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Original Article

Assessing changes in running kinematics at different intensities: a case study

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Abstract:
This study aimed to evaluate individual variations in running kinematics at various running intensities by considering the potential differences in runners' abilities. It is essential to recognize that running kinematic dynamics may not remain identical at different intensities, even among runners with similar performance abilities. To avoid assumptions based solely on group data, this study focused on individual variations as a key objective. The research involved three male runners who demonstrated similar 3000 m running times, ranging from 9:02 to 9:08 min. These participants underwent a series of running tests on a leveled treadmill, during which comprehensive measurements of running kinematics, heart rate, and blood lactate values were recorded. The running velocity was in the range of 12–20 km/h, and nine individual tests were conducted with a randomized order of velocities. Analysis of the heart rate data revealed variations in exercise response both within and between individuals. However, among these three runners, general physiological responses, including the heart rate and lactate concentration, were similar. This study shows that running velocity significantly affects various kinematic characteristics of running such as the step length, step frequency, contact time, and flight time. The findings indicate that with an increase in the running velocity, there is a corresponding increase in the step length and stride frequency, a decrease in the contact time, and an increase in the flight time. Furthermore, a strong positive correlation between the step length and running velocity is observed; there is also a general trend of stride frequency increasing with higher running velocity, although this result is not always statistically significant. In conclusion, this study highlights the importance of considering individual variations in running kinematics when assessing the effects of different running intensities.
Key Words: **running, step length, step frequency, contact time, asymmetry.**

Introduction

Running is a popular and accessible form of exercise that has been studied extensively in sports science. One area of focus in this field is the analysis of running biomechanics, including step frequency (SF) and step length (SL), which are two key metrics used to quantify running gait. These parameters are known to influence running velocity and can be used to analyze differences in running performance between individuals, as well as changes in running velocity over time. Understanding the interplay between SF and SL, and how they change with running velocity, is important for athletes, coaches, and researchers who seek to optimize performance and minimize the risk of injury (Van Oeveren et al., 2021).

SL is the distance between the touchdown point of one foot and the touchdown point of the other foot on the running surface (Williams, 2000). It is often used in research to investigate nuances in the action of each leg, including performance variability and fatigue (Garcia-Pinillos et al., 2020), asymmetry (Girard et al., 2019; Karamanidis et al., 2002), and other characteristics. An individual can increase their running velocity by increasing their SL and/or step SF (Brughelli et al., 2011; Weyand et al., 2000). However, the ratios of SL and SF are not only dependent on running velocity (Nilsson et al., 1985). They also vary depending on other factors such as the slope and roughness of the running surface (Gidley, 2022), the type of running shoes used (Shamsoddini & Hollisaz, 2022), anthropometric characteristics of the runner (Blazevic et al., 2015), as well as acute or chronic injuries and history of injuries (Johnson & Davis, 2021).

Athletes can increase their running velocity by increasing one of these parameters while keeping the other constant or increasing it as well (Hogberg, 1951; Hay, 1978; Hunter et al., 2004; Moore, 2016). Both long-distance running studies (Cavanagh & Kram, 1990) and sprint running research (Bezodis, 2012; Hunter et al., 2004) have experimentally demonstrated this phenomenon. It is possible for running velocity to increase while both SL and SF increase simultaneously, although it can be difficult to determine whether the changes in both parameters occur simultaneously. Conversely, it is also possible to maintain or increase running speed when one of the parameters decreases, provided the other parameter increases sufficiently to compensate for the potential loss of velocity (Hirano et al., 2014; Cavagna et al., 1988; Kaneko, 1990; Salo et al., 2011).

As running velocity increases towards maximal performance, SF has a greater impact on maintaining or increasing velocity compared to SL (Toyoshima & Sakurai, 2016). At lower running velocities, the time required to take a step is greater (Dorn et al., 2012). When running at approximately 7 m/s, the contact time becomes very

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short, limiting the ability of muscles to generate supporting reaction forces (force impulse) required to maintain a higher running velocity. When velocity exceeds 7 m/s, the strategy for increasing velocity switches from increasing SL to increasing SF, resulting in faster translation of the legs (Weyand et al., 2000).

