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Biomechanical differences between overground and treadmill running in professional runners – a pilot study

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Abstract
Purpose: The aim of this study was to compare the biomechanical parameters of runners during overground and treadmill running, to assess the significance of these differences for treadmill training, and to evaluate their relevance for physiotherapy.
Methods: Ten professional runners (mean age of 31.2 ± 6.8 years) were evaluated using a 10-camera Vicon motion capture system and a Phantom V12 high-speed camera. After completing a 200-meter overground run at a self-selected pace, each athlete entered the calibrated capture volume, where their running velocity and kinetic data were recorded. The individual mean velocities were then replicated on a treadmill positioned within the same capture space.
Results: Treadmill running altered lower limb biomechanics compared to over-ground running. Median step length was 3% longer and markedly less variable on the treadmill than over-ground ($p < 0.001$). The knee-flexion angle differed by surface and side ($p < 0.0001$), changes were (1° for left, -2° right) but variability narrowed on the treadmill, while the knee-impact angle remained unchanged. Relative to over-ground running treadmill running reduced the horizontal distance between the center of gravity and foot initial contact; ground-contact time (12%) and heel velocity after toe-off by 19 % ($p < 0.0001$).
Conclusions:
Treadmill running alters lower limb biomechanics by reducing ground contact time, heel velocity, and variability in movement patterns. The consistent mechanics observed on the treadmill may support its use in physiotherapy, particularly for hamstring rehabilitation. However, due to limited replication of natural conditions, treadmill training should complement rather than replace overground running.

Keywords: sports performance, elite athletes, 3D analysis

1. Introduction

Running is one of the most innate and universally practiced forms of physical activity, characterised by a cyclical pattern of movement comprising two main phases: stance and flight. The stance phase begins with initial ground contact, involving weight transfer to the supporting limb and subsequent propulsion. The flight phase is marked by both feet being simultaneously airborne - distinguishing running from walking. This coordinated sequence engages multiple muscle groups and demands high levels of neuromuscular control, balance, and stability. As a form of exercise, running is highly effective in enhancing cardiovascular health, physical fitness, and psychological well-being [12].

Given running's biomechanical complexity, the investigation of different modalities, such as treadmill and overground running, is essential due to the distinct mechanical and physiological demands each imposes. These differences affect movement biomechanics, joint loading, and adaptation patterns [12], and understanding them is crucial for improving performance, preventing injuries, and informing training and rehabilitation practices.

Treadmill running typically occurs in a controlled environment, with stable temperature, humidity, and no wind resistance. In contrast, outdoor running is subject to ever-changing environmental conditions, including terrain variability and wind, which can significantly alter running mechanics and impose greater adaptive demands on the musculoskeletal and neuromuscular systems [14, 29]. Research consistently shows biomechanical discrepancies between treadmill and outdoor running, especially in hip mobility, foot strike angle, and lower-limb kinematics. Treadmill running is often associated with a flatter foot position at contact and reduced variability in joint motion due to the uniform surface. In contrast, outdoor running requires constant adaptation to variable ground surfaces, leading to greater variability in muscle activation and joint angles [23, 33].

One major advantage of treadmills is their ability to precisely control pace and incline, offering a repetitive and consistent training environment. However, outdoor running presents natural variability, affecting both kinematic and kinetic parameters. Notably, stride length and foot strike mechanics have been shown to differ between these environments, with implications for energy expenditure and injury risk [2, 5, 18]. Furthermore, motorised treadmill running introduces additional biomechanical differences compared to overground running. These differences are partly due to the treadmill belt's motion, which assists in leg recovery by pulling the stance leg backward, reducing the muscular effort needed to advance the body [34].

Although it is theoretically possible to equate treadmill and outdoor running under certain biomechanical models - assuming constant belt speed and negligible air resistance - experimental data show that treadmill belts do not maintain perfectly stable speeds. The belt often decelerates during foot strike and accelerates during propulsion, subtly altering the natural running cycle [23]. Several other factors further influence treadmill biomechanics, including the runner's familiarity with the device [18], visual focus [19], treadmill belt dimensions [23], perceived exertion and motion [31], cushioning differences based on treadmill construction [13, 16], and variation across treadmill models [1].

