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Original Article

The Effect of Partial Sleep Deprivation on Ground Reaction Force Components Before and After Fatigue

Yasin Hosseini[1*], PhD; Leila Ghazaleh[2], PhD; Paria Mohammadi Rad[2],MSc; Fateme Badie[3], PhD

[1] Department of Sports Science, Faculty of Literature and Humanities, Malayer University, Malayer, Iran.
[2] Department of Exercise Physiology, Faculty of Sport Sciences, Alzahra University, Tehran, Iran.
[3] Department of Mechanical Engineering, Jundi-Shapur University of Technology, Dezful, Iran.

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ABSTRACT

Background: The combined effects of sleep deprivation and fatigue may increase the risk of injury. Analyzing ground reaction force (GRF) components during activities such as cutting maneuvers provides valuable insights into musculoskeletal function. This study aimed to investigate the effect of partial sleep deprivation on GRF components before and after fatigue.
Methods: This semi-experimental study included 14 young women who were evaluated twice, with a 5-day interval between sessions. During the pre-test, participants had full sleep, whereas during the post-test, they experienced partial sleep deprivation (4 hours of sleep at the beginning of the night). In each session, participants performed five attempts without fatigue and three attempts under fatigue. GRF components were measured using a Kistler force plate under all conditions.
Results: At the heel contact phase (FZ1), both fatigue ($P = 0.012$) and fatigue combined with partial sleep deprivation ($P = 0.025$) significantly reduced the time to reach peak vertical GRF. Moreover, the interaction between fatigue and partial sleep deprivation resulted in a significant decrease in vertical loading rate ($P = 0.019$). However, no significant differences were observed in the peak GRF or impulse across conditions.
Conclusion: The interaction of fatigue and partial sleep deprivation appears to exacerbate injury risk factors, particularly by increasing loading rates and reducing the time to reach peak GRF.

Introduction

Sleep is essential for physiological processes, metabolism, and brain function [1,2], with optimal adult sleep considered to be 7–9 hours per night [3]. The sleep–wake cycle is a fundamental component of the human circadian rhythm, and disruption of this cycle can negatively affect athletes' physical, cognitive, and psychomotor performance [4,5]. Insomnia can be classified as partial or complete; partial sleep deprivation (PSD), which typically occurs at the end of the night or early morning, is particularly common among athletes [6].

Research examining the effects of sleep deprivation on short-term, high-intensity exercise has reported conflicting results. Some studies suggest no significant

*Corresponding author: Yasin Hoseini; Department of Sports Science, Faculty of Literature and Humanities, Malayer University, Malayer, Iran, **Tel:** +989183525103, **Fax:** +98 81 38 38 14 21 **Email:** y.hoseini@malayeru.ac.ir

impact on maximal performance [7], while others indicate that partial or complete sleep deprivation reduces anaerobic performance [8,9]. These discrepancies may arise from differences in exercise modes, frequencies, intensities, durations, evaluation methods, participants' ages, and sleep deprivation protocols [6]. Overall, evidence indicates that athletes sleeping less than 7–8 hours per night experience reduced strength, muscular endurance, and movement speed [10].

Sleep deprivation also increases injury risk. Athletes sleeping less than 8 hours per night are 1.7 times more likely to sustain injuries than those obtaining adequate sleep [11,12]. Reduced sleep diminishes the body's recovery capacity after training or competition, indirectly increasing injury risk, and delays healing in injured athletes [10,13,14].

Fatigue is another significant factor contributing to sports injuries [15]. Defined as a decline in a muscle's ability to produce optimal force and disruption in neuromuscular signaling [16], fatigue alters joint movement patterns, decreases joint stability and muscle strength, and increases lower limb injury risk, especially during the latter stages of competition [17,18].

Examining ground reaction force (GRF) components provides clinically relevant insights into musculoskeletal function. Metrics such as vertical loading rate and impulse—calculated from GRF curves during the stance phase—have been associated with lower extremity injuries. For example, vertical loading rates exceeding 70 N/kg/s are associated with stress fractures, rates above 72 N/kg/s with patellofemoral pain, and rates above 100 N/kg/s with plantar fasciitis in runners [19].

