DOI: 10.48305/jrrs.2023.41417.1025 Published by Vesnu Publications

Comparison of Range of Motion of Lower Limb Joints during Walking on Flat and Sloping Surfaces in Middle-Aged Climbers with and without Backpacks: Quasi-Experimental Study

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Original Article

Abstract

Introduction: Understanding the biomechanical impact of carrying a backpack when walking downhill can be valuable in designing injury prevention programs and physical preparation plans. The aim of this study was to compare the range of motion of lower limb joints during walking on flat and sloped surfaces in middle-aged climbers with and without backpacks.

Materials and Methods: In the present study, 14 middle-aged mountaineers performed 4 walking trials with and without a backpack on a treadmill with a slope of 0 degrees and a negative slope of 15 degrees. Three-dimensional motion analysis system was used to record kinematic data. The range of motion (ROM) of the ankle, knee, and thigh joints was processed in the sagittal plane. If data followed a normal distribution, paired t-test was used.

Results: On a slope of -15 degrees with a backpack, hip joint (P = 0.044) and ankle joint (P = 0.007) ROM was significantly lower than without a backpack. In the case of using a backpack, knee joint ROM was significantly lower on a 0 degree slope (P = 0.038) and -15 degrees slope (P = 0.029) compared to without a backpack. Moreover, ankle joint ROM significantly differed only when using a backpack (P = 0.032). Furthermore, for the knee and thigh joints, there was a significant difference in the ROM between slopes with (P = 0.006 and P = 0.012, respectively) and without a backpack (P = 0.025 and P = 0.015 respectively).

Conclusion: Carrying a backpack with 25% of the body weight on a negative slope has significant effects on the ROM of the lower limb joints. It seems that negative slope may have far greater effects than load on the ROM of the lower limb joints, especially the ankle joint in middle-aged climbers. Since downhill descent is a part of every climbing program, using a light backpack and optimizing the style of carrying the backpack is recommended to climbers to prevent injuries and improve performance.

Keywords: Walking; Backpacking; Range of motion; Negative slope; Climbers; Middle-aged

Citation: Mahdavikhalilabad M, Amirseyfaddini M, Amiri-Khorasani M, Fadaei H. **Comparison of Range of Motion of Lower Limb Joints during Walking on Flat and Sloping Surfaces in Middle-Aged Climbers with and without Backpacks: Quasi-Experimental Study.** J Res Rehabil Sci 2022; 18: 75-83.

Received date: 04.04.2022 Accept date: 02.05.2022 Published: 06.07.2022

Introduction

Mountaineering is one of the most exhilarating outdoor sports and has positive effects not only on physical fitness, but also on individuals' mental and emotional well-being (1). While mountaineering at high altitudes provides excellent stimulation for the cardiovascular and respiratory systems and skeletal muscles, there are inherent dangers and risks associated with mountaineering in high-altitude environments (2). Mountaineering involves significant ups and downs in smooth and rugged terrains (4, 5). Walking on steep surfaces as a

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challenging task in everyday life can lead to musculoskeletal pain and injuries to the musculoskeletal system (6).

Researchers have extensively studied the effects of walking on slopes on posture and gait adaptations (7-8), muscle activity (8), joint kinetics and mechanics (9), lower limb kinematics (10), and load sharing within and between limb segments (11). The biomechanics of the lower limbs during walking on a sloped surface differ from those during walking on a flat surface. The step cadence decreases, and the step length reduces as the slope angle increases from 10- to 10+ degrees, with more excellent absolute positive and negative slopes (11). Walking downhill on an incline increases the risk of falling due to slipping or losing balance compared to walking on a flat surface. During downhill walking, the joints are forced into specific positions necessary to prevent falls, thus requiring controlled coordination of the lower limb joints, which is achieved through kinematic adjustments of different body segments, especially when carrying mountaineering equipment (12). Walking with a load on a flat surface requires different movement control strategies to that without a load. Differences in the pattern and amount of ground reaction force (GRF), and joint kinematics and kinetics between tasks and walking with different loads (13, 14) illustrate different strategies of posture control under these circumstances (15). Moreover, walking with a load on slopes requires another type of movement; depending on the kind of ascent, the specific area, the timing, and the program season, different tools and equipment may be used. Advancements in equipment and understanding of athletes' correct use of these tools can significantly reduce the number of casualties and financial damages (16). One common and popular tool among climbers is the backpack. Sport and regular backpacks differ significantly from professional backpacks designed for long journeys. These backpacks should be created with the consideration of two factors. First, they should be medically and physically designed, so that they do not cause any harm to the athletes' health due to their weight. Second, they should be prepared for space and safety so that various mountaineering equipment can be carried in them. Incompatibility between the backpack's weight and the climber's physical ability is one of the main reasons for failure and lack of success in mountaineering programs (17-18). Carrying a load in a backpack reduces stability and lateral balance, and can lead to a fall (19). Furthermore, having a bag can increase the loading on the lower limbs, exert excessive pressure on the soft tissues around the lower limb joints, and make the individual susceptible to injuries (20).

