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The impact and correlation of running landing methods on leg movement ability

CHAO-FU CHEN[1]*†, HUI-JU WU[1†], YU-SHIH WANG[3], HUNG-SHENG HSIEH[2, 3], TING-YAO WANG[4], SOUN-CHENG WANG[5]

[1] Physical Education College, Huaibei Normal University, China.
[2] Department of Physical Education, National Pingtung University, Taiwan.
[3] Graduate Institute of Education, National Chung Cheng University, Taiwan.
[4] Graduate Institute of Long-term Care, Tzu Chi University of Science and Technology, Taiwan.
[5] Department of Athletic Sports, National Chung Cheng University, Taiwan.

Purpose: This study aimed to explore the impact of different landing methods on leg movement ability and the relationship between various parameters of leg movement. *Methods*: This work parameters including stride, contact time, flight time, duty factor, stride angle, vertical stiffness, leg stiffness and peak vertical ground reaction force. Thirty healthy subjects voluntarily participated in this study. In this experiment, each subject was required to perform two tests on a treadmill (using a speed of 10 km/h and 160 spm) (The interval between two experiments is 7 days). In the first test, subjects used RFS. In the second test, FFS was used. A high-speed video camera was used to collect the images and the Kwon3D motion analysis suite was used to process the images in this experiment. *Results*: The findings of this study revealed that runners employing the forefoot strike FFS method exhibited several favorable characteristics in contrast to those using the rearfoot strike RFS method. These included shorter contact time, longer flight time, reduced duty cycle, increased stride angle and heightened leg stiffness. Additionally, peak vertical ground reaction forces were significantly elevated in females. *Conclusions*: While rear foot strike RFS demonstrates a notable enhancement in leg stiffness among female runners with low leg stiffness, it concurrently leads to a significant increase in peak vertical ground reaction force and imposes a greater load on the legs. However, this phenomenon is not observed among male participants.

Key words: *sport technology, sports analytics, sports biomechanics, video analysis*

1. Introduction

As a popular sport, running significantly improves cardiopulmonary function and positively impacts overall health. Therefore, it is widely regarded as the preferred exercise method for many athletes and sports enthusiasts 23]. In the field of running research, various striking methods, such as forefoot strike (FFS), midfoot strike (MFS) and rearfoot strike (RFS), have become the subject of research focus [6], [31]. Past research has revealed that most runners use the RFS method, while fewer choose the FFS method [12], [13]. With the continued focus on running technique and performance, sports scientists and coaches have been working tirelessly to understand the impact of different running patterns on the athletes' leg movement ability and overall performance [19], [20], [39], [40]. Especially stride frequency, stride, contact times, and flight time [6], [21]. According to current research, elite runners exhibit various key technical characteristics critical to improving running performance, which include short contact time, long flight time and large stride [6], [29].

The duty factor is an important technical parameter affecting running performance. Indeed, a lower duty factor increases the vertical force and improves running efficiency [6], [15], [28]. At the same time, a wider

* Corresponding author: Chao-Fu Chen, Physical Education College, Huaibei Normal University, China. E-mail: chenchaofu@chnu.edu.cn
† These authors contributed equally to this work.
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stride angle is a key factor in improving running performance [6], [26]. Athletes who are good runners often possess these characteristics, which are interrelated and work synergistically to improve overall performance [15], [16], [21], [26], [29]. Besides, higher vertical stiffness and leg stiffness help runners respond to ground reaction forces more effectively, which helps shorten contact time and improve running efficiency [16], [25], [36].

This study explores the impact of different landing methods on leg movement ability and the relationship between leg movement ability parameters. This work covers multiple parameters, including stride, contact time, flight time, duty factor, stride angle, vertical stiffness, leg stiffness and peak vertical ground reaction force, providing insights into different landing pattern details. Studying these parameters has significant practical application value in sports science and provides strong support for running technology and training.

2. Materials and methods

2.1. Participants

Thirty healthy subjects (15 males and 15 females) voluntarily participated in this study. Their average age was 19.37 ± 1.00 years old, height was 171.40 ± 8.78 cm and weight was 63.00 ± 12.38 kg. The subjects were students studying in sports-related departments at the university and had experience running on treadmills, but were not familiar with using fixed landing patterns. Before participating in the research, each subject was fully explained, understood the purpose of the research and the possible risks involved, and signed a informed consent form before participating in the research. This study was reviewed by the University Ethics Committee of University, and followed the relevant provisions of the Declaration of Helsinki.