Despite the clear relevance of both sleep deprivation and fatigue to injury risk, no studies have investigated their interactive effects on GRF components. Therefore, the present study aims to examine the combined influence of partial sleep deprivation and fatigue on ground reaction force metrics.

Methods

Study Design and Participants

Fourteen healthy, active young women (mean age: 22.66 ± 3.04 years; height: 168.14 ± 5.1 cm; weight: 60.97 ± 7.86 kg; BMI: 21.63 ± 2.18 kg/m²) participated in this semi-experimental study. Sample size was calculated using G*Power software, indicating that 14 participants were required for repeated-measures ANOVA to detect an effect size of 0.40 with a significance level of 0.05 and statistical power of 0.95.

Inclusion criteria included: Normal BMI (18.5–24.9 kg/m²) [19], no history of neuromuscular disorders, lower-limb injuries, or musculoskeletal anomalies [19], engaging in ≥150–300 minutes of moderate physical activity per week [20], consistent and appropriate sleep patterns (assessed via questionnaire) [22]. Exclusion criteria included: Consumption of caffeine-containing foods before testing, engaging in intense exercise within 24 hours before testing, and non-compliance with the sleep deprivation protocol [20].

The study was approved by the Ethics Committee of the Sports Sciences Research Institute, Ministry of Science, Research, and Technology (ethics code: IR.SSRI.REC.1400.1288). All participants provided written informed consent.

Experimental Procedure

Each participant visited the laboratory twice with a 5-day interval, following a **crossover design** to control for learning effects. Testing was conducted during the second week of the follicular phase of the menstrual cycle to minimize hormonal effects on sleep patterns [23].

- Sleep conditions: Participants completed one session after a full night of sleep according to their normal routine and one session after partial sleep deprivation (PSD), consisting of 4 hours of sleep at the beginning of the night [24].
- Ground Reaction Force Measurement: GRF was recorded using a Kistler force plate (2600 × 400 mm; Kistler AG, Winterthur, Switzerland) at a 1000 Hz sampling rate. Forces were measured in vertical (Fz), anterior-posterior (Fy), and medial-lateral (Fx) directions during lateral cutting maneuvers. The force plate was placed midway along a 20-meter path, allowing participants at least 10 steps before contacting the plate. Calibration was performed before testing.
- Warm-up: Participants performed a 5-minute run to familiarize themselves with the testing environment.
- Lateral Cutting Maneuver: Participants ran 5 meters and cut laterally at a 45° angle along a marked path (Figure 1). Each participant performed five trials with the right foot landing on the force plate; only successful trials were analyzed.
- Fatigue Protocol: After the initial trials, participants performed squats with 75% of their 1RM until failure. Individual 1RM values were calculated using the Berezinskii formula [25]. Immediately following the fatigue protocol, participants repeated the lateral cutting trials under fatigued conditions.

Data Processing

Force plate signals were smoothed using a fourth-order Butterworth low-pass filter with a cutoff frequency of 12 Hz and zero phase shift [26]. Key variables extracted included peak ground reaction forces (GRF), impulse, and loading rate. For the GRF variables, three vertical components, three medial-lateral components, and two anterior-posterior components were extracted. For ground reaction forces, three points are calculated in the vertical direction: the peak vertical force at initial contact (FzI.C), the mid-stance phase (FzM.S), and the push-off phase (FzP.O). In the anterior-posterior direction, two peaks are noted (forward (FyP.O) and braking (FyI.C)). In the internal-external direction, three points are calculated at the moment of initial contact (FzI.C), the mid stance phase (FzM.S), and the push-off phase (FzP.O) (Figure 1). All GRF variables were normalized to participants' body weight and analyzed for the dominant foot.

