Research Paper

Analysis of Lower Limb Joint Kinetics With Increasing Running Speed

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ABSTRACT

Purpose: Due to the paucity of information regarding the lower limb biomechanics in running at slow speed, as well as the concentration of most previous studies on a single movement plane, this study aimed to investigate lower limb joint kinetics with increasing running speed.

Methods: Twenty-eight runners were asked to stay on the treadmill at a bent velocity which was incrementally increased to 2.5 m/s, 3.5 m/s, and 4.5 m/s speeds. The three-dimensional joint moment and sagittal mechanical muscle power of the lower limb were calculated during the stance phase of running. Repeated measures analysis of variance (ANOVA) with Bonferroni post hoc test was used to examine the variables during running at various speeds.

Results: The results showed that at the hip joint in the frontal plane, an adduction moment developed in the middle of the stance phase, and the highest peak adduction moment was obvious at the highest speed condition (4.5 m/s). Also, the time elapsed to peak in the highest speed condition was less than the others. In the transverse plane, although the 3.5 m/s-speed condition experienced the maximum external rotation peak moment, the 4.5 m/s-condition speed reached the internal status earlier than the two other speeds. In the sagittal plane, the highest speed condition showed the highest extension and flexion moments.

Conclusion: Increasing running speed in runners leads to more kinetic output and mechanical power gradient.

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Highlights

- Biomechanics of lower joints during running.
- Power production and Absorption during running on different speeds.
- How increasing speed would affect the moments of the Hip, knee and ankle joints?

Plain Language Summary

Running is a fundamental skill and a vital requirement for almost all sports activities. Also, it is considered one of the best training modalities for athletes and coaches to increase critical components of physical fitness, such as strength and coordination in improving running speed. Due to the paucity of information regarding the lower limb biomechanics in the running at slow speed, by examining most previous studies on a single movement plane, the present study aimed to investigate lower limb joint kinetics with increasing running speed. Twenty-eight professional male athletes participated in the study by running on three progressive speeds, 2.5, 3.5 and 4.5 m/s on a force plate mounted treadmill while kinematics and kinetics data were captured. Hip, knee and ankle three dimensional Moments and joints mechanical powers were compared with each others using SPSS ($P<0.05$). The results showed that, at the hip joint in frontal plane, an adduction moment developed in the middle of stance phase, and the greatest peak adduction moment is obvious at the highest speed condition (4.5 m/s). Also, the time elapsed to peak in the highest speed condition is less than the others. In transverse plane, although 3.5 speed condition experienced the most external rotation peak moment, but 4.5 condition speed reached sooner to internal status than two other speeds. In sagittal plane, the highest speed condition showed the highest extension and also flexion moments.

1. Introduction

Running is a popular recreational activity with crucial benefits in terms of mental and physical health [1]. Running is a fundamental skill and a vital requirement for almost all sports activities [2]. Also, it is considered one of the best training modalities for athletes and coaches to increase critical components of physical fitness, such as strength and coordination in improving running speed [3]. Both biomechanical and neurological parameters are strongly affected by running and consequent changes in running speed [4, 5] because increased speed dramatically leads to higher levels of neuromuscular involvement [5]. Therefore, it is essential to study the lower limb biomechanics at different running speeds to understand high performance [6]. Running per se involves a high rate of injuries [7], which are prevalent among all runners [8]. The general problem is that inappropriate training programs and individual errors are major causes of such injuries [9]. Various reasons, including anatomical and biomechanical factors, are involved in this case [10]. Despite various research, the crucial biomechanical risk factors, including kinetics factors, especially in three dimensions, are not entirely evident [1]. Studies have shown that runners change their running speed by changing their kinetic behaviors [11], but some other studies believe that the kinetics remain constant with increasing speed, especially at high speeds [12-14].

Among the kinetic variables, "force" has been studied more than the others. The maximum horizontal and vertical force increases with increasing speed from slow to moderate (from 1.5 to 6.5) [3, 15]. Also, since the speed increases, the peak vertical and horizontal forces remain constant, but the lateral forces change [16], and no relationship is observed between maximum running speed and vertical force, and the peak vertical force does not affect increasing speed [12, 17, 18]. In addition to the force, moment, and mechanical power of the lower limb joints undoubtedly play a vital role in increasing speed. In these criteria, Schanche and Bredah (2018) concluded that the peak knee extensor and plantar flexor moment increase more than in other joints during acceleration, and the plantar flexor moment is also greater than in the knee [19]. Furthermore, the plantar flexor moment is higher than the knee during acceleration at slow speeds [19]. However, some studies have emphasized that increasing running speeds does not occur with a relative increase in lower limb joint moments [4, 6, 20]. Although several studies have been conducted in the field of mechanical power in the running [2, 5, 13], little research is available on the changes and differences of this variable at different speeds. Schache concluded that the generated power in the hip and the absorbed power in the knee increased with increasing speed [6]. Arampatzis also confirmed the effect of changing running speed on the mechanical power of the ankle and knee [21, 22].

