The Effect of Increasing Running Speed on Mechanical Work of the Lower Limbs in Elite Male Runners

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Abstract

Introduction: Understanding the biomechanical performance of the lower limb joint during running is of the utmost importance for enhancing our current understanding of high human performance, as well as for identifying potential factors that may be associated with injuries. Given that the mechanical work of the lower limb joints conveys crucial information about joint function, the objective of the present study was to examine the impact of increasing running speed on the mechanical work of elite male runners. **Materials and Methods**: The current study is an observational cross-sectional study.28 healthy male elite runners aged 22 - 51 years ran on a treadmill with a force plate in the middle of the walk-way, at three different speeds, 2.5, 3.5 and 4.5 m/s respectively, and the data related to the mechanical work of the lower limbs were recorded and extracted. Also, in order to compare the averages of the Hip, Knee and Ankle mechanical work variables, ANOVA repeated measurements method with Bonferroni post hoc test was used. **Results**: It was found that increasing the speed leads to a significant difference in the mechanical work of the joints of the lower limbs including hip and ankle in both absorption and production phases($P<0.05$) except in the knee joint at a speed of 3.5 to 4.5 in positive mechanical work ($P=0.121$). **Conclusion**: Considering the biomechanics of running is very important as a basic skill that every person performs during his life. The mechanical work aspects of the hip, knee, and ankle joints during increased running speed may potentially provide a biomechanical explanation for these clinical observations.

Keywords: Biomechanics; Lower limb; Joints; Mechanical work; Running velocity

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Introduction

Due to easy performance and excellent accessibility, running is recognized as one of the most popular sports activities in the world (1). In fact, running is one of the best training methods for athletes and coaches to increase important components of physical fitness such as strength and coordination (2). Running skills require complex coordination between different muscles, tendons and ligaments of the body (3), which relate to changes in the kinematic and kinetic pattern of joints and segments(4). Understanding the biomechanical performance of the lower limb joint complex during running is important to improve current knowledge of high human performance as well as identifying potential factors that may be associated with injury (2).

Humans possess the ability to traverse a vast range of velocities (2). Since running speed profoundly impacts biomechanical and neurological parameters (5, 6), this escalation in speed precipitates a significant elevation in neuromuscular engagement (6). Therefore, it is of paramount importance to scrutinize the biomechanics of the hip, knee, and ankle joints at varying running speeds (7). In other words, during running, the lower limb may be deemed a system necessitating coordination of dynamic patterns at the joint level. Consequently, as the pace of movement alters, the joints of the lower limbs undertake divergent functional roles (8), and the augmentation in running speed synchronizes with a surge in the kinetic energy of the entire body. This phenomenon arises due to the greater production of mechanical work and force in the joints (9).

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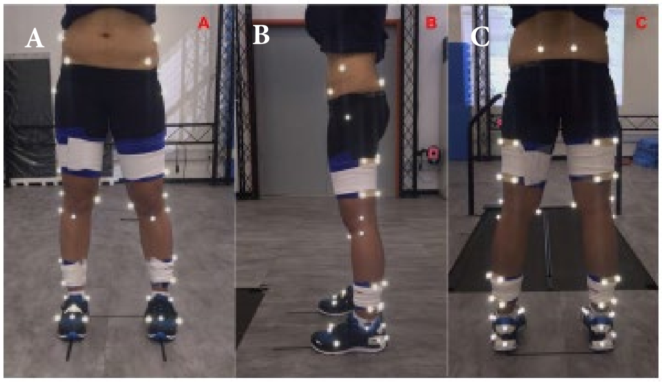

Figure 1. Marker collection protocol. Technical and anatomical marker collection protocol during the anatomical calibration test in anterior (A), lateral (B) and posterior (C) views.

The investigation of the mechanical work accomplished in the joints of the lower extremity imparts the most crucial details regarding joint functionality (10). When examining the correlation between work and running velocity for the entire stride cycle, it becomes clear that work is characterized both positively and negatively. Positive work denotes the energy production carried out during a concentric contraction, transferring energy from the muscles to the organs, whereas negative work denotes the energy absorption carried out during an eccentric contraction, transferring energy from organs to muscles (7). Various methods have been employed in prior studies to report the work executed in the joints of the lower extremity during an increase in running speed (11, 12). A study conducted by Bezodis *et al.* revealed that sprinters exhibit positive work by the hip extensors during the initial stage of stance, while the plantar flexors contribute positively in the latter stage. Meanwhile, the knee extensors have a minor role in generating work, but still have a positive effect during stance (11). In a similar vein, Hamill *et al.* (12) reported that joint mechanical work exhibited the greatest negative work on the ankle, depending on foot contact patterns during running. On the other hand, Schache *et al.* (7) demonstrated that the hip and knee exhibit the greatest increase in absolute value during the swing of running in fast running, while the work done in the knee joint during stance is not affected by increasing running speed. Conversely, the work done on the ankle joint during stance increases with increasing running speed.

