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Article

Running speed and slope effects on spatiotemporal parameters and running technology in male and female recreational runners

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Abstract: This study investigates the effects of speed and incline on spatiotemporal parameters (SPT) and performance-related parameters (PRT) in male and female recreational runners from the perspective of biomechanics. It aims to uncover the underlying biomechanical mechanisms governing human running motion under different conditions. 37 healthy adults (18 males and 19 females) who regularly performed running exercises were recruited as research participants. The speed test included five speeds (8, 9, 10, 11, 12 km/h), each for 1 min with 1-min rest intervals (9 min total). The incline test was at 10 km/h with inclines of 3%, 6%, 9%, and 12%, each for 1 min with 1-min rest intervals (7 min total). Video was captured at 240 fps, with sampling times of 45 s to 1 min. A mixed-design two-way ANOVA assessed the effects of speed on spatiotemporal and technique variables with gender interactions. From a biomechanical standpoint, changes in speed can significantly impact the runners' stride length and stride frequency. Faster speeds typically require greater muscular force generation and coordination, which in turn can affect the spatiotemporal characteristics of running. The results showed that there were significant differences between genders and speeds in PRT, but no significant differences in SPT. This could be attributed to the varying physiological and biomechanical characteristics between males and females. Males generally possess greater muscle mass and strength, which may allow them to generate more power at higher speeds, resulting in different performance-related parameter values. There were no significant differences between genders and slopes in SPT and PRT. These findings corroborate previous studies and provide a deeper understanding of SPT and PRT characteristics in male and female runners. Future research should explore differences across various populations and include downhill running to understand gender differences in running performance fully. Downhill running involves different biomechanical challenges, such as increased knee flexion and eccentric muscle contractions, which may lead to distinct performance differences between genders. By expanding the scope of research in this way, we can gain a more comprehensive understanding of the biomechanics of human running.

Keywords: duty factor; stride angle; biomechanics; vertical stiffness; leg stiffness; peak vertical ground-reaction force

1. Introduction

With the advancement of technology, the relationship between the spatiotemporal parameters (SPT) and performers running technology of running is an important indicator that can be used to evaluate running technology and performance [1,2]. SPT includes the stride frequency (SF), stride length (SL), contact time (CT), and flight time (FT), which can reflect the kinematic characteristics of the runner's movement technique. Performance-related parameters (PRT) include the duty factor (DF), stride angle (SA), vertical stiffness (Kvert), leg stiffness (Kleg), and peak vertical ground-reaction force (PVF). These features can describe a runner's technical level and dynamics in greater depth [1,2]. Understanding the intricate relationship between SPT and PRT is essential for coaches and athletes alike, as it allows for a more tailored approach to training regimens. By analyzing these parameters, one can identify specific areas of strength and weakness in a runner's technique, enabling targeted interventions that can enhance overall performance. For instance, a runner with a longer stride length may need to work on increasing their stride frequency to optimize their speed, while another may benefit from drills that focus on reducing contact time to improve efficiency.