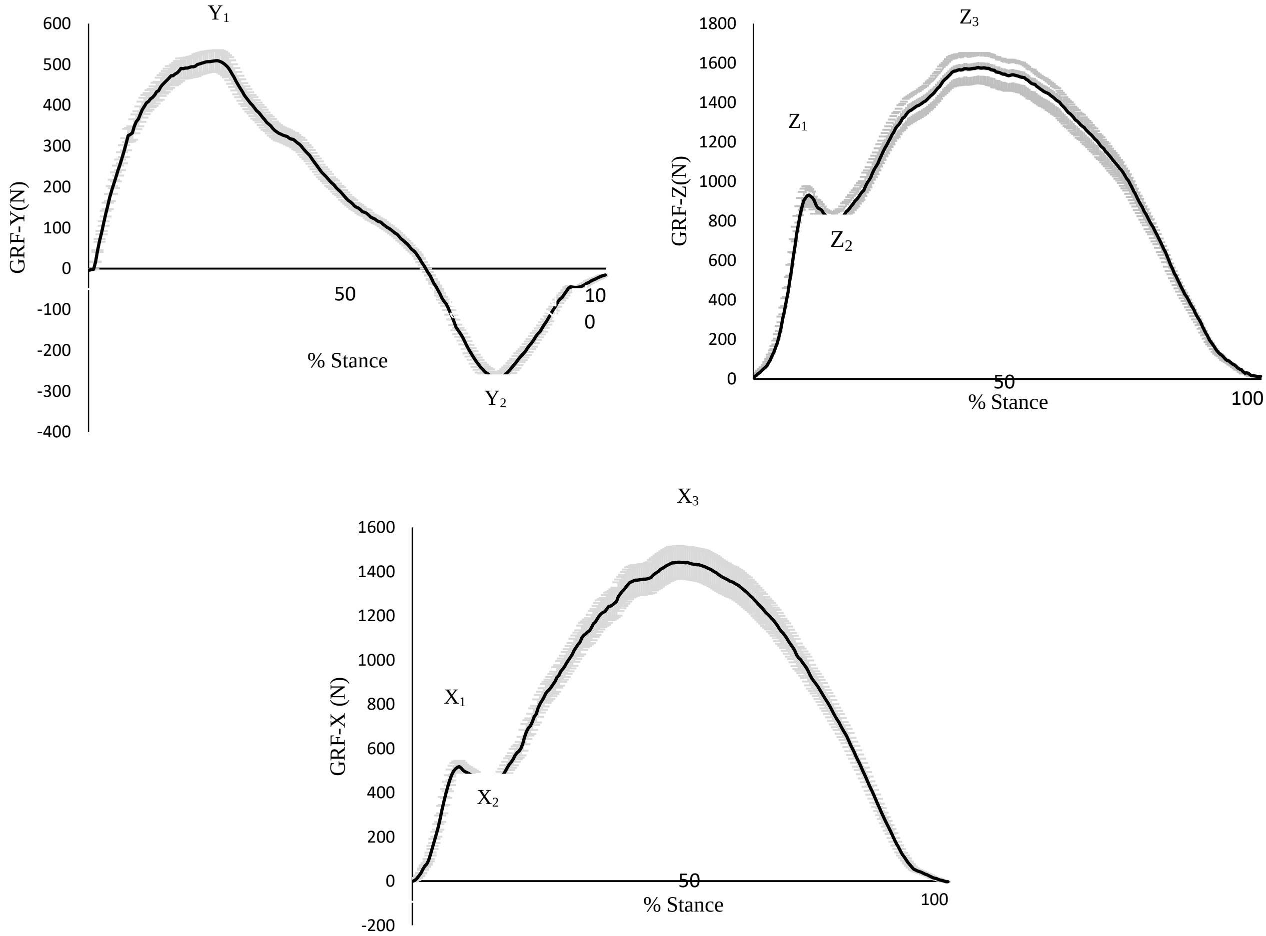

Figure 1: A time-normalized ensemble average of the ground reaction forces. Vertical force (Fz), anterior-posterior force (Fy), and internal-external force (Fx)

The impulse magnitude was also measured in three directions: x (Impx), y (Impy), and z (Impz). The trapezoidal integration method was used to calculate the impulse magnitude. [27]

$$Impulse = \Delta t(\left(\frac{F1 + Fn}{2}\right) + \sum_{i=2}^{n-1} \quad Fi)$$

The vertical loading rate was defined as the slope of the initial rising portion of the vertical ground reaction force curve, measured between the moment of heel contact and the first peak of the vertical GRF.[28]

$$\text{Loading rate} = [\![\frac{peak\ Fz(N)/body\ weight(N)}{time\ to\ peak\ Fz}]\!]$$

Statistical Analysis

The Shapiro–Wilk test was first applied to assess the normality of the data distribution. Given that all variables met the assumption of normality, a repeated-measures ANOVA was performed to examine the effects of fatigue and partial sleep deprivation. The significance level was set at $p < 0.05$. All statistical analyses were conducted using SPSS software (Version 19; SPSS Inc., Chicago, IL, USA).