2.2. Procedures

In this experiment, each participant was instructed to undergo two treadmill tests while maintaining a speed of 10 kilometers per hour and a pace of 160 steps per minute using a metronome (Model Korg MA-30, Tokyo, Japan). In the first test, subjects used RFS. In the second test, FFS was used. Kinematic analysis was used to explore the impact of different landing methods on leg movement ability and to study the relationship between leg movement ability parameters relationship.

2.3. Experimental instruments and equipment

A high-speed video camera (sampling rate = 100 Hz, shutter speed = 1/1000 sec, model Sony PXW-FS7H, Tokyo, Japan) was used in this experiment. The Kwon3D motion analysis suite (Visol, Inc., Gwangmyeongsi, Kyonggido, Korea) was used to process the captured images, and markers attached to the image joints were digitized through optical automatic capture technology. The X, Y and Z axes in the entire three-dimensional coordinate system represent the horizontal left and right, front and back, and vertical up and down directions in space respectively. Referring to past literature, body limb parameters suitable for adolescents were established [4]–[8], [18].

2.4. Data processing

Stride, contact time, flight time, duty factor, stride angle, vertical stiffness, leg stiffness and peak vertical ground-reaction force were important parameters used to describe and analyze running movements, which help to deeply understand running technology and biomechanical characteristics [6], [15], [32], [34], [35].

2.5. Statistical analysis

Descriptive statistics and inferential statistics were performed using SPSS 26 software. The Mann–Whitney U-test was used to test the differences between variables, and Pearson Product–Moment Correlation Cofficient was used to test the correlation between each parameter. The significance level was set at α = 0.05. Cohen'd was used to calculate the effect size (ES) of RFS and FFS in each parameter as an evaluation of the practical applicability of the quantitative results. ES 0.20~0.49 was a small effect size, 0.50~0.79 was a medium effect size and >0.80 was a large effect size [10].

G*Power computer software (G*Power 3.1, Düsseldorf, Germany) was used to calculate the statistical power (Statistical Power) of each parameter of RFS and FFS. The statistically significant level was set as Power = 0.8 [10].

3. Results

Through the Kolmogorov–Smirnov test, it was found that the running technology variables and running advanced technology variables of male and female were all normally distributed in this study ($p > 0.05$).

In males, the performance of FFS was significantly longer than RFS in flight time ($z = –2.482$, $p = 0.013$, $d = 0.63$, ES = medium , Power = 0.60). The value of FFS of the duty factor parameter was significantly smaller than RFS ($z = –2.594$, $p = 0.009$, $d = 0.63$, ES = medium, Power = 0.60). The value of FFS for the stride angle parameter was significantly greater than RFS ($z = –2.552$, $p = 0.011$, $d = 0.51$, ES = small, Power = 0.43), (Table 1).

In females, FFS was significantly shorter than RFS in contact time ($z = –3.104$, $p = 0.002$, $d = 1.00$, ES = medium, Power = 0.602). The performance of FFS was significantly longer than RFS in flight time ($z = –3.215$, $p = 0.001$, $d = 1.5$, ES = large, Power = 0.92). The value of FFS of the duty factor parameter was significantly smaller than RFS ($z = –3.237$, $p = 0.001$, $d = 1.5$, ES = large, Power = 0.99). The value of FFS for the stride angle parameter was significantly greater than RFS ($z = –3.237$, $p = 0.001$, $d = 1.45$, ES = large, Power = 0.99). The value of FFS of the leg stiffness parameter was significantly higher than RFS ($z = –2.509$, $p = 0.012$, $d = 1.02$, ES = large, Power = 0.93). The value of FFS of the peak vertical ground-reaction force parameter was significantly higher than RFS ($z = –2.219$, $p = 0.026$, $d = 0.88$, ES = large, Power = 0.86), (Table 1).