Previous research has demonstrated conflicting findings regarding the precise function of the hip, knee, and ankle joints in relation to the varying demands of running at different stages and speeds (7, 10-12). Furthermore, there remains a paucity of literature examining the mechanical work of the lower limb joints during this activity. It is obviously that running at different speeds may not be a completely focused endeavor. Therefore, considering the importance of this parameter and the effectiveness of factors such as energy, various lower limb injuries, etc., the purpose of this study was to investigate the effect of increasing running speed on the mechanical work of the lower limbs of the elite male runners.

Materials and Methods

The current study is an observational cross-sectional study.

Participants

Twenty-eight male elite runners aged 22 to 51 years with an average body mass of 69.64±7.67 kg, who ran more than 20 km per hour per week, with a minimum average speed of 1 km per 5 minutes during 10 km races and running background of 7.23±2.15 years participated in the study. We analyzed their complete familiarity and comfort with running on a treadmill. Exclusion criteria were the presence of any neurological or musculoskeletal disorder that compromised their movement, or the use of any assistive device. This study was approved by the Federal University of ABC (Brazil) ethics committee (CAAE: 53063315.7.0000.5594) and written and informed consent was obtained from each individual before participating in the study.

Equipment

The subject was introduced to the laboratory and a brief explanation was given about the experimental methods. Then, the subject was asked to provide written informed consent and complete a brief interview regarding eligibility criteria. Demographic characteristics of subjects including height and body mass were measured andshoe-fittingwas conducted to determine the appropriate shoe size. All participants wore neutrallaboratory-controlled shoes (Nike Dual Fusion X).48 anatomical and technical reflective markers were used (Figure 1).The running kinematics were collected via a 3D motion-capture system with 12 cameras having 4 Mb of resolution and the Cortex 6.0 software (Raptor-4, Motion Analysis, Santa Rosa, CA, USA). The GRF data was collected via an instrumented, dual-belt treadmill (FIT, Bertec, Columbus, OH, USA).The participant was instructed to mount the treadmill and commence walking at a pace of 1.2 m/s for a duration of 1 minute in order to acquaint himself with the equipment. Next, the participant was directed to position himself on the left belt of the treadmill, and the belt was progressively accelerated to 2.5 m/s. After sustaining this velocity for a period of 3 minutes, the pertinent data was documented over a period of 30 seconds. The same sequence was replicated with velocities of 3.5 m/s and 4.5 m/s. Following the running assessments, the treadmill pace was reset to 1.2 m/s for a 1-minute recuperative phase before cessation.