Results

Table 1 presents the mean peak values of the normalized ground reaction force components (Fx, Fy, and Fz) across the different experimental conditions. As shown, no significant differences were observed in any of the peak GRF components in the medial–lateral (Fx), anterior–posterior (Fy), or vertical (Fz) directions ($p > 0.05$).

Table 2 presents the results for the time-to-peak of the GRF components. The findings show that at heel contact (FZ1), fatigue (p = 0.012) and the combined condition of fatigue with partial sleep deprivation (p = 0.025) significantly reduced the time to peak vertical ground reaction force. Similarly, during the mid-stance phase, fatigue ($p = 0.007$) and fatigue combined with partial sleep deprivation ($p = 0.037$) also led to a significant reduction in time to peak vertical force. Under sleep deprivation alone ($p = 0.007$) and fatigue combined with sleep deprivation ($p = 0.025$), the time to peak ground reaction force at heel contact was significantly reduced, indicating a faster, potentially more hazardous loading pattern.

Table 1: Peak values of Ground Reaction Force (GRF) in the Z, Y, and X Axes

	Phases	**Full sleep without fatigue**	**Full sleep with fatigue**	**Loss of sleep without fatigue**	**Loss of sleep with fatigue**	**P value**
FZ (vertical)	FZ_1	135.32±43.17	128.78±46.98	137.16±58.21	120.60±53.99	NS
	FZ2	121.18±42.74	115.6864±44.99	107.45±42.08	96.97±41.71	NS
	FZ_3	177.63±39.68	197.34±43.54	151.39±58.36	153.62±39.12	NS
FY (anterior-posterior)	FY_1	29.47±14.31	28.88±16.42	31.15±12.49	32.07±8.57	NS
	FY_2	12.55±5.80	15.10±10.30	11.15±8.70	12.84±9.15	NS
FX (internal-external)	X_1	1.05±0.85	0.99±0.83	1.15±1.04	1.05±0.81	NS
	X_2	29.63±13.86	27.77±14.83	28.23±11.52	30.91±8.43	NS
	X_3	0.35±0.13	0.26±0.12	0.63±0.18	0.48±0.28	NS

Table 2: The time to the peak of ground reaction force (GRF)

		Full sleep without fatigue	**Full sleep with fatigue**	**Loss of sleep without fatigue**	**Loss of sleep with fatigue**	**P value**
TFZ	TFZ_1	0.05±0.02$^{£}$	0.04±0.01$^{¥}$	0.04±0.02$^{\&}$	0.03±0.02$^{€}$	£ vs ¥=0.012 £ vs €=0.025
	TFZ_2	0.07±0.025$^{£}$	0.06±0.024$^{¥}$	0.05±0.03$^{\&}$	0.04±0.02$^{€}$	£ vs ¥=0.007 £ vs €=0.037
	TFZ_3	0.14±0.02$^{£}$	0.14±0.03$^{¥}$	0.13±0.034$^{\&}$	0.13±0.04$^{€}$	NS
TFY	TFY_1	0.10±0.02$^{£}$	0.10±0.07$^{¥}$	0.08±0.02$^{\&}$	0.08±0.02$^{€}$	£ vs &=0.007 £ vs €=0.025
	TFY_2	0.31±0.10	0.31±0.13	0.31±0.07	0.34±0.09	NS
TFX	TX_1	0.01±0.008	0.013±0.0079	0.007±0.0038	0.006±0.004	NS
	TX_2	0.22±0.12	0.18±0.042	0.20±0.062	0.19±0.075	NS
	TX_3	0.46±0.186	0.44±0.122	0.45±0.065	0.50±0.068	NS

Figure 2 presents the results for Impx, Impy, and Impz across all experimental conditions. As shown, neither fatigue nor partial sleep deprivation produced a significant effect on impulse in any of the three directional components.

