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Original Research

The Effect of Acute Functional Fatigue on Plantar Pressure Distribution during Walking in Professional Volleyball Players

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ABSTRACT
The aim of this research was to investigate the effect of acute fatigue on the plantar pressure distribution in professional young male volleyball players. A total of 38 young male volleyball players (aged 16-20 years) volunteered for this study and were randomly divided into two groups: the experimental group (n=20) who performed the functional fatigue protocol, and the control group (n=18) who did not perform the fatigue protocol. The fatigue protocol in this study was of a functional and volleyball-specific nature, consisting of six repetitive cycles of movements until fatigue was reached. Plantar pressure distribution was measured using a foot scanner before and after the application of functional fatigue during walking task. One-way ANOVA was used to investigate between-group differences, and repeated measures ANOVA was used to examine the fatigue effect within each group. The data were analyzed using SPSS software (version 21) at a significance level of $p \leq 0.05$. The results showed that after fatigue, between-group differences of plantar pressure distribution increased in both feet. Significant differences between the two groups were observed in the force values of the left small toe, first, second, and third metatarsals, midfoot, and heel medial of the right foot ($p < 0.05$). The results indicated that fatigue leads to an increase in maximum distributed force. These factors can potentially increase the risk of injury in individuals.

Keywords: Plantar pressure, Fatigue, Footscan, Walking, Volleyball

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INTRODUCTION

Volleyball is recognized as one of the most popular and thrilling sports today, having evolved in various levels and forms across the globe. Players in this sport are typically engaged in three primary activities: receiving, serving, and spiking. Consequently, achieving an optimal balance and postural control is of paramount importance for athletes in volleyball. This not only helps prevent injuries but also enables them to sustain their performance during prolonged rallies, which can last for minutes, without succumbing to muscle or joint injuries. Furthermore, postural control plays a pivotal role in their rapid recovery between matches during tournaments, where they often need to compete in multiple games consecutively [1].

Fatigue is a ubiquitous phenomenon, experienced both in sports activities and daily life [2, 3]. Post-physical activity fatigue can exert a substantial impact on an individual's body stability, affecting it through various environmental factors and central mechanisms [4]. In recent decades, sports scientists have increasingly turned their attention to the adverse effects of fatigue on athletic performance and its correlation with postural control. Fatigue-induced impairments in postural control have been linked to a heightened risk of skeletal-muscular injuries and a decrease in athletic performance, both during exercise and competition [5, 6].

The foot serves as the sole anatomical structure in direct contact with the ground, representing the terminal component of the kinetic chain of the lower limb. It bears the responsibility of absorbing and distributing the forces applied to it during various activities. Incorrect force distribution can lead to unnatural movements, elevated stress levels, and damage to foot tissues and muscles [7, 8]. Volleyball players are exposed to a plethora of dynamic movements, including sudden directional changes, rapid accelerations, and repetitive jumping and landing actions. These demands increase the vulnerability of volleyball players to lower limb injuries, particularly those affecting the ankles [9].

Fatigue induces a decline in the ability to generate force, hampers neuromuscular coordination, reduces the precision of movement control, impairs proprioception, destabilizes joints, promotes muscle co-contraction, and prolongs reaction times. These consequences collectively result in a noticeable decrease in overall muscle performance [10-12]. The extent of this performance decline is contingent upon various factors, such as the type of muscle contraction, the specific muscle groups involved, the intensity, and the duration of the exercise [13]. Fatigue-related decrements in muscle performance can significantly heighten the risk of sports-related injuries [14, 15]. It has been observed that the majority of sports injuries tend to occur towards the end of sporting events and competitions, suggesting that the cumulative effects of fatigue, particularly in the later stages of competitions, can lead to the adoption of risky movement strategies [16-18]. However, it's important to note that fatigue is a modifiable risk factor, and enhancing athletes' ability to cope with it can lead to improved lower limb function [19]. Fatigue is rooted in physiological mechanisms that operate at both central and peripheral levels [20]. In a study conducted by Ribeiro et al (2008), the results, indicate that fatigue induced by a volleyball match significantly affects knee joint position sense in elite female volleyball players. Specifically, knee joint position sense was less accurate and less consistent after the volleyball match. The fatigue induced by a simulated competitive volleyball match led to proprioceptive deficits, reducing sensorimotor system acuity in female volleyball players [21]. In a study conducted by Farzami and Anbarian (2020), significant differences were observed in the maximum and mean plantar pressure as well as the contact surface of the right foot before and after fatigue. Furthermore, significant differences were found in the mean pressure and pressure distribution between the healthy foot and the injured leg in individuals with a history of ankle injury in volleyball players [22].