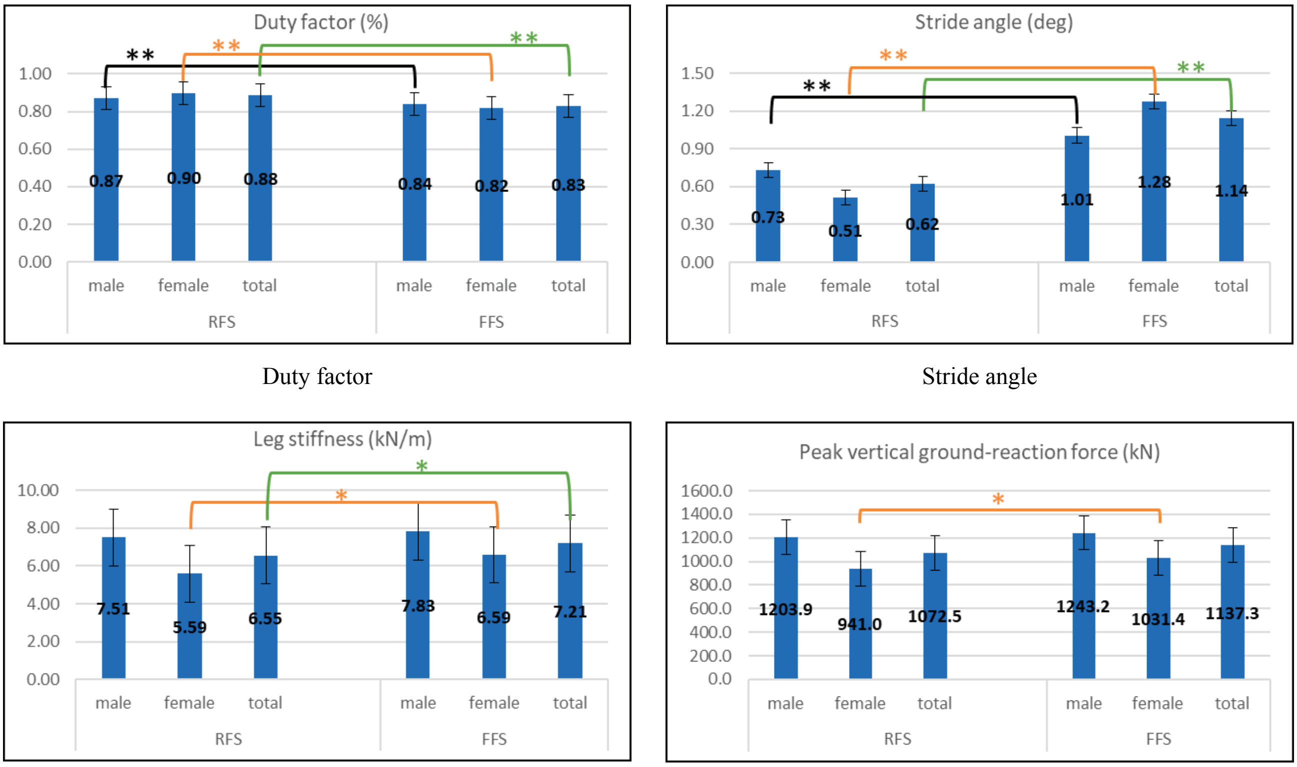
Among all participants, FFS was significantly shorter than RFS in contact time ($z = –3.230$, $p = 0.001$, $d = 1.00$, ES = large, Power = 0.96). The performance of FFS was significantly longer than RFS in flight time ($z = –4.011$, $p = 0.000$, $d = 1.00$, ES = large, Power = 0.96). The value of FFS of the duty factor parameter was significantly smaller than RFS ($z = –4.178$, $p = 0.000$, $d = 0.98$, ES = large, Power = 0.95). The value of FFS for the stride angle parameter was significantly greater than RFS ($z = –4.141$, $p = 0.000$, $d = 0.85$, ES = large, Power = 0.89). The value of FFS of the leg stiffness parameter was significantly higher than RFS ($z = –2.173$, $p = 0.030$, $d = 0.39$, Power = 0.31) (Table 1).