Male runners tend to outperform females at both elite and recreational levels, especially in marathons [3]. Studies have shown that mechanical work has a major impact on energy consumption during running. Factors such as kinematics, kinetics, and muscle activity have significant impacts on running performance [4]. This disparity in performance can be attributed to various physiological and biomechanical factors, including muscle mass, aerobic capacity, and even psychological aspects such as motivation and competitive drive. Moreover, the training methods employed by male and female runners may differ, further influencing performance outcomes. Understanding these differences is crucial for developing effective training programs tailored to individual needs. In addition, researchers examining the relationship between the running speeds of men and women, SPT, and PRT have pointed out that stride frequency is not an important factor affecting running performance; however, a longer stride length and a shorter contact time were significantly related to performance, as were a lower duty factor, smaller sagittal foot angles and calf angles, as well as smaller knee joint angles at ground instants [1,5–8]. These findings suggest that biomechanical efficiency, rather than just raw speed, plays a critical role in determining performance outcomes. Coaches should emphasize the importance of proper technique and biomechanics in training, as this can lead to improved performance and reduced injury risk. In a study of 22 male runners, García found that when professional runners increased their running speed, they had a longer FT, a larger SA and SL, and a lower SF [5]. As running speed increases, the SF and SL increase while the CT decreases. Recreational runners have a longer FT and a higher SF than professionals [9]. This distinction between professional and recreational runners highlights the variability in training adaptations and biomechanical efficiency. Recreational runners might not have the same level of conditioning or technical refinement, which can affect their performance metrics. Understanding these differences can help in designing appropriate training programs that cater to the specific needs of recreational runners. On the other hand, Roche found that as speed increases, the CT decreases while the SL and FT increase, even under nonfatigue conditions [10]. In addition, studies have revealed that as running speed increases, the DF gradually decreases and is negatively correlated with Kvert, Kleg, and PVF [11]. Related studies have demonstrated that changes in SF will affect the CT and FT [12]. In addition, in 100-m sprinters, an increase in the number of sprints will lead to decreases in parameters such as Kvert and maximum speed. Sprints of different distances affect Kvert, which decreases as the sprint distance increases [13,14]. Previous studies have indicated that Kvert and Kleg increase as the running speed and SF increase [15]. During the period from treadmill running to voluntary exhaustion, both Kvert and Kleg showed downward trends, but Kleg remained basically unchanged during the process [16].

In addition, the running incline has a significant impact on both SPT and PRT. Minetti pointed out that uphill running requires more energy than horizontal running, and it mainly involves concentric muscle contraction [17]. Long-term uphill exercise produces higher metabolic pressure. Comparisons of the effects of different slopes on running performance revealed that steeper slopes were associated with higher SF [18]. Townshend found that runners were significantly slower on uphill sections (23% slower) and 13.8% slower on downhill sections, compared to running on level sections [19]. García studied the running performance of amateur and professional runners on different slopes. The results showed that at fixed speeds, increasing the slope would mean increased CT and SF, as well as reduced FT, SL, and SA [20]. Lussiana found that as the slope increases, the SF of runners also increases significantly, regardless of the shoe type [18]. Studies by Telhan and Padulo support this conclusion, arguing that uphill running will mean increased SF and decreased SL [9]. Moore pointed out that having a larger Kleg is an important factor in improving running economy [21]. Meanwhile, Lussiana revealed that the Kvert of runners increased as the slope increased, while Kleg did not change significantly [18]. On the other hand, García's research indicated that regardless of a runner's level, compared with horizontal running, Kleg increased on severe slopes but decreased on moderate slopes [20].

This study aimed to analyze the differences between leisure runners of different genders in terms of the spatiotemporal variables of running—SPT (SF, SL, CT, FT) and PRT (DF, SA, Kvert, Kleg, PVF)—at different running speeds and at fixed speeds on treadmills. The results could assist in developing more effective running training strategies and improving runners' performance and technical levels.

2. Materials and methods

2.1. Participants

For this study, 37 healthy adults (18 males and 19 females) who regularly performed running exercises were recruited as research participants. Their average age was 27.6 ± 9.2 years old; their average height was 168.2 ± 7.8 cm; their average leg length was 93.9 ± 6.9 cm; and their average weight was 62.6 ± 10.0 kg. Male participants were required to complete a 5-km run within 25 min, while females were required to complete the same run within 30 min. Each participant needed to complete a participant consent form and a health questionnaire to confirm that they had no serious illnesses or major muscle injuries. Before the experiment began, the researchers uniformly explained the experimental procedures and purposes to ensure that the participants clearly understood the content of the experiment. The procedures performed in this study conformed to the standards and specifications of the 1964 Declaration of Helsinki.

2.2. Experimental process

After the consent form and health status questionnaire had been completed, each participant had their weight and leg length (measured from the hip bone (Greater Trochanter) to the ground) measured. Leg length was measured as the distance from the hip bone to the ground. Then, a warm-up was conducted, involving 10 min of exercise at a speed of the participant's choice [22]. Shooting was performed using a slow-motion high-speed camera (XR-A2107, Shenzhen, China) with a shooting frequency of 240 Hz. Then, the participants performed five tests on the treadmill, including running at 8, 9, 10, 11, and 12 km/h, and they performed incremental running tests. Each running test lasted for 1 min, and each speed test was separated by a period of standing followed by a 5-min quiet rest (rest for 1 min, totaling 9 min) [22]. Finally, the participants performed four different slope tests—including slopes at 3%, 6%, 9%, and 12%—at a fixed speed of 10 km/h. Each running test lasted for 1 min (rest in standing position for 1 min, total 7 min), and each slope test was conducted separately [22].

