applied sciences

Article

Changes in Ground Reaction Forces, Joint Mechanics, and Stiffness during Treadmill Running to Fatigue

Zhen Luo [1,†], Xini Zhang [1,†], Junqing Wang [1], Yang Yang [1], Yongxin Xu [1] and Weijie Fu [1,2,*]

1 School of Kinesiology, Shanghai University of Sport, Shanghai 200438, China; luozhen716@gmail.com (Z.L.); xinizhang.sus@gmail.com (X.Z.); wangjunqing.sus@gmail.com (J.W.); yangyang.sus@gmail.com (Y.Y.); xuyongxin266@gmail.com (Y.X.)

2 Key Laboratory of Exercise and Health Sciences of Ministry of Education, Shanghai University of Sport, Shanghai 200438, China

* Correspondence: fuweijie@sus.edu.cn; Tel.: +86-21-65507368; Fax: +86-21-51253242

† Zhen Luo and Xini Zhang contributed equally to this work.

Received: 31 October 2019; Accepted: 10 December 2019; Published: 13 December 2019

Abstract: Purpose: This study aimed to determine the changes in lower extremity biomechanics during running-induced fatigue intervention. Methods: Fourteen male recreational runners were required to run at 3.33 m/s until they could no longer continue running. Ground reaction forces (GRFs) and marker trajectories were recorded intermittently every 2 min to quantify the impact forces and the lower extremity kinematics and kinetics during the fatiguing run. Blood lactate concentration (BLa) was also collected before and after running. Results: In comparison with the beginning of the run duration, (1) BLa significantly increased immediately after running, 4 min after running, and 9 min after running; (2) no changes were observed in vertical/anterior–posterior GRF and loading rates; (3) the hip joint range of motion (θ_{ROM}) significantly increased at 33%, 67%, and 100% of the run duration, whereas θ_{ROM} of the knee joint significantly increased at 67%; (4) no changes were observed in ankle joint kinematics and peak joint moment at the ankle, knee, and hip; and (5) vertical and ankle stiffness decreased at 67% and 100% of the run duration. Conclusion: GRF characteristics did not vary significantly throughout the fatiguing run. However, nonlinear adaptations in lower extremity kinematics and kinetics were observed. In particular, a "soft landing" strategy, achieved by an increased θ_{ROM} at the hip and knee joints and a decreased vertical and ankle stiffness, was initiated from the mid-stage of a fatiguing run to potentially maintain similar impact forces.

Keywords: fatiguing run; instrumented treadmill; joint range of motion; stiffness

1. Introduction

Long-distance running has many benefits, including reducing the risk of cardiovascular disease [1]. Although there is not sufficient literature demonstrating that injuries are inevitable for all runners, running-related musculoskeletal injuries are still very common. Previous studies showed that the incidence of injury per runner for 1000 h is 18.2–92.4% [2–4] or 6.8–59% [5]. Amongst them, more than 74% of long-distance runners adopt the heel strike pattern [6]. The repetitive impact forces occurred during touchdown can reach a magnitude ranging from 2- to 3-times body weight [7], and are considered as high risk factors of lower limb injury [6].

Long-term and high-intensity running inevitably induces neuromuscular fatigue, which further influences musculoskeletal system of the lower limbs. Generally, the movement control of the lower extremity decreases after fatigue, which is an important cause of running injury [8,9]. However, conclusions on the relationship among fatigue, impact force, and lower extremity biomechanics during prolonged running remain uncertain [10]. Morin [11] found that vertical ground reaction forces (vGRF) decreases with fatigue after multiple groups of repeated sprints are performed on a force treadmill. By contrast, Christina et al. [12] observed that the impact peak and loading rate of the runners increase significantly after fatigue intervention. However, Gerlach et al. [13] found no significant differences in vGRF after fatigue intervention induced by repeated sprints. Similarly, Slawinski et al. [14] reported no changes in vGRF after nine well-trained runners performed an exhaustive exercise over 2000 m on an indoor track. Collectively, multifactorial causes underlie these different responses, and further studies beyond the analysis of the GRF level are warranted to provide insight on the joint mechanics strategies and the underlying stiffness characteristics occurring during running to fatigue.

Most previous studies focused on the direct relationship between fatigue and injury, especially the biomechanical changes in the lower extremities before and after fatigue [15–19]. For instance, Radzak et al. [14] reported the biomechanical asymmetry (e.g., loading rate and knee/vertical stiffness) of the lower limbs before and after fatigue. However, the fatigued state was considered to be achieved only by increased rated perceived exertion (RPE) scores. Abt et al. [17] compared the differences in running kinematics and shock absorption before and after fatigue. However, the influence of running fatigue on kinematics remains inconclusive, which might be partly due to the nonlinear adaptations in lower extremity biomechanics. Clansey et al. [18] reported an increased vertical force loading rate along with increased hip extension and ankle plantarflexion at incremental running speeds before and after two 20-min fatiguing treadmill runs. Nevertheless, they did not determine the threshold at which point the changes may occur. Thus, more investigations are necessary to examine fatigue-induced changes in lower extremity biomechanics not only in pre- and post-fatigue conditions but during the whole progress of a fatiguing run.

In addition, none of the aforementioned studies provided a direct accessible evaluation of running fatigue. Fatigue is generally associated with lactic acid accumulation [20]. Blood lactate concentration (BLa) is an indicator of muscle metabolites and recovery [21]. In the current study, BLa was used to help determine fatigue as a consequence of an insufficient oxygen supply in the capillary blood [22].

The purpose of this study, therefore, was to determine the changes in lower extremity biomechanics, namely, vertical and anterior–posterior GRFs, loading rates, joint mechanics and stiffness, during treadmill running to fatigue. It was hypothesized that joint mechanics and stiffness with fatigue would be changed. Specifically, runners would increase their vGRFs and joint range of motion. They would also have low vertical stiffness (k_{vert}) and joint stiffness during the progress of a fatiguing run.

2. Materials and Methods

2.1. Participants

Fourteen male recreational runners (age: 27.9 ± 7.5 years; height: 175.6 ± 5.5 cm; body mass: 70.4 ± 7.1 kg; weekly running volume: 29.3 ± 12.0 km) with a minimum of 15 km/week for at least 3 months prior to the study were recruited to participate in the study. All the participants had no history of musculoskeletal injuries to the lower extremity in the previous 6 months and did not engage in strenuous exercise for 24 h before the study. Each participant signed an informed consent form before the experiments. The study was approved by the Institutional Review Board of the Shanghai University of Sports (No. 2017007).

