Research Paper

Running Mechanics After Training on Sand in Runners With Pronated Feet: A Randomized Controlled Trial

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ABSTRACT

Purpose: Pronation in the foot is a normal rolling movement occurring at the subtalar joint during running. The human foot, as the primary interface with our environment, presents morphological and postural changes following prolonged running. This study aims to identify running mechanics while training on the sand in runners with pronated feet.

Methods: Thirty runners with pronated feet were in the control group, and 30 runners with pronated feet were in the experimental group. An experimental group conducted an 8-week corrective exercise program, while a control group did not exercise. A force plate was included to collect ground reaction forces in the walkway. An analysis of variance (ANOVA) with repeated measures test was conducted to identify the presence of an interaction between the within-and between-subject factors on the dependent variables. The significance level was set at $P<0.05$.

Results: The experimental group displayed lower first peak vertical ground reaction force (P=0.026), peak mediolateral ground reaction force (P=0.000), anterior-posterior impulse (P=0.032), loading rate (P=0.004) and a larger last peak vertical ground reaction force (P=0.000) during training on the sand. Irrespective of the group under consideration, a lower first peak mediolateral ground reaction force (P=0.000), peak positive free moment amplitude (P=0.001), and a larger last peak mediolateral ground reaction force (P=0.003) observed in the post-test compared to the pre-test.

Conclusion: We suggest that training on sand may be a suitable intervention to change running mechanics in male runners with pronated feet.

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Highlights

• The results demonstrated a decrease in peak vertical and mediolateral ground reaction forces at the heel contact phase.

• The results demonstrated a decrease in loading rate at the heel contact phase.

• The results demonstrated an increase in peak vertical ground reaction force at the push-off phase.

• The results demonstrated a decrease in peak positive free moment amplitude during training on the sand.

Plain Language Summary

A sand training surface can provide greater energy expenditure and less impact during training compared to a harder surface. This study aims to identify running mechanics during training on the sand in runners with pronated feet. The results demonstrated that a decrease in peak vertical and mediolateral ground reaction forces during the heel contact phase was observed in the experimental group compared to the control group. Training programs may have positive effects on individuals with pronated feet to reduce lower limb injuries during running by the lower ground reaction forces, loading rate, and peak positive free moment amplitude. An interpretation of the present results is that adaptations to enhance control of abnormal feet joint may have long-term negative consequences for joints structure.

Introduction

The foremost well-known sports are about maintaining physical shape, utilized either as a workout or as a physical discipline [1]. Of the injuries experienced by runners, approximately 60% happen in the feet and 29% in the knee, with foot posture and increases in plantar pressures being some of the main causes of those injuries [1]. Continuous running, although it can be practiced as a recreational activity, can be considered a high-impact practice [1]. Seventy-nine percent of individuals practicing continuous running experience injuries in their lower limbs, such as knee injuries, due to reasons, such as pronated feet (PF) [1].

The human feet, as the essential interface with our environment, present morphological and postural changes following prolonged running, which is a key intrinsic factor contributing to running-related injuries [2]. A 6-item scale (feet posture index) was previously developed and validated to characterize feet postures, including high supination, supination, neutral pronation, and high pronation in multiple planes and anatomical segments under static palpation measurements and clinical settings [2]. Feet pronation or supination is a normal rolling movement occurring during running at the subtalar joint of the feet [3]. However, PF can lead to serious injuries, such as shin splints, anterior compartment syndrome, patellofemoral pain syndrome, plantar fasciitis, tarsal tunnel syndrome, Achilles tendonitis, heel spurs, and others [3].

A sand training surface can provide a greater energy expenditure and less impact during training compared to a harder surface [4]. Training on sand leads to significant changes in body movements and muscle activation patterns when running, resulting in a significant increase in energy usage [4]. The sand's ability to absorb shock reduces the impact forces experienced during intense activities, potentially leading to less muscle damage, soreness, and performance declines [4].

Sand running is often seen as a beneficial addition to regular training on hard surfaces, according to athletes and coaches. From a biomechanical perspective, running on sand leads to increased knee extensor activity compared to running on stable ground [5]. In a study conducted by Jafarnezhadgero et al., it was observed that training on sand resulted in lower peak free moment (FM) and loading rate during walking [6]. Additionally, evidence suggests that sand training affects the mechanics and forces involved in individuals with PF [5, 7]. As a result, it is hypothesized that training on sand alters biomechanical factors and modifies PF [5, 6]. The unique aspect of this study lies in the duration of sand training for runners with PF because, currently limited evidence exists on how sand training affects performance on hard ground. Thus, this study was conducted to investigate ground reaction forces in male runners with PF after training on sand.