2.3. Data processing

Running spatiotemporal parameters: This study will study the changes in time and space variables such as stride frequency, stride length, contact time, and flight time during running [1].

Performers running technology variables: This study will analyze runners' advanced running technology variables, including duty factor, stride angle, vertical stiffness, leg stiffness, and peak vertical ground-reaction force [1].

This study analyzes the definitions and calculation methods of SPT and PFT, aiming to gain an in-depth understanding of key indicators during running. The following are the definitions and related formulas of each parameter: (1) SF: The average cadence is within 45 s to 1 min. The calculation formula is SF = 60/(CT + FT); (2) SL: The average stride length within 45 s to 1 min. The calculation formula is SL = treadmill speed/SF; (3) CT: The average ground contact time between 45 s and 1 min. The calculation formula is CT = 60/SF; (4) FT: Air time further calculated based on the average value within 45 seconds to 1 minute. The calculation formula is FT = 60/SF−CT; (5) DF: The ratio of CT to FT plus CT during running. The calculation formula is DF = CT/(CT + FT); (6) SA: The tangent angle when running and landing. The calculation formula is SA = Atn ((4 × height)/SL), where Atn = 180/π; height = $(9.8 \times FT^2)/8$; (7) Kvert: The elastic coefficient calculated from the maximum ground reaction force (Fmax) during running and the vertical displacement of the body's center of gravity (Δy). The calculation formula is Kvert = Fmax/Δy, where Fmax = (weight × gπ/2) × (FT/CT + 1); $\Delta y = -(\text{Fmax} \times CT^2)/(\text{weight} \times \pi^2) + (g \times CT^2)/8$; (8) Kleg: maximum ground reaction during running. The elastic coefficient calculated from the force (Fmax) and the vertical displacement of the leg length (ΔL), the calculation formula is Kleg = Fmax/ΔL, where $\Delta L = \text{leg length} - \sqrt{\text{leg length}^2 - ((\text{speed} \times \text{CT}^2)/2)) + \Delta y}$ [1,11,23–25].

2.4. Statistical analysis

SPSS 25.0 for Windows statistical software (IBM Corp., Chicago, Illinois, USA) was utilized for statistical processing. First, descriptive statistical analysis was conducted to enable an understanding of the participants' profiles. Next, a mixed-design two-factor analysis of variance was undertaken to determine any interaction between different treadmill speeds (8, 9, 10, 11, 12 km/h), SPT (SF, SL, CT, FT), and PRT (DF, SA, Kvert, Kleg, PVF) for males and females. Similarly, based on a fixed speed of 10 km/h, a mixed design two-factor analysis of variation was used to, firstly, study the effects of different slopes (3%, 6%, 9%, 12%) on SPT and PRT and, secondly, test whether there was any interaction between males and females. If the interaction reached a significant level, the LSD method was used to compare the between-group differences post hoc. The significance level was set at $\alpha = 0.05$.

3. Results and discussion

Through two-factor mixed design variation analysis, it was found that there was no significant difference in SPT between male and female runners at different speeds ($p > 0.05$) (**Table 1**).

Table 1. Differences in SPT between male and female runners of different speeds.