In addition to all of the above, the biomechanical and kinetics investigations in these areas are mainly conducted on high-speed changes during running [2, 4, 5, 19, 23], and few studies examined the kinetics-based performance of the lower limb while increasing the speed at slow ranges, especially focusing on muscle activities, stiffness, force, etc. [24-26]. Therefore due to the paucity of information regarding the lower limb biomechanics in the running at slow speed, by examining most previous studies on a single movement plane [10], the present study aimed to investigate lower limb joint kinetics with increasing running speed.

2. Materials and Methods

The present research was conducted as a quasi-experimental study at the laboratory of biomechanics and motor control (BMClab) at the Federal University of ABC (UFABC). The data were collected by experienced physiotherapist researchers, and the procedures were approved by the local Ethics Committee of the UFABC (CAAE: 53063315.7.0000.5594), and written, informed consent was obtained from each subject before participating in the study [27].

Study participants

Twenty-eight professional male athletes participated in this study. They were runners with a weekly mileage of more than 20 km, a minimum average running speed of 1 km in 5 minutes during a 10-km race and familiarity and comfort with running on a treadmill. The inclusion criteria included professional runners with at least 8 years of consecutive running experience, aged 30-40, and BMI between 18 kg/m to 22 kg/m. The exclusion criteria included the presence of any neurological or musculoskeletal disorder that compromises the movement or the use of any assistive device.

Equipment

The running kinematics was collected via a 3D motion capture system with 12 cameras (4 Mb, resolution, the Cortex 6.0 software, Raptor-4®, motion analysis, and Santa Rosa, CA, USA). The GRF (Ground Reaction Force) data were collected via an instrumented dual-belt treadmill (FIT, Bertec®, Columbus, OH, USA). The cameras were distributed around the laboratory in such a way that they aimed at the instrumented treadmill's motion capture volume. The cameras were mounted in a metallic truss structure with a length of 11.5 m, a width of 9.3 m, and a height of 2.8 m. This structure allowed the positioning of some cameras with varying elevations (Figure 1). The instrumented treadmill was mounted over a pit, with the treadmill surface at the same level as the laboratory floor (Figure 1). The Cortex 6.0 software (motion analysis, Santa Rosa, CA, USA) was used to first calibrate the motion capture volume, and the second capture and identify the reflective markers. The motion capture volume consisted of an area 3.1 m long, 2.3 m wide, and 1.2 m high, and this volume was calibrated daily. The acquisition rate of the kinematics and kinetics data was set at 150 Hz and 300 Hz, respectively. The laboratory coordinate system used for the study was the same as that proposed by the International Society Of Biomechanics (ISB) (Wu & Cavanagh, 1995) and, as shown in Figure 1, contained the following criteria:

- X-axis in the direction of gait progression and positive pointing forward (Frontal plane),

- Y-axis in the vertical direction and positive pointing upward (Transverse plane), and

- Z-axis in the medial-lateral direction and positive pointing to the right (Sagittal plane).

Study protocol

The data-collection protocol involved the following procedures:

Upon arrival, participants were given a brief explanation of the experimental procedures and asked to provide written informed consent and a brief interview regarding eligibility criteria, demographic data, and running habits. Based on Helen Hayes's standard of maker settings, 48 technical and anatomical reflective markers beside clusters with four technical markers placed in a rigid shell were used on the thigh and shank segments. These shells were securely fastened to the segments using a combination of elastic and Velcro straps according to pelvis markers: right and left (R&L) ASIS (anterior superior iliac spine), R&L PSIS (posterior superior iliac spine), R&L iliac crest; thigh markers: R&L top lateral, R&L bottom lateral, R&L top medial, R&L bottom medial, R&L GTR; shank markers: R&L top lateral, R&L bottom lateral, R&L top medial, R&L bottom medial, R&L HF, R&L TT, heel markers: R&L heel top, R&L