Materials and Methods

A randomized controlled design with equal group allocation was used (Figure 1). We used the freeware tool G*Power to calculate a one-sided a priori power analysis with the F test family (analysis of variance [ANOVA] repeated measures within-between interaction) and the appropriate statistical test based on a related study that looked at running kinetics in adults with [8]. The power analysis was computed with an assumed type I error of 0.05, a type II error rate of 0.20 (80% statistical power), 2 tests (pre and post), a correlation coefficient of 0.5 between observations, and an effect size of 0.80 (i.e. interaction effects) for running kinetics (i.e. peak vertical ground reaction forces [GRF]). The analysis revealed that 30 participants were sufficient to observe large group x time interactions. According to Cohen, a large effect size (>0.8) implies that the means of the one experimental group differ by 0.8 standard deviations [9]. Participants (age range: 18–26 years) were recruited in physical therapy clinics in Ardabil, City Iran, in November 2019. Sixty runners with PF, eligible to participate in this study, were randomly and equally assigned to the experimental and control groups. Only men were recruited to eliminate any potential factors that can affect the results, such as differences in biomechanical characteristics [10, 11]. Allocation concealment was ensured using envelopes, containing cards indicating the group to which each participant was assigned. The assessors evaluating the participants were also unaware of the group allocation, ensuring blindness. Both groups included participants with a navicular drop of over 10 mm and a feet posture index larger than 10 [12]. The navicular drop was measured by comparing the navicular height during non-weight bearing with that during full weight bearing of the feet while standing alone on one leg [13]. The exclusion criteria for both groups included a history of musculoskeletal surgery in the trunk or lower limbs, neuromuscular or orthopedic disorders (except for PF), and differences in limb length exceeding 5 mm. The procedures were explained to the participants before obtaining their informed consent, following the guidelines of the declaration of Helsinki. Demographic information, such as age, limb dominance, and injury history, was reported by all participants. All participants were determined to be right-feet based on a kicking ball test [14].

Experimental setup and data processing

A Bertec force plate (1000Hz, Bertec Corporation, Columbus, OH, USA) was used to record the GRF components during running. Kinetic data were processed as described by Jafarnezhadgero et al. [15]. GRFs were low-pass filtered at 20 Hz (4th order Butterworth filter, zero lag). Specific gait characteristics (heel strike and toe-off) were identified using the Bertec force plate. For this purpose, a 10 N threshold was used to detect the stance phase of the gait cycle. The following dependent variables were extracted from GRF data [15]: First (peak vertical ground reaction force during heel contact [Fz_{HC}]) and second (peak vertical ground reaction force during push-off [Fz_{PO}]) vertical peak force as well as the minimum force between peaks (vertical ground reaction force during mid-stance [Fz_{MS}]). Braking (braking force [Fy_{HC}]) and propulsion forces (propulsion force [Fy_{PO}]) were recorded from the anterior-posterior force curve. From the medial-lateral curve, we calculated the positive (lateral) peak (peak lateral ground reaction force during heel contact [Fx_{HC}]), which occurs right after heel contact. Moreover, we additionally assessed the negative peak which corresponds to the transfer of body mass to the supporting limb (*Peak* lateral ground reaction force during mid-stance [Fx_{MS}]) and subsequently to the contralateral limb (Peak lateral ground reaction force during push-off [Fx_{PO}]). GRF amplitudes were normalized to body weight (BW) and reported in % BW. Time to peak (TTP) was defined as the time between the initial heel contact and the corresponding peak of GRF components. The loading rate was defined as the slope between heel contact and FzHC on the vertical force curve. Impulse was calculated using the trapezoidal integration method and expressed as Equation 1:

1. $\text{Impulse}=\Delta t(F1+Fn/2)+\sum_{i=2}^{n-1}Fi$

In this equation, delta t is the period for which the impulse was calculated, F_1 and F_n are reaction forces at the first and the last frame. The FM of the feet was computed as Equation 2:

2. $FM=Mz+(Fx\times COPy)-(Fy\times COPx)$

Where Mz is the moment around the vertical axis; x and y are the horizontal components of the center of pressure (COP), and Fx, Fy are the horizontal GRF components. Moreover, FM amplitudes were normalized with regard to BW×height. All gait variables were averaged across three trials [15].