Additionally, fatigue was found to result in reduced balance among adolescent volleyball players without a history of unilateral ankle injury in the open eyes mode, and it also led to reduced balance in adolescent volleyball players with a history of unilateral ankle injury in both open and closed eyes conditions. These changes could potentially increase the risk of lower limb injuries.

Despite the critical importance of this topic, there is a noticeable gap in the existing research literature regarding the impact of competition-induced fatigue and specific exercise protocols on athletes' performance and balance. Therefore, the primary objective of our study is to address this research gap. We intend to achieve this by employing a volleyball-specific fatigue protocol to induce generalized muscle fatigue in elite young volleyball players. Subsequently, we will thoroughly examine how this induced fatigue influences the distribution of plantar pressure, shedding light on the intricate relationship between fatigue, postural control, and foot biomechanics. By doing so, we aim to contribute valuable insights that can inform injury prevention strategies and performance enhancement techniques for these athletes.

MATERIAL AND METHODS

Participants

This study is of a semi-experimental design with a pre and post-test format conducted in the Sports Biomechanics Laboratory. To determine the sample size, G*Power software with $\alpha = 0.05$ and a statistical power of 80% ($1 - \beta$) was used, and a minimum of 16 participants per group was considered [23]. The target population for this research consisted of young male volleyball players, from which 38 individuals were selected using convenience sampling. They were then randomly assigned to two groups: control (18 participants, not participating in the functional fatigue protocol) and experimental (20 participants, participating in the functional fatigue protocol). Both groups underwent three walking test before and after the fatigue protocol.

Inclusion criteria for participants were individuals aged between 16 and 20 years old, with a history of participating in provincial volleyball competitions, and regular and consistent involvement in training over the past two years [24]. Exclusion criteria included any pre-existing injuries or any physical abnormalities that could affect the results. Participants completed informed consent forms to participate in the study, and all procedures, including the measurement of variables and testing protocols, were fully explained to them. The current research protocol was approved by the ethics committee of the Research Institute of Physical Education and Sports Sciences with the number IR.SSRI.REC.1400.1110.

Instruments and Examinations

In this research, the foot scanner (Footscan (RsScan International, Belgium, 578 mm *418 m* 12 mm, 4096 sensors)) with a frequency of 253 Hz was used to measure the variables of maximum plantar pressure distribution during the execution of tasks. Foot was automatically divided into ten anatomical zones including medial heel (HM), lateral heel (HL), midfoot (MF), first to fifth metatarsals (M1-5), big toe (T1) and lesser toes (T2-5) via Footscan 7 Gait 2nd Generation software. For each of these zones, peak plantar force (%BW) were calculated.

To examine the desired variables during gait analysis, participants were asked to walk at self selected speed in a 12-meter walkway where the Footscan was placed at the center of this path. The distance from the starting point of walking to the device was sufficient to ensure that the participants had taken at least 7 steps before reaching the Footscan [25]. Additionally, the length of the 12-meter path allowed participants to take at least 7 additional steps after passing the device. This setup eliminated the effect related to the initiation and termination of gait. The average of three repetitions of gait analysis was considered as the pre-test. Similarly, after performing the fatigue protocol, the average of three repetitions of gait analysis was obtained for both groups. In the control group where no fatigue protocol was implemented, there was a 120-minute interval between the pre-test and post-test [26].