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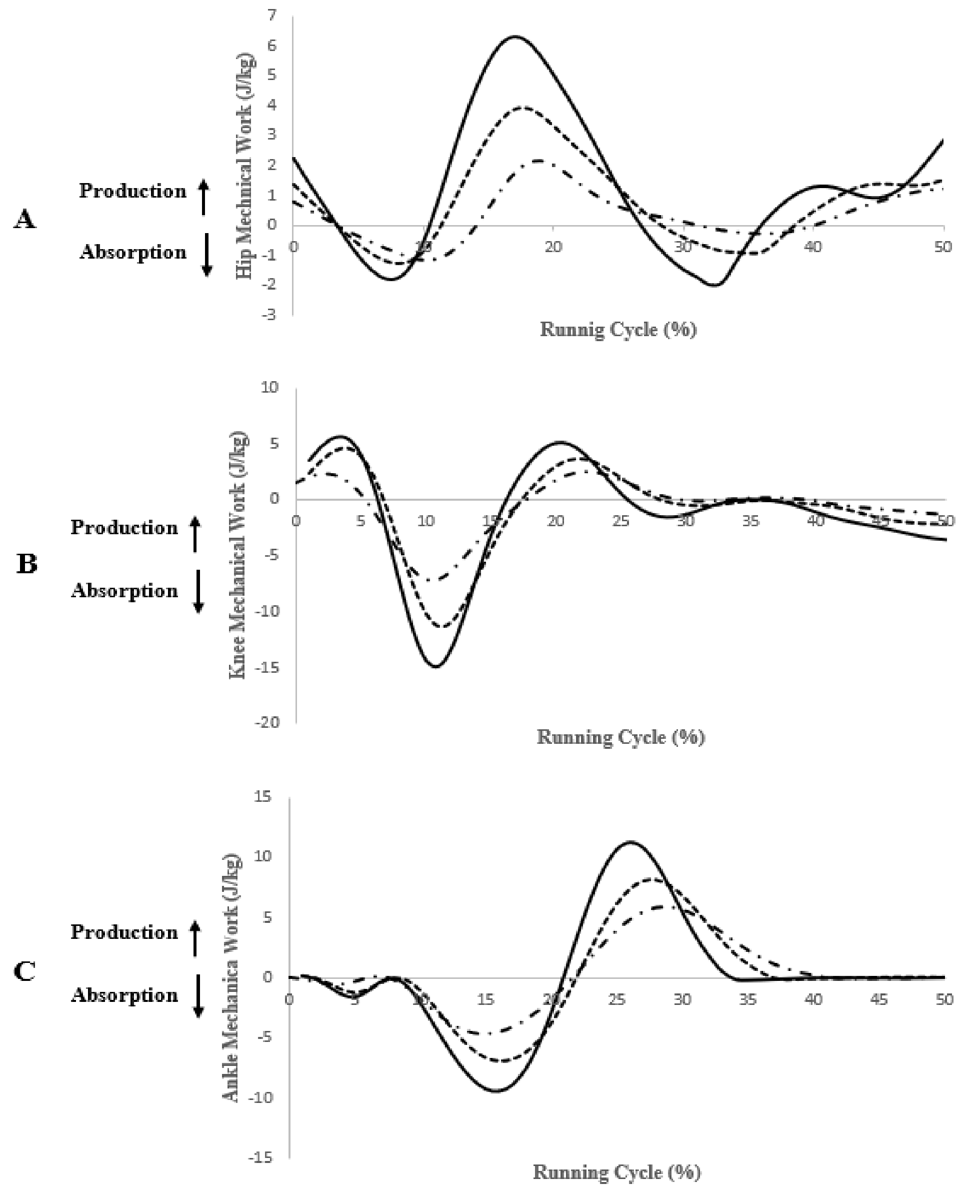

Figure 2- Mechanical work respect to running cyclein stance phase in *A*). hip; *B*) knee; *C*) ankle in three different speeds regarding production and absorption phases. V1= 2.5 m/s (- - -), V2= 3.5 m/s (........), and V3= 4.5 m/s (——).

Running kinematics were collected through a 3D motion-capture system with 12 cameras at 4 MB resolution and Cortex 6.0 software (Raptor-4, Motion Analysis, Santa Rosa, CA, USA). Cameras were distributed around the laboratory in such a way as to target the recording volume of the treadmill movement. The cameras are installed in a metal structure 11.5 meters long, 9.3 meters wide and 2.8 meters high. This structure made it possible to place some cameras at different heights. However, most of them were placed on top of the metal structure (Figure 1). The instrumented treadmill was installed on a pit, and the treadmill and the laboratory floor were level with each other (Figure 1). Cortex 6.0 software (Motion Analysis, Santa Rosa, CA, USA) was used to (1) calibrate the motion recording volume (2) to record and identify reflective markers (3) prepare the data and save it to file format. Further processing (e.g., filtering, gap filling, etc.) was performed on the data to provide a raw dataset containing marker trajectories and force signals. The motion capture volume included an area with 3.1 m long, 2.3 m wide, and 1.2 m high, and this volume was calibrated daily. The system was considered correctly calibrated only if the length of the calibration rod, as measured by the recording system, was within 0.10 mm of the actual rod length. The rate of kinematic and

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Table 1. Results of descriptive and statistical data analysis of work variable while running at different speeds