Other researchers have also noted a similar dynamic pattern between ground contact time, SL and SF, and running velocity in studies of treadmill running (Högberg, 1952; Sinning & Forsyth, 1970; Simoni et al., 2020) and sport-specific conditions (Luhtanen & Komi, 1978; Larsson & Baum, 1980; Dorn et al., 2012). Contact time, which is the time when the foot is in contact with the running surface, decreases as running velocity increases (Dron, 2012). As running velocity changes, the duration of the different phases of the running cycle also changes (Karamanidis et al., 2016). Contact time serves as a frequently utilized biomechanical characteristic in the analysis of running technique, particularly in the development of various wearable devices (Muniz-Pardos et al., 2018; Oks et al., 2017). Contact time might change in different running conditions, also such as barefoot running (Abolins et al., 2018).

The duration of the contact time could have different effects on running economy. Studies have found that contact time duration has no relationship with economy (Heise & Martin, 2001; Kyrolainen et al., 2001; Støren et al., 2011), increasing contact phase time has a positive effect on economy (Di Michele & Merni, 2014), and conversely, decreasing contact time duration increases running economy (Nummela et al., 2007; Santos-Concejero, 2014). It is hypothesized that a shorter contact time duration increases metabolic energy expenditure because faster force production is required during the contact time, which is associated with less economical recruitment of fast-twitch muscle fibers (Kram & Taylor, 1990; Roberts et al., 1998). A longer contact phase increases metabolic energy expenditure due to force production over a longer period (Nummela et al., 2007).

The purpose of this study was to investigate the changes in SL, SF, contact time, and flight time in three subjects while running at different velocities. Understanding how these parameters change with increasing velocity is important for improving running performance (Quinn et al., 2021) and economy (Bernans et al., 2023). Additionally, determining individual variability in these parameters may aid in developing personalized training programs for runners (De Ruiter et al., 2020).

Material & methods

The study recruited three long-distance runners who were at a similar level of athletic ability and in the same off-season training phase. Table 1 provides a summary of their age, height, weight, and 3000 m running times.

Table 1. Overall characteristics of runners

Runner	**R1**	**R2**	**R3**
Age (years)	**29**	**20**	**26**
Height (cm)	**191**	**187**	**171**
Weight (kg)	**74**	**66**	**61**
3000m running time	**9:02**	**9:02**	**9:08**

Procedure

In this study, the runners underwent 9 separate 1-minute running trials on a motorized treadmill, with the trials taking place at 4 different test times. The intensity levels were chosen at random, with slower and faster runs performed in a predetermined order. Prior to each test, the runners performed a 10-15 minute low intensity warm-up to prepare their bodies for the upcoming exercise.

During each test, the treadmill was set to 0% incline, and the intensity level was set to a range of 12-20 km/h. A 45-second pre-run was conducted before each 1-minute running trial, during which the treadmill's speed gradually increased from 0 km/h to the required velocity for the pre-run. The runners then ran at a constant velocity for 20-30 seconds at the designated intensity level before the measurement procedure began. A minimum of 10 minutes of passive or active rest (such as standing or walking) was taken between each running trial.

Measuring

Heart rate was continuously monitored during the running trials using a Polar Vantage V heart rate monitor and chest strap. Electrode gel was applied to the heart rate belt electrodes to ensure optimal signal transmission. Heart rate data was recorded every second, with every fourth second selected for analysis.

Capillary blood lactate concentration was measured immediately (within 5-10 seconds) after each running trial using the Lactate Plus portable lactate analyzer from Nova Biomedical. All lactate analyses were conducted by the same trained personnel.