To investigate the effect of the fatigue protocol on the subjects, the maximum vertical jump height was recorded for each participant using Sargent's test [27]. For this purpose, after each cycle of the fatigue protocol, the maximum vertical jump height is immediately evaluated until the jump height of each person is reduced to 30% of the initial maximum jump height, which was considered to determine the point of fatigue [30]. The fatigue protocol in this study included functional volleyball movements, which included several repeated cycles until the desired fatigue level was reached. Each cycle includes: 1) ten repetitions of the claw skill along with going back and forth at a distance of 3 meters, 2) ten repetitions of the forearm skill with the lower guard along with going back and forth with the side leg at a distance of 3 meters, 3) 10 consecutive ankle jumps on the ladder, 4) 10 times performing the defense movement on the net with the maximum possible jump on the net, 5) 10 times performing the three-step spike 6) 10 times performing the follow-up movement (i.e., short jump and chest press) was consecutive [28].

Statistical Analysis

In this study, the Shapiro-Wilk test was used to assess the normality of the data. Given the normal distribution of the data, parametric statistical methods were used to test the hypothesis. One-way analysis of variance (ANOVA) was employed to investigate between-group differences. This study included 3 within-group factors, namely fatigue (before and after fatigue), leg (right and left), and leg regions (10 areas), which were analyzed using repeated measures analysis of variance (ANOVA) to assess the effects of these factors. The data were analyzed using SPSS software (version 21) at a significance level of $p \leq 0.05$.

RESULTS

The means and standard deviations of participants' characteristics are presented in Table 1. As observed, individuals in the control group did not have significant differences in demographic characteristics compared to those in the experimental group.

Table 1. Demographic characteristics of the research participants

	Groups		
	Control	**Experimental**	**Sig.(F)**
Number	18	20	-
Age (year)	17.05 ± 0.63	17.55 ± 0.99	0.08 (3.22)
Height (M)	1.84 ± 0.06	1.85 ± 0.06	0.60 (0.27)
Weight (kg)	71.72 ± 5.07	70.15 ± 6.72	0.42 (0.64)
BMI	21.27 ± 2.46	20.52 ± 2.35	0.34 (0.90)

BMI: Body mass index (weight/height squared)

The results of between-group comparisons before the induction of fatigue are depicted in Fig. 1. According to the results, before fatigue induction, there were significant differences in maximum distributed forces in the toe 1, second metatarsal, medial and lateral of heel in left foot between the two groups ($p < 0.05$). However, after fatigue, the intergroup differences increased in both feet. Based on Table 2 and Fig. 2, the differences between the two groups in the force values in the left toe 5, metatarsals 1, 2, and 3 in both feet, the medial and lateral of right heel were reported to be statistically significant ($p < 0.05$).

Table 2. Results of between-group comparison of plantar pressure distribution during walking in control and experimental groups before and after fatigue

		Control	Experimental	F	Sig.
Maximum force of left T1	pretest	15.69 (5.93)	11.33 (5.38)	5.64	**0.023**
	Postest	13.10 (5.78)	10.13 (5.14)	2.80	0.103
Maximum force of left T5	pretest	6.35 (4.19)	3.91 (3.46)	3.85	0.057
	Postest	7.24 (5.76)	3.11 (2.08)	8.98	**0.005**
Maximum force of M1of left foot	pretest	23.97 (8.29)	25.20 (13.41)	0.11	0.739
	Postest	18.43 (8.76)	27.49 (11.61)	7.23	**0.011**
Maximum force of M2 of left foot	pretest	15.15 (7.45)	20.49 (6.94)	5.21	**0.028**
	Postest	14.94 (5.77)	20.11 (5.61)	7.84	**0.008**
Maximum force of M3 of left foot	pretest	19.71 (7.98)	22.04 (8.03)	0.80	0.377
	Postest	15.88 (7.43)	22.91 (7.67)	8.19	**0.007**
Maximum force of M4 of left foot	pretest	16.97 (6.42)	18.69 (7.85)	0.53	0.468