Variables		V1=2.5 m/s	V2=3.5 m/s	V3=4.5 m/s	Mean relative difference (*P*-Value)		
		Mean (SD)	Mean (SD)	Mean (SD)	V1-V2	V1-V3	V2-V3
Hip	Positive work (J/kg)	0.80 (0.20)	1.49 (0.30)	2.43 (0.39)	0.69* (0.000)	1.62* (0.000)	0.94* (0.000)
	Negative work(J/kg)	-0.27 (0.09)	-0.42 (0.12)	-0.66 (0.22)	0.16* (0.000)	0.39* (0.000)	0.24* (0.000)
Knee	Positive work (J/kg)	0.69 (0.17)	0.86 (0.19)	0.92 (0.23)	0.17* (0.000)	0.23* (0.000)	0.06 (0.121)
	Negative work(J/kg)	-1.50 (0.18)	-2.15 (0.24)	-3.03 (0.30)	0.65* (0.000)	1.53* (0.000)	0.88* (0.000)
Ankle	Positive work (J/kg)	0.64 (0.10)	0.78 (0.10)	0.95 (0.15)	0.14* (0.000)	0.32* (0.000)	0.17* (0.000)
	Negative work(J/kg)	-0.56 (0.13)	-0.77 (0.14)	-0.96 (0.15)	0.19* (0.000)	0.39* (0.000)	0.19* (0.000)

**Significant difference (P<0.05); V: velocity of running*

kinetic data acquisition was determined to be 150 Hz and 300 Hz, respectively. The laboratory coordinate system used for the study was the one proposed by the International Society of Biomechanics (Wu & Cavanagh, 1995) and, as shown in Figure 1, includes the following:

- X-axis in the direction of walking and positively forward.
- Y-axis in the vertical and positive direction upwards.
- Z-axis in the lateral and positive direction to the right.

Protocol

Data processing and analysis

Initially, data from cameras and markers were filtered using a fourth-order Butterworth filter and low-pass with the same frequency of 10 Hz (Kristianslund, Krosshaug& Van den Bogert 2012). Measurements were taken while running on a treadmill rather than on the ground as suggested by Cavanagh &LA fortune (1980).

Raw marker-trajectory and ground reaction force (GRF) data were subjected to filtration utilizing a fourth-order low-pass Butterworth filter. The cut-off frequency employed in the filtration process was 10 Hz. The instances of foot strike and toe off were deduced based on the point at which the vertical GRF crossed a threshold level of 20 N. According to the magnitude of GRF on the force platform, the stance phase of running at various speeds was extracted. Additionally, 3D hip, knee, and ankle angles were computed by means of Cardan angles. The internal joint torques were represented in the joint-coordinate system, ascertained using a standard inverse-dynamics methodology. Joint powers were determined by computing the scalar product of joint torques and joint angular velocities. The joint kinetic and GRF variables were normalized with respect to the subject's body mass. The joint work was computed as the area enclosed by the joint power-time curves (Formula 1).

Formula 1. Mechanical work $= \int \boldsymbol{p.\,dt}$

Statistical analysis of processed data

Shapiro-wilk test was used to investigate normality of the data. The homogeneity of variance assumptions of the dependent variables was tested using Bartlett's test (5). ANOVA Repeated measurement test was used to investigate the effect of increasing running speed on the work of lower limb joints. Post hoc analysis was also performed using Bonferroni adjustments to minimize type I statistical errors. All statistical calculations were performed on SPSS 21.0 software at a significancant level of 0.05.

Results

The mean and standard deviation as well as the results of the ANOVA repeated measurement test of the mechanical work variables of the lower limb joints resulting from the analysis of descriptive and inferential statistics are shown in Table 1.

The research results show that, in the hip, knee, and ankle joints with increasing running speed, the positive and negative mechanical work significantly increased from 2.5 to 3.5, 2.5 to 4.5, and 3.5 to 4.5 speeds, except in the knee, with an increase in speed from 3.5 to 4.5 that significant increase in not observed

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Discussion

The objective of this investigation was to ascertain the impact of increasing the velocity of running on the mechanical work carried out in the joints of the hip, knee and ankle. This study scrutinized the mechanical work in the joints of the lower limb at three different velocities of 2.5, 3.5 and 4.5 m/s, and it was observed that the increase of velocity resulted in a significant dissimilarity in the mechanical work of the lower limb joints, encompassing both the absorption and production of energy. Furthermore, it was demonstrated that there was a noteworthy difference solely in the knee joint, in the positive mechanical work, during the speed range of 3.5 to 4.5.