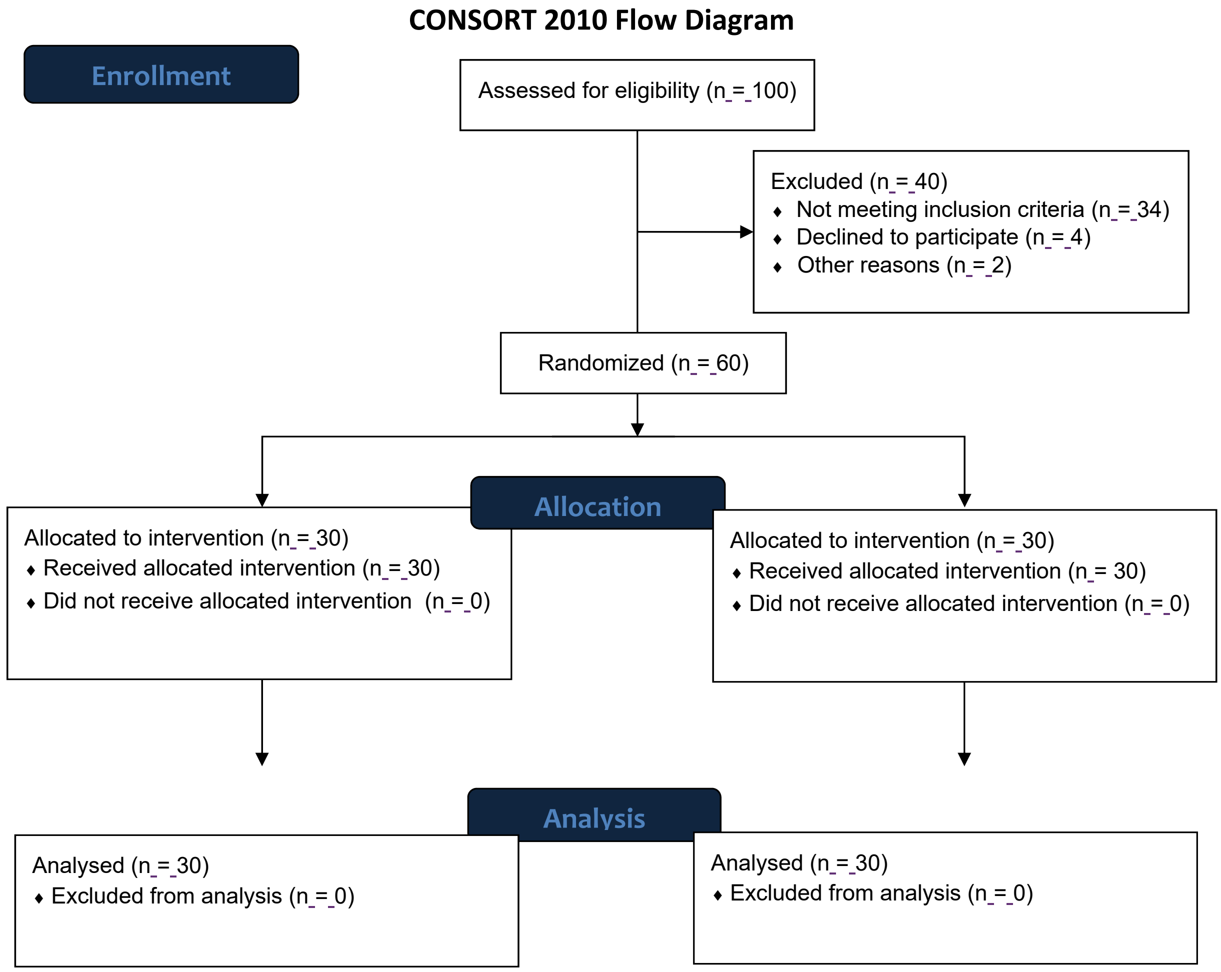

Figure 1. Flow diagram of randomized control trial in this study

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Training program and experimental procedures

The individuals in the experimental group underwent an eight-week sand-running training program. This program included activities, such as walking, continuous jogging, striding, bounding, galloping, and short sprints [16]. These training sessions took place three times a week, with a warm-up and stretching session at the beginning, and a cool-down session at the end. [16]. Each session lasted for a total of 50 minutes [16]. The individuals in the control group did not engage in any exercise and were reassessed after 8 weeks. All participants were advised not to participate in any other sports or exercise during the intervention period. Table 1 presents the training exercises used in the experimental group.

Participants completed a standardized 5-minute warm-up session before the testing. This warm-up included 3 minutes of stretching after 2 minutes of low-to-moderate intensity jogging. To familiarize participants with the laboratory environment, they ran across a runway three times. This familiarization process helped determine the optimal distance to the force plate, ensuring that participants would make contact with it during the runway trials. During testing, participants were required to take a minimum of eight steps before hitting the force plate with their right feet. They ran their preferred speed and in a randomized order over the runway. A trial was considered successful if the feet landed in the middle of the force plate. Three successful running trials were assessed for each condition and used for further data analysis.

The block randomization method was used to allocate study participants to experimental groups. One examiner determined whether a participant was eligible for inclusion in the trial, while the other performed the gait analyses of the eligible participants. Both examiners and the participants were unaware of group allocation. During the randomization process, a set of sealed, opaque envelopes was used to ensure the concealment of the allocation. Each envelope contained a card stipulating to which group the participant was allocated. Participants were not aware of the group they were allocated to. A physiotherapist supervised each session to modify the exercise or the progression to meet the given training program and ensure the correct technique. We evaluated the experimental group after the intervention, scheduled 6 days after the final session. We used this procedure to avoid interference with acute physiological responses to training. We also evaluated the control group for the second time after 9 weeks, but the group participants did not receive any exercise. Individuals from the control group followed their regular daily routine and did not perform additional exercise during the intervention period. All participants were asked not to take up any extra physical activity or exercise during the experimental period. This two-step process, consisting of a pre-test and a post-test, was performed for each group.