	Postest	15.77 (6.41)	17.12 (7.03)	0.37	0.542
Maximum force of M5 of left foot	pretest	2.95 (2.22)	4.37 (3.59)	2.09	0.156
	Postest	3.27 (1.96)	2.70 (2.09)	0.76	0.387
Maximum MF force of the left foot	pretest	13.13 (6.25)	15.87 (11.97)	0.75	0.390
	Postest	12.60 (7.07)	13.93 (8.07)	0.29	0.593
Maximum HM force of the left foot	pretest	34.56 (11.34)	41.94 (10.46)	4.35	**0.044**
	Postest	29.79 (8.98)	37.39 (13.93)	3.89	0.056
Maximum HL force of the left foot	pretest	17.30 (4.88)	22.41 (7.39)	6.15	**0.018**
	Postest	19.79 (7.57)	19.58 (7.49)	0.00	0.930
Maximum force of Right T1	pretest	16.29 (5.81)	17.37 (7.20)	0.25	0.617
	Postest	12.88 (5.23)	14.50 (5.80)	0.81	0.374
Maximum force of Right T5	pretest	7.61 (4.44)	8.08 (8.51)	0.04	0.836
	Postest	6.62 (5.27)	7.49 (10.27)	0.10	0.747
Maximum force of M1 of Right foot	pretest	25.86 (11.02)	24.80 (10.80)	0.09	0.765
	Postest	17.92 (6.52)	27.77 (12.17)	9.35	**0.004**
Maximum force of M2 of Right foot	pretest	18.39 (8.08)	20.91 (6.69)	1.10	0.301
	Postest	16.76 (6.86)	22.18 (7.37)	5.47	**0.025**
Maximum force of M3 of Right foot	pretest	18.50 (6.77)	23.12 (8.37)	3.43	0.072
	Postest	13.99 (4.74)	24.64 (9.65)	17.96	**0.000**
Maximum force of M4 of Right foot	pretest	15.76 (8.35)	19.81 (7.67)	2.42	0.128
	Postest	16.33 (5.32)	19.67 (5.87)	3.33	0.076
Maximum force of M5 of Right foot	pretest	3.34 (2.09)	5.01 (2.82)	4.19	**0.048**
	Postest	2.99 (2.11)	3.86 (2.28)	1.46	0.233
Maximum MF force of the Right foot	pretest	12.79 (6.27)	14.87 (9.96)	0.57	0.453
	Postest	11.87 (5.56)	19.58 (11.04)	7.11	**0.011**
Maximum HM force of the right foot	pretest	43.98 (10.82)	42.58 (10.70)	0.16	0.692
	Postest	27.48 (10.35)	42.40 (12.79)	15.39	**0.000**
Maximum HL force of the Right foot	pretest	19.17 (9.01)	20.88 (8.10)	0.37	0.543
	Postest	16.59 (5.88)	19.01 (4.74)	1.96	0.170

Note: Medial heel (HM), lateral heel (HL), midfoot (MF), first to fifth metatarsals (M1-5), big toe (T1) and lesser toes (T2-5).

The results of within-group comparisons (fatigue effect) in the control group indicated a significant effect of fatigue on foot regions ($p < 0.05$). This means that there is a significant difference in the performance of the two feet in post test. Also, the interaction between fatigue and foot regions was significant ($p < 0.05$). Furthermore, the interaction between fatigue and various foot regions in force distribution was also significant, indicating that post-fatigue force distribution differed from the pre-fatigue assessment in some foot regions ($p < 0.05$). Comparisons among different foot regions in the control group showed a significant decrease in the post-fatigue assessment in the force applied to the toe 1, metatarsals 1 and 3, and the mid heel regions ($p < 0.05$). However, within-group comparisons in the experimental group indicated no significant effect of fatigue ($p > 0.05$), as shown in Table 3. The only difference in force levels before and after fatigue was observed in the toe 1 and metatarsal 5 ($p < 0.05$).