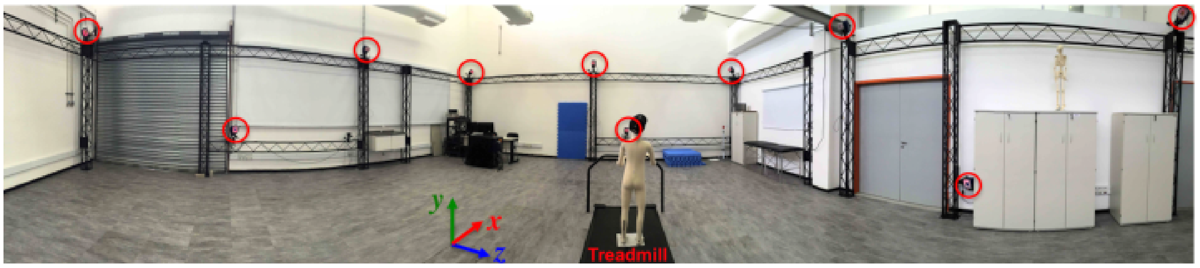

Figure 1. Overview of the laboratory of biomechanics and motor control

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Expanded view of the laboratory of Biomechanics And Motor Control (BMClab), showing 10 of 12 motion-capture system cameras (marked with red circles), the instrumented treadmill, and the laboratory coordinate system.

heel bottom, R&L heel lateral; knee markers: R&L knee, R&L knee medial; ankle markers: R&L ankle, R&L ankle medial; toe markers: R&L MT1, R&L MT5, R&L MT2 [27]. The following protocol was followed for running the assessment:

The subject walked at 1.2 m/s for 1 minute to familiarize with the treadmill. Next, the subject was asked to stay on the left belt of the treadmill, the belt speed was incrementally increased to 2.5 m/s, and after a 3-minute accommodation period at this velocity, the data were recorded for 30 s. This procedure was repeated at speeds of 3.5 m/s and 4.5 m/s, always in the same sequence. After the running trails, the treadmill speed was reset to 1.2 m/s for 1 minute before stopping. The three-dimensional joint moment and sagittal mechanical muscle power of lower limbs during the stance phase of running were represented in the joint-coordinate system and calculated using a standard inverse dynamics approach. Derived moments were normalized by the subject's body mass, the running cycle over 101 time-points, mechanical power by multiplying joint moment, and angular velocity was calculated on each frame. The stance phase of running was considered via GRF values of the force plate directly when they reached zero for each running speed separately. Considering the stance phase for the kinetics during running at three speeds, peak values of movements in each plane - minimum and maximum - lower limb joint moment were considered for further analysis. In hip and knee joints, flexion-extension in the sagittal plane, adduction-abduction in the frontal plane, and internal rotation-external rotation in the transverse plane and the ankle, dorsiflexion-plantar flexion in sagittal, inversion-eversion in the frontal plane and adduction-abduction in transverse plane were considered as the positive-negative values in three-speeds, respectively. Joint's mechanical powers were obtained according to the multiple of the moment and angular velocity concerning the time domain. The positive and negative values for power were employed for further analysis in each direction and speed.

Statistical analysis

The normality and homogeneity of variances assumptions of the dependent variables were tested using Bartlett's and Levene's tests, respectively. Repeated measures analysis of variance with Bonferroni post hoc test were used to examine the variables (peak moments and power of the hip, knee, and ankle) during running at various speeds. The statistical calculations were performed in SPSS software v. 22 ($P<0.05$). To obtain the effect size, Cohen's coefficient was used according to the Equation 1, as the difference between two means (d) divided by the pooled standard deviation (s) for the data:

$$1.\ d=\frac{x_1 x_2}{s}$$

$$s=\frac{(n_1-1)s_1^2+(n_2-1)s_2^2}{n_1+n_2-2}$$

Also, the relative change is a fraction that describes the size of the absolute change compared to the reference value: according to the Equation 2, the relative change is calculated as the division of the final value minus the initial value to the initial value in percentage:

$$2.\ s=\frac{\text{final value-initial value}}{\text{initial value}}$$

3. Results

Table 1 lists the Mean±SD of the variables, as well as the results from statistical analysis. Overall, the results of the repeated measures analysis of variance showed that with increasing velocity, significant differences were obvious in all moments and net mechanical muscle power variables in three planes. Also, a post hoc test revealed no significant relationship between knee YIntR-extR and ankle YAdd by increasing the speed at all levels. In hip YIntrot-extrot and ZFlx-ext, significant correlations have been observed with increasing

