Inter-Individual Variability in The Joint Negative Work During Running

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ABSTRACT

The inter-individual variability of running technique is an important factor affecting the negative work of lower extremity joints that leads to muscle damage. Our study examines the relationships between the negative work of the lower extremity joints and the associated mechanical parameters that account for inter-individual variability in the negative work. Twenty-four young male adults were asked to run on a runway at a speed of $3.0\,\mathrm{m\cdot s^{-1}}$. Multiple linear regression analysis was conducted to examine the relationships between the negative work and the associated mechanical parameters for each lower extremity joint. With regards to the results, 76.3 % of inter-individual variability in the negative work of the hip joint was accounted for by inter-individual variabilities in the corresponding moment (25.4 %) and duration (50.9 %). For the knee joint, the inter-individual variabilities in the moment (40.6 %), angular velocity (24.5 %), and duration (23.8 %) accounted for 88.9 % of inter-individual variability in the negative work. The inter-individual variability in the moment of the ankle joint alone accounted for 89.3 % of the inter-individual variability in the corresponding negative work. These results suggest that runners can change the negative work by adapting their running techniques to influence the relevant mechanical parameter values; however, major parameters corresponding to the change in the negative work are not the same among the lower extremity joints.

Introduction

Muscles attached to lower extremity joints are chronically exposed to great mechanical load during running, which can lead to damage. Muscle damage is necessary for muscle adaptation, whereas the accumulation of muscle damage develops muscle injury [11, 30]. Muscle damage accompanied by soreness is generally developed by repeated eccentric muscle contraction [1]. Eccentric muscle contraction recruits a small number of muscle fibers to exert a given amount of force as compared with concentric and isometric muscle contractions [10, 31]. Therefore, muscle fibers recruited for eccentric muscle contraction are required to bear considerable stress, which can lead to increased muscle damage [28]. Because the negative work of the joint corresponds to the negative work generated by the associated eccentric muscle contraction [7, 8, 38], the negative work of the joint is thought to be associated with muscle damage [12, 19].

Previous biomechanical studies have reported that mechanical parameters are affected by factors such as the running technique, running speed, type of running shoes, shoe material, and running surface [6, 18, 33, 35, 36]. Mechanical parameters are thought to influence acute and chronic training workloads and provide important information for selecting adaptations and preventing injury [14]. Among these factors, the inter-individual variability of running technique is considered an important factor affecting the mechanical parameters of lower extremity joints [20, 27]. As for mechanics, we note that mechanical work is the time integral value of power, and power is denoted by the dot product of moment and angular velocity [21]. These relationships indicate that inter-individual variability (between participant variability) in the negative work of each lower extremity joint can be accounted for by the duration of the negative power, moment, and angular velocity of the corresponding lower extremity joint. Understanding the specific contributions from each of these factors to the negative work of the lower extremity joints may aid in improving running technique, such as the development of gait re-training and a motion feedback system for promoting muscle adaptation and reduction of the potential risk of injury to the lower extremity muscles. However, it is unclear as to what major mechanical parameters account for inter-individual variability in the negative work of each lower extremity joint. Thus, the purpose of this study was to examine the relationships between the negative work of the lower extremity joints and the mechanical parameters that account for inter-individual variability in the negative work. A previous study reported that the activation pattern of lower extremity muscles varied among individuals and these variations were not the same among the muscles [15]. Hence the joint angular velocity, moment and power differ at each lower extremity joint during running, and therefore we hypothesized that the major mechanical parameters that account for inter-individual variability in the negative work would not be the same among the lower extremity joints.

Materials and Methods

Participants

Twenty-four young male adult volunteers without musculoskeletal injuries of the lower extremities participated in the study (age: 25.9 ± 4.7 years, height: 1.74 ± 0.04 m, body mass: 65.1 ± 6.6 kg). Written informed consent was obtained from each participant before the experiment. The experimental protocol employed in this study was approved by the local institutional board. This study was conducted in accordance with the Declaration of Helsinki and met the standards of the International Journal of Sports Medicine [17].