Speed (km/h)	Gender	SF (spm)	SL (m)	CT (sec)	FT (sec)
8	Male	160.207 ± 9.495	0.835 ± 0.052	0.323 ± 0.021	0.053 ± 0.007
	Female	157.808 ± 10.830	0.863 ± 0.017	0.330 ± 0.026	0.052 ± 0.005
9	Male	167.513 ± 8.699	0.898 ± 0.048	0.296 ± 0.019	0.063 ± 0.010
	Female	165.232 ± 10.511	0.911 ± 0.056	0.304 ± 0.019	0.061 ± 0.008
10	Male	170.323 ± 8.699	0.981 ± 0.052	0.277 ± 0.014	0.076 ± 0.013
	Female	169.095 ± 13.363	0.991 ± 0.073	0.285 ± 0.024	0.072 ± 0.010
11	Male	171.172 ± 8.824	1.074 ± 0.058	0.264 ± 0.015	0.087 ± 0.011
	Female	172.206 ± 11.834	1.079 ± 0.069	0.266 ± 0.024	0.084 ± 0.010
12	Male	173.757 ± 11.537	1.156 ± 0.078	0.250 ± 0.020	0.096 ± 0.012
	Female	174.240 ± 12.295	1.154 ± 0.084	0.254 ± 0.024	0.092 ± 0.011

Kvert and Kleg showed that the gender factor was significant ($p < 0.05$) in the main effects test (**Table 2**). Post hoc comparisons showed significant gender differences in Kvert and Kleg at 8, 9, 10, 11, and 12 km/h ($p < 0.05$). After two-factor mixed design variance analysis, the results showed that PVF reached an interaction effect ($p < 0.01$). In the main effect test, the gender factor was significant ($p < 0.05$), and post hoc comparisons showed that there were significant gender differences at 10, 11, and 12 km/h ($p < 0.05$).

Table 2. Differences in PRT between male and female runners of different speeds.

Speed (km/h)	Gender	DF (%)	SA (degree)	Kvert (kN/m)	Kleg (kN/m)	PVF (kN)
8	Male	0.859 ± 0.016	0.960 ± 0.246	19.229 ± 2.479*	9.180± 1.324*	1.180 ± 0.163
	Female	0.863 ± 0.017	0.911 ± 0.191	17.008 ± 2.806	7.630 ± 1.468	1.070 ± 0.181
9	Male	0.825 ± 0.026	1.254 ± 0.366	21.086 ± 2.475*	9.436 ± 1.357*	1.228 ± 0.174
	Female	0.833 ± 0.019	1.159 ± 0.291	18.695± 3.251	7.752 ± 1.473	1.109 ± 0.191
10	Male	0.784 ± 0.029	1.700 ± 0.490	22.138 ± 2.681*	9.506 ± 1.454*	1.295 ± 0.192*
	Female	0.799 ± 0.025	1.478 ± 0.374	19.828 ± 3.987	7.751 ± 1.622	1.156 ± 0.190
11	Male	0.751 ± 0.024	2.016 ± 0.420	22.804 ± 2.779	9.324 ± 1.515*	1.352 ± 0.204*
	Female	0.760 ± 0.032	1.869 ± 0.472	20.947 ± 3.601	7.856 ± 1.400	1.213 ± 0.184
12	Male	0.722 ± 0.030	2.280 ± 0.494	24.144 ± 3.406	9.400 ± 1.712*	1.406 ± 0.203*
	Female	0.732 ± 0.033	2.106 ± 0.480	21.890 ± 3.689	7.768 ± 1.429	1.259 ± 0.196

Note: * represents a significant difference between male and female $p < 0.05$.

Through two-factor mixed design variance analysis, it was found that there was no significant difference in SPT and PRT between male and female runners at different slopes ($p > 0.05$) (**Tables 3** and **4**).

Table 3. Differences in SPT between male and female runners at different slopes.

slopes (%)	Gender	SF (spm)	SL (m)	CT (sec)	FT (sec)
3	Male	167.204 ± 7.966	0.999 ± 0.049	0.289 ± 0.015	0.071 ± 0.012
	Female	168.666 ± 9.600	0.991 ± 0.055	0.291 ± 0.018	0.066 ± 0.008
6	Male	166.640 ± 7.624	1.002 ± 0.046	0.288 ± 0.014	0.072 ± 0.011
	Female	168.281 ± 5.821	0.992 ± 0.034	0.288 ±0.014	0.069 ± 0.005
9	Male	167.480 ± 7.265	0.997 ± 0.043	0.286 ± 0.013	0.073 ± 0.012
	Female	168.847 ± 6.064	0.988 ± 0.036	0.287 ± 0.013	0.069 ± 0.005
12	Male	166.641 ± 6.982	1.002 ± 0.043	0.288 ± 0.015	0.073 ± 0.010
	Female	168.738 ± 5.554	0.989 ± 0.033	0.286 ± 0.012	0.070 ± 0.005