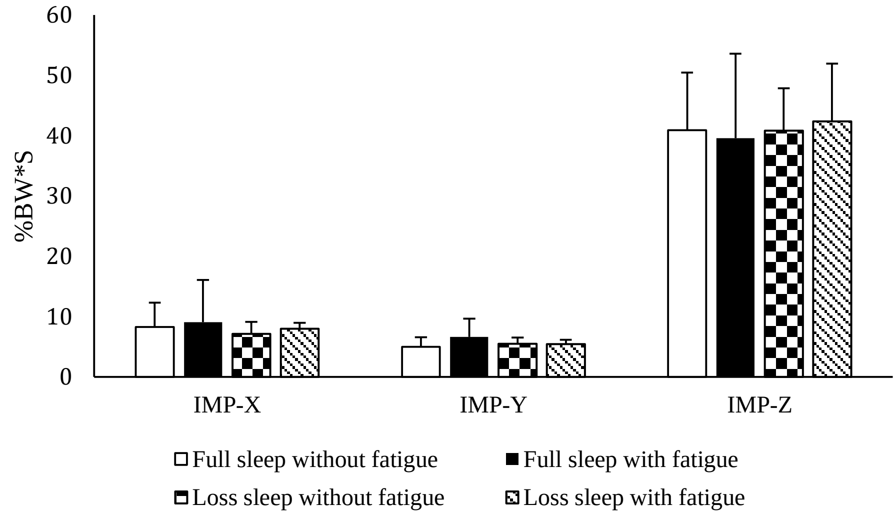

Figure 2: Impulse value in the stance phase of the cutting maneuver

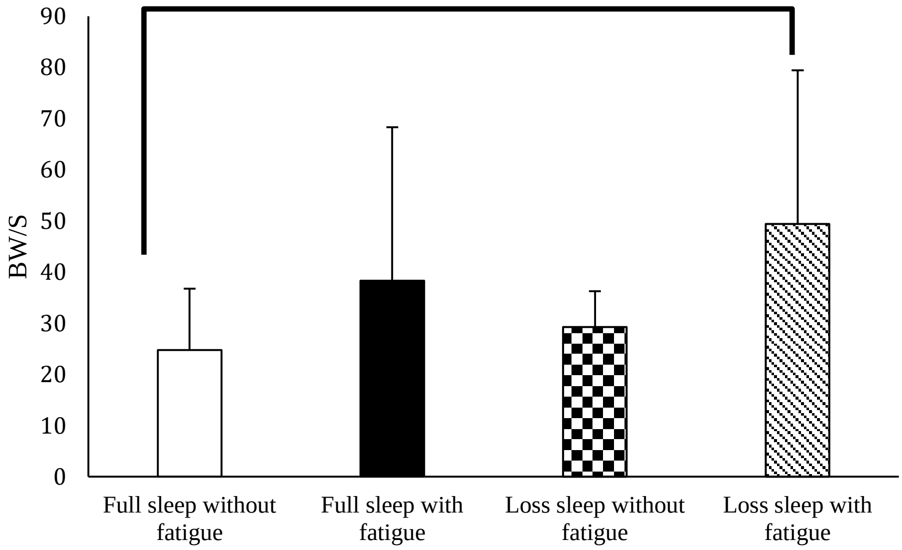

Figure 3: Loading rate value in the stance phase of the cutting maneuver

Figure 3 illustrates the loading rate across the different experimental conditions. The vertical loading rate during the cutting maneuver without sleep deprivation or fatigue was 24.74% of body weight per second (BW/s). Under combined partial sleep deprivation and fatigue, the loading rate increased by approximately 104%, a change that was statistically significant ($p = 0.019$).

Discussion

The present study aimed to compare the components of ground reaction force, impulse (Impx, Impy, and Impz), and vertical loading rate during the initial phase of a cutting maneuver under conditions of fatigue, partial sleep deprivation, and their combined effects. When the heel contacts the ground during running, landing, or cutting maneuvers, several factors—including surface type, footwear, muscle activation patterns, and joint range of motion—influence the magnitude of the ground reaction forces (GRFs) [29]. Because the surface and footwear were kept constant across all testing conditions, any observed differences in GRF components may be attributed to impairments in muscle function or alterations in lower-limb joint kinematics, particularly at the ankle and knee [30].