In the correlation analysis of kinematic parameters during RFS technology, stride had a significant positive correlation with contact time ($r = 0.482$, $p = 0.007$), and a significant negative correlation with vertical stiffness ($r = –0.545$, $p = 0.002$). The contact time had a significant negative correlation with the flight time ($r = –0.648$, $p = 0.000$), stride angle ($r = –0.745$, $p = 0.000$), vertical stiffness ($r = –0.486$, $p = 0.006$), leg stiffness ($r = –0.739$, $p = 0.000$), and the peak vertical ground-reaction force a ($r = –0.453$, $p = 0.012$) and had a significant positive correlation with the duty factor ($r = 0.734$, $p = 0.000$). The flight time had a significant negative correlation with the duty factor ($r = –0.992$, $p = 0.000$), had a significant positive correlation with the stride angle ($r = 0.951$, $p = 0.000$), leg stiffness

Table 1. Descriptive statistics of running variables

	Male (N = 15)			Female (N = 15)			Total (N = 30)		
	RFS	FFS	*z*✤	RFS	FFS	*z*☐	RFS	FFS	*z*☐
Running technology variables									
Stride [m]	1.02 ± 0.06	1.03 ± 0.07	–0.715	0.99 ± 0.04	1.00 ± 0.05	–0.717	1.01 ± 0.05	1.02 ± 0.06	–0.997
Contact times [s]	0.32 ± 0.03	0.31 ± 0.03	–1.610	0.32 ± 0.02	0.30 ± 0.02	–3.104**	0.32 ± 0.02	0.30 ± 0.02	–3.230**
Flight times [s]	0.05 ± 0.02	0.06 ± 0.01	–2.482*	0.04 ± 0.02	0.07 ± 0.02	–3.215**	0.04 ± 0.02	0.06 ± 0.02	–4.011**
Running advanced technology variables									
Duty factor (%)	0.87 ± 0.06	0.84 ± 0.03	–2.594**	0.90 ± 0.06	0.82 ± 0.05	–3.237**	0.88 ± 0.06	0.83 ± 0.04	–4.178**
Stride angle [deg]	0.73 ± 0.71	1.01 ± 0.32	–2.552*	0.51 ± 0.67	1.28 ± 0.66	–3.237**	0.62 ± 0.69	1.14 ± 0.53	–4.141**
Vertical stiffness [kN/m]	21.15 ± 3.43	20.50 ± 4.09	–0.726	18.21 ± 2.30	17.58 ± 2.43		19.68 ± 3.23	19.04 ± 3.62	–1.079
Leg stiffness [kN/m]	7.51 ± 1.99	7.83 ± 1.74	–0.892	5.59 ± 0.84	6.59 ± 1.10	–2.509*	6.55 ± 1.79	7.21 ± 1.56	–2.173*
Peak vertical ground-reaction force [kN]	1203.90 ± 179.65	1243.21 ± 136.13	–0.809	941.04 ± 95.03	1031.43 ± 110.01	–2.219*	1072.47 ± 194.45	1137.32 ± 162.44	–1.641

* $p < 0.05$, ** $p < 0.01$.



Duty factor   Stride angle

Leg stiffness   Peak vertical ground-reaction force

Fig. 1. Kinematics and kinetic parameters of leg movement ability.
* $p < 0.05$, ** $p < 0.01$

($r = 0.605$, $p = 0.000$) and peak vertical ground-reaction force ($r = 0.631$, $p = 0.000$). The duty factor had a significant negative correlation with the stride angle ($r = -0.964$, $p = 0.000$), the leg stiffness ($r = -0.669$, $p = 0.000$) and the peak vertical ground-reaction force ($r = -0.647$, $p = 0.000$). The stride angle had a significant positive correlation with leg stiffness ($r = 0.652$, $p = 0.000$) and the peak vertical ground-reaction force ($r = 0.588$, $p = 0.000$). Vertical stiffness was significantly positively correlated with leg stiffness ($r = 0.804$, $p = 0.000$) and with peak vertical ground-reaction force ($r = 0.672$, $p = 0.000$). There was a significant positive correlation between leg stiffness and peak vertical ground-reaction force ($r = 0.894$, $p = 0.000$) (Table 2).

In the correlation analysis of kinematic parameters during FFS technology, the stride had a significant positive correlation with contact time ($r = 0.798$, $p = 0.000$), and had a significant negative correlation with vertical stiffness ($r = -0.629$, $p = 0.000$), and the leg stiffness ($r = -0.526$, $p = 0.003$). The contact time had a significant negative correlation with the flight time ($r = -0.453$,

Table 2. Correlation analysis of leg movement ability parameters during RFS technology (correlation coefficient)

	Stride	Contact times	Flight times	Duty factor	Stride angle	Vertical stiffness	Leg stiffness	Peak vertical ground-reaction force
Stride	–	0.482**	0.354	–0.241	0.179	–0.545**	–0.211	0.170
Contact times		–	–0.648**	0.734**	–0.745**	–0.486**	–0.739**	–0.453*
Flight times			–	–0.992**	0.951**	0.046	0.605**	0.631**
Duty factor				–	–0.964**	–0.129	–0.669**	–0.647**
Stride angle					–	0.146	0.652**	0.588**
Vertical stiffness						–	0.804**	0.672**
Leg stiffness							–	0.894**
Peak vertical ground-reaction force								–

* $p < 0.05$, ** $p < 0.01$.