2.2. Instrumentation

Kinematic data were collected using an eight-camera infrared 3D motion capture system (Vicon T40, Oxford Metrics, UK) at a sampling rate of 100 Hz. Forty infrared retroreflective markers, each with a diameter of 14.0 mm, were attached bilaterally to both lower extremities to define hip, knee, and ankle joints by using a plug-in gait marker set (Figure 1). GRFs were measured with a split-belt fully instrumented treadmill (Bertec Corporation, Columbus, OH, USA) at a sampling rate of 1000 Hz. The 3D kinematic and GRF data were synchronized using the Vicon system. A heart rate (HR) monitor (V800, Polar Electro-OY, Kempele, Finland) was attached to each participant's chest to continuously monitor their HR during the entire fatiguing run procedure. Blood lactate concentration (BLa) was collected at different time points that were determined from the capillary blood sampled from the right fingertip and assessed with a Biosen C-line glucose analyzer (EKF Diagnostics, Magdeburg, Germany). Specifically, after cleaning with a sterile alcohol swab, a finger prick capillary puncture was performed and approximately 10 µL of sampled whole blood was aspirated into an EKF Diagnostics glucose and lactate analyzer [23]. Four measurement time points were obtained [21,24]: upon arrival at the laboratory (pre-), immediately after running (post-0 min), 4 min after running (post-4 min), and 9 min after running (post-9 min).

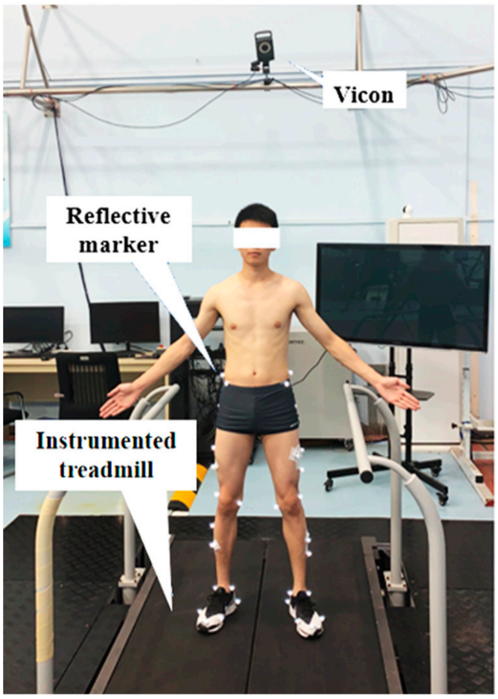

Figure 1. Marker set and experimental setup.

2.3. Running-Induced Fatigue Protocol

The participants were naked from the waist up and run at their self-selected speed for 5 min on the instrumented treadmill as a warm-up and familiarization. Standardized neutral running shoes (Nike Air Pegasus 34) were provided (Nike, Beaverton, OR, USA). Afterwards, they were required to run at 3.33 m/s [25] until they could not continue running [26]. They were considered to have experienced fatigue, and intervention was terminated when both following criteria were met: (1) the HR of the participants reached 90% of their age-calculated maximum HR, and (2) the participants could not continue running.

During the fatiguing run, the running time and the highest HR were recorded. The rated perceived exertion (RPE) using a Borg 6–20 scale was acquired immediately after running.

2.4. Data Processing

For the marker trajectories and GRF data, the measurements of at least 20 steps (15 s) were recorded intermittently every 2 min during the fatiguing run [22]. The sagittal plane kinematic data of the dominant lower extremity, defined as the preferred kicking leg, were filtered through a Butterworth fourth-order, low-pass filter at a cut-off frequency of 14 Hz with V3D software (v5, C-Motion Inc., Germantown, MD, USA) [27]. The kinematic variables of the hip, knee and ankle joints included the following: (1) joint angles (θ_0) at initial contact (Figure 2), (2) maximum joint extension/dorsiflexion angles ($\theta_{max\text{-}ext}$) and peak joint flexion/plantar flexion angles ($\theta_{max\text{-}flx}$) during stance, (3) joint ranges of motion (θ_{ROM}, $\theta_{\mathrm{ROM}} = \theta_{max\text{-}ext} - \theta_{max\text{-}flx}$) during stance, (4) changes in joint angle ($\Delta\theta$, $\theta_{max\text{-}flex} - \theta_0$), and (5) maximum extension/plantarflexion angular velocity ($\omega_{max\text{-}ext}$) during the stance.

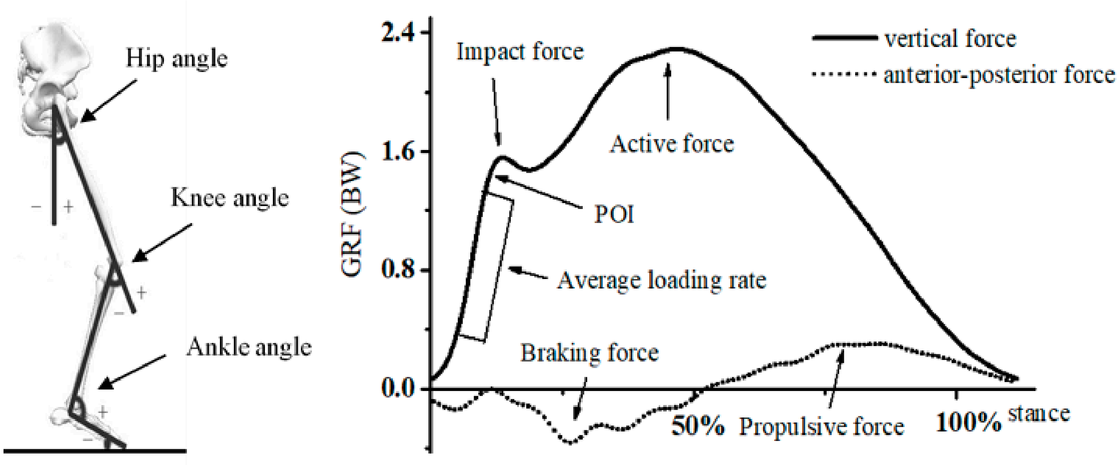

Figure 2. Scheme of lower extremity kinematics and ground reaction force variables. Note: GRF, ground reaction force; BW: body weight; POI: a point of interest.