Table 1. Results of statistical data analysis

Variables	Direction	Speed (m/s)	Mean Bonferroni	SD	Repeated Measures	Direction	Speed (m/s)	Mean BF	SD	Repeated Measures
Moment (N.m/kg)										
Hip	XAdd	2.5	$1.626^{3.5,4.5}$	0.190	0.000*	XAbd	2.5	$-0.106^{3.5,4.5}$	0.086	0.000*
		3.5	$1.821^{2.5,4.5}$	0.259			3.5	$-0.180^{2.5,4.5}$	0.093	
		4.5	$1.916^{2.5,3.5}$	0.313			4.5	$-0.281^{2.5,3.5}$	0.107	
	YIntrot	2.5	$0.035^{4.5}$	0.064	0.000*	YExtrot	2.5	$-0.408^{4.5}$	0.157	0.000*
		3.5	$0.030^{4.5}$	0.061			3.5	$-0.482^{4.5}$	0.170	
		4.5	$0.177^{2.5,3.5}$	0.142			4.5	-0.5382.5,3.5	0.184	
	ZFlx	2.5	$0.593^{4.5}$	0.169	0.000*	ZExt	2.5	$-1.003^{4.5}$	0.172	0.000*
		3.5	0.6444.5	0.180			3.5	$-1.290^{4.5}$	0.212	
		4.5	$0.836^{2.5,3.5}$	0.269			4.5	$-1.582^{2.5,3.5}$	0.207	
Knee	XAdd	2.5	0.9523.5,4.5	0.254	0.000*	XAbd	2.5	$-0.034^{3.5,4.5}$	0.033	0.000*
		3.5	$1.031^{2.5,4.5}$	0.305			3.5	$-0.064^{2.5,4.5}$	0.035	
		4.5	$1.081^{2.5,3.5}$	0.348			4.5	$-0.115^{2.5,3.5}$	0.059	
	YIntrot	2.5	0.154	0.136	0.019*	YExtrot	2.5	-0.075	0.080	0.000*
		3.5	0.169	0.140			3.5	-0.104	0.088	
		4.5	0.177	0.142			4.5	-0.130	0.099	
	ZFlx	2.5	$2.836^{3.5,4.5}$	0.417	0.000*	ZExt	2.5	$-0.478^{3.5,4.5}$	0.079	0.000*
		3.5	$3.180^{2.5,4.5}$	0.473			3.5	$-0.607^{2.5,4.5}$	0.094	
		4.5	3.4152.5,3.5	0.442			4.5	$-0.753^{2.5,3.5}$	0.094	
Ankle	XInv	2.5	$0.119^{3.5,4.5}$	0.090	0.000*	XEver	2.5	$-0.185^{3.5,4.5}$	0.115	0.000*
		3.5	$0.144^{2.5,4.5}$	0.097			3.5	$-0.238^{2.5,4.5}$	0.120	
		4.5	$0.166^{2.5,3.5}$	0.103			4.5	$-0.299^{2.5,3.5}$	0.145	
	YAdd	2.5	0.089	0.085	0.004*	YAbd	2.5	$-0.277^{3.5,4.5}$	0.285	0.000*
		3.5	0.0931	0.088			3.5	$-0.342^{2.5,4.5}$	0.307	
		4.5	0.105	0.094			4.5	$-0.410^{2.5,3.5}$	0.329	
	ZDF	2.5	$2.076^{3.5,4.5}$	0.212	0.000*	ZPF	2.5	$-0.110^{3.5,4.5}$	0.105	0.000*
		3.5	$2.277^{2.5,4.5}$	0.224			3.5	$-0.188^{2.5,4.5}$	0.158	
		4.5	$2.392^{2.5,3.5}$	0.249			4.5	$-0.277^{2.5,3.5}$	0.191	

Variables	Direction	Speed (m/s)	Mean Bonferronni	SD	Repeated Measures
Mechanical Power (W/kg)					
Hip	ZFlx	2.5	2.8813.5, 4.5	1.213	0.000*
		3.5	5.0312.5, 4.5	1.525	
		4.5	7.2402.5, 3.5	1.718	
	ZExt	2.5	-1.9883.5, 4.5	1.092	0.000*
		3.5	-2.9322.5, 4.5	1.380	
		4.5	-3.9432.5, 3.5	1.303	
Knee	ZFlx	2.5	5.9593.5, 4.5	1.388	0.000*
		3.5	6.8622.5, 4.5	1.383	
		4.5	7.5472.5, 3.5	1.429	
	ZExt	2.5	-10.5113.5, 4.5	2.582	0.000*
		3.5	-14.6422.5, 4.5	2.894	
		4.5	-17.6572.5, 3.5	3.555	
Ankle	ZFlx	2.5	6.1933.5, 4.5	1.236	0.000*
		3.5	8.6762.5, 4.5	1.407	
		4.5	11.3082.5, 3.5	1.637	
	ZExt	2.5	-5.2403.5, 4.5	1.786	0.000*
		3.5	-7.2752.5, 4.5	1.259	
		4.5	-9.7372.5, 3.5	1.831	

* Significant difference ($P < 0.05$).

