinematics, we characterized ankle, knee, and hip joint kinematic and ground reaction forces (GRFs) before and after a 5 km run. We hypothesized that gender differences in the hip, knee, ankle kinematics, and ground reaction forces would change after a 5 km run.

2. Materials and Methods

2.1 Participants

Fifteen male (age = 23.40 $\pm$ 0.55 yrs, mass = 74.10 $\pm$ 12.72 kg, height = 174.60 $\pm$ 4.77 cm, weekly running amount $\leq$5 km) and fifteen females (age = 23.33 $\pm$ 0.58 yrs, mass = 55.67 $\pm$ 2.08 kg, height = 163.67 $\pm$ 0.58 cm, weekly running amount $\leq$5 km) novice runners with rearfoot strike were recruited as participants of this study and their dominant leg was the right leg. Rearfoot strike is defined as running of the heel strike to toe-off in the stance phase. We observed the running posture presented by the participants running at adaptive speed to determine whether rearfoot strike. A novice runner is defined as someone who has not run regularly in the past year [19,20]. Participants were recruited through social media and a club at Ningbo University. All participants had no health problems and neuromuscular disease, and had no lower extremity injuries in the past 6 months. Before the trial, all participants obtained and signed a written permission form authorized by the institutional review committee

2.2 Experimental Procedures

According to the model of 6 DOF placed reflective markers (Fig. 1). Thirty-six spherical reflective (14 mm) markers were placed on the lower limbs. The location of the markers as specified by skeletal landmarks included: left/right anterior superioriliac spine, left/right posterior superior iliac spine, left/right femur lateral epicondyle, left/right femur medial epicondyle, left/right first and fifth metatarsal heads, left/right distal interphalangeal joint of the second toe, left/right medial and lateral malleoli, left/right medial and lateral epicondyle of the femur. Clusters of 4 markers were placed laterally on the left and right thigh and shank segments [21]. Thirty-six reflective markers were reinforced to ensure they didn't fall off while running.

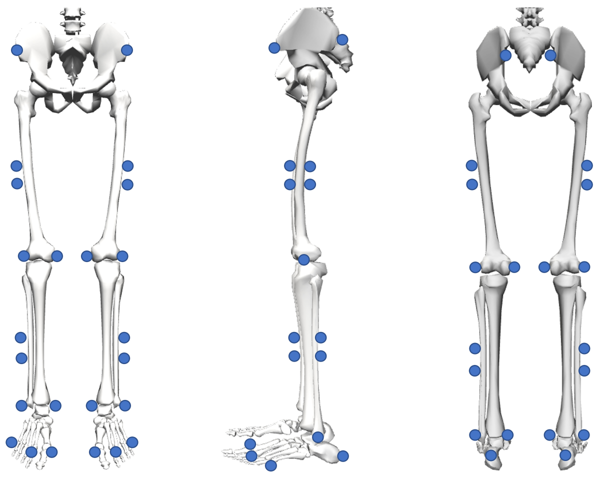

Fig. 1. The reflective markers placement (front view, side view, and back view).

All tests were conducted at Ningbo University's sports biomechanics laboratory. The marked trajectory and GRFs data were collected before the 5 km run. Then, participants were asked to warm up by walking at 2.2 m/s for 1 min on the treadmill [12]. After warming up, the participants performed a 5 km run on the treadmill at their self-selected speed with reflective markers on the lower limbs [22]. After the participants finished the 4 km run, we started pre-tuning the equipment to ensure that the data could be collected immediately after the participant completed the 5 km run. The marked trajectory and GRFs data were collected again as quickly as possible after the 5 km run.

The VICON MX motion analysis system (Oxford Metrics Ltd, Oxford, UK) was used to capture the 3D

Table 1. Mean (SD) of peak angle of the stance phase.