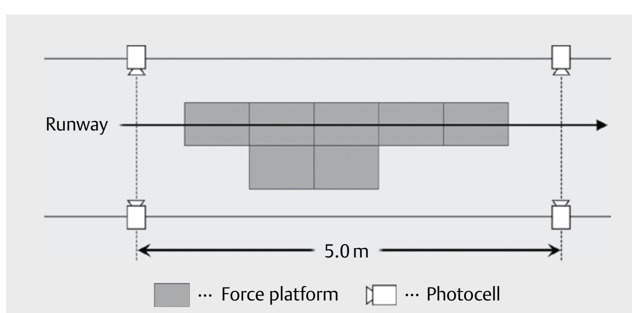
Data collection

All participants were asked to wear the same type of running shoes (GT-2000 NEW YORK 4, ASICS, Hyogo, Japan) for the study. A total of 14 retro-reflective markers were attached to the following anatomical landmarks of the pelvis, right thigh, right shank, and right foot: right and left anterior superior iliac spines, first sacral vertebrae, greater trochanter, medial and lateral epicondyle of the femur, mid-point of the greater trochanter and lateral epicondyle of the femur, medial and lateral malleolus, mid-point of the lateral epicondyle of the femur and lateral malleolus, heel, the first and the fifth heads of the metatarsal bone, and mid-point of second and third heads of the metatarsal bone [9].

Participants performed running for a self-selected time as a warm-up at least 5 min before the experimental trials were conducted. After resting for more than 5 min, each participant was then asked to run on a 40-m straight runway at a speed of $3.0\,\mathrm{m \cdot s^{-1}}$. Five successful trials were recorded during the contact phase of running. A successful trial was defined as one that fulfilled the following conditions: 1) the mean value of the running speed was within 10 % of the target running speed; 2) the participant's right foot contacted the force platform; and 3) the participant identified that the running technique used in the trial was natural to him. The experimental setup is depicted in ▶ **Fig. 1**. An optical motion capture system with 15 cameras (VICON MX system, VICON Motion Systems, Oxford, UK) was used to record the three-dimensional (3D) coordinates of the retro-reflective markers at 200 Hz. The ground reaction force was recorded simultaneously at 2000 Hz by using seven force platforms (BP400600-1000PT, BP400600-2000PT, AMTI, Watertown, MA, USA) that were electronically synchronized with the optical motion capture system. Photocells (TC Timing System, Brower Timing Systems, Draper, UT, USA) were placed before and after the force platform systems to control the running speed.

Data reduction

The collected data were filtered by using a zero-lag fourth-order Butterworth low-pass filter. The cut-off frequencies were set as 10 Hz [3] and 50 Hz [4] for the marker coordinate data and force data, respectively. A threshold of 20 N for the vertical component of the ground reaction force was used to identify the instances of initial foot contact and toe-off. Right-handed orthogonal local coordinate systems were defined for the pelvis, right thigh, right shank, and right foot using the 3D coordinates of the retro-reflective markers. The joint angle was determined as the orientation of the local coordinate system embedded in the distal segment relative to that embedded in the proximal segment using the Cardan X-Y-Z rotation sequence. The inertia parameters of each segment were estimated using the method proposed by the previous study [16]. The Newton–Euler inverse dynamics approach was used to compute the moments of each lower extremity joint during the contact phase of running. In this study, the positive and negative values of the moment and angular velocity represent extension (and plantarflexion) and flexion (and dorsiflexion), respectively. The power of the flexion-extension movement was calculated as the



▶ **Fig. 1** Experimental setup for data collection. Two sets of photocells were placed before and after the force platforms that were embedded on the runway. The distance between the two sets of photocells was set at 5.0 m. The time when each participant passed through this distance was measured using the photocells.