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2.5, 3.5, 4.5 significantly different from running speed 2.5, 3.5, 4.5, respectively ($P<0.05$).

Add: adduction: Abd: abduction; Flex: flexion; Ext: extension; Introt: internal rotation: Extrot: external rotation; PF: plantar flexion; DF: dorsiflexion; Min: minimum; Max: maximum; X: frontal plane; Y: transverse plane; Z: sagittal plane.

speed from 2.5 to 4.5m/s and 3.5 to 4.5m/s. Also, in all other variables, a significant relationship was observed by increasing the speed at all levels.

Figure 2 shows the normalized Mean±SD sagittal, frontal and horizontal plane moments developed about the hip, knee, and ankle joints across the stance cycle for all running speeds. At the hip joint, an adduction moment developed in the middle of the stance phase; the 4.5m/s-speed condition shows the highest peak adduction moment. Also, 4.5 reaches to abduction moment earlier than other conditions (around 30% of running cycle), 3.5m/s speed experienced abduction moment around 35% of running gait cycle and at the end, 2.5m/s speed after 40% of running cycle, the abduction moment is experienced. Although the 3.5m/s-speed condition experienced the highest external rotation peak at the hip transverse plane, the 4.5m/s-condition speed reached the internal status earlier than the other speeds. Also, after 30% of the running cycle, this condition again experiences an external rotation, but two other conditions show almost linear behavior. In the sagittal plane, the hip joint shows ascending behavior at all speeds. The 4.5m/s-speed condition shows the highest extension and flexion, and the 2.5m/s-speed condition shows the lowest. In all conditions, the extensor and the flexor moment change about 25% of the running cycle.

At the knee joint, in the frontal plane, all three conditions show adduction moment behavior, almost during all stance phases. The highest peak adduction moment belongs to the 4.5m/s-condition speed at around 15% of the running cycle, but after 20%, the 2.5m/s-speed condition has the highest peak. In the transverse plane,