Despite valuable insights, much of the existing research on running biomechanics has been conducted under highly controlled experimental conditions that may limit ecological validity. In many studies, runners were confined to short tracks [13, 16, 20], preventing them from reaching a steady pace and natural stride, thereby focusing the analysis on acceleration phases rather than stable locomotion [28, 33, 34]. Laboratory constraints - such as running distances of only 15 - 20 meters - often force unnatural technique adaptations [1, 4, 7, 10, 11, 17, 21], which can significantly affect biomechanical outcomes, including stride length, joint range of motion, and muscle activation patterns [23-26, 29, 30]. Furthermore, several studies did not report the actual distance run by participants, limiting the reliability and comparability of the findings [3, 22]. The literature review reveals several limitations in previous research on runners. Based on this review, the most significant methodological shortcomings were identified, leading to the development of a novel measurement approach that enables greater freedom of movement during running by removing spatial constraints inherent to laboratory environments. This change removes running restrictions and allows runners to achieve their natural running rhythm. As a result, when running into a measurement space that is unconstrained, their measured biomechanical parameters are natural Therefore, the present study aimed to evaluate the kinematic parameters of professional runners during both treadmill and overground running in order to determine the impact of treadmill running on running mechanics. Additionally, changes in the runners' biomechanical parameters were assessed with respect to the effects of treadmill training and its potential applications in physiotherapy.

2. Material and Methods

2.1. Participants

Ten runners, each with at least five years of running experience, participated in the study. The participants had a mean age of 31.2 ± 6.8 years, a mean height of 179.5 ± 5.67 cm, and a mean body weight of 70.4 ± 7.34 kg. The study involved nine male and one female participants. All participants trained a minimum of three times per week under the guidance of a personal trainer.

They had been injury-free for at least three years and were in good health throughout the study. Before participation, each runner was fully briefed on the study's objectives and procedures. The study was approved by the University Review Committee (no. SKE01-15/2023) and adhered to the ethical guidelines outlined in the Declaration of Helsinki.

2.2. Experimental protocol

A motion analysis system (Vicon Metrics Ltd., Oxford, UK) operating at 150 Hz, consisting of 10 Vantage V5 cameras, was used for the study. To facilitate unrestricted movement during running, the system was set up outdoors (Fig. 1A). The cameras were strategically placed on specialized tripods surrounding the pavement where the athletes performed their runs. Testing was conducted on windless days to minimize environmental interference. Any reflective surfaces on the athletes' sportswear, footwear, or surrounding objects were masked to prevent errors in data collection.

At the beginning of the study, participant’s anthropometric data were recorded. A full-body plug-in gait marker set, consisting of 36 reflective markers, was then applied to track movement. Nexus software v. 2.16 (Vicon Metrics Ltd., Oxford, UK) was used for model fitting, perturbation control, and data collection [8].

Before data collection, each athlete completed a warm-up session, after which the measurement markers were applied to their bodies. Static and dynamic calibrations were performed to minimize errors due to soft tissue artefacts (Fig. 1B, C).

Mechanical treadmill testing (Fig. 1D) was conducted on the same day as the outdoor testing to avoid the need for reattaching markers. Additionally, a high-speed Phantom V12 camera operating at 500 Hz and positioned perpendicular to the measurement area was used during the tests.

Fig. 1 A) Measurement space; B) Motorcyclist position - standard calibration; C) Dynamic calibration; D) Tests on a mechanical treadmill.

The first phase of the study involved determining the speed at which the athletes ran during free-running training. The athletes ran 200 meters along a straight concrete pavement (free of holes and irregularities) before entering the measurement area of the Vicon system, which recorded their speed and biomechanical parameters. They then continued for an additional 50 meters beyond the measurement area to minimize the influence of anticipatory stopping on the results. This extended measurement distance allowed the runners to stabilize their movement and maintain their natural running cadence before entering the measurement area. Each athlete completed the run six times to calculate their average speed. Individual analysis was performed for each runner. The distances and rest intervals between trials were carefully selected to minimize the risk of excessive fatigue. The participants themselves did not report any feelings of fatigue, which was attributed to the relatively short distance compared to their regular training routines.

The second phase involved recording biomechanical parameters using the Vicon system. Each athlete ran through the measurement area six times, following the protocol from the first phase.