SL and SF were measured using the OptoJump Next optical system from Microgate, Italy. The system consisted of two bars, each with 32 LEDs spaced 3.12 cm apart along the bottom of the bar. The bars were placed at the height of the treadmill and measured flight and ground contact times at a sampling rate of 1 Khz.

Ground contact time was defined as the time from foot contact with the ground to the time the foot leaves the ground, as detected by a break in the infrared gates of the system. Swing time was defined as the time from toe-off to when the foot first contacts the ground. SL and SF were calculated based on the distance traveled by the treadmill between toe-off and the next ground contact and the number of ground contacts per minute, respectively. SL and SF were monitored continuously throughout the running trials, and 64 successful steps of each leg at all intensity levels were analyzed.

Data analysis

The data analysis involved the use of descriptive statistics, as well as tests for normal distribution such as the graphical method and Shapiro-Wilk test. To compare the samples, either a T-test or Wilcoxon test was used. Additionally, correlation between variables was assessed using either the Pearson or Spearman test. The data was analyzed and processed using the R Studio software (R Studio Team, 2020).

Results

As the running velocity increased, both heart rate and blood lactate values showed a significant increase ($p<0.001$) in all runners. The correlation coefficients between heart rate and running velocity were greater than 0.96 and 0.79, respectively ($p<0.001$), except for a few instances. Specifically, in the first runner (R1), heart rate did not show a significant change at 17 km/h compared to 16 km/h, and the same was observed in the third runner (R3) at 15 km/h ($p > 0.05$). Table 2 presents the detailed data on lactate and heart rate for all runners at different velocities.

Table 2. Lactate concentration and heart rate values

Velocity (km/h)	**Runner**	**12.0**	**13.0**	**14.0**	**15.0**	**16.0**	**17.0**	**18.0**	**19.0**	**20.0**
Lactate (mmol/l)	**R1**	0.6	1.0	0.8	0.8	1.0	1.3	2.2	2.7	3.7
	R2	0.7	0.9	0.8	1.7	1.5	1.7	2.2	3.3	3.8
	R3	0.8	1.1	1.5	1.5	1.5	1.7	2.0	2.6	3.8
Heart rate (b./min)	**R1**	105	118	125	134	137	133	136	142	146
	R2	127	132	137	146	153	154	159	166	168
	R3	132	141	149	144	151	156	159	170	169
SD Heart rate (b./min)	**R1**	2.22	2.86	2.15	4.27	6.04	6.97	6.59	4.98	7.20
	R2	3.76	3.60	4.99	5.20	5.00	5.83	4.67	5.89	7.43
	R3	1.50	2.75	2.28	1.17	1.52	2.44	2.38	8.52	1.36

Heart rate is represented in mode values.

The analysis of heart rate data revealed that the response to exercise can differ both within and between individuals. However, in the case of these three runners, their general physiological responses in terms of heart rate and lactate concentration were similar. Thus, we can conclude that any self-comparison of biomechanical characteristics is not influenced by differences in physical fitness or individual response to the running task.