GRF variables included (1) first and second peak vertical GRFs (F_{zmax1} and F_{zmax2}) and the occurrence time of F_{zmax1} and F_{zmax2} (t_F_{zmax1} and t_F_{zmax2}), (2) maximum and average loading rates (LR_{max} and LR_{avg}; Figure 2), (3) contact time (CT) and (4) maximum propulsive and braking GRF (F_{ymax} and F_{ymin}). Loading rate was calculated on the basis of the method described by Futrell et al. [28]. In brief, a point of interest (POI) was defined as the first point above 75% of a participant's body weight with the instantaneous loading rate less than 15 body weight/s. LR_{max} (i.e., the maximum instantaneous slope) and LR_{avg} (the average slope) were calculated from 20% to 100% and from 20% to 80% of the force at the POI, respectively (Figure 2).

Kinetic variables included the peak moments and joint stiffness [29] [k_j, Equation (1)] of hip, knee and ankle the vertical stiffness of the lower extremity [30] [k_{vert}, Equation (2)], and they were expressed as follows:

$$k_j = \frac{\Delta M}{\Delta \theta} \tag{1}$$

where ΔM is the joint moment difference between initial contact and mid-stance, and $\Delta\theta$ is the joint angle difference between initial contact and mid-stance.

$$k_{vert} = \frac{GRF_i}{\Delta y} \tag{2}$$

where GRF_i is the vertical ground reaction force at the lowest position of the center of gravity (CoG), and Δy is the maximum vertical displacement of CoG.

2.5. Statistics

All data are given as mean ± standard deviation. A power analysis was performed prior to the study to indicate the statistical power. It revealed that a sample size of 14 was sufficient to minimize the probability of Type II error for our variables of interest. A repeated measures ANOVA was performed to determine the effects of time points (pre-, post-0 min, post-4 min, and post-9 min) on BLa. Moreover, the variables from the relative time points of beginning, 33%, 67%, and end of each participant's test were included in this analysis because the participants fatigued at varying periods [31]. Thus, repeated measures analysis of variance (ANOVA) was performed to determine the effects of periods on GRFs, loading rates, joint mechanics, and stiffness (20.0, SPSS, Inc., Chicago, IL, USA). Partial eta squared (η_p^2) was used as an estimate of effect size. Post-hoc pairwise comparison tests were used to assess the changes at the different time points. The level of significance was set at 0.05.

3. Results

3.1. Running-Induced Fatigue Intervention

The intervention time to produce a fatigue state was 28.5 ± 10.4 min. The maximal HR and RPE scale observed during fatigue were 182.9 ± 7.7 bpm and 17.2 ± 0.9, respectively. Moreover, a main effect of time points was observed for BLa ($p < 0.001$, $\eta_p^2 = 0.76$). Specifically, a significant increase in BLa was observed immediately after running (+329.9%, $p < 0.001$), 4 min after running (+251.6%, $p < 0.001$), and 9 min after running (+135.9%, $p = 0.006$) compared with that in the time point corresponding to the pre-running (Figure 3).

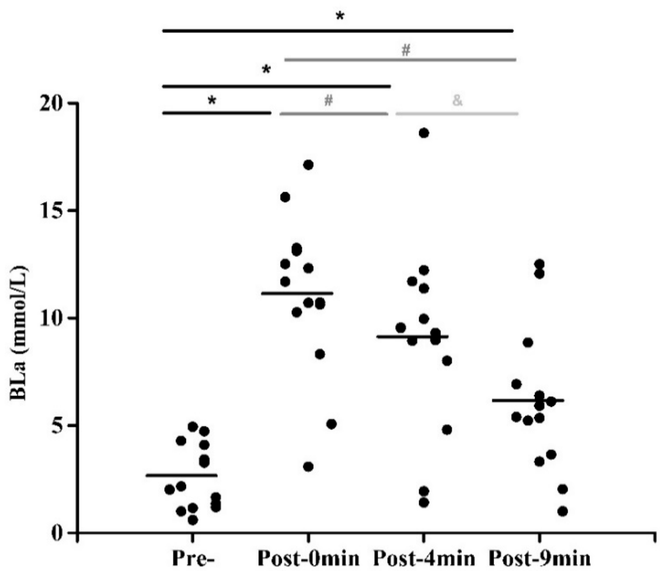

Figure 3. Blood lactate concentration (BLa) at time points corresponding to (**1**) upon arrival at the laboratory (pre-), (**2**) immediately after running (post-0 min), (**3**) 4 min after running (post-4 min), and (**4**) 9 min after running (post-9 min). *, #, and & significantly different from the pre-, post-0 min, and post-4 min with $p < 0.05$, respectively.

3.2. Ground Reaction Force

No significant differences were observed in F_{zmax1}, t_F_{zmax1}, LR_{max}, LR_{avg}, F_{zmax2}, t_F_{zmax2}, F_{ymax}, and F_{ymin} at four time points corresponding to the beginning, 33%, 67%, and 100% of the run duration (Table 1). CT increased significantly at 67% of the run duration compared to the beginning ($p < 0.05$).

Table 1. Ground reaction forces (GRF) characteristics at time points corresponding to the beginning, 33%, 67%, and 100% of the run duration.

Parameter	Beginning	33%	67%	100%	*p*-Value	η_p^2
F_{zmax1} (BW)	1.93 ± 0.21	1.87 ± 0.22	1.90 ± 0.21	1.88 ± 0.22	0.45	0.07
t_F_{zmax1} (s)	0.03 ± 0.01	0.03 ± 0.01	0.03 ± 0.00	0.03 ± 0.01	0.11	0.14
LR_{max} (BW/s)	120.88 ± 25.71	112.58 ± 24.20	118.80 ± 26.14	121.62 ± 27.15	0.04	0.19
LR_{avg} (BW/s)	102.34 ± 22.72	99.58 ± 20.58	102.82 ± 23.09	106.64 ± 25.64	0.16	0.12
F_{zmax2} (BW)	2.48 ± 0.20	2.45 ± 0.14	2.52 ± 0.15	2.51 ± 0.16	0.25	0.10
t_F_{zmax2} (s)	0.09 ± 0.01	0.09 ± 0.00	0.09 ± 0.01	0.09 ± 0.01	0.85	0.02
CT (s)	0.22 ± 0.01	0.22 ± 0.01	0.23 ± 0.01 *	0.23 ± 0.01	0.01	0.25
F_{ymax} (BW)	0.32 ± 0.03	0.32 ± 0.03	0.32 ± 0.03	0.32 ± 0.03	0.89	0.02
F_{ymin} (BW)	−0.47 ± 0.06	−0.48 ± 0.06	−0.49 ± 0.08	−0.48 ± 0.07	0.76	0.03

Note: F_{zmax1}, first peak vGRF; t_F_{zmax1}, the occurrence time of F_{zmax1}; LR_{max}, maximum loading rate; LR_{avg}, average loading rate; F_{zmax2}, second peak vGRF; t_F_{zmax2}, the occurrence time of F_{zmax2}; CT, contact time; F_{ymax}, maximum propulsive GRF; and F_{ymin}, maximum braking GRF. * indicates significant differences from the values obtained at the beginning ($p < 0.05$).