The final stage of the test protocol took place on a mechanical treadmill, which was positioned within the measurement field of the Vicon system. The treadmill speed was individually calibrated for each runner based on the average speed determined in the first phase of testing. Each participant ran on the mechanical treadmill for 5 minutes, with movement being recorded at random intervals to prevent any awareness of the measurements, ensuring that natural behaviour was captured. Three 15-second measurements were taken for each runner, and six running cycles were determined from each measurement. All tests for each participant were conducted on a single day to prevent the need for removing and reattaching the markers.

2.3. Parameters and statistical analysis

First, a self-selected running speed analysis was conducted for each subject across the six trials. Medians and quartiles were calculated, and variability was evaluated using the interquartile range (IQR), defined as the difference between the first (Q1) and third quartiles (Q3). Subsequently, six biomechanical parameters were analysed during both treadmill and overground running. Five of these parameters were assessed separately for the right and left lower limbs: (1) the distance between the center of gravity and the foot at ground contact, reflecting stability and alignment during initial impact; (2) knee flexion angle during the stabilization phase, associated with shock absorption; (3) ground contact time; (4) heel strike velocity following heel-off; and (5) the impact angle, defined as the angle between the foot's long axis and the ground at initial contact. Step length was included as a general parameter, analysed without differentiating between limbs.

Statistical analyses were performed using Statistica v. 12 (StatSoft, Tulsa, USA), with the significance level set at $p < 0.05$. The Shapiro-Wilk test assessed normality for all parameters. As most variables did not follow a normal distribution, non-parametric tests were employed. The Wilcoxon test was used to compare step length between treadmill and overground running. For the remaining parameters, the Friedman ANOVA with Dunn-Bonferroni post-hoc correction was applied to compare right and left limb performance across both running conditions. To compute the effect size for a Wilcoxon test, the following formula was used: $r = \frac{Z}{\sqrt{N}}$, where Z is the Z-score from the test, and N is the total number of observations. In this case, N = 60. The effect size interpretation was as follows: $r < 0.3$ - small effect, $0.3 \leq r \leq 0.5$ - medium effect, and $r > 0.5$ - large effect [27]. The effect size for the Friedman test was calculated using the following formula: $W = \frac{12\aleph^2}{k^2(n)(k+1)}$, where: $\aleph^2$ is the Chi-square value from the Friedman test, n is the number of subjects, and k is the number of conditions. The interpretation follows the same guidelines as for the Wilcoxon test.

3. Results

3.1. Self-selected running speed

The median and quartile analysis of the runners' speeds provides a deeper understanding of their performance consistency and central tendency (Table 1). Among all participants, runner R3 demonstrated the highest median speed at 19.4 km/h, confirming their position as the fastest and most consistent high performer. On the other hand, R6 had the lowest median speed at 12.3 km/h, indicating either a lower endurance level or a more conservative pace during trials.

Runner R8 also showed a high median speed of 17.4 km/h, placing them among the top performers. Runners such as R5, R6, and R7 had lower median speeds, ranging from 12.3 km/h to 13.25 km/h, highlighting a slower performance group.

In terms of variability, the interquartile range (IQR) – the difference between the first quartile (Q1) and the third quartile (Q3) – was narrowest for R7 and R5, indicating a high level of consistency in their running speeds. Conversely, R3 and R8 had the widest IQRs, suggesting that their performance varied more between trials, possibly due to changes in pacing strategy or adaptation to the running conditions.

Table 1. Median and quartile analysis (Q1, Q3) of runners' speeds.