Table 3. Examination of within-group factors in the maximum force variable in different foot regions

	Control			Experimental		
	F	Sig.	Eta	F	Sig.	Eta
fatigue	33.41	0.000	0.663	0.33	0.570	0.017
foot (right/left)	0.82	0.376	0.046	6.96	0.016	0.268
foot area	71.74	0.000	0.808	73.35	0.000	0.794
fatigue * foot	11.97	0.003	0.413	2.14	0.159	0.101
fatigue * foot area	9.05	0.000	0.348	1.18	0.311	0.058
Foot * Foot area	1.12	0.349	0.062	1.44	0.172	0.071

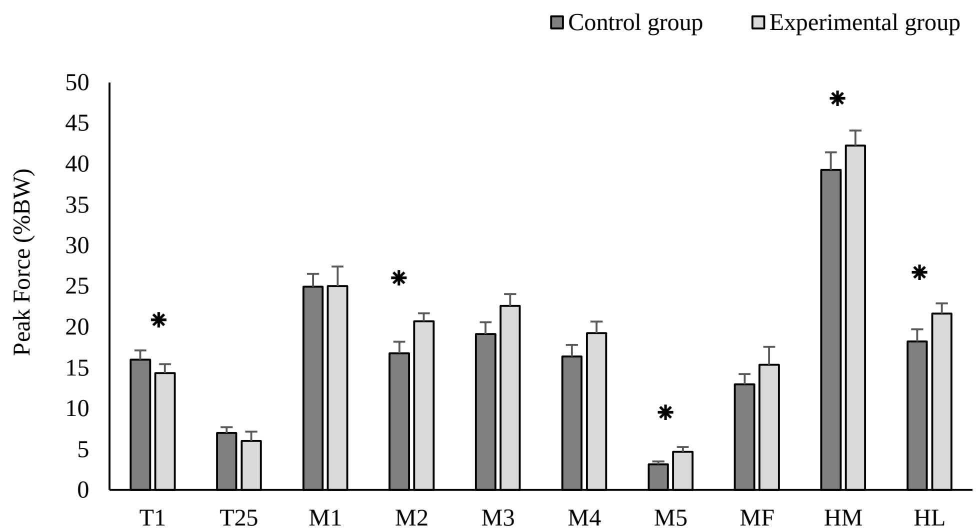

Fig. 1. Between-group differences in the pre-fatigue stage on force distribution in two control and experimental groups

Note: Medial heel (HM), lateral heel (HL), midfoot (MF), first to fifth metatarsals (M1-5), big toe (T1) and lesser toes (T2-5).

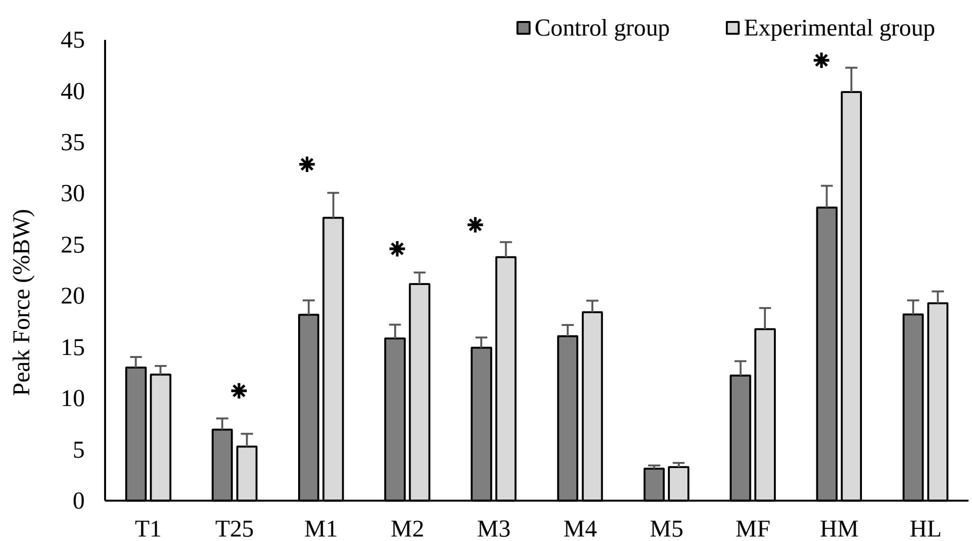

Fig. 2. Between-group differences in the post-fatigue stage on force distribution in two control and experimental groups