3.3. Joint Mechanics

In comparison with joint range of motion (θ_{ROM}) at the beginning, θ_{ROM} of the knee joint significantly increased at 33% and 67% of the run duration, and θ_{ROM}, $\Delta\theta$, θ_0, and $\theta_{max\text{-}ext}$ of the hip joint significantly increased at 33%, 67%, and 100% of the run duration (Figure 4 and Table 2). No significant differences were observed in θ_0, θ_{max}, $\omega_{max\text{-}ext}$, and M_{max} of the three joints, and θ_{ROM} and $\Delta\theta$ of the ankle joint amongst four time points (Table 2).

Table 2. Kinematics and joint moment of hip, knee, and ankle joints at time points corresponding to the beginning, 33%, 67%, and 100% of the run duration.

Joint	Parameter	Beginning	33%	67%	100%	*p*-Value	η_p^2
Ankle	θ_0 (°)	2.11 ± 2.80	0.87 ± 3.57	0.92 ± 3.32	0.84 ± 3.41	0.05	0.18
	$\theta_{max\text{-}ext}$ (°)	19.40 ± 3.09	19.49 ± 3.52	19.88 ± 3.08	19.90 ± 2.98	0.25	0.10
	$\theta_{max\text{-}flex}$ (°)	−21.61 ± 4.01	−21.07 ± 2.75	−22.06 ± 3.90	−21.73 ± 2.77	0.51	0.06
	θ_{ROM} (°)	41.01 ± 4.06	40.56 ± 3.18	41.94 ± 3.49	41.63 ± 2.37	0.24	0.12
	$\Delta\theta$ (°)	23.72 ± 4.14	21.94 ± 3.49	22.98 ± 3.46	22.57 ± 3.17	0.23	0.10
	$\omega_{max\text{-}ext}$ (°/s)	584.90 ± 56.63	577.63 ± 48.96	584.13 ± 46.71	567.19 ± 64.55	0.77	0.03
	M_{max} (N·m/kg)	−3.69 ± 0.42	−3.65 ± 0.53	−3.71 ± 0.48	−3.76 ± 0.61	0.83	0.02
Knee	θ_0 (°)	−17.08 ± 5.81	−18.15 ± 4.90	−18.89 ± 5.09	−18.67 ± 5.00	0.04	0.24
	$\theta_{max\text{-}ext}$ (°)	−14.16 ± 4.30	−13.15 ± 5.27	−13.56 ± 5.06	−14.54 ± 5.30	0.09	0.15
	$\theta_{max\text{-}flex}$ (°)	−37.63 ± 5.34	−38.60 ± 5.56	−37.92 ± 8.63	−39.47 ± 5.54	0.37	0.08
	θ_{ROM} (°)	23.47 ± 4.17	25.45 ± 3.17 *	25.97 ± 2.76 *	24.93 ± 2.59	<0.01	0.32
	$\Delta\theta$ (°)	20.56 ± 3.80	20.45 ± 3.45	19.03 ± 7.36	20.81 ± 3.30	0.46	0.06
	$\omega_{max\text{-}ext}$ (°/s)	492.84 ± 78.22	460.21 ± 91.37	479.65 ± 95.40	462.48 ± 83.61	0.12	0.14
	M_{max} (N·m/kg)	−1.77 ± 0.48	−1.79 ± 0.38	−1.84 ± 0.60	−1.91 ± 0.56	0.69	0.04
Hip	θ_0 (°)	26.93 ± 8.88	29.48 ± 3.83 *	29.70 ± 9.68 *	30.74 ± 9.98 *	<0.01	0.47
	$\theta_{max\text{-}ext}$ (°)	27.78 ± 8.35	30.05 ± 8.58 *	30.92 ± 8.64 *	30.47 ± 9.69 *	<0.01	0.45
	$\theta_{max\text{-}flex}$ (°)	−9.24 ± 8.22	−9.8 ± 9.41	−9.87 ± 8.34	−10.60 ± 10.18	0.28	0.09
	θ_{ROM} (°)	37.02 ± 3.00	39.88 ± 2.84 *	40.79 ± 3.10 *	40.07 ± 4.27 *	<0.01	0.44
	$\Delta\theta$ (°)	36.17 ± 3.83	39.31 ± 2.84 *	39.57 ± 3.13 *	41.34 ± 4.38 *	<0.01	0.41
	$\omega_{max\text{-}ext}$ (°/s)	307.81 ± 30.56	311.94 ± 23.54	316.99 ± 28.24	308.58 ± 29.92	0.62	0.04
	M_{max} (N·m/kg)	2.97 ± 0.50	3.23 ± 0.86	3.22 ± 0.86	3.45 ± 0.74	0.09	0.15

Note: θ_0, angle at initial contact; $\theta_{max\text{-}ext}$, maximum extension/dorsiflexion angle during the stance phase; $\theta_{max\text{-}flx}$, maximum flexion/plantar flexion angle during the stance phase; θ_{ROM}, joint range of motion; $\Delta\theta$, $\theta_{max\text{-}flx}-\theta_0$; $\omega_{max\text{-}ext}$, maximum extension/plantarflexion angular velocity during the stance phase; M_{max}, peak joint moment maximum. * indicates significant differences from the values at the beginning ($p < 0.05$).