Joint	Variables	Male pre	Female pre	Male post	Female post	Independent samples *t*-Test	
						Pre	Post
Ankle	Sagittal (°)	21.61 (1.64)	22.40 (1.29)	22.66 (2.47)	20.00 (1.04)	0.059	**0.013**
	Frontal (°)	2.71 (1.98)	–1.30 (1.73)	5.61 (2.99)	–1.49 (1.49)	**0.001**	**0.004**
	Horizontal (°)	4.04 (2.08)	–3.11 (1.65)	9.54 (5.47)	–4.44 (2.77)	**0.001**	**0.001**
Knee	Sagittal (°)	–14.75 (3.59)	–24.90 (5.68)	–15.24 (4.10)	–26.96 (4.78)	**0.001**	**0.001**
	Frontal (°)	5.36 (4.15)	6.21 (4.02)	6.31 (3.53)	9.43 (5.20)	0.345	**0.014**
	Horizontal (°)	5.54 (2.05)	2.37 (3.45)	6.52 (4.34)	3.40 (3.89)	**0.001**	**0.001**
Hip	Sagittal (°)	30.28 (3.96)	35.72 (6.36)	32.72 (6.58)	35.63 (7.44)	**0.001**	**0.001**
	Frontal (°)	12.56 (5.15)	18.02 (3.21)	12.75 (3.67)	20.04 (3.37)	**0.001**	**0.001**
	Horizontal (°)	8.76 (4.07)	11.91 (5.17)	1.55 (1.08)	9.01 (5.06)	**0.001**	**0.001**

Note: compare the gender difference before and after a 5 km run; contrast content was the peak angle of the hip, knee and ankle on the sagittal, frontal, and horizontal planes; statistical significance was set as $p < 0.05$; bold the p-values with statistical differences.

marked trajectory with 8 cameras. The camera captures at a frequency of 200 Hz. During all running trials (before and after 5 km runs), the right foot of each participant was measured [23]. GRFs data acquisition using the 600 × 400 mm force platform (AMTI, Watertown, MA, USA). The sampling frequency of the force platform is 1000 Hz. The force and maker data were collected synchronously.

Participants were instructed to run at a speed of 3.3 m/s [23]. Running speed was recorded by Brower timing lights (Brower Timing System, Draper, UT, USA) located 1.2 m at the center of the force platform. Five successful trials were grasped for each running speed with a variance of less than 5% and within 5% of the intended running speed.

2.3 Data Process and Analysis

This study analyzed running in the stance phase, including right heel strike to toe lift. The C3D files were first exported using Vicon Nexus Software, and then Visual 3D (C - Motion Inc., Germantown, MD, USA) was applied to process and quantify the kinematic parameters of the ankle, knee, and hip joints during the stance phase. The kinematics data and the ground reaction forces were filtered by a 10 Hz fourth-order zero-phase low-pass Butterworth filter [24]. The joint angle of the ankle, hip, and ankle were calculated using sagittal, frontal, and horizontal gimbal angles [25].

To identify initial foot contact and toe-off, set a vertical ground response force threshold of 20 N. The GRFs was then standardized to the body weight of each participant (BW). Selected GRFs parameters were peak vertical active force, peak vertical impact force, vertical instantaneous loading rate (VILR) and vertical average loading rate (VALR), contact time, peak medial force, vertical impulse, peak lateral force, peak braking force, and peak propulsive force. These variables are the most relevant parameters selected based on previous studies on GRFs during running.

2.4 Statistical Analysis

Using independent Samples *t*-Test to evaluate differences in kinematic and ground reaction forces (GRFs) between males and females before and after a 5 km run. The alpha level was set to = 0.05. SPSS 23.0 software (IBM, Armonk, NY, USA) was used for statistical calculation.

SPM1d is a package for one-dimensional Statistical Parametric Mapping. It uses random field theory to make statistical inferences regarding registered (normalized) sets of 1D measurements and supports various statistical analyses. Joint kinematics and ground reaction forces are one-dimensional time-varying characteristics [26]. Our research met the conditions of statistical analysis using the independent sample T-test. The independent sample T-test was applied by using one-dimensional statistical parameter mapping (SPM1d) to compare the mean joint angles and ground reaction forces during the stance phase. Statistical analysis was performed in Matlab R2016b and the alpha level was set to = 0.05.

3. Results

3.1 Kinematics

Gender differences existed in ankle sagittal peak angle (pre: $p = 0.059$; post: $p = 0.013$), knee frontal peak angle (pre: $p = 0.345$; post: $p = 0.014$), knee horizontal nadir angle (pre: $p = 0.056$; post: $p = 0.005$) and hip frontal nadir angle (pre: $p = 0.103$; post: $p = 0.001$) after a 5 km run, but there were no gender differences before a 5 km run (Tables 1,2).

The consequence obtained by SPM1d analysis are as follows (Fig. 2).

Ankle motion on the sagittal plane: gender differences existed in the range of 5%–52% and 70%–100% before a 5 km run; gender differences existed in the range of 0%–4%, 8%–52%, and 69%–100% after a 5 km run. Ankle motion on the horizontal plane: gender differences existed in the range of 0%–8%, 13%–49%, and 71%–100% before a 5

Table 2. Mean (SD) of nadir angle of the stance phase.