Statistical analyses

The data are presented as group Mean±SD. After normal distribution was examined and confirmed using the Shapiro-Wilk test, an independent samples t-test was conducted to determine baseline between-group differences. A separate 2 (time: Pre-test vs post-test)×2 (groups: Control vs experimental) analysis of variance (ANOVA) with repeated measures was conducted to identify the presence of an interaction between the within-and between-subject factors on the dependent variables. Post hoc analyses were calculated using Bonferroni-adjusted paired sample t-tests. Additionally, effect sizes were determined by converting partial eta-squared (η^2_p) to Cohen's d. According to Cohen [9], d<0.50 indicates small effects, 0.50≤d <0.80 indicates medium effects and d≥0.80 indicates large effects. The significance level was set at P<0.05. All analyses were performed using SPSS software, version 26.

Results

Table 2 presents participant characteristics and outcome variables at baseline. No significant between-group differences were found at baseline for all examined variables (Table 2).

No statistically significant main effects of "time" and "group" were found for stance time (P>0.05; d=0.090-0.110). Also, no statistical analysis significance was identified for the group by time interactions at stance time during training on sand (P>0.05; d=0.155).

Significant main effects of "time" were found for Fx_{HC}, Fx_{PO}, Fy_{HC}, and TTP Fz_{MS} (P<0.039; d=0.533-1.173) (Table 3). Pair-wise comparisons revealed significantly lower Fx_{HC} (P<0.001; d=1.243) and Fy_{HC} (P=0.023; d=0.629) and larger Fx_{PO} (P=0.003; d=0.893) in the post-test compared to the pre-test (Table 3). Also, pair-wise comparisons revealed significantly shorter TTP FzMS (P=0.039; d=0.411) in the post-test compared to the pre-test (Table 3).

Moreover, we observed significant main effects of "group" for TTP Fx_{HC} (P<0.012; d=0.681) (Table 3). Pair-wise comparisons revealed significantly shorter TTP Fx_{HC} (P=0.012; d=0.678) in the experimental group compared to the control group (Table 3).

Finally, the statistical analysis showed significant group-by-time interactions for Fz_{HC}, Fz_{PO}, and Fx_{HC} (P<0.047; d=0.532-1.009) (Table 3). In the experimental group but not the control group, significantly lower Fz_{HC} (P=0.026; d=0.868) and Fx_{HC} (P=0.047; d=1.277) larger Fz_{PO} (P<0.001; d=0.121) during training on sand (Table 3).

The statistical analyses indicated significant main effects of "time" for peak positive FM amplitude (P<0.001; d=0.915) (Table 4). Pair-wise comparisons revealed a significantly lower peak positive FM amplitude (P=0.001; d=0.819) in the post-test compared to the pre-test (Table 4).

Table 1. Protocol for experimental group

No.	Exercise Name	Duration (m)	Repetition	Distance (m)	Recovery Period (m)
1	Walking and continuous jogging	20	-	50	-
2	Striding	3	2-3	50	1
3	Bounding	3	2-3	30	1
4	Galloping	3	2-3	30	1
5	Short sprints	6	3-5	25	2

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Table 2. Group-specific baseline values of all reported kinetic and muscular activity outcome variables

Characteristics		Mean±SD		P*
		Control	Experimental	
Parameter	Age (y)	22.36±2.34	22.86±2.12	0.390
	Haigh (cm)	172.76±8.37	174.76±7.12	0.323
	Weight (kg)	72.40±11.18	73.90±11.61	0.612
	BMI (kg/m²)	24.38±4.29	24.27±3.97	0.919
GRFs	Fz_{HC}	87.79±16.07	94.47±14.68	0.098
	Fz_{MS}	72.01±14.13	72.62±10.71	0.847
	Fz_{PO}	186.93±31.01	174.86±30.40	0.133
	Fx_{HC}	7.87±1.36	8.21±1.11	0.292
	Fx_{PO}	-7.03±1.78	-5.73±3.73	0.092
	Fy_{HC}	-10.58±2.50	-10.04±2.73	0.429
	Fy_{PO}	10.78±2.71	9.97±3.17	0.288
TTP GRFs	Fz_{HC}	25.90±7.04	25.83±12.32	0.980
	Fz_{MS}	41.63±6.98	40.26±13.55	0.625
	Fz_{PO}	189.56±21.43	180.10±22.49	0.101
	Fx_{HC}	24.30±8.57	20.73±4.87	0.053
	Fx_{PO}	146.53±22.65	145.30±21.66	0.830
	Fy_{HC}	81.60±11.64	80.76±10.75	0.774
	Fy_{PO}	256.56±50.93	260.36±45.24	0.761
Variables	Impulse x	2.02±0.41	2.11±0.55	0.480
	Impulse y	3.13±0.52	3.25±0.68	0.443
	Impulse z	39.76±4.79	39.15±3.85	0.595
	Free moment (negative)×10^{-3}	-1.02±0.36	-0.91±0.32	0.206
	Free moment (positive)×10^{-3}	1.95±0.39	2.12±0.49	0.139
	Loading rate	36.77±13.70	44.19±22.53	0.129
	Time stance	0.37±0.06	0.37±0.05	0.960