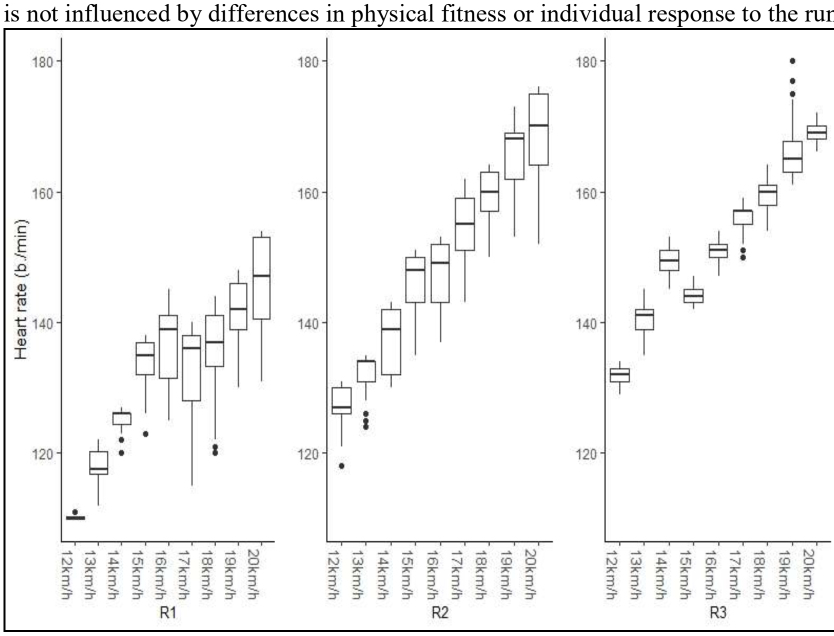

Fig. 1. Heart rate values for all runners

Running kinematics

In this study, the researchers analyzed four kinematic characteristics of running, namely SL, SF, duration of contact time, and duration of flight time, for both the right and left legs. The changes in these parameters were compared between consecutive changes in velocity as well as between the two legs.

The findings revealed a strong positive correlation between SL and running velocity in all three runners, with correlation coefficients greater than 0.99 ($p<0.001$). SF also showed a significant increase with velocity, with correlation coefficients higher than 0.92 ($p<0.001$). On the other hand, the duration of the contact time was found to be negatively correlated with running velocity, with correlation coefficients greater than -0.97 ($p<0.001$). Finally, the flight time was found to increase with intensity, with correlation coefficients greater than 0.87 ($p<0.001$).

Step length

As the running speed increased, all three runners showed a statistically significant increase in SL ($p<0.001$). However, when comparing the data between the right and left legs, statistically significant differences were found for R1 in all cases ($p<0.001$). R2 showed a similar difference at running speeds of 14, 18, 19, and 20 km/h ($p<0.05$), and R3 showed differences at speeds of 12, 15, 17, 19, and 20 km/h ($p<0.05$). At other running speeds, SL was considered similar for both legs ($p>0.05$). Figure 2 and Table 3 provide a visual representation and summary of all the data.