Joint	Variables	Male pre	Female pre	Male post	Female post	Independent samples *t*-Test	
						Pre	Post
Ankle	Sagittal (°)	–17.24 (5.41)	0.60 (2.18)	–17.08 (5.71)	0.61 (2.59)	**0.001**	**0.001**
	Frontal (°)	–10.52 (4.12)	–13.29 (4.87)	–9.54 (5.46)	–12.93 (3.85)	**0.001**	**0.004**
	Horizontal (°)	–13.89 (2.68)	–11.48 (2.62)	–15.11 (2.37)	–12.44 (2.63)	**0.001**	**0.001**
Knee	Sagittal (°)	–37.29 (4.92)	–44.10 (9.53)	–37.38 (7.16)	–46.39 (9.35)	**0.001**	**0.001**
	Frontal (°)	–3.12 (3.32)	–0.61 (1.66)	–5.91 (3.96)	1.76 (2.48)	**0.001**	**0.001**
	Horizontal (°)	–4.60 (3.41)	–6.08 (6.91)	–7.02 (6.77)	–4.95 (2.91)	0.056	**0.005**
Hip	Sagittal (°)	–10.34 (4.45)	–3.04 (3.36)	–11.36 (3.62)	–5.18 (3.40)	**0.001**	**0.001**
	Frontal (°)	3.95 (4.47)	4.97 (4.31)	2.39 (3.19)	6.50 (4.34)	0.103	**0.001**
	Horizontal (°)	–0.62 (2.23)	–2.84 (2.63)	–10.30 (3.43)	–5.71 (4.68)	**0.002**	**0.001**

Note: compare the gender difference before and after a 5 km run; contrast content was the nadir angle of the hip, knee and ankle on the sagittal, frontal, and horizontal planes; statistical significance was set as $p < 0.05$; bold the *p*-values with statistical differences.