Runner	Median speed [km/h]	Q1 (25%)	Q3 (75%)	The interquartile range (IQR)
R1	16.00	15.58	16.28	0.7
R2	16.30	16.05	16.63	0.575
R3	19.40	18.78	19.95	1.175
R4	14.20	13.93	14.40	0.475
R5	13.25	13.20	13.38	0.175
R6	12.30	11.90	12.48	0.575
R7	13.20	13.10	13.30	0.2
R8	17.40	16.68	17.60	0.925
R9	13.95	13.60	14.00	0.4
R10	15.50	15.00	16.00	1

3.2. Step length

The Wilcoxon test for step length showed significant differences between overground and treadmill running ($p < 0.001$). The effect size was moderate, with a value of 0.44. The median step length was slightly longer during treadmill running (779.62 mm) than during overground running (755.79 mm), indicating a tendency for participants to take longer steps on the treadmill. The first quartile (Q1) was also higher on the treadmill (740.15 mm) than during overground running (697.21 mm), suggesting that even the shorter steps were generally longer in the treadmill condition. However, the third quartile (Q3) was greater in overground running (868.75 mm) than on the treadmill (847.92 mm), reflecting a wider range of step lengths and the occurrence of longer strides during overground running. Overall, treadmill running appeared to produce more consistent and slightly longer step lengths, while overground running allowed for greater variability and occasionally longer steps.

3.3. Friedman ANOVA of side-specific kinematic and temporal parameters in running

This section presents an analysis of five biomechanical parameters measured separately for the right and left lower limbs during treadmill and overground running.

The Friedman ANOVA revealed statistically significant differences in knee flexion angle during the stabilization phase ($F(N = 60, df = 3) = 40.82$, $p < 0.001$, effect size = 0.6 - large) (Fig. 2A). The post-hoc analysis identified significant differences ($p < 0.05$) between the following conditions: overground running vs. treadmill running on the left side, overground running on the left side vs. treadmill running on the right side, and between treadmill running on the left vs. right side.

Median knee flexion angles during the stabilization phase showed modest variations across conditions and sides. On the left side, the median angle was slightly greater during treadmill running (48.1°) than during overground running (47.0°). In contrast, on the right side, the median angle was lower during treadmill running (44.0°) than during overground running (46.05°).
The interquartile range (IQR) also varied between conditions, reflecting differences in the consistency of knee flexion. Treadmill running resulted in a narrower range of motion on both sides, suggesting more consistent movement patterns. On the left side, the IQR for treadmill running was 41.0° to 49.93°, compared to 43.95° to 52.98° during overground running. On the right side, the IQR was 40.9° to 47.6° on the treadmill and 43.53° to 48.48° during overground running. These findings indicate reduced variability and subtly altered knee flexion patterns during treadmill running, particularly on the right side.

For the impact angle, the Friedman ANOVA did not reveal any statistically significant differences across the tested conditions (F(N = 60, df = 3) = 4.65, p = 0.1991, effect size = 0.06 - small) (Fig. 2B). This suggests that the type of surface (overground vs. treadmill) and the side (left vs. right) did not significantly affect the knee angle at the moment of impact. The median impact angles were relatively consistent across all conditions, ranging from 97.75° to 99.95°. The highest median value was observed during overground running on the right side (99.95°), while the lowest was during treadmill running on the right side (98.49°).