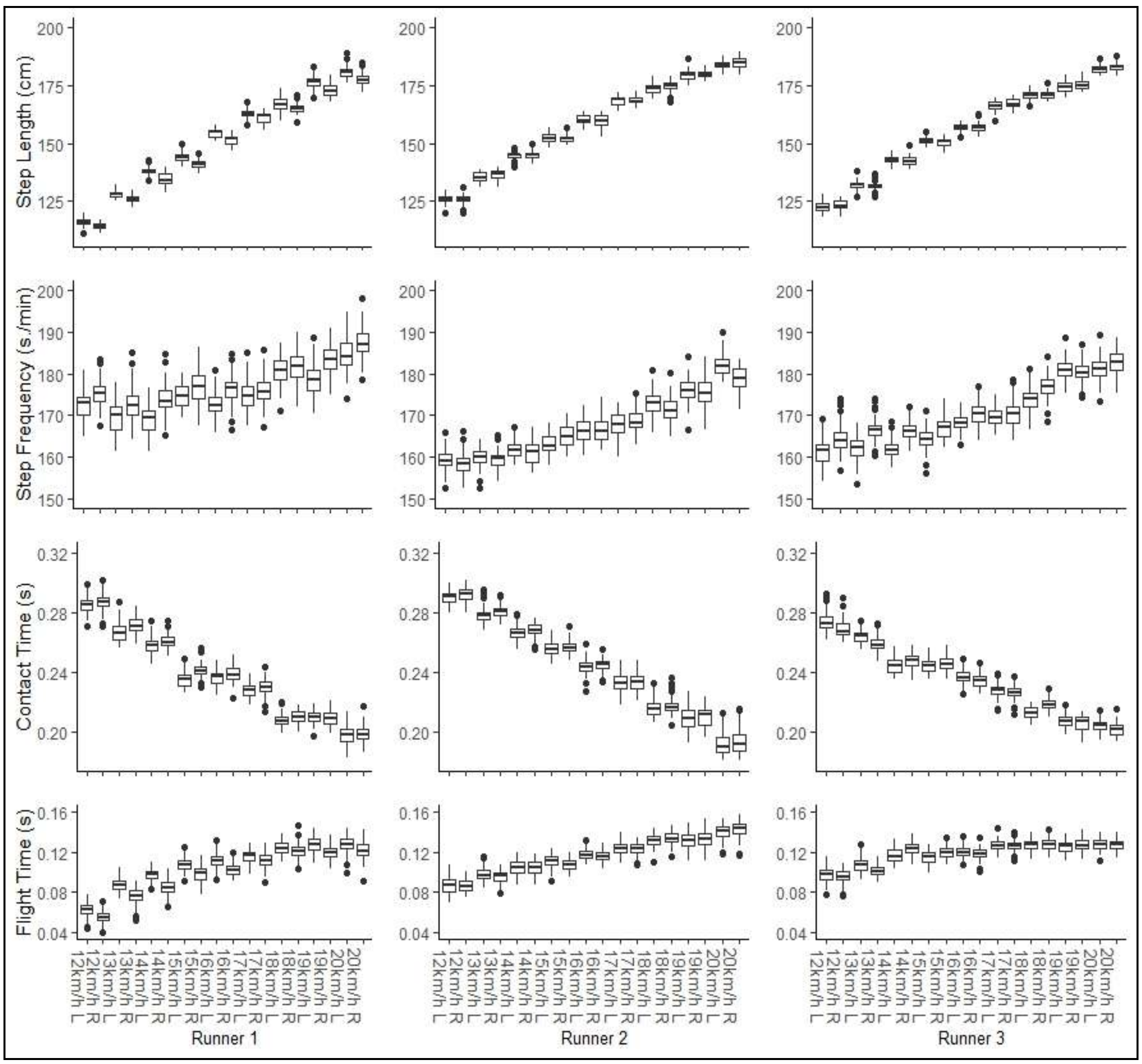

Figure 2. Step length, step frequency, contact time and flight time. (R/L stands for right and left leg)

The data showed that the coefficients of variation for SL were consistently low, ranging from 1-2% across all runners and running velocities. This indicates that there was minimal variation in SL at a constant running velocity, and the variation values were similar for slower and faster running.

Table 3. Mean step length values

Running velocity (km/h)	12.0	13.0	14.0	15.0	16.0	17.0	18.0	19.0	20.0
MEAN L S1	116	128	138	144	154	163	167	177	181
MEAN R S2	114	126	135	141	151	161	165	173	178
MEAN L S2	126	136	144	152	160	169	174	179	184
MEAN R S2	126	136	145	152	160	169	175	180	185
MEAN L S3	122	132	143	151	157	166	171	175	182
MEAN R S3	123	132	142	150	157	167	172	176	183

R/L stands for right and left leg; step length values are given in centimeters.

Step frequency

Overall, there was a general trend of SF increasing with increasing running velocity, but the changes were not always significant for all runners and legs. Specifically, there were several instances where a 1 km/h increase in running velocity did not result in a significant change in SF. For R1, there were no significant changes in SF at 14 km/h (left leg), 16 km/h (right leg), and 17 km/h (right leg). Similarly, for R2, there was no significant change in SF at 13 km/h (left leg), and for R3, changes in SF were not significant at 13 km/h (left leg), 14 km/h (both legs), 17 km/h (right leg), and 20 km/h (left leg) ($p>0.05$). The specific changes in SF for each runner and leg are listed in Table 4 and illustrated in Figure 2.

Table 4. Mean step frequency values

Running velocity (km/h)	12.0	13.0	14.0	15.0	16.0	17.0	18.0	19.0	20.0
MEAN L S1	173	169	169	175	173	175	181	178	185
MEAN R S2	175	173	174	177	176	176	182	183	187
MEAN L S2	159	160	162	163	166	168	173	176	182
MEAN R S2	158	159	161	165	166	169	172	176	179
MEAN L S3	161	162	162	164	168	170	174	181	181
MEAN R S3	164	167	166	167	170	170	177	180	183

R/L stands for right and left leg; step frequency values are given in steps per minute.