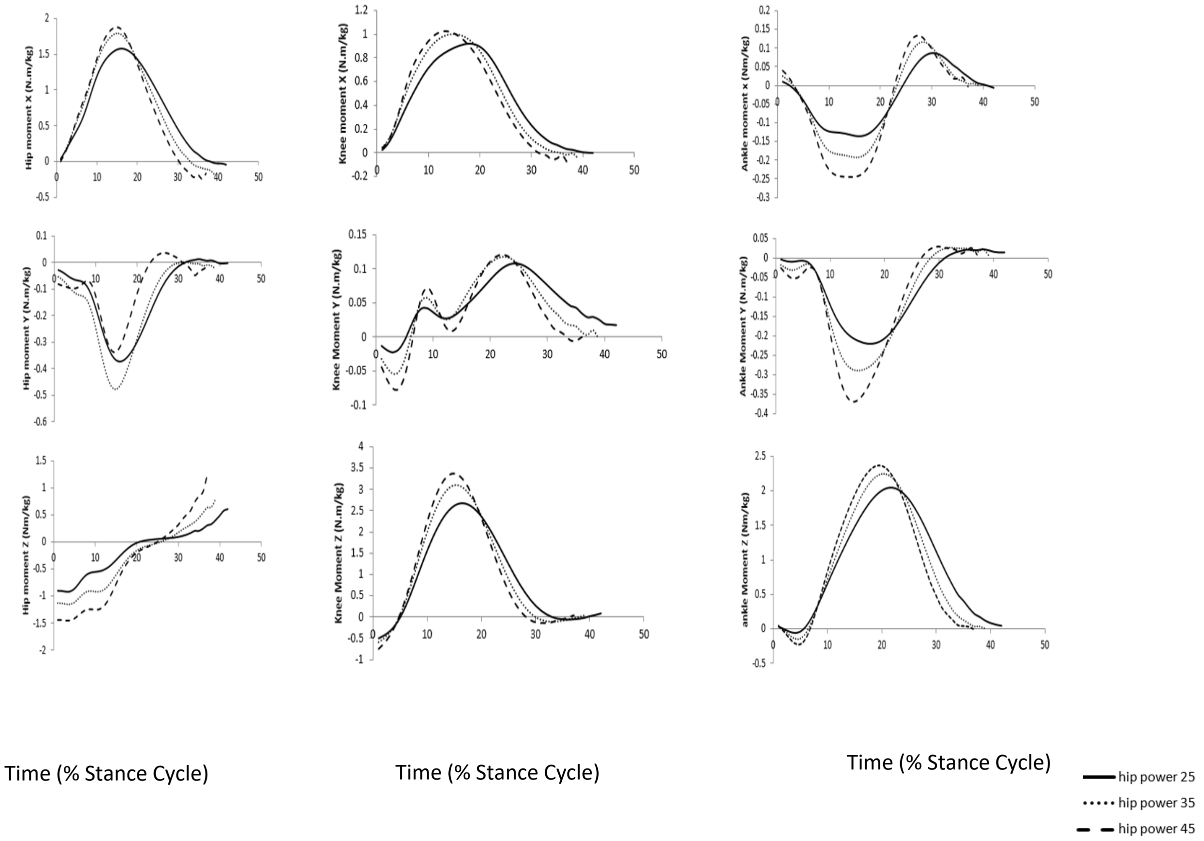

Figure 2. Ensemble time series of 3D hip, knee, and ankle joints moment during running

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During running cycle at 2.5 (solid line), 3.5 (dashed line), and 4.5 (dotted line) speed condition (m/s); X: frontal plane; Y: transverse plane; Z: sagittal plane.

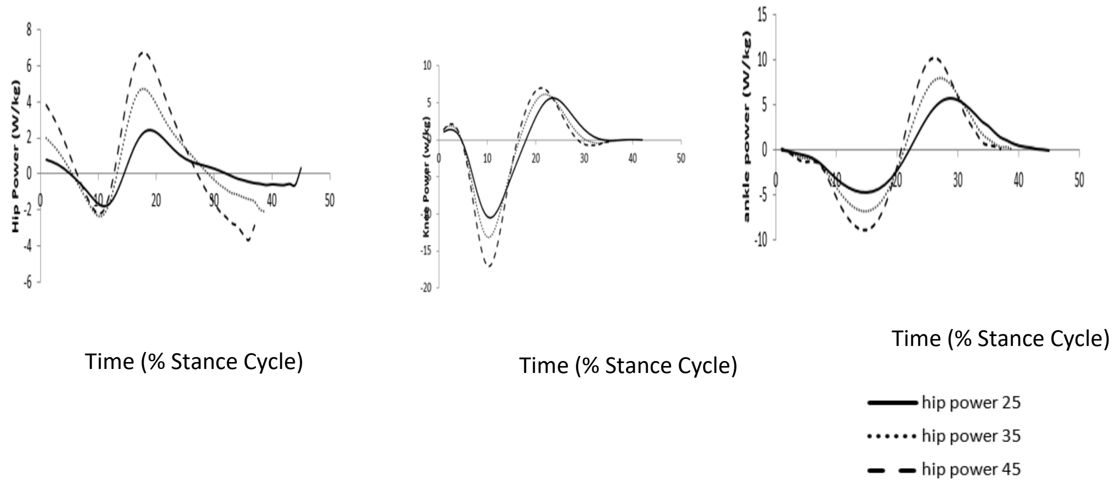

Figure 3. Ensemble time series of 3d hip, knee, and ankle joints mechanical powers

PHYSICAL TREATMENTS

During running cycle at 2.5 (solid line), 3.5 (dashed line), and 4.5 (dotted line) speed conditions (m/s); X: frontal plane; Y: transverse plane; Z: sagittal plane.

peak external rotation happens around 5% of the running cycle, and the 4.5 m/s-condition speed shows the highest amount. After entering the internal rotation peak again, the 4.5 m/s-speed condition shows the highest peaks except for about 15% and after 25% of the running cycle. In the sagittal plane, the knee shows flexor moment behavior after around 5% running cycle up to around 15%-30%. Before 25% of the running cycle, the 4.5 m/s-speed condition showed the highest amount, but after that, the 2.5 m/s-speed condition showed more flexor moment.

In the ankle joint, after a bit adduction moment and 5% of the running cycle, the abduction moment is evident, then around 23% of the cycle, the 4.5 m/s- and 3.5 m/s-speed condition, and around 25% of the cycle, 2.5 m/s-speed condition adduction moment happens. Also, up to 30% of the running cycle, the 4.5 m/s-condition shows the highest peaks, but after that, the 2.5 m/s-speed condition shows the highest value. In the transverse plane, the ankle shows external rotation behavior until the end of the stance phase, after 25% external rotation moment stars, although the 2.5 m/s-speed condition shows this moment later. Also, up to around 25% of the running cycle, the 4.5 m/s-speed condition shows the highest peaks and external rotation behaviors, but after that and until about 30%, the 2.5 m/s-speed condition shows the highest external rotation moment. In the sagittal plane, the ankle shows around 5% of the dorsiflexion moment behavior after a bit of plantar flexion moment behavior, and before the 30% running cycle, the 4.5 m/s condition shows the highest peaks and values. However, after that, the 2.5m/s-speed condition and then 3.5 m/s-speed condition shows more dorsiflexion values.