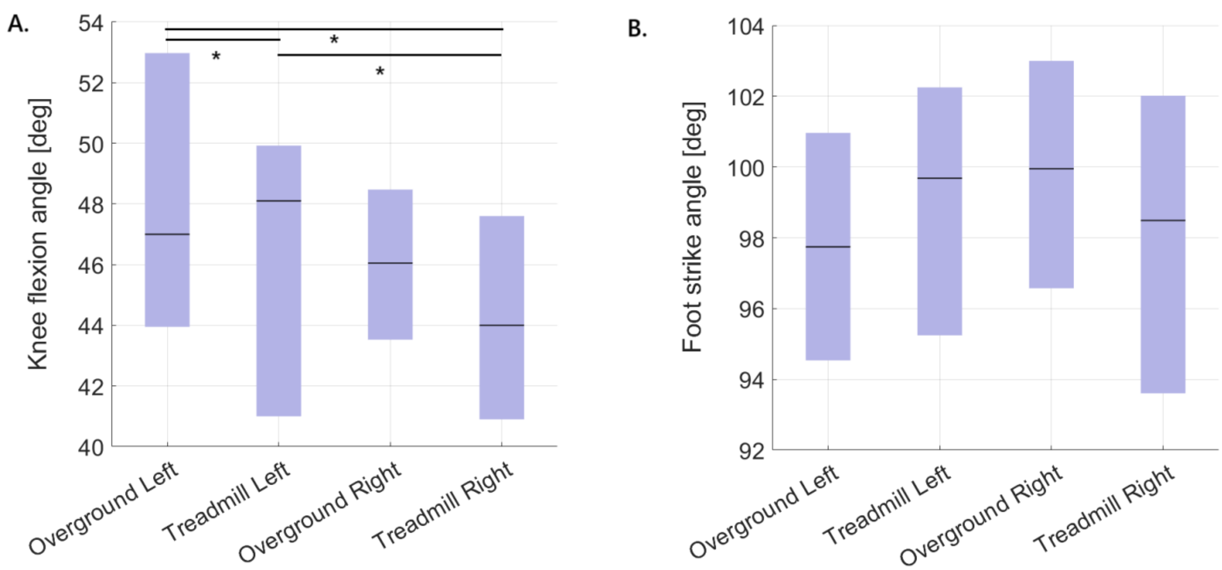

Fig. 2. Median (black line) and interquartile range (IQR) from Q1 to Q3 for A. Knee flexion angle during the stabilization phase and B. The impact angle, * denote statistically significant differences, $p < 0.05$.

Analysis of spatiotemporal parameters using the Friedman ANOVA revealed statistically significant differences in several key running metrics. These included the distance between the center of gravity and the foot at ground contact, which reflects stability and alignment during initial impact (F(N = 60, df = 3) = 145.28, p < 0.001, effect size = 0.9 - large) (Fig. 3A), ground contact time (F(N = 60, df = 3) = 55.34, p < 0.001, effect size = 0.8 - large) (Fig. 3B), and heel strike, velocity following heel-off (F(N = 60, df = 3) = 118.24, p < 0.001, effect size = 1.7 - large) (Fig. 3C). Post-hoc analysis further identified four statistically significant pairwise differences across all parameters: between the overground left side and treadmill right side, overground left side and treadmill left side, treadmill left side and overground right side, and finally, between the overground right side and treadmill right side. These findings suggest that both the running surface and the body significantly influence running mechanics, particularly in terms of stability, contact dynamics, and movement velocity during key phases of the movement.

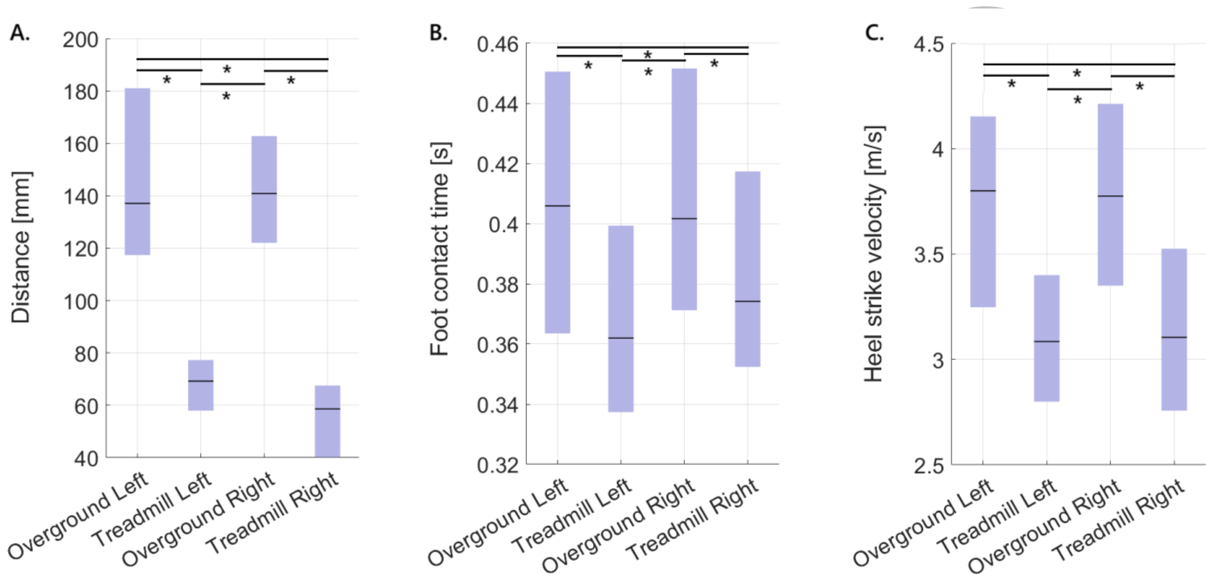

Fig. 3 Median (black line) and interquartile range (IQR) from Q1 to Q3 for A. The distance between the center of gravity and the foot at ground contact, B. Ground contact time and C. Heel strike velocity following heel-off, * denote statistically significant differences, p < 0.05.