Note: Medial heel (HM), lateral heel (HL), midfoot (MF), first to fifth metatarsals (M1-5), big toe (T1) and lesser toes (T2-5).

DISCUSSION

The main objective of this research was to investigate the effect of functional fatigue on the plantar pressure distribution during walking in young professional volleyball players. The results of the comparison between the two groups indicated that before fatigue, the maximum force applied to regions T1, M2, HM, HL, and

M5 showed a significant difference between the two groups. In all cases except T1, the experimental group had higher pressure distribution in various leg regions. According to the study by Chung et al. (2012) [29] walking speed has a significant effect on plantar pressure distribution. In this study, walking speed was not controlled, so one of the reasons for the difference between the two groups before fatigue may be attributed to differences in their walking speed. Comparison of the post-test results revealed that after fatigue induction, there was a significant difference between the two groups in the distribution of force in regions M5, M1, M2, M3, and HM. Examination of the means indicated that, except for M5, fatigue induction resulted in an increase in force in the experimental group in the other cases.

Comparing our results with previous studies, we observe both consonant and discordant outcomes. Similar to earlier investigations, we observed significant alterations in plantar pressure distribution following acute functional fatigue. This aligns with the findings of studies that reported significant changes in force distribution during walking after fatigue induction [30, 31]. However, some disparities emerge when comparing our results to previous research. Notably, the specific locations within the foot where significant differences were observed before fatigue induction differed from some prior studies. While we found differences in the toe 1, second metatarsal, and medial and lateral heel regions of the left foot, other studies have reported variations in different foot regions [30, 32, 33]. This suggests that the effects of acute functional fatigue on plantar pressure distribution may vary depending on the specific activities or sports being studied and the characteristics of the participants. Furthermore, our study highlighted an increase in intergroup differences after fatigue induction. This divergence from previous studies may suggest that acute functional fatigue has a more pronounced effect on plantar pressure distribution in professional volleyball players [34]. It is plausible that the unique biomechanical demands of volleyball, such as sudden changes in direction and explosive movements, could contribute to these discrepancies. The observed alterations in plantar pressure distribution during walking, both before and after inducing acute functional fatigue in young professional volleyball players, can be attributed to several factors. Firstly, the distinct biomechanical demands of volleyball as a sport play a pivotal role. Volleyball involves rapid movements, including sudden changes in direction, explosive jumps, and precise footwork, all of which require quick adjustments in weight distribution and foot positioning. These dynamic and high-impact movements can lead to unique patterns of force distribution within the foot. The escalation of intergroup differences in plantar pressure distribution after fatigue induction can be attributed to the impact of acute functional fatigue on the neuromuscular system. Fatigue can lead to changes in muscle activation patterns and proprioception, affecting how the foot interacts with the ground during walking. In professional volleyball players, who are accustomed to intense physical training and competition, the response to acute fatigue may be heightened due to their finely-tuned neuromuscular systems. This heightened response could result in more pronounced changes in plantar pressure distribution.

The results of our within-group comparisons, specifically examining the effect of fatigue within the control group, offer valuable insights into the impact of acute functional fatigue on foot regions during walking. These findings are particularly relevant when considered alongside previous research, both consonant and discordant. In the control group, the analysis revealed a noteworthy effect of fatigue on various foot regions, signifying that there was a significant difference in performance between the two feet in the post-fatigue assessment. This finding is in line with several studies that have reported significant alterations in foot biomechanics following fatigue induction [22, 35]. Similar studies have shown that fatigue can lead to changes in force distribution across different regions of the foot, which can subsequently affect overall walking performance [22]. Moreover, the significant interaction identified between fatigue and foot regions within the control group underscores the nuanced impact of fatigue on force distribution. This interaction suggests that the post-fatigue force distribution pattern differed from the pre-fatigue assessment in specific foot regions. These observations align with research that has highlighted the complex relationship between fatigue and foot biomechanics, indicating that the effects can be region-specific.