There were significant differences in SF between the right and left leg for all runners at various running velocities ($p<0.05$). For R1, significant differences were found at all running velocities except 17 and 18 km/h ($p>0.05$). For R2, significant differences were found at running velocities of 12, 14, 15, 17, 18, and 20 km/h ($p<0.05$), while there was no significant difference in other cases ($p>0.05$). For R3, significant differences were only found at a running velocity of 17 km/h ($p<0.05$).

Contact time

Generally, as running velocity increases, the duration of contact time decreases significantly ($p<0.05$). However, there were some cases where a change of 1 km/h in velocity did not result in a statistically significant change in contact time ($p>0.05$).

For R1, no statistically significant changes were observed ($p>0.05$) when comparing 15 and 16 km/h and 18 and 19 km/h for the left and right leg, respectively. For R2, contact phase time decreased significantly in all cases ($p<0.001$). Only one case showed no statistically significant change in contact time for R3, when comparing 14 to 15 km/h for the left leg ($p>0.05$). The values are presented in Figure 2 and Table 5.

Table 5. Mean contact time values

Running velocity (km/h)	12.0	13.0	14.0	15.0	16.0	17.0	18.0	19.0	20.0
MEAN L S1	0.285	0.276	0.258	0.235	0.236	0.228	0.207	0.209	0.198
MEAN R S2	0.287	0.272	0.260	0.241	0.238	0.230	0.210	0.208	0.199
MEAN L S2	0.290	0.278	0.266	0.256	0.243	0.233	0.216	0.209	0.191
MEAN R S2	0.292	0.281	0.268	0.257	0.244	0.233	0.217	0.210	0.193
MEAN L S3	0.274	0.264	0.245	0.244	0.237	0.227	0.213	0.207	0.204
MEAN R S3	0.269	0.259	0.248	0.246	0.234	0.226	0.218	0.206	0.201

R/L represents right and left leg; contact time values are presented in seconds.

When comparing the contact phase duration of R1 between the right and left leg, they were found to be the same only when running at 19 and 20 km/h (p>0.05). For R2, more instances were observed where no statistically significant difference was found between the contact phase duration of the right and left legs when running at 15, 16, 17, 18, 19, and 20 km/h (p>0.05). In the case of R3, the contact phase time did not differ between the left and right legs in three instances, when running at 15, 17, and 19 km/h (p>0.05).

Flight time

The duration of the flight time tends to increase as the running velocity increases. For R1, this did not happen (p>0.05) only by increasing the running velocity from 19 to 20 km/h (left leg data). Also, for R2 it didn't increase in only one situation (p> 0.05), when comparing 18 km/h to 19 km/h (left and right leg). For R3, there was no statistically significant change in the duration of the flight time (p> 0.05) increasing running velocity to: 15 km/h (left leg data), 16 km/h (right leg data), 18 km/h (both legs data), 19 km/h (right foot data) and 20 km/h (right foot data). Values are presented in Figure 2 and Table 6.

Table 6. Mean flight time values

Running velocity (km/h)	12.0	13.0	14.0	15.0	16.0	17.0	18.0	19.0	20.0
MEAN L S1	0.063	0.087	0.097	0.108	0.112	0.116	0.125	0.127	0.127
MEAN R S1	0.055	0.076	0.085	0.096	0.104	0.112	0.121	0.119	0.122
MEAN L S2	0.087	0.098	0.105	0.112	0.117	0.124	0.131	0.131	0.140
MEAN R S2	0.087	0.096	0.104	0.107	0.116	0.123	0.133	0.132	0.143
MEAN L S3	0.098	0.107	0.117	0.115	0.120	0.126	0.127	0.125	0.127
MEAN R S3	0.096	0.101	0.123	0.120	0.118	0.126	0.127	0.128	0.127

R/L represents right and left leg; flight time values are presented in seconds.