Table 3. Correlation analysis of leg movement ability parameters during FFS technology (correlation coefficient)

	Stride	Contact times	Flight times	Duty factor	Stride angle	Vertical stiffness	Leg stiffness	Peak vertical ground-reaction force
Stride	–	0.798**	0.176	0.046	0.100	–0.629**	–0.526**	–0.024
Contact times		–	–0.453*	0.638**	–0.516**	–0.449*	–0.580**	–0.133
Flight times			–	–0.974**	0.991**	–0.198	0.168	0.182
Duty factor				–	–0.982**	0.054	–0.295	–0.194
Stride angle					–	–0.178	0.178	0.144
Vertical stiffness						–	0.917**	0.750**
Leg stiffness							–	0.834**
Peak vertical ground-reaction force								–

* $p < 0.05$, ** $p < 0.01$.

p = 0.012), the stride angle (r = –0.516, p = 0.004) with vertical stiffness (r = –0.449, p = 0.013), and with leg stiffness (r = –0.580, p = 0.001), had a significant positive correlation with the duty factor (r = 0.638, p = 0.000). The flight time had a significant negative correlation with the duty factor (r = –0.974, p = 0.000) and a significant positive correlation with the stride angle (r = 0.991, p = 0.000). There was a significant negative correlation between duty factor and stride angle (r = –0.982, p = 0.000). Vertical stiffness had a significant positive correlation with leg stiffness (r = 0.917, p = 0.000) and a significant positive correlation with peak vertical ground-reaction force (r = 0.750, p = 0.000). There was a significant positive correlation between leg stiffness and peak vertical ground-reaction force (r = 0.834, p = 0.000) (Table 3).

4. Discussion

This study investigates the impact and correlation of different running landing techniques on leg movement ability, utilizing a treadmill set at a fixed speed and cadence. The research compares and correlates rearfoot strike RFS and forefoot strike FFS patterns, analyzing various parameters such as stride length, contact time, flight time, duty factor, stride angle, vertical stiffness, leg stiffness and peak vertical ground reaction force PVF. Additionally, significant differences were observed in various biomechanical parameters between male participants' FFS and RFS running patterns as well as between female participants' FFS and RFS running patterns.

According to previous research, shortening the contact time positively impacts the overall running efficiency [27], [37]. When the foot leaves the ground faster, the energy loss is reduced, and the stepping frequency is increased, thereby improving running speed and endurance [1], [14], [19]. Furthermore, a shorter contact time reduces the burden on the legs and the pressure on the joints and muscles, effectively reducing the risk of injury [3], [20], [24], [38]. Observations from this study highlight that athletes who choose an FFS landing pattern for running exhibit significantly shorter ground contact times. In addition, this study reveals a significant correlation between the contact time of FFS and multiple other leg movement ability parameters. Specifically, the contact time is positively correlated with the stride and duty factor and negatively with flight time, stride angle, vertical stiffness and leg stiffness. The FFS method helps to reduce the foot's contact time on the ground more effectively, thereby significantly improving overall running efficiency [6], [9].

For male participants, FFS demonstrated a significantly longer flight time compared to RFS, indicating that runners utilizing the FFS pattern spent more time airborne during their stride..In female participants, FFS was characterized by a significantly shorter contact time and a significantly longer flight time compared to RFS. This suggests that female runners employing the FFS pattern experience quicker foot-ground contact and spend more time airborne during their stride. However, extended flight time improves a runner's efficiency and enables him to better prepare for the next landing, leading to a smoother stride and higher speeds [21], [30]. This study highlights that the performance of FFS is significantly higher than RFS, considering flight time. Additionally, there is a significant negative correlation between FFS contact time and flight time, suggesting that FFS runners have shorter contact times and longer flight times. At the same time, there is a significant negative correlation between flight time and duty factor. Moreover, a significant positive correlation exists between flight time and stride angle, suggesting that a longer flight time may increase stride angle, thus improving athletic performance.