Further investigation into the control group's comparisons among different foot regions revealed a significant decrease in post-fatigue force applied to the toe 1, metatarsals 1 and 3, as well as the mid heel regions. This decrease aligns with findings from some previous studies that have reported reduced force levels in specific foot regions after the induction of fatigue [30, 34]. These findings suggest that acute functional fatigue can indeed impact force distribution in certain regions of the foot, potentially affecting gait and performance. In contrast, the within-group comparisons within the experimental group yielded different results. In this group, there was no significant effect of fatigue on foot regions, except for the observed differences in force levels before and after fatigue in the toe 1 and metatarsal 5. This discrepancy from the control group's results may be attributed to the specific nature of the experimental group, which could include individuals with different levels of conditioning or adaptation to fatigue. When individuals experience acute fatigue, there is a tendency for the neuromuscular system to become less efficient, leading to alterations in force production and distribution. The decreased force in the toe 1, metatarsals 1 and 3, and mid heel regions can potentially influence the overall gait and walking performance. For example, reduced force in the toe region may affect the push-off phase of gait, leading to alterations in propulsion. Similarly, decreased force in the heel regions may impact shock absorption during the heel strike phase of walking.

CONCLUSION

The results of this study showed that fatigue leads to an increase in maximum plantar pressure distribution. These factors may increase the risk of injury in individuals. Considering that the most common time for sports injuries to occur is at the end of a game, fatigue accompanied by an increase in activity intensity or the sudden application of force may lead to injuries. Therefore, delaying fatigue or controlling it during competitions is important for proper technique execution and achieving game results.

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تاثیر خستگی حاد عملکردی بر توزیع فشار کف پایی طی راه رفتن در والیبالیست حرفه‌ای جوان

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چکیده:
هدف از این تحقیق بررسی تأثیر خستگی حاد عملکردی بر توزیع فشار کف پایی در بازیکنان حرفه‌ای جوان والیبال مرد بود. در مجموع ۳۸ بازیکن جوان والیبال برای این مطالعه داوطلب شدند و به صورت تصادفی به دو گروه تقسیم شدند: گروه آزمایشی (۲۰ نفر) و گروه کنترل (۱۸ نفر). توزیع فشار کف پایی با استفاده از یک اسکنر پا قبل و بعد از اعمال خستگی عملکردی در حین راه رفتن اندازه‌گیری شد. از تحلیل واریانی یک طرفه برای بررسی اختلاف‌های بین دو گروه استفاده شد و تحلیل واریانس ویژه داده‌های تکراری برای بررسی اثر خستگی در هر گروه استفاده شد. داده‌ها با استفاده از نرم‌افزار SPSS (نسخه ۲۱) در سطح معناداری $p \leq 0.05$ تحلیل شدند. نتایج نشان داد که پس از خستگی، اختلاف‌های بین گروهی در توزیع فشار کف پا در هر دو پا افزایش یافت. اختلاف‌های معنی‌داری بین دو گروه در مقادیر نیروی اعمالی بر انگشت کوچک چپ، متاتارس اول، دوم و سوم، میانه پا، و قسمت داخلی پاشنه پا راست مشاهده شد ($p < ۰/۰۵$). نتایج نشان داد که خستگی منجر به افزایش میزان نیروی حداکثر کف پایی می‌شود. این عوامل ممکن است خطر ابتلا به آسیب در افراد را افزایش دهند.

واژه های کلیدی: فشار کف پا، خستگی، اسکنر کف پا، راه رفتن، والیبال