Median values of the distance between the center of gravity and the foot at ground contact were notably higher during overground running (137.08 mm left, 140.88 mm right) compared to treadmill running (69.27 mm left, 58.65 mm right), indicating a more compact and possibly more controlled gait on the treadmill (Fig. 3A). The interquartile ranges (IQRs) further support these findings, with values of 117.33 - 181.03 mm for overground left, 57.97 - 77.28 mm for treadmill left, 122.04 - 162.78 mm for overground right, and 40.20 - 67.56 mm for treadmill right. These ranges indicate that overground running is associated with greater variability and generally longer distances between the foot and the center of gravity, potentially reflecting differences in stride mechanics and forward momentum. In contrast, the narrower IQRs observed during treadmill running suggest a more consistent and repetitive gait pattern.

Median values of foot contact time (Fig. 3B) were slightly longer during overground running (0.41 s left, 0.40 s right) than during the treadmill running (0.36 s left, 0.37 s right), indicating a modest reduction in ground contact duration on the treadmill. The interquartile ranges further support this pattern, showing greater variability in overground running (0.36 - 0.45 s left, 0.37 - 0.45 s right) and narrower, more consistent ranges on the treadmill (0.34 - 0.40 s left, 0.35 -

0.42 s right). These results suggest a more uniform and possibly more efficient contact phase during treadmill running.

Median values of heel strike velocity (Fig. 3C) were higher during overground running (3.80 m/s left, 3.78 m/s right) compared to treadmill running (3.09 m/s left, 3.11 m/s right), indicating a faster heel movement at initial contact in overground conditions. The interquartile ranges echoed this trend, with broader and higher ranges in overground running (3.25 - 4.15 m/s left, 3.35 - 4.21 m/s right) versus narrower and lower ranges on the treadmill (2.80 - 3.40 m/s left, 2.76 - 3.53 m/s right). These findings suggest that treadmill running may result in a more controlled and consistent heel strike pattern.

4. Discussion

This study aimed to explore the biomechanical differences between overground running and treadmill running, with a specific focus on how treadmill conditions influence spatiotemporal and kinematic parameters. The goal was to assess the degree to which treadmill data can be extrapolated to outdoor running and provide insights into the practical applications of treadmill running in training and rehabilitation.

In order to deepen the interpretation of the obtained results, a comparison was made with selected studies from the last 10-15 years, including an analysis of the biomechanics of running on a treadmill and in field conditions. Studies [9, 30] and the meta-analysis [32], were incorporated into the analysis. Key biomechanical variables under consideration included stride length, ground contact time, knee joint kinematics (e.g., peak flexion and extension angles), lower limb segmental dynamics, and variability in movement patterns. These parameters were selected due to their critical role in understanding locomotor adaptations and assessing the transferability of treadmill running to real-world running conditions.

In the current study, a 3% increase in step length was observed during treadmill running, along with reduced intertrial variability compared to overground running. This finding aligns with Dejong Lempke, et al. [9], who reported an average increase of 0.20 meters in step length on the treadmill. However, Van Hooren, et al. [32] found no significant differences in mean step length, though they did note substantial inter-study variability. In contrast, Sinclair, et al. [30] reported only a modest increase in step length under treadmill conditions. These collective findings suggest that the consistent belt speed and mechanical feedback inherent to treadmill running may encourage a slightly longer and more uniform stride.

The present study also demonstrated a 12% reduction in ground contact time during treadmill running, which may reflect enhanced running efficiency and neuromuscular coordination. This contrasts with the findings of Dejong Lempke, et al. [9] and Van Hooren, et al. [32], who both reported a slight increase in contact time on the treadmill (+8 ms and +5 ms, respectively). Meanwhile, Sinclair, et al. [30] reported no statistically significant difference between running surfaces. The reduction observed in this study may reflect greater technical proficiency and surface-specific adaptation among professional athletes. Minor differences (±1–2°) in maximum knee flexion were noted in the present study, accompanied by lower variability across trials. Van Hooren, et al. [32] reported a greater increase in knee flexion during treadmill running (+6.3°), whereas Sinclair, et al. [30] found only a marginal change. The reduced variability in our findings may indicate greater motor control and joint stability among the tested athletes.