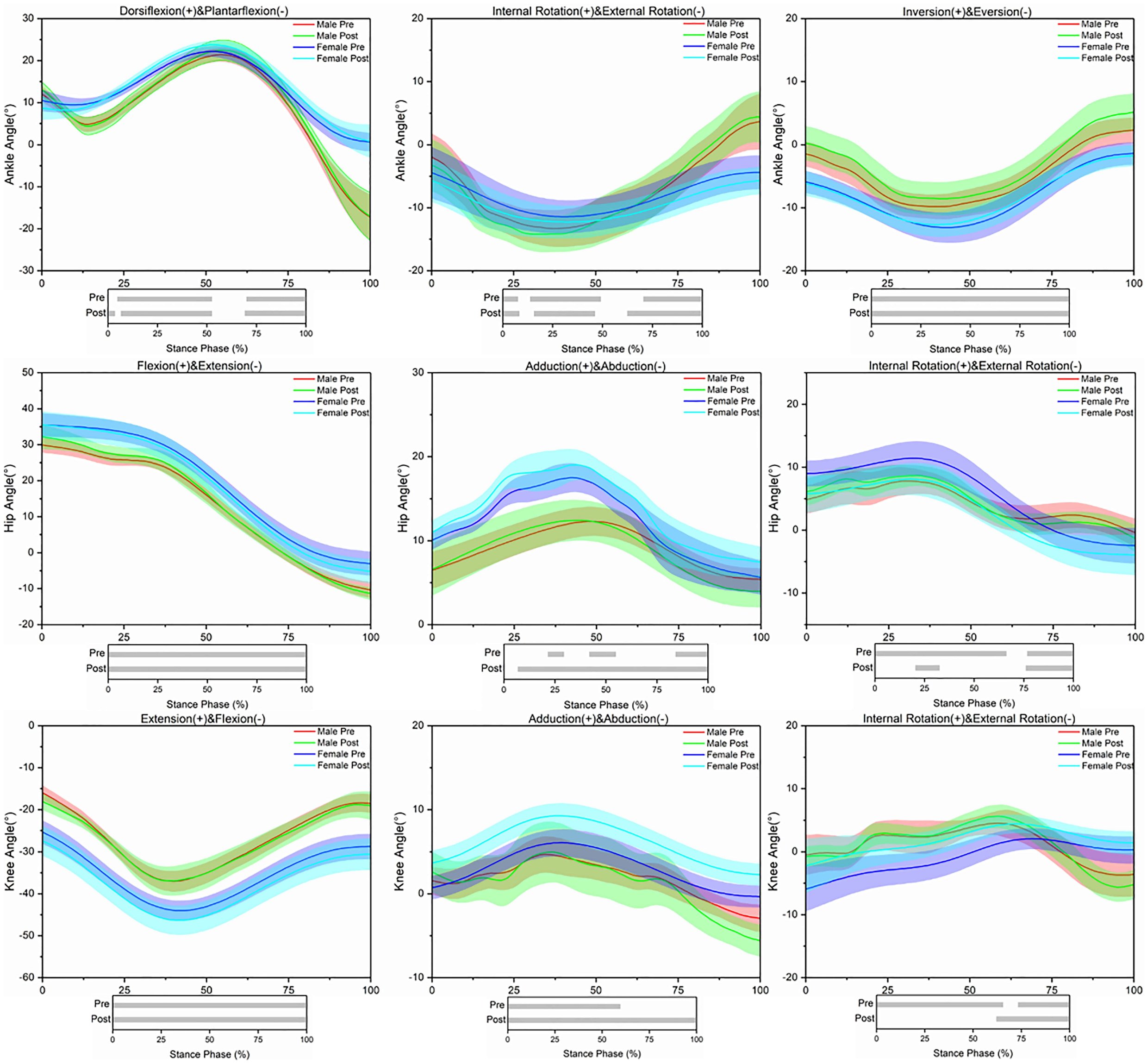

Fig. 2. The mean and standard deviation of lower limb joint angles during the stance phase. Gender differences before and after a 5 km run ($p < 0.05$) are highlighted in the corresponding time period of the SPM1d analysis (grey horizontal bars in the figure bottom).

Table 3. Mean (SD) of ground reaction forces (GRFs) characteristics of the stance phase.

Variables	Male/Pre	Female/Pre	Male/Post	Female/Post	Independent samples *t*-Test	
					pre	post
Peak vertical impact force (BW)	1.84 ± 0.31	1.82 ± 0.37	1.93 ± 0.30	1.82 ± 0.40	0.443	0.093
Peak vertical active force (BW)	2.53 ± 0.23	2.76 ± 0.10	2.58 ± 0.26	2.68 ± 0.10	**0.001**	**0.006**
VALR (BW/s)	74.02 ± 16.29	78.23 ± 31.49	75.19 ± 17.59	73.48 ± 21.35	0.490	0.587
VILR (BW/s)	118.44 ± 25.48	131.69 ± 45.64	125.19 ± 27.50	129.90 ± 43.17	0.080	0.613
Vertical impulse (BW% × s)	32.63 ± 2.28	32.02 ± 1.76	31.99 ± 1.49	31.83 ± 6.25	**0.001**	**0.001**
Peak medial force (BW)	–0.08 ± 0.12	–0.24 ± 0.08	–0.12 ± 0.08	–0.25 ± 0.08	**0.001**	**0.001**
Peak lateral force (BW)	0.05 ± 0.13	0.04 ± 0.02	0.12 ± 0.08	0.03 ± 0.02	0.564	**0.001**
Peak propulsive force (BW)	–0.32 ± 0.07	–0.39 ± 0.05	–0.12 ± 0.08	–0.39 ± 0.07	**0.001**	**0.004**
Peak braking force (BW)	0.38 ± 0.05	0.44 ± 0.04	0.12 ± 0.08	0.41 ± 0.08	**0.001**	**0.040**
Contact time (s)	0.23 ± 0.01	0.21 ± 0.01	0.23 ± 0.01	0.22 ± 0.01	**0.001**	**0.001**

Note: compare the gender difference before and after a 5 km run; contrast content was the parameters of ground reaction forces in the table; statistical significance was set as $p < 0.05$; bold the p-values with statistical differences. note: VALR, vertical average loading rate; BW, body weight; VILR, vertical instantaneous loading rate.