If the duration of the flight time of the right and left legs is compared, then for R1 it differed statistically significantly at all running velocities (p <0.001). For R2, it differed significantly only at 15 km/h and 20 km/h (p<0.05). For R3, the duration of the flight time did not differ at: 12, 17, 18 and 20 km/h (p>0.05).

Discussion

Heart rate and blood lactate values were used as indicators of running intensity, and a significant positive correlation was found between running velocity and both heart rate and blood lactate values. Overall, the similarity in physiological responses among the runners implies that any self-comparison of biomechanical characteristics is not influenced by differences in physical fitness or individual response to the running task.

The results showed that as running velocity increased, step length and stride frequency increased, while contact time decreased and flight time increased. However, individual variations in response to exercise were observed. There were also significant differences between the right and left legs in terms of step length for all three runners.

Step length showed a strong positive correlation with running velocity, while stride frequency showed a general trend of increase with velocity, but not always significant. Contact time decreased and flight time increased with increasing running velocity. The low coefficient of variation in step length measurements indicates that the runners maintained a consistent stride length across different velocities, indicating good running technique and efficiency.

The study also highlighted the problem of asymmetry in running gait, with significant differences found between the right and left legs in terms of step length for all three runners. This may have implications for injury prevention and rehabilitation. Finally, the study used a leveled treadmill, which may not be the most accurate to reflect the physiological characteristics of running (Jones & Doust, 1996). However, the study's purpose was to measure the kinematics of running, and lactate concentration and heart rate data were used as the physiological characteristics of running load.

The study focused on three experienced male runners, which means the participants were likely to have similar physical abilities and training backgrounds. This allowed the researchers to compare the kinematic and physiological responses of the runners in a relatively controlled environment. Additionally, the study used multiple measurement techniques, including heart rate monitoring, blood lactate analysis, and motion capture technology, to provide a comprehensive analysis of the runners' biomechanical and physiological responses to running. However, case study design limits the generalizability of the findings. The study included three runners, and it is unclear whether the results would be similar for runners of different ages, genders, or fitness levels. Additionally, the study was conducted in a laboratory setting, which may not accurately reflect the conditions of outdoor running. Finally, the study only examined the short-term effects of running on biomechanical and physiological parameters, and it is unclear whether these effects would persist over longer periods of time or with different training protocols.

Due to the small sample size and the specific characteristics of the runners selected for the study (e.g., male, similar age, and fitness level), the results may not be generalizable to other populations, such as female runners, older individuals, or individuals with different levels of fitness. However, the study does provide valuable insights into the biomechanical and physiological responses of these runners to different running velocities, which may be useful in designing further studies with larger sample sizes.

Long-term follow-up studies could help to evaluate changes in running performance over time and assess the impact of different training regimes on performance. However, it is also possible that the general trends observed in this study would remain consistent over time. Overall, while this study provides valuable insights into the kinematic and physiological aspects of running, it is important to consider the potential limitations and further research is needed to fully understand the complex nature of running performance.

Conclusions

While there are individual variations in kinematic variables among runners, there is a general consistent trend in their changes with speed. It should be noted that in certain instances, the observed changes in kinematic variables are too small to exhibit statistically significant increasing or decreasing trends ($p>0.05$) with a 1 km/h increase in speed. Moreover, when running at a constant intensity, there is noticeable variation in kinematic parameters. Notably, statistically significant differences ($p<0.05$) between the data of the right and left legs are observed, indicating the presence of an asymmetry issue and highlighting the necessity for further investigation.

By acknowledging the individual variations in kinematic variables among runners, the paper recognizes the complexity of the subject matter. This information is useful for researchers, coaches, and practitioners as it emphasizes the need to consider individual differences when analyzing and interpreting kinematic data. It highlights that generic conclusions cannot be drawn without accounting for individual variation.

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