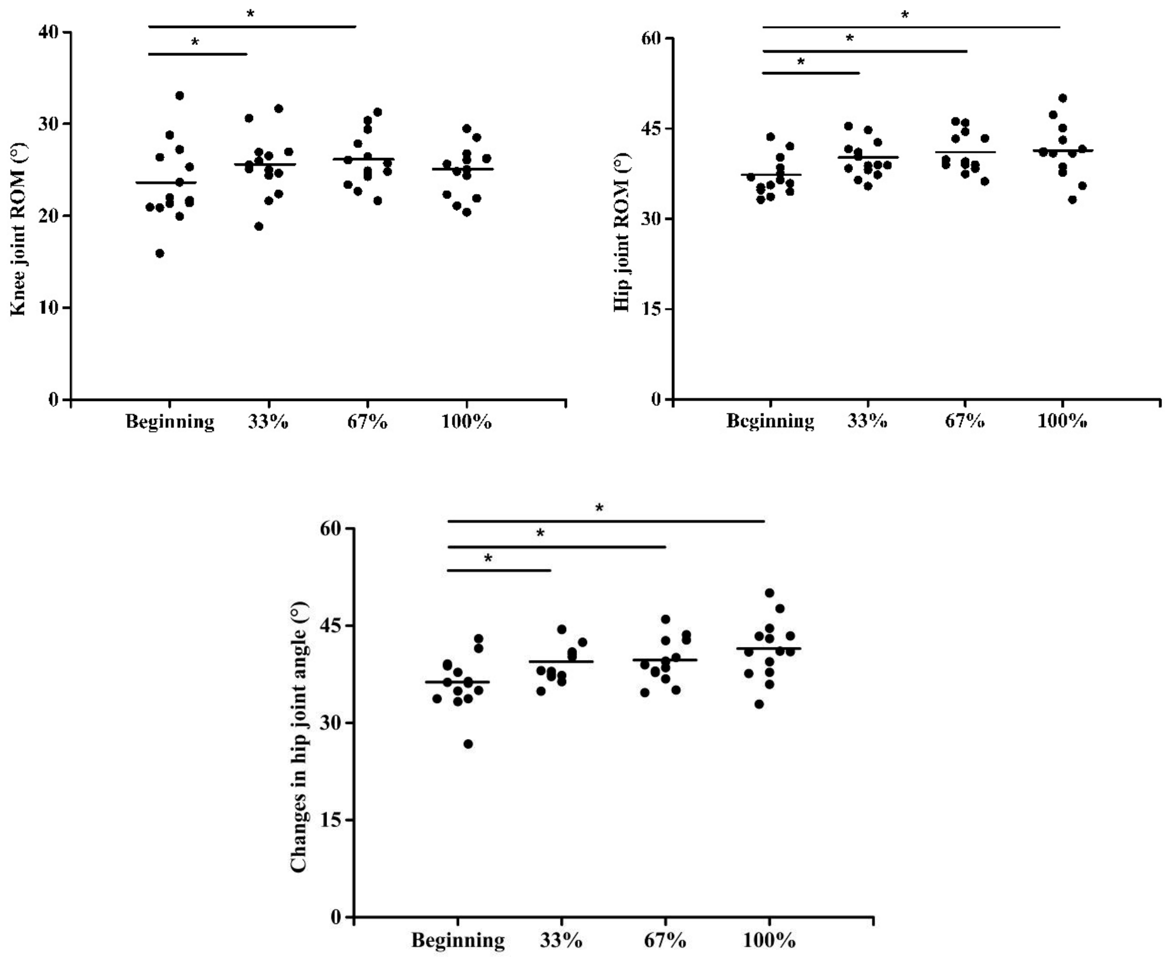

Figure 4. Knee joint range of motion (ROM), hip joint ROM, and changes in angle ($\Delta\theta$) of the hip joint at time points corresponding to the beginning, 33%, 67%, and 100% of the run duration. * significantly different from the beginning with $p < 0.05$.

3.4. Stiffness

In comparison with k_{vert} at the beginning, k_{vert} showed a trend towards a decrease at 67% and 100% of the run duration, respectively (Table 3). Meanwhile, significant main effects of time points were observed for Δy and k_{ankle} (Table 3). Specifically, k_{ankle} significantly increased at 33%, 67%, and 100% of the run duration (Figure 5).

Table 3. Vertical stiffness and joint stiffness at time points corresponding to the beginning, 33%, 67%, and 100% of the run duration.

Parameter	Beginning	33%	67%	100%	*p*-Value	η_p^2
k_{vert} (N/kg/m)	67.41 ± 10.54	65.65 ± 6.97	63.05 ± 8.23	61.32 ± 6.67	0.06	0.17
Δy (m)	0.038 ± 0.004	0.038 ± 0.004	0.040 ± 0.005	0.041 ± 0.004	0.03	0.20
k_{hip} (N·m/kg/°)	0.55 ± 0.35	0.62 ± 0.22	0.56 ± 0.28	0.77 ± 0.45	0.07	0.16
k_{knee} (N·m/kg/°)	0.04 ± 0.03	0.06 ± 0.03 *	0.05 ± 0.03	0.06 ± 0.03	<0.01	0.33
k_{ankle} (N·m/kg/°)	0.21 ± 0.03	0.19 ± 0.03	0.20 ± 0.03 $^{*\#}$	0.20 ± 0.04 $^{*\#\&}$	0.03	0.20

Note: k_{vert}, vertical stiffness; Δy, changes in the vertical displacement of the center of gravity; k_{joint}, joint stiffness. *, #, and & significantly different from the pre-, post-0 min, and post-4 min with $p < 0.05$, respectively.

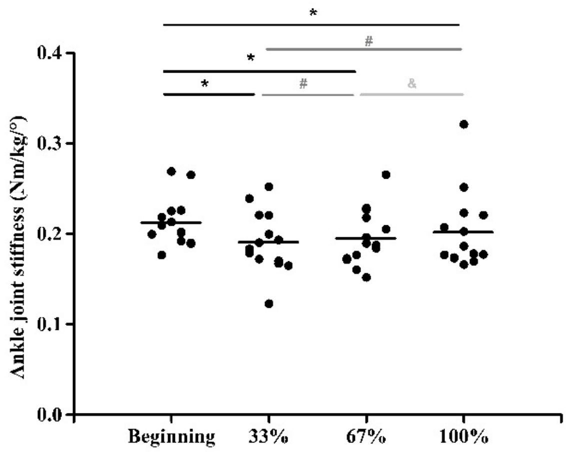

Figure 5. Stiffness of the ankle joint at time points corresponding to the beginning, 33%, 67%, and 100% of the run duration. *, #, and & significantly different from the beginning, 33%, and 67% of the run duration with $p < 0.05$, respectively.

4. Discussion

This study aimed to determine the changes in lower extremity biomechanics, i.e., vertical and anterior–posterior GRFs, loading rates, joint mechanics and stiffness, during treadmill running to fatigue. Our findings supported the hypotheses that an increased range of motion at the hip and knee joints and a decreased vertical and ankle stiffness of the lower extremity were observed during the progress of a fatiguing run. However, GRF characteristics, i.e., vertical/propulsive/braking GRF and peak loading rates, did not vary significantly throughout the fatiguing run.