The investigation revealed that the augmentation of velocity within the hip joint has a significant impact on both positive and negative mechanical work in the said joint. At a pace of 4.5 m/s, the hip demonstrated the minimum amount of positiveand negative mechanical work. The findings of the current study are congruent with some of the preceding research, namely, Jin *et al.*'s (14) study, which demonstrated that a rise in running speed coincides with an increase in the positive work of the hip joint. The study conducted by Schache *et al.* (9) demonstrated that during the stance phase, the positive work of the hip experiences a considerable increase when the running speed exceeds 5.01 ± 0.11 m/s. The hip joint exhibited the strongest correlation between work and running speed (7) as the subjects opted for longer strides and higher stride frequencies. Consequently, the stride length exceeded the stride frequency, which resulted in increased mobility (13). In general, it is evident that the work of the lower limb joints is also influenced by the rise in running speed. Specifically, the hip work (both positive and negative) was significantly impacted by running speed in all the tested conditions. Concerning hip joint loading, there is non-linear evidence that the hip contribution to force production increases as a function of running speed (7).In the study conducted by Fukuchi *et al.* (13) a comparable pattern was observed whereby the rate of augmentation in hip force production was not uniform in comparison to knee and ankle work. This particular discovery can be explicated by the fact that the hip muscles' task of hastening the leg during the swing phase experiences a more rapid escalation, resulting in the leg advancing at a swifter pace.

In the context of the knee joint, the findings indicate that there is no significant difference in positive mechanical work with an increase in running speed, except for when the speed ranges from 3.5 to 4.5. Perhaps the primary function of the knee joint in maintaining balance and stabilizing the lower extremity may account for the observed lack of significant differences. However, the positive mechanical work increases with an increase in running speed in all other speed ranges, and there is an increase in both positive and negative mechanical work. This contradicts the results of Schache *et al.* (7) study, which suggests that an increase in running speed does not affect the mechanical work during the stance phase in the knee joint. Furthermore, an increase in running speed leads to negative knee work during the swing phase. Another study conducted by Schache *et al.* (7) reveals that there is a strong correlation between works and running speed of the knee joint. In contrast, the work performed at the knee joint during stance demonstrated a relatively constant nature at running speed (7). Although our results appear to be consistent with those of a few other studies, Schache *et al.* (9) demonstrated in another study that negative work increased continuously when the running speed exceeded 5.01±0.11 m/s. Therefore, these correlations indicate that, overall, the moments of the lower limb joints and the mechanical work of the knee joint were also influenced by the increase in running speed, as the angle of the knee joint increased with increasing running speed (13).

The present study observed a significant increase in positive and negative work in the ankle joint with an increase in speed. This finding is consistent with previous research by Schache *et al.* (7) that demonstrated an increase in ankle joint work during stance with an alteration in running speed. Jain *et al*. (14) also reported that an increase in running speed results in an increase in positive work during the stance phase of the ankle. These results are generally in agreement with the findings reported by Ae *et al* (15). In the present context, the findings of Schache *et al.* (9) demonstrated that altering the movement mode and running pace at a constant rate cannot be attained merely by a proportional escalation in the joint work of the lower extremities. The ankle joint moment increases with an increase in running speed, and the constructive work in the ankle was considerably impacted by the running speed in all evaluated conditions (13). Based on the outcomes, it can be inferred that augmenting the running speed considerably amplifies the mechanical work in the ankle joint.

One of the primary constraints of the current investigation was the management of the dietary profile of the participants. Additionally, all individuals involved were professional athletes who engaged in outdoor running rather than laboratory-based exercises. For further investigation, it is recommended to focus on the impacts of running velocity on the biomechanics of the lower joints across diverse groups exhibiting distinct forms of disorders in lower limbs, as well as various stages of life and gender.

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Conclusion

The present investigation was carried out with regard to the biomechanics of running, a fundamental and vital skill that each individual performs throughout their lifespan. As such, the findings disclose significant information concerning the biomechanics of running. The sensitivity of the hip, knee, and ankle joints during elevated running velocity could potentially furnish a biomechanical explanation for these clinical observations. For further exploration, future research utilizing computer-based musculoskeletal modeling techniques to quantify individual joint performance with increasing running speed is essential.

Ethical considerations

This study was approved by the UFABC ethics committee (CAAE: 53063315.7.0000.5594) and written and informed consent was obtained from each individual before participating in the study.

Practical application of the study

The mechanical work of the hip, knee, and ankle joints during increased running speed may potentially provide a biomechanical explanation for these clinical observations. Future studies using computer-based musculoskeletal modeling techniques to quantify individual joint performance with increasing running speed are needed for further investigation.

Conflict of interest

None.

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None.

Authors' contributions

All authors made substantial contributions to the conception, design, analysis, and interpretation of data.

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