Regarding foot biomechanics, no significant differences in pronation were observed between treadmill and overground conditions. In contrast, Dejong Lempke, et al. [9] reported increased pronation velocity (+138°/s), while both Van Hooren, et al. [32] and Sinclair, et al. [30] noted trends toward greater pronation angles during treadmill running. The absence of significant changes in the current data suggests that highly trained runners may effectively modulate their movement strategies, maintaining consistent foot strike mechanics across different surfaces.

A convergence of findings is evident in the case of step length, which was greater during treadmill running both in our study and in the work of Dejong Lempke, et al. [9]. A similar effect is also confirmed by Sinclair, et al. [30], supporting the notion that treadmill conditions may promote longer stride patterns. However, discrepancies arise regarding ground contact time—our study showed a decrease, whereas prior studies [9, 32] reported an increase under treadmill conditions. This divergence may be attributed to the higher technical proficiency and movement optimization observed in professional athletes.

Reduced variability in biomechanical parameters was observed during treadmill running in our study, suggesting greater consistency and stability in movement patterns among trained runners when operating in controlled, repetitive conditions. Additionally, heel velocity following toe-off was found to be lower on the treadmill, aligning with existing hypotheses regarding reduced loading on the ischiofemoral musculature. This observation supports the potential use of treadmill running in physiotherapeutic contexts, particularly in the management or prevention of posterior chain injuries.

Significant reductions in knee flexion during the stabilization phase were observed during treadmill running (48.1° left, 44.0° right) compared to overground running (47.0° left, 46.05° right), reflecting altered knee mechanics (Fig. 2A). This could be due to the treadmill's consistent, flat surface, which reduces the need for dynamic shock absorption. The consistency of knee flexion was also evident in the narrower interquartile ranges (IQRs) observed during treadmill running, particularly on the right side (40.9° to 47.6°) compared to overground running (43.53° to 48.48°). These findings reinforce the idea that treadmill running may result in a more predictable, less variable running pattern. This finding aligns with the work of Van Hooren, et al. [32], who reported a reduced knee flexion range of motion during the stance phase, along with a slight increase in knee flexion at foot strike, though the latter was of trivial magnitude.

Notably, step length analysis revealed significant differences between overground and treadmill running ($p = 0.0005$). Participants tended to have slightly longer step lengths on the treadmill (779.62 mm) compared to overground running (755.79 mm), which could be attributed to the treadmill's mechanical propulsion and constrained environment that promotes a more upright posture. The first quartile (Q1) for step length was also greater on the treadmill (740.15 mm) than during overground running (697.21 mm), suggesting that even the shorter steps were generally longer in the treadmill condition. This indicates that treadmill running may encourage longer, more consistent steps, whereas overground running allows for greater variability in step length.

In contrast, the strike angle remained stable across both environments, indicating that the foot strike is a more ingrained and automatic aspect of running mechanics. This was consistent with the results from the analysis of impact angles, which showed no significant differences across conditions (Friedman ANOVA, $p = 0.1991$), suggesting that the surface type did not influence knee angle at impact significantly. The foot strike angle's stability emphasizes its robustness as a core feature of running technique that is resistant to changes in the environment.

Additionally, the center of gravity displacement during treadmill running was reduced, likely due to the treadmill's mechanical propulsion, which contributes to a more controlled and stable gait. This reduction in center of gravity displacement further emphasizes the difference in movement dynamics between treadmill and overground running, particularly in the context of spatiotemporal parameters.

In summary, treadmill running introduces specific biomechanical adaptations, including reduced center of gravity displacement, shorter ground contact time, decreased heel-off velocity, and diminished engagement of the posterior kinetic chain. These adaptations may provide therapeutic benefits by reducing joint loading and providing a controlled environment for rehabilitation. However, treadmill running does not replicate the full biomechanical demands of outdoor running, especially in terms of performance optimization.