4.1. Fatigue Intervention

In this experiment, after the fatigue intervention, the blood lactic acid was changed from 2.5 ± 1.5 mmol/L (at rest) to 11.1 ± 3.6 mmol/L (immediately after fatigue), which was consistent with a previous study (from 1.9 ± 0.8 mmol/L to 12.4 ± 3.8 mmol/L) [32]. Specifically, in comparison with the rest state, the blood lactic acid at the ninth minute still significantly increased, and the intervention intensity could be considered the standard of running fatigue. The average intervention time of this experiment was 28.5 min, the maximum heart rate reached 182.9 bpm, and the RPE scale was 17.2 (corresponding to "very hard"). These values were supported by our previous study [33,34].

4.2. Ground Reaction Force

In our study, ground reaction forces, such as first and second peaks, had no significant difference before and after fatigue. Our observation was consistent with the findings of m [35] and Abt et al. [18], who used the same test speed or a faster speed in their experiments. It implied that the impact forces as well as the active forces would not change significantly throughout the whole fatiguing run. Generally, repetitive and passive impact forces in running are considered to be one of the main causes of the overuse injury of the lower extremities; these forces elicit a comprehensive fatigue effect and inhibit musculoskeletal remodeling and repair [36]. According to this mechanism, one of the key factors causing running overuse injury is fatigue, and the repeatability of running is one of the potential factors that may cause fatigue [18]. In addition, the loading rate is considered a sensitive impact force parameter in the run-and-jump motion [4,37,38], which is more reflective of the relationship between running impact and running injury compared with the impact peak. However, in our study, the average loading rate, along with vertical GRFs, did not vary significantly during the whole fatigue process. This observation also supported that of Zadpoor et al. [39]. In summary, fatigue intervention had no significant effect on the impact force and loading rate during a fatiguing run because the impact and loading rate were closely related to the strike pattern. This finding indicated that no linear relationship was found between the impact and loading rate and the muscle fatigue of lower extremities without changing the running strike pattern. Three joints and the surrounding muscles would adapt, transmit, and further attenuate the impact force, avoiding damage caused by repeated impacts when individuals were running for a long time.

4.3. Joint Mechanics

In this study, θ_{ROM} of the knee joint increased significantly at 33% and 66% of the run duration. However, no changes were observed for the maximum knee flexion. Abt et al. [18] required the male participants to run on a treadmill at 3.3 m/s speed until exhaustion. Similarly, no significant differences existed for maximum knee and ankle flexion after fatigue. On the other hand, θ_{ROM} and $\Delta\theta$ of the hip joint at 33%, 67% and 100% of the run duration significantly increased compared with those at the beginning. This finding supported the results of Sara et al. [40] possibly because θ_{ROM} of hip and knee joints, as the large joints of the lower extremities, increased, leading to a decrease in Δy during the stance phase rather than relying solely on the single joint of the knee joint. It is speculated that the kinematic changes after running fatigue may be a compensation mechanism to reduce the possibility of injury rather than the result of fatigue [9]. θ_{ROM} of the hip and knee joints decreased starting from the middle stage of the fatiguing run. This finding seems to be another evidence of the abovementioned explanation. Generally, approximately 70–80% of the impact force is absorbed by the knee joint during running, and the resolution of this impact force is crucial to prevent overuse damage [41]. To absorb these impact forces, the human body properly coordinates the joint activities of the lower limbs through the regulation of joint activities in the musculoskeletal system [31,42]. The current findings indicated that the hip and knee kinematic chains of human lower extremities played an important role in response to the progress of fatigue but did not passively attenuate the impact.

4.4. Stiffness

In the progress of a fatiguing run, k_{vert} showed a trend towards a decrease at 67% and 100% of the running period compared with that of the pre-fatigue period. Meanwhile, Δy significantly increased at the middle and late stages. However, no differences were observed in vGRF. These findings might explain the nonlinear relationship between vGRF and k_{vert}. Furthermore, the stiffness of the ankle joints significantly reduced at 33%, 67%, and 100% of the running period compared with that of the pre-fatigue period.

Generally, vertical stiffness is considered an important factor in the spring-mass model of the musculoskeletal system, which is closely related to injuries [43]. Previous studies [31] suggested that k_{vert} decreases during fatigue if an individual is fatigued at a constant speed, and changes in k_{vert} are inversely related to Δy rather than vGRF during the stance phase. These results were supported by our findings. Goodwin et al. [44] showed that the reduction in k_{vert} during running was related to the range of motion (ROM) of the larger joint. To maintain the stability of the lower extremity and reduce the cumulative impact injuries, the human body automatically reduces Δy and k_{vert}. This strategy achieves a “soft landing” within a certain joint ROM. Previous studies [31,45] found that the “soft landing” was related to the decreased stiffness of the ankle joints after fatigue, which was in accordance with our findings. Moreover, k_{vert} is also related to running economy and energy efficiency. Another study [46] has shown that the energy utilization rate increased with k_{vert}. In the later stage of medium/high-intensity long-term exercise, k_{vert} might decrease as oxygen uptake increases, and the energy utilization and running economy gradually decrease. Future studies should focus on the effects of fatigue on the running economy of the joints of the lower extremities after runners’ transition from a rearfoot strike to a forefoot strike. Future studies should also investigate the differences in running economy between different strike patterns.

4.5. Limitations

In this study we required participants to run on the treadmill, but one cannot be certain that their running pattern was not affected by factors such as the adaptation of the lower extremity to the running belt transfer speed and the instability of treadmill itself. Furthermore, we did not collect surface electromyographic data to simplify the design by focusing on GRFs and joint mechanics and by limiting the experimental devices that were attached to the runners. Finally, the role of gender should also be taken into account in the future study.

5. Conclusions

GRF characteristics, i.e., vertical/propulsive/braking GRF and peak loading rates, did not vary significantly throughout the fatiguing run. However, nonlinear adaptations in lower extremity kinematics and kinetics were observed. In particular, a "soft landing" strategy, achieved by an increased range of motion at the hip and knee joints and a decreased vertical and ankle stiffness of the lower extremity, was initiated from the mid-stage (e.g., 33% and 67%) of a fatiguing run to potentially maintain similar impact forces. These findings provide preliminary evidence suggesting the hip and knee kinematic chains played an important role in response to the progress of running to fatigue which may require additional attention during training.