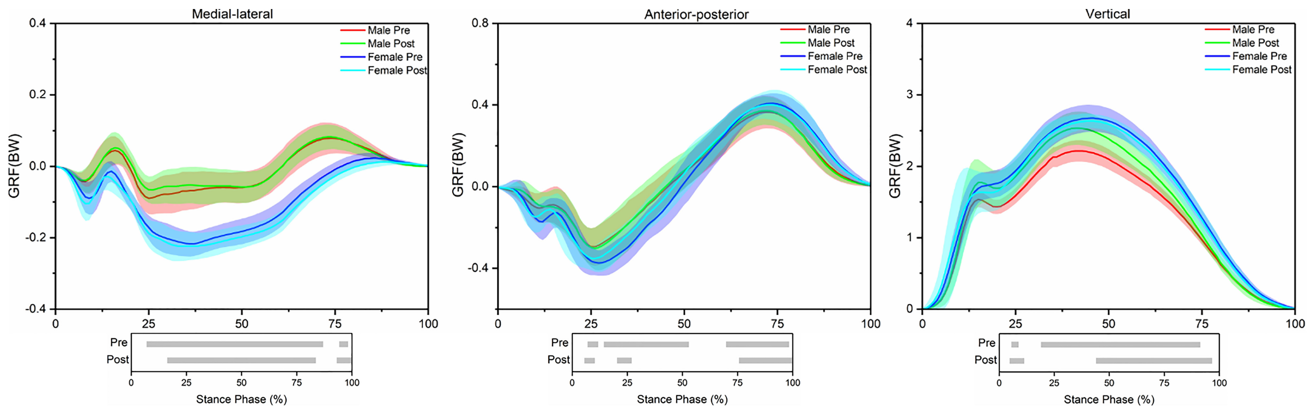

Fig. 3. Ground reaction forces (GRFs) of the mean (SD) over the stance period. Gender differences before and after a 5 km run ($p < 0.05$) are highlighted in the corresponding time period of the SPM1d analysis (grey horizontal bars in the figure bottom).

km run; gender differences existed in the range of 0%–9%, 15%–46%, and 62%–100% after a 5 km run.

Knee motion on the frontal plane: gender differences existed in the range of 22%–28%, 42%–54%, and 86%–100% before a 5 km run; gender differences existed in the range of 5%–100% after a 5 km run. Knee motion on the horizontal plane: gender differences existed in the range of 0%–68% and 77%–100% before a 5 km run; gender differences existed in the range of 22%–31% and 76%–100% after a 5 km run.

Hip motion on the frontal plane: gender differences existed in the range of 0%–60% before a 5 km run; gender differences existed in the range of 0%–100% after a 5 km run. Hip motion on the horizontal plane: gender differences existed in the range of 0%–65% and 74%–100% before a 5 km run; gender differences existed in the range of 63%–100% after a 5 km run.

3.2 Ground Reaction Forces (GRFs)

Gender differences existed in peak lateral force (pre: p = 0.564; post: p = 0.001) after a 5 km run, but there were no gender differences before a 5 km run (Table 3).

The consequence obtained by SPM1d analysis are as follows (Fig. 3).

In medial-lateral GRFs: gender differences existed in the range of 7%–87% and 95%–99% before a 5 km run; gender differences existed in the range of 16%–83% and 93%–100% after a 5 km run.

In anterior-posterior GRFs: gender differences existed in the range of 7%–12%, 16%–53%, and 71%–99% before a 5 km run; gender differences existed in the range of 5%–10%, 21%–27%, and 76%–100% after a 5 km run.

In vertical GRFs: gender differences existed in the range of 5%–8% and 19%–90% before a 5 km run; gender differences existed in the range of 4%–11% and 43%–97% after a 5 km run.

4. Discussion

The purpose of this study was to investigate whether the kinematic and ground reaction forces (GRFs) differences between males and females were altered by a 5 km run. Although there were some studies on the kinematic and ground reaction forces (GRFs) between males and females [27], the results suggested that gender differences in biomechanics may lead to different incidences of running-related sports injuries in males and females [28]; But in the long-distance running, the kinematic characteristics of the initial stage were different from those of the final stage [12]. We investigated the differences in the biomechanics of lower limbs between males and females before and after a long-distance run. The results supported our hypothesis, that gender differences in kinematic and ground reaction forces (GRFs) changed after a 5 km run.

The ankle has an important cushioning effect when the foot contacts the ground, and the change of dorsiflexion of the ankle joint will affect GRFs [29]. Previous studies have shown that higher dorsiflexion of the ankle leads to an increase in loading rate and the first peak, while lower dorsiflexion occurs during fatigue [30], which is consistent with what we observed in the study. There was no gender difference in the peak ankle angle of the sagittal plane before the 5 km run, but there was a gender difference after a 5 km run. The peak ankle angle of the sagittal plane in male runners was larger than that in female runners after a 5 km run. The non-contact eversion ankle sprains are associated with dorsiflexion and eversion velocity and magnitude of the ankle joint. After a 5 km run, males showed higher dorsiflexion of the ankle joint than females, which may be related to the higher rate of low limb injury in males [31].