Figure 3 illustrates the normalized Mean±SD sagittal plane mechanical muscle power developed at the hip, knee, and ankle joints across the stance cycle for all running speeds. At the hip joint, after a bit of flexor and power generation, around 5% to 15% of the running cycle, extensor power happens and reveals an absorption power with eccentric contraction. After 15% of the cycle, a concentric contraction with hip flexion happened in all three conditions. Until about 30% of the running cycle, an extensor muscle power is recreated for 4.5 and 3.5-speed condition, and then after 30% of the cycle, the same happens for the 2.4 m/s condition. In all trend charts and peaks, the 4.5-speed condition has a higher amount and peak, except for the first extensor peak, which is very close to the 3.4-speed condition.

At the knee joint, peak flexor power happened from the beginning up to 5% of the running cycle, then the peak of extensor mechanical muscle power showed about 10% of the cycle with eccentric contraction and absorption. Then, after about 15% of the cycle, flexor power behavior is created for 4.5 and 3.5-condition speed and a little delay for 2.5 m/s-speed level. This generation condition continues until about 35% of the cycle; in all graph processes, the 4.5 m/s-speed condition has the highest peaks and amounts except after the second power flexor peak (after 25% of the cycle), the 2.5 m/s-speed condition shows higher values than two other speed levels.

At the ankle joint, plantarflexion with an absorption contraction is evident from the beginning to about 20% of the running cycle. Then, after this stage, dorsiflexion with a generation contraction happened in this joint until about 40% of the cycle. In all stages, the 4.5 m/s-speed condition shows the highest values and peaks, except after the dorsiflexion peak and 30% of the running cycle, the 2.5-speed condition shows higher amounts.

4. Discussion

The present study investigated the lower limb joint kinetics with increasing running speed. The results showed that at the hip joint in the frontal plane, an adduction moment is developed in the middle of the stance phase, and the highest peak adduction moment is obvious at the highest speed condition (4.5 m/s). Also, the time elapsed to reach the peak in the highest speed condition is less than the others (ES: 2.5-3.5=0.5; 2.5-4.5=0.7; 3.5-4.5=0.2). Although 3.5m/s speed condition experienced the highest external rotation peak moment in transverse plane, the 4.5m/s condition speed reached the internal status earlier than two other speeds (ES: 2.5-3.5=0.5; 2.5-4.5=0.1; 3.5-4.5=-0.3). In the sagittal plane, the highest speed condition showed the highest extension and also flexion moments (ES: 2.5-3.5=-0.2; 2.5-4.5=-1.08; 3.5-4.5=-0.1). These results are consistent with Schache et al. [6] and Edward's research in the sagittal plane [10] but inconsistent in other planes. Runners change their running speed by changing their kinetic behaviors [10]. At higher speed, foot contact time, step and stride length, and adduction force increase. With increased speed conditions during running, the biceps femoris muscle will be active more than others in the lower limb, and the hamstring muscle has a vital role in activating the extensor muscles to produce more force in the sagittal plane [23].

At the knee joint, in the frontal plane, all three conditions show close adduction moment behavior, almost during all stance phases. The highest peak adduction moment belongs to the 4.5 m/s-speed condition (ES: 2.5-3.5=-0.2; 2.5-4.5=-0.4; 3.5-4.5=-0.1). In the transverse plane, the external rotation peak moment in the initiation of the running cycle and 4.5 m/s-speed condition show the maximum. After entering the internal rotation peak again, the 4.5m/s-speed condition shows the highest peaks compared to the others (ES: 2.5-3.5=-0.1; 2.5-4.5=-0.1; 3.5-4.5=-0.06). In the sagittal plane, the knee shows about 15%-30% of that flexor moment after the primary of the running cycle. Before a quarter of the running cycle, the 4.5-speed condition showed the highest value, but after that 2.5m/s-speed condition showed the higher value of flexor moment (ES: 2.5-3.5=-0.7; 2.5-4.5=-1.3; 3.5-4.5=-0.5). These results are consistent with Fukuchi [27], who showed that the maximum knee moment is influenced by increasing speed, but inconsistent with some others because these studies insist that the extensor moment is constant at the knee joint while the flexor moment in the knee joint happens at the end of running cycle [28, 29]. Previous studies have proven the relations between changing knee joint dynamics and increasing speed, especially in the frontal plane [6, 30], and also the increase in load on this joint is clear [10] . Increased knee moments in the frontal and transverse plane are related to more injuries [4, 31, 32] because the knee joint has a crucial role in modifying running stability and control [33]. During running, the quadriceps muscle is the main active muscle, and it is considered the most supportive muscle for the center of mass; the triceps surreal and posterior tibialis are the main interveners in the propulsion of the center of mass during running [19].