Table 4. Differences in PRT between male and female runners at different slopes.

slopes (%)	Gender	DF (%)	SA (degree)	Kvert (kN/m)	Kleg (kN/m)	PVF (kN)
3	Male	0.803 ± 0.031	1.445 ± 0.464	21.143 ±2.225	8.708 ± 1.064	1.263 ± 0.173
	Female	0.815 ± 0.020	1.252 ± 0.277	19.504 ± 2.979	7.375 ± 1.281	1.134 ± 0.194
6	Male	0.816 ± 0.026	1.489 ± 0.429	21.022 ± 2.349	8.722 ± 1.115	1.267 ± 0.171
	Female	0.806 ± 0.017	1.357 ± 0.212	19.468 ± 2.817	7.492 ± 1.167	1.144 ± 0.188
9	Male	0.797 ± 0.029	1.528 ± 0.480	21.281 ± 2.439	8.876 ± 1.158	1.272 ± 0.173
	Female	0.806 ± 0.015	1.358 ± 0.193	19.583 ± 2.763	7.545 ± 1.164	1.145 ± 0.190
12	Male	0.797 ± 0.026	1.520 ± 0.392	21.052 ± 2.392	8.779 ± 1.140	1.271 ± 0.169
	Female	0.802 ± 0.015	1.411 ± 0.196	19.592 ± 2.805	7.622 ± 1.274	1.151 ± 0.197

4. Discussion

This study aimed to explore the differences between male and female runners in terms of SPT and PRT at different running speeds and on different slopes.

Experimental research indicated that as the speeds of both male and female runners increase, the stride frequency reduces, and both the stride length and flight time become longer; however, these differences were not statistically significant. However, male runners performed significantly better than females in regard to Kvert, Kleg, and PVF. On the other hand, there were no significant differences between the SPT and PRT of male and female runners on different slopes.

The numerous modern sensor technology measurement methods include the Global Positioning System (GPS), accelerometers, gyroscopes, footpods, and the inertial measurement unit (IMU) [26,27]. GPS technology is widely used to measure running speed. Many wearable devices—such as sports watches and smartphones—are equipped with GPS chips that can instantly track the location and speed of a runner [1,28]. These sensors can not only measure the runner's movement and posture changes but also calculate parameters like speed and cadence through algorithms, providing more comprehensive and detailed sports data on aspects including posture, movement, and speed [26]. In a pilot experiment, SPT and PRT were measured using COROS-Vertix2 and COROS-POD2 sensor devices. The results showed that at different speeds, there were no significant differences between the SF, SL, CT, and FT of male and female runners. However, the genders differed significantly in terms of Kvert and Kleg. Furthermore, the PVF showed significant interactions at different speeds. There were no significant differences between the male and female runners in terms of SPT and PRT on different slopes. These results were consistent with those from the photographic analysis [29].

In this study, the SPT of the male and female runners at different speeds revealed no significant differences in regard to gender. This is consistent with the results of some previous studies. For example, García-Pinillos observed no significant gender differences in SPT gait characteristics [30]. Roche-Seruendo conducted similar research on 97 endurance runners, discovering that gender had no significant impact on the SPT gait characteristics of endurance runners, which is consistent with the findings of the current study [31]. In addition, Takabayashi conducted a treadmill experiment involving males and females, observing the three-dimensional kinematics and SPT of the hindfoot, midfoot, and forefoot. The results showed that men and women did not differ significantly in terms of the standardized SPT, which is also consistent with the results of this study [32]. The SL and FT results identified by García-Pinillos were similar. No significant differences were found between males and females at 10 and 11 km/h. Despite the tests being conducted at different speeds, the results were identical for tests at the same speed [33]. However, the genders differed significantly in regard to CT. Although inconsistent with these new results, the CT of male runners was still higher than that of females. The results of the current study support the findings of previous related work, and they represent valuable information that could improve the running performance of males and females, as well as provide a reference for sports training and technical improvement.