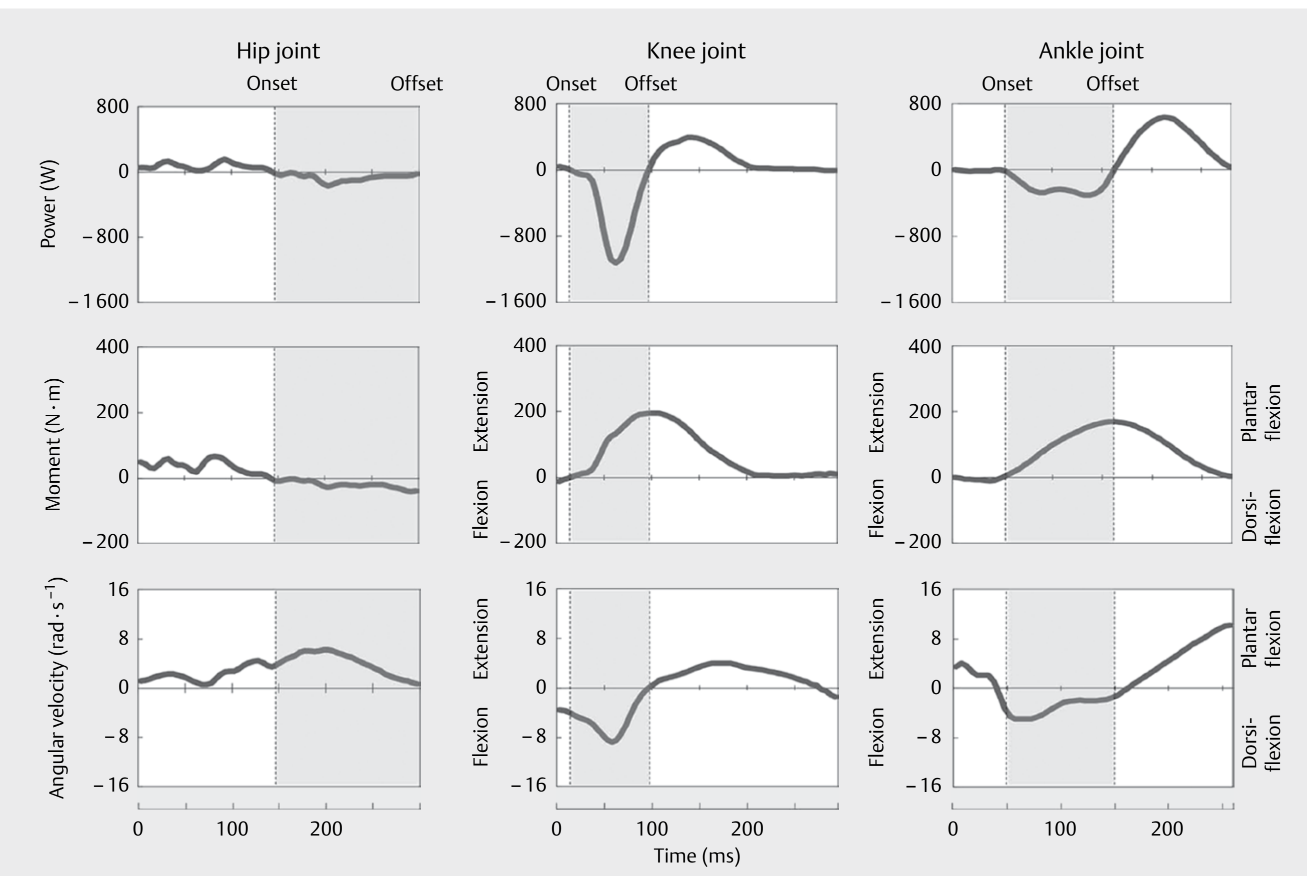
dot product of the moment and the corresponding angular velocity for each lower extremity joint. The negative work of each lower extremity joint was then determined as the time integral value of the negative power. Visual 3D software (C-Motion Inc., Germantown, MD, USA) was used to perform these computations. We extracted the following mechanical parameters during the interval over which the negative power was observed: the amplitude and duration of the negative power of flexion-extension movement, net flexion-extension moment, and flexion-extension angular velocity. The mean value of the five successful trials was used as the representative value for individuals.