In the ankle joint, after a bit of adduction, an abduction moment happened. Also, up to 30% of running cycle, 4.5m/s condition shows the highest peaks, but after that, the 2.5m/s-speed condition shows the highest value (ES: 2.5 3.5=-0.2; 2.5-4.5=-0.4; 3.5-4.5=-0.2). In the transverse plane, the ankle shows external rotation behavior until the end of the stance phase. Also, up to a quarter of running cycle, the 4.5m/s-speed condition shows the highest peaks and external rotation behaviors (ES: 2.5-3.5=-0.4; 2.5-4.5=-0.1; 3.5-4.5=-0.1). In the sagittal plane, ankle shows the dorsiflexion moment after a bit of plantar flexion moment behavior and 4.5 condition shows the highest peaks and values (ES: 2.5-3.5=-0.9; 2.5-4.5=-1.3; 3.5-4.5=-0.4). While the loading speed of the ankle is higher than the knee [19]. Because the plantar flexion moment has a higher value than the knee extensor moment, this fact may relate to more specific ankle injuries compared to knee injuries during running [13]. Consistent with this study, Dorne et al. suggested that the peak force in medial gastrocnemius and soleus would be significantly higher with increasing speed, which could influence plantar flexion and inversion more than dorsiflexion and eversion in the ankle [4].

According to the results of power changes in the sagittal plane, the hip joint shows an extensor eccentric contraction at the begging of the cycle, but before around 15% of the stance cycle to 30% of the cycle, flexor concentric contraction happened. In all stages of eccentric/concentric contractions, 4.5m/s running speed showed the highest amounts of behavior (ES: 2.5-3.5=-1.5; 3.5-4.5=-1.35; 2.5-4.5=-2.9). After a bit concentric contraction knee joint showed eccentric contraction with flexor behavior from 5% to 35%, in all stages, 4.5, 3.5, and 2.5m/s speeds showed higher amount of power peaks and progress respectively, except after 25% of stance cycle that 2.5m/s speed has the highest amount until the end (ES: 2.5-3.5=-0.6; 3.5-4.5=-0.4; 2.5-4.5=-1.1). In the ankle joint, we observed an almost sinusoidal behavior with an eccentric plantarflexion contraction followed by a concentric dorsiflexion contraction from the beginning to around 20% of the gait cycle. In all stages, 4.5m/s speed has higher amount, except after 30% of running cycle, when 2.5 running speed has the highest values compared to other conditions (ES: 2.5-3.5=-1.8; 3.5-4.5=-1.7; 2.5-4.5=-3.5). The results are consistent with previous studies. Arampatzis et al. found that maximum mechanical muscle power in the knee and ankle was influenced by increasing running speed [22]. Also, Kyrola Inen et al. confirm these results and stated that because of the importance of the eccentric activity of extensor muscles like hamstrings in producing force, during the stance phase, the positive power and work activity of the hip which is transferred to the knee and ankle and the closed kinetic chain is created, leads to lower muscle activity which starts from gluteus muscle, then conducts to vastus muscles and then shifts to plantar flexor muscles [24].

The present research was conducted according to the biomechanics of running as one of the most fundamental skills people would perform during their life span. Therefore the results indicated crucial information regarding the biomechanics of the running. In the present study, running skill was performed in an isolated laboratory on the treadmill. It rarely happens that the runner runs at a constant speed and state. Hence, it is recommended to conduct similar research on outdoor running to include ordinary conditions. Also, assessing the muscles' electrical activities during the increasing speed of running seems to be an appropriate title for further research.

5. Conclusion

The results show a significant difference in the moments and power of hip, knee, and ankle joints of many planes by increasing speed in athlete runners. Therefore increasing running speed in runners leads to more kinetic output and energy consumption. Hence runners and coaches should consider this basis in improving the quality of training and decreasing injuries.

Ethical Considerations

Compliance with ethical guidelines

All ethical principles are considered in this article. The participants were informed about the purpose of the research and its implementation stages. They were also assured about the confidentiality of their information and were free to leave the study whenever they wished, and if desired, the research results would be available to them.

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Authors' contributions

All authors contributed to all parts of the research.

Conflict of interest

The authors declared no conflict of interest.

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