The results of this study showed no significant differences in peak GRF values during the stance phase across the various experimental conditions. In other words, fatigue, sleep deprivation, and their interaction did not affect peak GRFs in any of the three planes. These findings are consistent with previous studies. McLean et al. reported that fatigue did not influence peak GRFs during cutting tasks [31], and Muir et al. similarly found that fatigue did not affect shock absorption or GRF components during weight-bearing activities [32]. Conversely, some studies have reported decreases in GRF following fatigue, which may be attributable to differences in task type, methodological variations, or participant sex.

Notably, no prior research has examined the effects of sleep deprivation on GRF variables, making the present study one of the first to investigate this interaction. Analysis of peak GRF timing revealed that both fatigue and partial sleep deprivation significantly shortened the time to peak vertical GRF. Research suggests that sleep deprivation reduces maximal performance in tasks involving large muscle groups—such as the bench press, leg press, and deadlift—likely due to impaired neuromuscular function [6]. Both fatigue and sleep deprivation appear to reduce muscle force-generating capacity, impair joint coordination, slow muscle reaction time, and diminish proprioception [32].

Fatigue has also been shown to impair postural control and shock absorption capabilities [32,33]. Under normal conditions, muscles act as primary shock absorbers during high-impact movements such as landing and cutting. However, when neuromuscular performance is compromised due to fatigue, passive structures—such as ligaments and joint capsules—are forced to absorb greater loads. This compensatory shift increases injury risk, particularly during rapid changes of direction [32].

One strategy the neuromuscular system uses to protect joints is increasing lower-limb flexion, thereby lengthening the time available for force attenuation [32,33]. In contrast, the present findings indicate that fatigue and sleep deprivation reduced the time to peak GRFs, thereby shortening the force transmission time and increasing mechanical loading on lower-limb structures. This shortened time to peak force also elevates the loading rate—a key risk factor for lower-extremity injuries [28].

Because loading rate is determined by both GRF magnitude and the time to peak force, any reduction in the latter will increase loading rates even if peak GRFs remain unchanged [28]. Biological tissues are viscoelastic, meaning their susceptibility to injury depends on the rate of loading; tissues fail more readily at high loading rates [34]. Research indicates that lower loading rates are associated with more efficient lower-extremity adaptations during ground contact [35]. Furthermore, lower-limb stiffness—affected by the joints at the ankle, knee, and hip—also plays a crucial role in determining how the body absorbs forces during locomotion [35].

As proposed by the mass–spring model, reduced lower-limb and foot adaptability leads to higher loading rates during dynamic movements. Numerous scientific reports have demonstrated that elevated loading rates are strongly associated with an increased risk of musculoskeletal injury. Specifically, higher loading rates have been linked to a greater likelihood of stress fractures and patellofemoral pain, and excessive loading rates during running have been identified as a key risk factor for the development of plantar fasciitis. In the context of the present study, the observed increase in vertical loading rate following sleep deprivation and fatigue appears to be primarily driven by a reduction in the time required to reach the initial peak of the vertical ground reaction force. This accelerated force application places additional stress on passive structures and may heighten injury susceptibility.

A principal limitation of this study is that the sample consisted exclusively of young women. Given established anthropometric and biomechanical differences between males and females, the findings cannot be generalized to broader athletic populations. Future research should therefore include more diverse participant groups to improve the external validity of the results.

Conclusion

According to the findings of this study, neither fatigue nor partial sleep deprivation alone produced significant changes in ground reaction force components. However, their interaction led to notable alterations. When fatigue was combined with partial sleep deprivation, the resulting decline in optimal muscle force production reduced the time to reach peak ground reaction forces. This, in turn, significantly increased key injury-related risk factors, particularly the loading rate.

Author Contributions

Y. H: Methodology, Investigation, Conceptualization, Software, Validation, Formal analysis, writing original draft– review & editing. **L. Gh:** Conceptualization, Methodology, Software, Writing – review & editing. **P.M:** contributed **to** data acquisition, data interpretation, and writing the manuscript. **F.B:** contributed **to** data analysis.

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Conflict of Interest: The authors declare that they have no conflict of interest.

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