The essence of running is the storage and recovery of elastic energy in the tendon structure of lower limbs during the drafting cycle [32]. When the body meets the ground, the knee plays an important function in absorbing shock and dissipating stress [33]. Recent research reported that kinematic changes in the knee joint may be explained by stress transfer applied to the cartilage and meniscus [34]. In this study, we found that there was no gender difference in the peak knee angle of the frontal plane and the nadir knee angle of the horizontal plane before a 5 km run. After a 5 km run, the peak knee angle of the frontal plane in female runners was larger than that in male runners and the nadir knee angle of the horizontal plane was smaller than that of the male runners, showing gender difference. This may be related to the lower incidence of knee injuries in males, such as patellofemoral joint injuries [5].

In addition, the study found that the frontal nadir angle of the hip had no gender difference before a 5 km run; while there was a gender difference after a 5 km run. The nadir hip angle of the frontal plane in male runners was smaller than that of female runners; previous research has shown that this may be related to anterior cruciate ligament injury [35].

Through the analysis of SPM1d, we found that the gender difference in the knee and hip movement in the horizontal plane and frontal plane changed obviously in the stance phase before and after a 5 km run. The change in the difference may be the reason for the gender difference in the occurrence rate of sports injuries [36,37]. Changes in knee movement may be caused by changes in hip movement in the stance phase. The pattern was similar to that observed prospectively in runners who developed iliotibial band syndrome (ITBS), compared with those who were healthy; the runners who later developed ITBS displayed greater peak knee internal rotation, apparently due to a less internally rotated femur [10].

We found gender differences changed in the peak lateral force. There was no significant difference in peak lateral force between males and females before the 5 km run, but significant differences appeared after the 5 km run. The peak lateral force of males was significantly larger than female runners after a 5 km run, changes in lateral force may lead to internal rotation of the foot. Excessive internal rotation is related to calf and knee pain [38,39].

Through the analysis of SPM1d, we found that the gender difference in anterior-posterior GRFs changed obviously in the stance phase before and after a 5 km run. Since the running speed remains the same over the course of measuring, the anterior-posterior GRFs was changed to compensate for attitude control [40]. Gender differences in postural control changed before and after a 5 km run. This may account for changes in the incidence of ankle instability between genders [41].

There are some limitations to this research. Firstly, we studied the biomechanical characteristics of running in the stance phase, because previous studies have shown that biomechanical characteristics of running in the stance phase are significantly associated with running injury [42,43]. However, the biomechanical characteristics of lower limbs in both males and females during the swing phase should not be ignored. Secondly, when we applied the reflective markers to the participants, the reflective markers on the foot were attached to the outside of the shoe, which may be different from the reflective markers on the skin of the foot (such as using the hollowed-out shoe), and the biomechanics of the joint was different [44]. Finally, the shoe mass is not matched to the participant's weight; we know that increased shoe weight can negatively affect body weight, and in terms of economic performance, similar studies are needed to do at the differences in the biomechanics of running between males and females after shoe mass correction.

5. Conclusions

The research showed that under the intervention of a 5 km run, the gender differences in ankle sagittal peak angle, knee frontal peak angle, knee horizontal nadir angle, hip frontal nadir angle, and peak lateral force changed before and after running. Gender differences in the knee and hip movement of frontal plane and horizontal plane and anterior-posterior GRFs changed obviously in the stance phase. The result showed that gender differences in lower limb biomechanics are not constant during running. Gender differences in some biomechanical characteristics of lower limbs changed after a 5 km run. Differences change in peak angle, peak lateral force, knee and hip movement in the frontal plane and horizontal plane, and anterior-posterior GRFs between males and females were associated with the different incidence of running-related injuries, such as patellofemoral joint injuries, anterior cruciate ligament injury and iliotibial band syndrome, etc. These changes can give some concrete details to explore the imparity incidence rates of lower limb sports injuries in novice runners of different genders. The follow-up research can explore the biomechanical characteristics of different stages in the process of long-distance running and further understand the relationship between gender and sports injury.

Author Contributions

HC, FR, and YG designed the research study. HC and QL performed the research. FR and IB provided help and advice on research study. HC and QL analyzed the data. HC, YS, and YG wrote the manuscript. All authors contributed to editorial changes in the manuscript. All authors read and approved the final manuscript.

Ethics Approval and Consent to Participate

Informed written consent was obtained from all included participants, and this study was approved by the Ethics Committee in Ningbo University (RAGH20210613).

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Conflict of Interest

The authors declare no conflict of interest.

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