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Abbreviations: Fz_{HC}: Peak vertical ground reaction force during heel contact; Fz_{MS}: Vertical ground reaction force during mid-stance; Fz_{PO}: Peak vertical ground reaction force during push-off; Fy_{HC}: Braking force; Fy_{PO}: Propulsion force; Fx_{HC}: Peak lateral ground reaction force during heel contact; Fx_{HC}: Peak medial ground reaction force during push of phase; TTP: Time to peak; x: Medio-lateral direction; y: Anterior-posterior direction; z: Vertical direction; GRF, ground reaction forces.

*Independent samples t-test.

Table 3. Mean±SD for GRF during training on sand in individuals with PF

GRF	Control				Experimental				Sig. (Effect Size)		
	Mean±SD		95% CI	Δ%	Mean±SD		95 % CI	Δ%	Time	Group	Group*Time
	Pre-test	Post-test			Pre-test	Post-test					
Fz_{HC}	87.79±16.07	92.50±28.32	-16.20, 6.79	5.36	94.47±14.68	84.66±7.90	3.78, 15.84	-10.38	0.424 (0.211)	0.869 (0.000)	0.026 (0.602)
Fz_{MS}	72.01±14.13	74.43±24.96	-12.33, 7.45	3.36	72.62±10.71	71.60±10.26	-3.68, 5.73	-1.40	0.793 (0.063)	0.731 (0.090)	0.521 (0.168)
Fz_{PO}	186.93±31.01	183.04±27.75	-0.13, 7.90	-2.08	174.86±30.40	178.55±30.14	-4.05, -3.33	2.11	0.924 (0.000)	0.283 (0.286)	0.000 (1.009)
Fx_{HC}	7.87±1.36	7.12±1.83	-0.17, 1.67	-9.52	8.21±1.11	6.21±2.02	1.14, 2.86	-24.36	0.000 (1.173)	0.323 (0.263)	0.047 (0.532)
Fx_{PO}	-7.03±1.78	-7.61±1.05	-0.03, 1.20	8.25	-5.73±3.73	-7.61±1.13	0.38, 3.36	32.80	0.003 (0.817)	0.121 (0.414)	0.107 (0.429)
Fy_{HC}	-10.58±2.50	-9.38±2.19	-2.55, 0.15	-11.34	-10.04±2.73	-8.57±4.41	-3.38, 0.44	-14.64	0.023 (0.610)	0.228 (0.320)	0.816 (0.063)
Fy_{PO}	10.78±2.71	10.02±1.41	-0.36, 1.89	-7.05	9.97±3.17	10.06±1.85	-1.42, 1.23	0.90	0.435 (0.211)	0.390 (0.230)	0.316 (0.263)
TTP Fz_{HC}	25.90±7.04	23.66±8.23	-1.26, 5.72	-8.64	25.83±12.32	27.53±12.77	-5.65, 2.25	6.58	0.837 (0.063)	0.423 (0.211)	0.133 (0.403)
TTP Fz_{MS}	41.63±6.98	41.10±11.46	-3.70, 4.77	-1.27	40.26±13.55	34.20±12.96	1.28, 10.85	-15.05	0.039 (0.553)	0.108 (0.429)	0.082 (0.464)
TTP Fz_{PO}	189.56±21.43	187.20±21.43	-4.97, 9.71	-1.24	180.10±22.49	175.70±29.93	-4.86, 13.66	-2.44	0.246 (0.307)	0.097 (0.444)	0.726 (0.090)
TTP Fx_{HC}	24.30±8.57	24.43±8.24	-2.44, 2.18	0.53	20.73±4.87	19.83±3.93	-0.97, 2.77	-4.34	0.601 (0.142)	0.012 (0.681)	0.481 (0.191)
TTP Fx_{PO}	146.53±22.65	148.06±23.41	-13.09, 10.02	1.04	145.30±21.66	145.36±23.76	-9.26, 9.12	0.04	0.825 (0.063)	0.676 (0.110)	0.840 (0.063)
TTP Fy_{HC}	81.60±11.64	79.60±14.36	-2.59, 6.59	-2.45	80.76±10.75	77.36±10.37	-0.06, 6.86	-4.21	0.060 (0.505)	0.576 (0.142)	0.621 (0.127)
TTP Fy_{PO}	256.56±50.93	256.76±37.66	-16.56, 16.16	0.07	260.36±45.24	257.90±80.08	-29.14, 34.08	-0.94	0.897 (0.000)	0.831 (0.063)	0.879 (0.000)

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Abbreviations: Fz_{HC}: Peak vertical ground reaction force during heel contact; Fz_{MS}: Vertical ground reaction force during mid-stance; Fz_{PO}: Peak vertical ground reaction force during push-off; Fy_{HC}: Braking force; Fy_{PO}: Propulsion force; Fx_{HC}: Peak lateral ground reaction force during heel contact; Fx_{HC}: Peak medial ground reaction force during push of phase; TTP: Time to peak; CI: Confidence interval.