In this study, males and females displayed no significant differences in terms of PRT between the DF and SA. However, few previous studies have compared the differences between the DF and SA in relation to gender. The results obtained by García-Pinillos et al. demonstrated that the SA of males and females did not differ significantly at a speed of 12 km/h, which was similar to the results of the current study [30]. Takabayashi et al. explored whether males and females differed in landing methods [32]. The study found that from walking to running, the genders did not differ significantly in SA; the same results were obtained in this study. However, Kleg, Kvert, and PVF differed significantly when comparing males to females. Relatively sparse research has been undertaken on the lower limb stiffness of males and females during running, but this form of stiffness appears to be related to factors such as jumping, running performance, and running economy [16,34,35]. Carrard conducted a treadmill running test with 12 male endurance athletes at four running speeds and at different gravity levels. Kleg, Kvert, and PVF were found to differ significantly in the running tests involving runners of different body weights [36]. The authors speculated that body weight was one factor affecting the difference in lower limb stiffness between males and females. In addition, Barnes and Lehnert used countermovement jumps and drop jumps to conduct Kleg tests on male and female long-distance runners and adolescents, finding that male Kleg was significantly greater than the female equivalent [37]. This study found that male recreational runners exhibited larger Kvert, Kleg, and PVF at different speeds. These findings provide a deeper understanding of lower limb stiffness during running in both men and women, as well as a valuable reference for training and technical improvement.

In this study, no significant differences in SPT and PRT were observed between male and female runners at different inclines. However, past research has revealed that as the slope increases, running speed decreases by 0.1–0.3 km/h for every 1% increase [19]. In addition, researchers have noted that increasing the SA and Kleg is crucial to improving running economy [21]. In excellent runners, a larger SA can improve their running economy [2]. Additionally, studies have shown that elite distance runners have a greater SA at the same speed compared to recreational runners, so increasing the SA while running may be a way to improve running efficiency. The current study participants were recreational runners. When male and female recreational runners were compared, no significant difference in SA was observed in relation to gender [24]. Gottschall conducted downhill, horizontal, and uphill running at a fixed speed, discovering that the SPT parameters did not change significantly as the slope changed; the same results were obtained in the current study [38]. Nardello conducted random speed-walking and running tests with 70 participants (35 males and 35 females). Each test lasted 60 s, and the walking and running tests involved various slopes (−25% to 25%) [39]. The results showed significant differences in SF and DF as the speed increased, but no significant differences in these factors as the slope decreased or increased. Gender differences between males and females were not compared in this study, but similar outcomes were recorded: as the slope increased, no significant difference was identified in the degree of change between males and females. However, few past studies have explored the relationship between lower limb stiffness and the slope in regard to gender differences. According to research by Cronin, Kvert increases with weight gain, and the author speculated that the higher Kvert in males compared to females was related to weight [40]. In addition, García-Pinillos et al. showed that the Kvert of professional runners was significantly lower than that of recreational runners, but no significant difference was found in Kleg [22]. In this study, no significant difference was observed between male and female runners in terms of changes in lower limb stiffness, possibly because those recruited were all recreational runners. However, the participants in this study were healthy adults who participated in treadmill exercises, so these results may not be applicable to other groups. In addition, this study only explored horizontal and uphill running conditions, so more extensive research could be undertaken on factors related to downhill running.

5. Conclusion

Male recreational runners had a smaller SF, longer SL, and longer FT time at different speeds, but the differences were not significant. However, when male recreational runners walked at different speeds, their Kvert and Kleg were significantly larger than those of females, forming a significantly larger PVF. When the incline was raised while running, there were no differences between males and females in terms of SPT or PRT. These findings corroborate those of past related studies and provide a deeper understanding of the SPT and PRT characteristics of males and females while running. In future research, differences between various ethnic groups could be explored, and more relevant factors could be considered, including downhill running, in order to fully understand gender differences in running performance.

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