Statistical analysis

The relationships between the negative work (dependent variable) and the associated mechanical parameters (independent variables are duration of the negative power, moment, and angular velocity) were examined by using multiple linear regression analysis with a stepwise technique for each lower extremity joint. A significance level of 0.05 was applied in all statistical analyses. The variance inflation factor (VIF) was determined to confirm multicollinearity. Multicollinearity is considered to be high when VIF is greater than 10 [22]. Statistically, the coefficient of determination coincides with the sum of the product of the standardized partial regression coefficient and the correlation coefficient of each parameter. We, therefore, computed the percent (%) contribution to account for inter-individual variability in the negative work as a hundredfold of the product of the standardized partial regression coefficient and the correlation coefficient. Statistical analyses were performed using IBM SPSS 22.0 statistical software (SPSS Inc., Chicago, IL, USA).

Results

The typical time-history data of the power, moment, and angular velocity are represented for each lower extremity joint in ▶ **Fig. 2**. The means and standard deviations (SDs) of each parameter are listed in ▶ **Table 1**. With regards to the results of multiple linear regression analysis with stepwise techniques, the coefficients of determination were found to be 0.763 ($p < 0.01$), 0.889 ($p < 0.01$), and 0.893 ($p < 0.01$) for the hip, knee, and ankle joints, respectively. The partial regression coefficient, standardized partial regression coefficient, and correlation coefficient for each mechanical parameter of the lower extremity joints are listed in ▶ **Table 2**. The % contributions to account for inter-individual variability in the negative work are shown for each lower extremity joint in ▶ **Fig. 3**. For the hip joint, the partial regression coefficient was significant for the moment (% contribution = 25.4 %, $p < 0.01$, VIF = 1.195) and the duration of the negative power (% contribution = 50.9 %, $p < 0.01$, VIF = 1.195). A significant partial regression coefficient was ob-



▶ **Fig. 2** Typical time-series power, moment, and angular velocity of each lower extremity joint. The subject whose negative work was the closest to the corresponding average value was selected as typical for each lower extremity joint. The shaded area represents the duration over which negative power was generated.

served for the moment (% contribution = 40.6 %, $p < 0.01$, VIF = –1.260), angular velocity (% contribution = 24.5 %, $p < 0.01$, VIF = 1.520), and duration of the negative power (% contribution = 23.8 %, $p < 0.01$, VIF = 1.239) of the knee joint. For the ankle joint, the partial regression coefficient was significant for the moment (% contribution = 89.3 %, $p < 0.01$, VIF = 1.000).

Discussion

The purpose of this study was to examine the mechanical parameters that account for inter-individual variability in the negative work of each lower extremity joint by using multiple linear regression analysis with the stepwise technique. Our results indicate that inter-individual variability in the negative work of the hip joint was attributable to the inter-individual variabilities in the corresponding moment (25.4 %) and the duration of the negative work (50.9 %), but not the angular velocity. For the knee joint, inter-individual variabilities in the moment, angular velocity, and duration could account for inter-individual variability in the corresponding negative work, and the % contributions were 40.6, 24.5, and 23.8 %, respectively. The inter-individual variability in the moment of the ankle joint alone accounted for 89.3 % of the inter-individual variability in the corresponding negative work. The current results support our initial hypothesis that the major mechanical parameters accounting for inter-individual variability in the negative work would not be the same among the lower extremity joints.