Table 4. Mean±SD for impulses, free moments, and vertical loading rate during training on sand in individuals with PF

Variables	Control				Experimental			
	Mean±SD		95% CI	Δ%	Mean±SD		95 % CI	Δ%
	Pre-test	Post-test			Pre-test	Post-test		
Impulse x	2.02±0.41	1.88±0.72	-0.19, 0.48	-6.93	2.11±0.55	2.09±1.01	-0.41, 0.46	-0.94
Impulse y	3.13±0.52	3.24±0.54	-0.33, 0.10	3.51	3.25±0.68	3.01±0.55	-0.01, 0.49	-7.38
Impulse z	39.76±4.79	39.34±4.11	-0.65, 1.48	-1.05	39.15±3.85	38.56±7.97	-2.42, 3.61	-1.50
Free moment (negative)×10^{-3}	-1.02±0.36	-0.95±0.34	-0.26, 0.13	-6.86	-0.91±0.32	-0.84±0.50	-0.29, 0.15	-7.69
Free moment (positive)×10^{-3}	1.95±0.39	1.74±0.43	-0.01, 0.42	-10.76	2.12±0.49	1.78±0.54	0.10, 0.58	-16.03
Loading rate	36.77±13.70	44.15±19.67	-15.14, 0.39	20.07	44.19±22.53	36.10±13.25	0.74, 15.43	-18.30

Variables	Sig. (Effect Size)		
	Time	Group	Group×Time
Impulse x	0.547 (0.155)	0.232 (0.320)	0.662 (0.110)
Impulse y	0.410 (0.220)	0.650 (0.127)	0.032 (0.578)
Impulse z	0.522 (0.168)	0.556 (0.155)	0.910 (0.000)
Free moment (negative)×10^{-3}	0.375(0.238)	0.102(0.434)	0.999 (0.000)
Free moment (positive)×10^{-3}	0.001 (0.915)	0.249 (0.307)	0.406 (0.220)
Loading rate	0.892 (0.000)	0.934 (0.000)	0.004 (0.777)

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x: Medio-lateral direction; Y: Anterior-posterior direction; Z: Vertical direction; CI: Confidence interval.

The statistical analyses did not demonstrate any significant main effects of “group” for impulses, peak FM amplitudes and loading rate (P>0.05; d=0.000-0.434) (Table 4).

Finally, the statistical analysis showed significant group-by-time interactions for impulse y and loading rate (P<0.032; d=0.578-0.777) (Table 4). In the experimental group but not the control group, a significantly lower impulse y (P=0.032; d=0.390) and loading rate (P=0.004; d=0.452) was observed during training on sand (Table 4).

Discussion

This study was conducted to investigate running mechanics during training on the sand for runners with PF. The main results of this study can be summarized as follows, irrespective of the group under consideration, a lower Fx_{HC}, peak positive FM amplitude, and a larger Fx_{PO} were observed in the post-test compared to the pre-test, irrespective of the time, shorter TTP Fx_{HC} observed in the experimental group compared to the control group, in the experimental group but not the control group, lower Fz_{HC}, Fx_{HC}, impulse y, loading rate and a larger Fz_{PO} were observed during training on the sand.

This study showed that training on sand resulted in lower peak lateral and vertical forces. Previous research has shown that high lateral GRF results in excessive pronation during running [17]. Our results showed that sand training significantly reduces peak lateral GRF, and the large effect size indicates that this finding is practically relevant. Additionally, increased impact vertical GRF can be a risk factor for orthopedic injuries [18]. In this study, training on sand resulted in a significantly lower vertical impact peak force. The above-mentioned study is the first to provide preliminary evidence for training on sand in male runners with PF. The mechanisms by which the change in sand density reduces the magnitude of the peak vertical GRF may be due to changes in lower limb muscle activities (e.g. tibialis posterior activity). However, muscle activity was not measured in this study; therefore, further research is needed to explore this issue. Our results demonstrate that sand training is effective in maintaining early vertical (Fz_{HC}) and lateral forces (Fx_{HC}) during running. The peak vertical GRF during the stance phase of running may already exceed the capacity of the intrinsic foot muscles to control arch deformation. Excessive arch deformation can increase the loading and tension on the medial side of the feet, potentially leading to overuse injuries.