Author Contributions: Z.L., X.Z., contributed equally. Conceptualization, W.F.; methodology, Z.L.; formal analysis, Z.L., X.Z., J.W., and Y.Y.; investigation, Z.L., X.Z., J.W., Y.Y., and W.F.; resources, W.F.; data curation, Z.L., X.Z.; writing—original draft preparation, Z.L., X.Z., J.W., and Y.X.; writing—review and editing, X.Z. and W.F.; project administration, W.F.; funding acquisition, W.F.

Funding: This work was supported by the National Natural Science Foundation of China (11772201, 11572202); Talent Development Fund of Shanghai Municipal (2018107); Shanghai Committee of Science and Technology (17080503300); the National Key Technology Research and Development Program of the Ministry of Science and Technology of China (2019YFF0302100); the "Dawn" Program of Shanghai Education Commission (19SG47), China.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Williams, P.T. Dose of exercise and health benefit. *Arch. Intern. Med.* **1997**, *157*, 1774. [CrossRef] [PubMed]
2. Saragiotto, B.T.; Yamato, T.P.; Hespanhol Junior, L.C.; Rainbow, M.J.; Davis, I.S.; Lopes, A.D. What are the main risk factors for running-related injuries? *Sports Med.* **2014**, *44*, 1153–1163. [CrossRef] [PubMed]
3. Van Middelkoop, M.; Kolkman, J.; Van Ochten, J.; Bierma-Zeinstra, S.M.; Koes, B.W. Risk factors for lower extremity injuries among male marathon runners. *Scand. J. Med. Sci. Sports* **2008**, *18*, 691–697. [CrossRef] [PubMed]
4. van Gent, R.N.; Siem, D.; van Middelkoop, M.; van Os, A.G.; Bierma-Zeinstra, S.M.; Koes, B.W. Incidence and determinants of lower extremity running injuries in long distance runners: A systematic review. *Br. J. Sports Med.* **2007**, *41*, 469–480. [CrossRef] [PubMed]
5. Buist, I.; Bredeweg, S.W.; Bessem, B.; van Mechelen, W.; Lemmink, K.A.; Diercks, R.L. Incidence and risk factors of running-related injuries during preparation for a 4-mile recreational running event. *Br. J. Sports Med.* **2010**, *44*, 598–604. [CrossRef] [PubMed]
6. Bonacci, J.; Saunders, P.U.; Hicks, A.; Rantalainen, T.; Vicenzino, B.G.; Spratford, W. Running in a minimalist and lightweight shoe is not the same as running barefoot: A biomechanical study. *Br. J. Sports Med.* **2013**, *47*, 387–392. [CrossRef]
7. Lieberman, D.E.; Venkadesan, M.; Werbel, W.A.; Daoud, A.I.; D'Andrea, S.; Davis, I.S.; Mang'eni, R.O.; Pitsiladis, Y. Foot strike patterns and collision forces in habitually barefoot versus shod runners. *Nature* **2010**, *463*, 531–535. [CrossRef]
8. Lieber, R.L. Biomechanical response of skeletal muscle to eccentric contractions. *J. Sport Health Sci.* **2018**, *7*, 294–309. [CrossRef]
9. Derrick, T.R.; Dereu, D.; McLean, S.P. Impacts and kinematic adjustments during an exhaustive run. *Med. Sci. Sports Exerc.* **2002**, *34*, 998–1002. [CrossRef]

10. Zadpoor, A.A.; Nikooyan, A.A. The effects of lower extremity muscle fatigue on the vertical ground reaction force: A meta-analysis. *Proc. Inst. Mech. Eng. H* **2012**, *226*, 579–588. [CrossRef]
11. Morin, J.B.; Samozino, P.; Edouard, P.; Tomazin, K. Effect of fatigue on force production and force application technique during repeated sprints. *J. Biomech.* **2011**, *44*, 2719–2723. [CrossRef] [PubMed]
12. Christina, K.A.; White, S.C.; Gilchrist, L.A. Gilchrist. Effect of localized muscle fatigue on vertical ground reaction forces and ankle joint motion during running. *Hum. Mov. Sci.* **2001**, *20*, 257–276. [CrossRef]
13. Gerlach, K.E.; White, S.C.; Burton, H.W.; Dorn, J.M.; Leddy, J.J.; Horvath, P.J. Kinetic changes with fatigue and relationship to injury in female runners. *Med. Sci. Sports Exerc.* **2005**, *37*, 657–663. [CrossRef] [PubMed]
14. Slawinski, J.; Heubert, R.; Quievre, J.; Billat, V.; Hanon, C. Changes in spring-mass model parameters and energy cost during track running to exhaustion. *J. Strength Cond. Res.* **2008**, *22*, 930–936. [CrossRef] [PubMed]
15. Radzak, K.N.; Putnam, A.M.; Tamura, K.; Hetzler, R.K.; Stickley, C.D. Asymmetry between lower limbs during rested and fatigued state running gait in healthy individuals. *Gait Posture* **2017**, *51*, 268–274. [CrossRef] [PubMed]
16. Kuhman, D.; Melcher, D.; Paquette, M.R. Ankle and knee kinetics between strike patterns at common training speeds in competitive male runners. *Eur. J. Sport Sci.* **2016**, *16*, 433–440. [CrossRef]
17. Brown, A.M.; Zifchock, R.A.; Hillstrom, H.J.; Song, J.; Tucker, C.A. The effects of fatigue on lower extremity kinematics, kinetics and joint coupling in symptomatic female runners with iliotibial band syndrome. *Clin. Biomech.* **2016**, *39*, 84–90. [CrossRef]
18. John, P.; Abt, A.S.M.L.; Sell, T.C. Running kinematics and shock absorption do not change after brief exhaustive running. *J. Strength Cond. Res.* **2011**, *25*, 1479–1485.
19. Clansey, A.C.; Hanlon, M.; Wallace, E.S.; Lake, M.J. Effects of fatigue on running mechanics associated with tibial stress fracture risk. *Med. Sci. Sports Exerc.* **2011**, *44*, 1917–1923. [CrossRef]
20. Jan Hoff, Y.S. Arnstein finstad, eivind wang, and jan helgerud increased blood lactate level deteriorates running economy in world class endurance athletes. *J. Ofstrength Cond. Res.* **2016**, *30*, 1373–1378. [CrossRef]
21. Hsu, W.-C.; Tseng, L.-W.; Chen, F.-C.; Wang, L.-C.; Yang, W.-W.; Lin, Y.-J.; Liu, C. Effects of compression garments on surface EMG and physiological responses during and after distance running. *J. Sport Health Sci.* **2017**. [CrossRef]
22. Weist, R.; Eils, E.; Rosenbaum, D. The Influence of Muscle Fatigue on Electromyogram and Plantar Pressure Patterns as an Explanation for the Incidence of Metatarsal Stress Fractures. *Am. J. Sports Med.* **2004**, *32*, 1893–1898. [CrossRef] [PubMed]
23. Tanner, R.K.; Fuller, K.L.; Ross, M.L. Evaluation of three portable blood lactate analysers: Lactate Pro, Lactate Scout and Lactate Plus. *Eur. J. Appl. Physiol.* **2010**, *109*, 551–559. [CrossRef] [PubMed]
24. Devlin, J.; Paton, B.; Poole, L.; Sun, W.; Ferguson, C.; Wilson, J.; Kemi, O.J. Blood lactate clearance after maximal exercise depends on active recovery intensity. *J. Sports Med. Phys. Fit.* **2014**, *54*, 271–278.
25. Maas, E.; De Bie, J.; Vanfleteren, R.; Hoogkamer, W.; Vanwanseele, B. Novice runners show greater changes in kinematics with fatigue compared with competitive runners. *Sports Biomech.* **2018**, *17*, 350–360. [CrossRef]
26. Koblbauer, I.F.; van Schooten, K.S.; Verhagen, E.A.; van Dieen, J.H. Kinematic changes during running-induced fatigue and relations with core endurance in novice runners. *J. Sci. Med. Sport* **2014**, *17*, 419–424. [CrossRef]
27. Fu, W.; Fang, Y.; Gu, Y.; Huang, L.; Li, L.; Liu, Y. Shoe cushioning reduces impact and muscle activation during landings from unexpected, but not self-initiated, drops. *J. Sci. Med. Sport* **2017**. [CrossRef]
28. Futrell, E.E.; Jamison, S.T.; Tenforde, A.S.; Davis, I.S. Relationships between Habitual Cadence, Footstrike, and Vertical Loadrates in Runners. *Med. Sci. Sports Exerc.* **2018**, *50*, 1837–1841. [CrossRef]
29. Hamill, J.; Moses, M.; Seay, J. Lower extremity joint stiffness in runners with low back pain. *Res. Sports Med.* **2009**, *17*, 260–273. [CrossRef]
30. Liu, Y.; Peng, C.H.; Wei, S.H.; Chi, J.C.; Tsai, F.R.; Chen, J.Y. Active leg stiffness and energy stored in the muscles during maximal counter movement jump in the aged. *J. Electromyogr. Kinesiol.* **2006**, *16*, 342–351. [CrossRef]
31. Dutto, D.J.; Smith, G.A. Changes in spring-mass characteristics during treadmill running to exhaustion. *Med. Sci. Sports Exerc.* **2002**, *34*, 1324–1331. [CrossRef]