With regards to the results of the multiple linear regression analysis with the stepwise technique, 76.3 % of inter-individual variability in the negative work of the hip joint could be accounted for by the combination of inter-individual variabilities of the corresponding moment and duration of the negative power. The negative work of the joint is thought to underlie muscle soreness and the associated muscle injury [12, 19]. In this regard, previous studies have reported that the negative work of the hip joint during the contact phase of running could not be reduced by reduction in the running speed [33], change in the type of running shoes [19], and the use of a brace [8]. However, the present results suggest that runners can change the negative work of the hip joint by adapting their running technique even if the running speed is constant. Furthermore, the contribution to account for inter-individual variability in the negative work of the hip joint was found to be 25.4 % and 50.9 % for the moment and duration, respectively (▶ **Fig. 2**). Similar to the results of previous studies [19, 26, 37], we observed that the negative power of the hip joint was generated in the latter part of the contact phase during running. In this phase, the hip flexion moment was generated although the hip joint moved into extension (▶ **Fig. 1**). The previous study [20] revealed that increase in step rate induces a decrease in the negative work of the hip joint, suggesting that associated mechanical parameters are also affected by a change in step rate. Therefore, runners with muscle soreness and muscle/tendon injuries could run with low negative work of the hip joint by suppressing the corresponding flexion moment and/or duration of the negative power. Contrarily, healthy runners can increase the negative work of the hip joint for further muscle adaptation by increasing these corresponding parameters. The present results suggest that runners can change the damage to the muscles around the hip joint by adapting their running technique to reduce the flexion moment and/or the duration of the negative power of the hip joint rather than reduce the corresponding extension angular velocity.

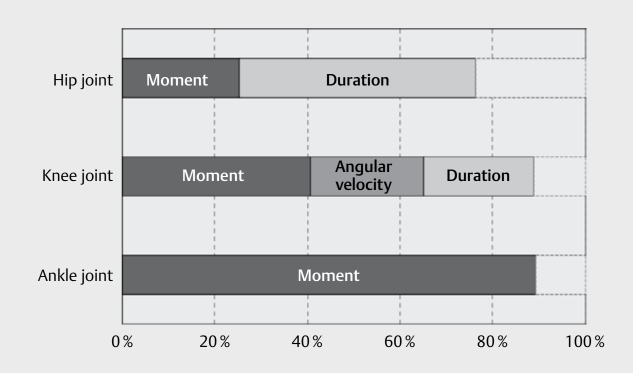
The present results indicate that inter-individual variabilities in the moment, angular velocity, and duration of the negative power of the knee joint could account for 88.9 % of the inter-individual

▶ **Table 1** Means, standard deviations (SDs) and 95 % CIs of calculated mechanical parameters.

	Hip joint (95 % CI)	**Knee joint (95 % CI)**	**Ankle joint (95 % CI)**
Negative work (J)	−15.2 ± 7.7 (−19.9, −10.4)	−33.5 ± 10.2 (−39.8, −27.2)	−22.0 ± 7.6 (−26.7, −17.2)
Amplitude of negative power (W)	−82.2 ± 33.8 (−103.2, −61.3)	−480.3 ± 136.4 (−564.8, −395.8)	−167.7 ± 73.8 (−213.5, −122.0)
Duration of negative power (ms)	169 ± 35 (148, 191)	72 ± 14 (63, 81)	134 ± 13 (126, 142)
Moment of joint (N·m)	−11.7 ± 13.3 (−19.9, −3.5)	94.9 ± 14.5 (85.9, 103.9)	63.3 ± 20.1 (50.9, 75.8)
Angular velocity of joint ($rad \cdot s^{-1}$)	3.18 ± 0.42 (2.92, 3.44)	−5.61 ± 0.93 (−6.19, −5.03)	−1.39 ± 1.40 (−2.26, −0.52)

▶ **Table 2** Partial regression coefficient (b), standardized partial regression coefficient (b *) and correlation coefficient (r) for each mechanical parameter.

		b	b *	r
Hip joint	Moment of joint	− 0.225	− 0.391	− 0.649
	Angular velocity of joint	-	-	-
	Duration of negative power	− 0.141	− 0.639	− 0.797
Knee joint	Moment of joint	− 0.385	− 0.551	− 0.736
	Angular velocity of joint	5.517	0.506	0.485
	Duration of negative power	− 0.444	− 0.623	− 0.382
Ankle joint	Moment of joint	0.359	0.945	0.945
	Angular velocity of joint	-	-	-
	Duration of negative power	-	-	-