This study showed that training on sand resulted in significantly lower average loading rates, with a large effect size indicating the relevance of this outcome. It has previously been demonstrated that repetitive loading during heel contact to mid-stance phase results in subchondral bone microdamage associated with cartilage thinning [19, 20]. The lower loading rate during running after sand training is related to a longer period to reach peak vertical GRF at heel contact.

The training on sand led to a significant decrease in peak positive FM amplitude for runners. Previous research has suggested that this amplitude may indicate the torsional stress exerted on the lower extremities [21]. The foot muscles that control excessive pronation, which is accompanied by excessive internal rotation of the leg [22], cannot be strong enough to counteract these forces from the hip and lower leg [23]. Additionally, studies have shown that runners with a history of injuries, such as medial tibial stress syndrome had greater free moment amplitudes compared to uninjured runners [24, 25]. This emphasizes the importance of assessing free moments and biomechanical loading of the lower extremities while running. Our study revealed that training on sand resulted in significantly lower peak positive FM amplitude in runners with PF. Given the large effect size, this result is practically relevant.

Conclusion

The current study found that an 8-week training on sand led to a reduction in peak lateral and vertical forces of the dominant lower limb during running in male runners with PF. The results may indicate a reduced injury risk for the intervention group. Running after training on sand resulted in lower loading rates and free moment amplitudes in male runners with PF. Therefore, training on sand appears to change running mechanics in male runners with PF.

This study has limitations that should be considered in interpreting the results. First, we included only male runners, which is why the outcomes of this study are specific to the population under investigation. Accordingly, they cannot be transferred to female runners or runners of different expertise levels. More research is needed in this area. Second, we did not record electromyographic activity in this study. Accordingly, we do not know how the neuromuscular system responded to the different exercises.

Ethical Considerations

Compliance with ethical guidelines

The research protocol was approved by the Ethics Committee of the Medical Sciences University of Ardabil (IR.ARUMS.REC.1397.091) and registered by the Iranian Clinical Trial Organization (IRCT) (Code; IRCT20191211045704N1). All participants provided written informed consent to participate in this study.

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Authors' contributions

Conceptualization and supervision: Amir Fatollahi and Amir Ali Jafarnezhadgero; Methodology: Amir Ali Jafarnezhadgero and Seyed Hamed Mousavi; Data collection: Amir Fatollahi and Amir Ali Jafarnezhadgero; Data analysis: Amir Fatollahi; Funding acquisition, resources, investigation and writing: All authors.

Conflict of interest

The authors declared no conflict of interest.

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References

[1] Bravo-Aguilar M, Gijón-Noguerón G, Luque-Suarez A, Abian-Vicen J. The influence of running on foot posture and in-shoe plantar pressures. Journal of the American Podiatric Medical Association. 2016; 106(2):109-15. [DOI:10.7547/14-056] [PMID]

[2] Mei Q, Gu Y, Xiang L, Baker JS, Fernandez J. Foot pronation contributes to altered lower extremity loading after long distance running. Frontiers in Physiology. 2019; 10:573. [DOI:10.3389/fphys.2019.00573] [PMID]

[3] Eizentals P, Katashev A, Okss A, Pavare Z, Balcuna D. Detection of excessive pronation and supination for walking and running gait with smart socks. In: In: Lhotska L, Sukupova L, Lacković I, Ibbott G, editors. World Congress on Medical Physics and Biomedical Engineering 2018. IFMBE Proceedings. vol 68/2. Singapore: Springer; 2019. [DOI:10.1007/978-981-10-9038-7_112]

[4] Binnie MJ, Dawson B, Pinnington H, Landers G, Peeling P. Sand training: A review of current research and practical applications. Journal of Sports Sciences. 2014; 32(1):8-15. [DOI:10.1080/02640414.2013.805239] [PMID]

[5] Pinnington HC, Lloyd DG, Besier TF, Dawson B. Kinematic and electromyography analysis of submaximal differences running on a firm surface compared with soft, dry sand. European Journal of Applied Physiology. 2005; 94(3):242-53. [DOI:10.1007/s00421-005-1323-6] [PMID]

[6] Jafarnezhadgero AA, Fatollahi A, Granacher U. Eight weeks of exercising on sand has positive effects on biomechanics of walking and muscle activities in individuals with pronated feet: A randomized double-blinded controlled trial. Sports. 2022; 10(5):70. [DOI:10.3390/sports10050070] [PMID]

[7] van den Berg MEL, Barr CJ, McLoughlin JV, Crotty M. Effect of walking on sand on gait kinematics in individuals with multiple sclerosis. Multiple Sclerosis and Related Disorders. 2017; 16:15-21. [DOI:10.1016/j.msard.2017.05.008] [PMID]