32. Stajer, V.; Vranes, M.; Ostojic, S.M. Correlation between biomarkers of creatine metabolism and serum indicators of peripheral muscle fatigue during exhaustive exercise in active men. *Res. Sports Med.* **2018**. [CrossRef] [PubMed]
33. Zhang, X.; Xia, R.; Dai, B.; Sun, X.; Fu, W. Effects of Exercise-Induced Fatigue on Lower Extremity Joint Mechanics, Stiffness, and Energy Absorption during Landings. *J. Sports Sci. Med.* **2018**, *17*, 640–649. [PubMed]
34. Avela, J.; Kyröläinen, H.; Komi, P.V.; Rama, D. Reduced reflex sensitivity persists several days after long-lasting stretch-shortening cycle exercise. *J. Appl. Physiol.* **1999**, *86*, 1292–1300. [CrossRef] [PubMed]
35. Bazuelo-Ruiz, B.; Dura-Gil, J.V.; Palomares, N.; Medina, E.; Llana-Belloch, S. Effect of fatigue and gender on kinematics and ground reaction forces variables in recreational runners. *Peer J.* **2018**, *6*, e4489. [CrossRef] [PubMed]
36. Hreljac, A.; Marshall, R.N.; Hume, P.A. Evaluation of lower extremity overuse injury potential in runners. *Med. Sci. Sports Exerc.* **2000**, *32*, 1635–1641. [CrossRef]
37. Pohl, M.B.; Hamill, J.; Davis, I.S. Biomechanical and anatomic factors associated with a history of plantar fasciitis in female runners. *Clin. J. Sport Med.* **2009**, *19*, 372–376. [CrossRef]
38. Milner, C.E.; Ferber, R.; Pollard, C.D.; Hamill, J.; Davis, I.S. Biomechanical factors associated with tibial stress fracture in female runners. *Med. Sci. Sports Exerc.* **2006**, *38*, 323–328. [CrossRef]
39. Zadpoor, A.A.; Nikooyan, A.A. The relationship between lower-extremity stress fractures and the ground reaction force: A systematic review. *Clin. Biomech.* **2011**, *26*, 23–28. [CrossRef]
40. Winter, S.; Gordon, S.; Watt, K. Effects of fatigue on kinematics and kinetics during overground running: A systematic review. *J. Sports Med. Phys. Fit.* **2017**, *57*, 887–899.
41. Kim, W.; Voloshin, A.S.; Johnson, S.H. Modeling of heel strike transients during running. *Hum. Mov. Sci.* **1994**, *13*, 221–244. [CrossRef]
42. Mercer, J.A.; Bates, B.T.; Dufek, J.S.; Hreljac, A. Characteristics of shock attenuation during fatigued running. *J. Sports Sci.* **2003**, *21*, 911–919. [CrossRef] [PubMed]
43. Jordan, M.J.; Aagaard, P.; Herzog, W. A comparison of lower limb stiffness and mechanical muscle function in ACL-reconstructed, elite, and adolescent alpine ski racers/ski cross athletes. *J. Sport Health Sci.* **2018**, *7*, 416–424. [CrossRef] [PubMed]
44. Jonathan, S.; Goodwin, J.T.B.; Todd, A.; Schwartz, D.S. Blaise Williams III. Clinical predictors of dynamic lower extremity stiffness during running. *J. Orthop. Sports Phys. Ther.* **2018**, *49*, 98–104.
45. Kuitunen, S.; Komi, P.V.; Kyröläinen, H. Knee and ankle joint stiffness in sprint running. *Med. Sci. Sports Exerc.* **2002**, *34*, 166–173. [CrossRef]
46. Perl, D.P.; Daoud, A.I.; Lieberman, D.E. Effects of footwear and strike type on running economy. *Med. Sci. Sports Exerc.* **2012**, *44*, 1335–1343. [CrossRef]