▶ **Fig. 3** Contribution of mechanical parameters for each lower extremity joint. Stacked black, gray, and white bars represent the contributions of the moment, angular velocity, and duration of the negative power, respectively. Statistically, the sum of the contributions (a hundredfold of the product of the standardized partial regression coefficient and the correlation coefficient) equals a hundredfold of the coefficient of determination.

variability in the corresponding negative work. Previous studies have reported that the negative work of the knee joint can be influenced by a change in the running speed [33] and the type of running shoes [19, 29], but not with the use of a brace [8]. In addition, the present results suggest that adapting the running technique can also change the negative work of the knee joint. The contributions accounting for inter-individual variability in the negative work of the knee joint were 40.6 %, 24.5 %, and 23.8 % for the moment, angular velocity, and duration of the negative power, respectively. The negative power of the knee joint was generated by the corresponding extension moment and flexion angular velocity in the early part of the contact phase of running [5, 19, 26, 33] (▶ **Fig. 1**). Several interventions in the running technique may have the potential to change the mechanical parameters associated with the negative work of the knee joint. Previous studies reported that the extension moment, angular displacement and negative power of the knee joints were greater for the rearfoot strike than that for the forefoot strike [23, 24, 34]. Real-time visual feedback of mechanical gait parameters helped reduce the negative power for the knee joint [2]. Furthermore, 12 weeks of gait re-training tended to reduce the negative power of the knee joint and corresponding flexion moment [25]. Runners with muscle soreness and muscle/tendon injuries could run with low negative work of the knee joint by suppressing the corresponding extension moment, flexion angular velocity, and duration of the negative power either separately or together, and vice versa.

With regards to the results of multiple linear regression analysis with the stepwise technique, the inter-individual variability in the moment of the ankle joint alone accounted for 89.3 % of the inter-individual variability in the corresponding negative work. Previous studies have reported that decrease in running speed [33], change in the type of running shoes [19], and the use of a brace [8] could not reduce the negative work of the ankle joint during the contact phase of running. Therefore, adapting the running technique to change the plantarflexion moment is thought to be one of the few strategies that can reduce the corresponding negative work. Similar to the case of the knee joint, the negative power of the ankle joint was also observed in the early part of the contact phase of running [5, 19, 26, 33] (▶ **Fig. 1**). In this phase, the ankle plantarflexion moment was generated although the ankle joint moved into dorsiflexion (▶ **Fig. 1**). Previous studies reported that a forefoot strike induced a greater negative power of the ankle joint, corresponding plantarflexion moment, and angular displacement, as compared to that of a rearfoot strike [18, 23, 34]. The present results suggest that runners can change the damage to muscles around the ankle joint by adapting their running technique to change the plantar flexion moment rather than the dorsiflexion angular velocity and duration of the negative power.

The following points should be considered when interpreting the results of the current study. First, the present study recruited only adult males, and the applicability of the present findings are thought to be limited. Previous studies have reported that the kinetic and kinematic parameters of the lower extremity joints are partly different between males and females [13, 32]. These differences were thought to be attributable to gender differences in terms of body dimensions, composition, and alignment. The range of observable values of each mechanical parameter collected from males and females may be larger than that in the present study, and the relationships between the negative work of the lower extremity joints and the associated mechanical parameters may be not the same between males and females. Sensitivity analysis in multivariate methods with wide range values of mechanical parameters may have the potential to advance the present findings. Second, the present study could not determine the negative work of the associated muscles attached around each lower extremity joint.

Our study examined the mechanical parameters that account for inter-individual variability in the negative work that relate to the damage to muscles attached to each lower extremity joint. With regards to the results of our multiple linear regression analysis, the major mechanical parameters affecting inter-individual variability in the negative work of each lower extremity joint were determined as follows: the moment and duration of the negative work of the hip joint; moment, angular velocity, and duration of the negative power for the knee joint; and the moment for the ankle joint. These results suggest that runners can change the damage to muscles attached to each lower extremity joint by adapting their running technique to change the associated mechanical parameter values; however, the major mechanical parameters corresponding to the negative work are not the same among the lower extremity joints.

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Conflict of Interest

The authors declare that they have no conflict of interest.

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