[8] Barrios JA, Heitkamp CA, Smith BP, Sturgeon MM, Suckow DW, Sutton CR. Three-dimensional hip and knee kinematics during walking, running, and single-limb drop landing in females with and without genu valgum. Clinical Biomechanics. 2016; 31:7-11. [DOI:10.1016/j.clinbiomech.2015.10.008] [PMID]

[9] Cohen J. Statistical power analysis for the behavioral sciences. New York: Routledge; 1988. [DOI:10.4324/9780203771587]

[10] Jakobsen MD, Sundstrup E, Andersen CH, Bandholm T, Thorborg K, Zebis MK, et al. Muscle activity during knee-extension strengthening exercise performed with elastic tubing and isotonic resistance. International Journal of Sports Physical Therapy. 2012; 7(6):606-16. [PMID]

[11] Sundstrup E, Jakobsen MD, Andersen CH, Bandholm T, Thorborg K, Zebis MK, et al. Evaluation of elastic bands for lower extremity resistance training in adults with and without musculo-skeletal pain.Scandinavian Journal of Medicine & Science in Sports. 2014; 24(5):e353-9. [DOI:10.1111/sms.12187]

[12] Jafarnezhadgero A, Fatollahi A, Amirzadeh N, Siahkouhian M, Granacher U. Ground reaction forces and muscle activity while walking on sand versus stable ground in individuals with pronated feet compared with healthy controls. PloS One. 2019; 14(9):e0223219. [DOI:10.1371/journal.pone.0223219] [PMID]

[13] Cote KP, Brunet ME, Gansneder BM, Shultz SJ. Effects of pronated and supinated foot postures on static and dynamic postural stability. Journal of Athletic Training. 2005; 40(1):41-6. [PMID]

[14] Jafarnezhadgero AA, Shad MM, Majlesi M. Effect of foot orthoses on the medial longitudinal arch in children with flexible flatfoot deformity: A three-dimensional moment analysis. Gait & Posture. 2017; 55:75-80. [DOI:10.1016/j.gaitpost.2017.04.011] [PMID]

[15] Jafarnezhadgero AA, Oliveira AS, Mousavi SH, Madadi-Shad M. Combining valgus knee brace and lateral foot wedges reduces external forces and moments in osteoarthritis patients. Gait & Posture. 2018; 59: 104-10. [DOI:10.1016/j.gaitpost.2017.09.040] [PMID]

[16] Durai DB, Shaju MF. Effect of sand running training on speed among school boys. International Journal of Physical Education, Sports and Health. 2019; 6:117-22. [Link]

[17] Rodrigues P, TenBroek T, Hamill J. Runners with anterior knee pain use a greater percentage of their available pronation range of motion. Journal of Applied Biomechanics. 2013; 29(2):141-6. [DOI:10.1123/jab.29.2.141] [PMID]

[18] Bates NA, Ford KR, Myer GD, Hewett TE. Impact differences in ground reaction force and center of mass between the first and second landing phases of a drop vertical jump and their implications for injury risk assessment. Journal of Biomechanics. 2013; 46(7):1237-41. [DOI:10.1016/j.jbiomech.2013.02.024] [PMID]

[19] Jafarnezhadgero AA, Shad MM, Majlesi M, Granacher U. A comparison of running kinetics in children with and without genu varus: A cross sectional study. PloS One. 2017; 12(9):e0185057. [DOI:10.1371/journal.pone.0185057] [PMID]

[20] Burr DB, Radin EL. Microfractures and microcracks in subchondral bone: Are they relevant to osteoarthrosis? Rheumatic Diseases Clinics of North America. 2003; 29(4):675-85. [DOI:10.1016/S0889-857X(03)00061-9] [PMID]

[21] Yang PF, Sanno M, Ganse B, Koy T, Brüggemann GP, Müller LP, et al. Torsion and antero-posterior bending in the in vivo human tibia loading regimes during walking and running. PloS One. 2014; 9(4):e94525. [DOI:10.1371/journal.pone.0094525] [PMID]

[22] Bellchamber TL, van den Bogert AJ. Contributions of proximal and distal moments to axial tibial rotation during walking and running. Journal of Biomechanics. 2000; 33(11):1397-403. [PMID]

[23] Chuter VH, Janse de Jonge XA. Proximal and distal contributions to lower extremity injury: A review of the literature. Gait & Posture. 2012; 36(1):7-15. [DOI:10.1016/j.gaitpost.2012.02.001] [PMID]

[24] Milner CE, Davis IS, Hamill J. Free moment as a predictor of tibial stress fracture in distance runners. Journal of Biomechanics. 2006; 39(15):2819-25. [DOI:10.1016/j.jbiomech.2005.09.022] [PMID]

[25] Holden JP, Cavanagh PR. The free moment of ground reaction in distance running and its changes with pronation. J Biomech. 1991; 24(10):887-97. [DOI:10.1016/0021-9290(91)90167-L] [PMID]