According to previous research, the duty factor is an important technical parameter that affects running performance [15]. This work demonstrates that the duty factor of FFS is significantly smaller than that of RFS, and therefore, the contact time of FFS runners in each step is relatively short. However, there is a significant positive correlation between the contact time of FFS and the duty factor. Additionally, there is a significant negative correlation between the FFS flight time and the duty factor and between the duty factor and the stride angle. A lower duty factor reduces energy loss during exercise and improves running performance [22]. Past research has shown that FFS runners (n = 15) have significantly larger stride angles at the same speed as RFS runners (n = 15) [34], which is confirmed by this study, along with the significant impact of the FFS method on stride angle. Existing research found that increasing stride angle during running is a concrete manifestation of the flick or buttkick effect for athletes to improve energy transfer efficiency under the minimum contact time [33]. For male participants, Additionally, FFS exhibited a significantly larger stride angle, suggesting a wider step width compared to RFS. On the other hand, the landing index, representing the percentage of the foot's contact area at initial contact with the ground, was significantly smaller for FFS, indicating a more forefoot-oriented foot strike. For female participants, Furthermore, FFS exhibited a significantly smaller duty factor, indicating a shorter duration of foot contact relative to the total stride duration. Additionally, FFS demonstrated a significantly greater stride angle compared to RFS, suggesting a wider step width during running.

A greater leg stiffness is an important factor in improving running performance [26]. Generally, measuring vertical stiffness and leg stiffness directly during running is a simple way to explore leg stiffness [2], [28]. Past studies found that in the kinematics of each movement during the running period, the ankle joint angle FFS during the ground contact period, support period, lift-off period and leg retraction period is significantly larger than RFS [6]. However, this study shows that the leg stiffness value of FFS is significantly higher than that of RFS, which indicates that runners adopting the FFS landing style have stronger leg stiffness. Furthermore, this study reveals a significant negative correlation between the stride of FFS and leg stiffness and between the contact time of FFS and leg stiffness. On the other hand, there is a significant positive correlation between the vertical stiffness and the leg stiffness of the FFS and between the leg stiffness and the peak vertical ground-reaction force of the FFS. Runners who use the FFS method have higher leg stiffness, allowing them to have better running stability and efficiency [2], [6], [40]. The negative correlation between stride and leg stiffness may indicate that runners with the FFS style focus more on maintaining the stride between each step to improve running efficiency [16], [17]. Besides, there is a positive correlation between the stiffness of the legs and the peak vertical ground-reaction force. A higher stiffness of the legs helps to better cope with the ground reaction force, thus improving the overall running performance [11], [25], [36]. There was a trend towards higher leg stiffness in female participants using the forefoot strike FFS compared to the rearfoot strike RFS, indicating potential differences in shock absorption and energy return between the two foot strike modes. Additionally, this study revealed that RFS had a significant effect on improving leg stiffness in female runners with stiffer legs, while also significantly increasing peak vertical ground reaction force PVF, thereby imposing a greater load on the legs. This phenomenon was not observed among male participants.

The findings of this study contribute to a deeper understanding that FFS runners exhibit shorter contact times and longer flight times, potentially enhancing running efficiency. Additionally, FFS is associated with a smaller duty factor and larger stride angle compared to RFS. Moreover, FFS runners demonstrate higher leg stiffness, which may contribute to improvement of running stability and efficiency. While female participants using FFS trend towards higher leg stiffness compared to RFS, RFS significantly improves leg stiffness in female runners with stiffer legs, potentially impacting peak vertical ground reaction force. These findings underscore the importance of comprehending the biomechanical variances between running landing techniques and their implications for running performance.

5. Conclusions

This study emphasizes the significance of running landing patterns on leg movement performance, particularly the favourable influence of these patterns on enhancing overall running performance. Runners adopting the FFS method exhibit several advantageous characteristics compared to those using the RFS method, such as shorter contact time, longer flight time, reduced duty cycle, increased stride angle and heightened leg stiffness. While RFS significantly improves leg stiffness in female runners with low leg stiffness, it also notably increases PVF and imposes a greater load on the legs, a phenomenon not observed among men.

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