Thus, treadmill running should be seen as a complement to outdoor running rather than a replacement. A hybrid approach can help balance safety, recovery, and biomechanical fidelity while addressing individual training goals. Further, the variability observed in the runners' speeds (Table 1), as well as the consistency in biomechanical responses, underscores the importance of individual adaptation to different running environments. Longitudinal studies are needed to explore the long-term effects of these biomechanical differences on running performance and injury risk.

The results of the study showed that running on a treadmill significantly alters the biomechanical parameters of the lower limbs compared to running in the field. Among other things, a 3% increase in average stride length, a significant decrease in stride length variability, a 12% decrease in ground contact time, and a 19% decrease in heel velocity during the explosive phase were observed. In addition, although the changes in knee flexion angle were small (±1-2°), their variability was significantly lower during treadmill running. All of these changes have important practical implications for physiotherapists, especially when working with runners returning after injuries to the ischiofemoral group.

First, a reduction in heel velocity during the explosive phase may indicate a reduction in lower limb dynamics during the final phase of support. This may mean less involvement of the posterior chain muscles, including the biceps femoris and gluteus maximus muscles, which is beneficial in the context of rehabilitation of injuries to these structures. The mechanical assistance of the treadmill belt to move the body likely reduces the demands on the concentric work of this muscle group, allowing functional loads to be safely implemented during the return-to-running phase [29]

The third important element is less variability in stride length and knee flexion angle, indicating a more reproducible movement pattern. The treadmill allows running in conditions with limited environmental variability, which can be beneficial in the motor reeducation phase after injury [15]. The stability of movement allows for more accurate monitoring of running techniques and rapid detection of abnormalities, making the treadmill a tool not only for rehabilitation but also for diagnosis.

In addition, it is important to keep in mind that in the later stages of rehabilitation - especially during progression to higher speeds - the importance of the coasting phase may increase as the moment that puts the most stress on the muscles of the ischiofemoral group. Chumanov et al. pointed out that the biceps femoris muscle reaches its peak of activity during the dynamic phases of the limb in running, which can provide a reference point for planning load progression at a later stage of return to sport [6].

In conclusion, the results of the study confirm that the treadmill can be an effective therapeutic environment for runners with injuries to the ischiofemoral group. It offers biomechanical conditions conducive to reduced overload, increased repetition of movement, and precise control over training parameters, which can be used at any stage of the return to running process.

This study supports the notion that treadmill running may induce specific biomechanical adaptations that differ from overground running. While treadmill running offers a controlled environment for rehabilitation, it is essential to consider that it does not entirely replicate the natural variability or mechanical demands of overground running [6, 34]. Further research into the long-term impact of these biomechanical changes on running performance and injury prevention is warranted to enhance our understanding of treadmill-based training.

5. Conclusion

This study provides a thorough examination of the biomechanical differences between overground and treadmill running, revealing that running on a motorized treadmill reduces the dynamics of lower limb propulsion, notably through a decrease in foot velocity. This reduction likely results from the assistance provided by the treadmill's moving belt, which aids forward propulsion and lessens the load on posterior muscle groups such as the hamstrings. These changes can be beneficial in rehabilitation settings, offering a controlled environment for gradually reintroducing mechanical load to musculoskeletal structures and supporting a progressive return to function.

The results from the spatiotemporal and kinematic parameters - such as reduced center of gravity displacement, shorter ground contact time, and altered knee flexion patterns - underscore the unique biomechanical effects of treadmill running. These findings carry significant practical implications for rehabilitation and training. While treadmill running can be an effective tool for restoring load tolerance, it does not fully replicate the biomechanical demands of outdoor running. Exclusive reliance on treadmill training may compromise running technique and performance, particularly for athletes preparing for outdoor competitions. Therefore, treadmill use should complement, not replace, field training. A combined approach allows for tailored training programs that cater to individual needs while aligning with performance goals.

In conclusion, this study highlights the importance of understanding how training environments influence running biomechanics. The findings inform not only current rehabilitation strategies but also provide valuable insights for future research on how treadmill adaptation affects athletic performance and musculoskeletal health in the long term.

Declaration of conflicting interests

All authors declare no competing interests.

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