Due to their lack of consideration of their physical readiness, many climbers have been unable to reach the summit because of carrying heavy backpacks and have caused problems in the rhythm of their group's ascent. In a study, it was observed that walking uphill increased the stride length by 10% compared to walking on a flat surface, and the effect of the slope on stride length was more significant than the effect of backpack load (21). Additionally, 8% of the 5,000 reported injuries in the Australian Defense Force from January 2009 to December 2010 were related to carrying heavy backpacks, which had resulted in muscular stress. Furthermore, an increase in backpack load decreased soldiers' physical performance by approximately 1% per kilogram of imposed load (3).

Various findings have been reported regarding the parameters of gait and walking on uphill slopes (4-6). In a study examining the effects of walking with an empty backpack versus carrying a 25 kg load on the kinetics and kinematics of ankle and knee joints in men during walking on a 15-degree uphill slope, the stance phase time was reduced when carrying a backpack, indicating an increase in walking speed and a compensatory mechanism for reducing body instability during uphill walking. Additionally, the internal and external vertical and anterior-posterior impacts of uphill walking with a backpack were significantly more significant than in controlled conditions without a load (22). A 25% body weight load in the backpack on a positive or negative 15% slope resulted in increased trunk flexion, and consequently, reduced trunk range of motion (ROM), which negatively affected the trunk movement pattern (6). With an increase in slope up to 15% and carrying a 25% body weight load, optimal speed decreased (23). A significant number of initial biomechanical studies have focused on the mechanical effects of backpack load on the lower extremities and the spinal column (7-10), and it has been shown that carrying a backpack increases the risk of injury to the lower extremities and the spine (10, 11). However, most studies have examined muscular activity (12-14) and joint torques (15) during walking on slopes with and without load.

Most studies have focused on studying positive slopes, and no study has specifically examined the kinematics of walking on negative slopes, especially in mountaineers. Additionally, the importance of kinematic studies on negative slopes compared to positive slopes is that the body faces significantly greater challenges on negative slopes, and the muscles and joints must exert more effort to maintain balance and support the body (16). Investigating these variables can increase our understanding of different control strategies during walking on slopes with a backpack

(16). Various studies have examined the effects of carrying a backpack, particularly its weight relative to gender. A survey of the results of carrying backpacks with different weights on selected biomechanical variables of the lower extremities during walking showed that backpacks weighing 15% and 20% of body weight create various biomechanical changes in the lower extremities and may not be suitable for carrying (17). Gender differences in energy expenditure during backpack walking have been demonstrated, with healthy young women having significantly lower energy expenditure than men during a 10-minute walking exercise (18). A study on the effects of backpacks on temporal walking characteristics did not show any differences between boys and girls (19). These results differ from those of adult studies, indicating that women show apparent changes in temporal aspects of walking compared to men when carrying a backpack (20). No study has compared the ROM of the lower extremities on flat surfaces and negative slopes in middle-aged climbers with and without a backpack. Additionally, to control for the effect of gender in the current study, only men will be examined. Therefore, the following study was conducted with the aim to determine whether the weight of the backpack affects the ROM of middle-aged climbers on flat surfaces and negative slopes.

Materials and Methods

The present quasi-experimental, cross-sectional, applied research was conducted at the Movement Analysis Laboratory of Shahid Bahonar University of Kerman, Iran, in the summer of 2021. The participants of this study consisted of professional middle-aged mountaineers from the city of Kerman. The sample size estimation was based on the inclusion criteria, and thus, 12 middle-aged male climbers were selected through public announcements and purposive sampling. Before beginning the experiment, all participants were provided with a detailed description of the testing procedures and were asked to complete and sign a consent form and personal information questionnaire. The execution of this study was approved by the Ethics Committee of Shahid Bahonar University of Kerman.

For the registration of three-dimensional kinematic data, the Qualisys motion analysis system (model Raptor-H Digital Real-Time System; Qualisys AB, Gothenburg, Sweden), with 6 cameras and a maximum frame rate of 900 frames per second, was utilized. Initially, anthropometric dimensions were measured using a scale and a height gauge. Then, based on the Plug-in Gait marker model for the lower limbs, 14 markers with a diameter of 19 millimeters were placed on the anatomical landmarks of the participants' bodies (52-53) (Figure 1).

Figure 1. Placement of lower limb markers

First, a static test was performed in standard anatomical position. Before the test execution, the participants engaged in a 5-minute warm-up on a stationary bicycle. The treadmill, with the necessary settings, was prepared at the beginning of each session and before the data recording process. The measurements were then initiated at predetermined stations. To familiarize the participants with the prepared treadmill and select their preferred walking speed, they were asked to walk on it for 6 minutes (24). The walking speed for each participant was their self-selected and customary speed, which was maintained throughout all their experiments. Each participant completed the following 4 randomized experiments (the order of the tests was written on a piece of paper and placed inside an opaque box, and they were drawn out one by one until the desired sample size for each participant was completed):

- Walking without a backpack on a zero-degree incline treadmill
- Walking with a backpack weighing 25% of their body weight on a zero-degree incline treadmill
- Walking without a backpack on a -15-degree incline treadmill
- Walking with a backpack weighing 25% of their body weight on a -15-degree incline treadmill

The duration of each experiment was 2 minutes, and the final 20 seconds of each trial were recorded without the participant's knowledge. Since the kinematic data for the last 20 seconds of each trial were recorded, each 20-second segment contained a minimum of 15 cycles, considered 1 trial based on the average of the trials for each participant (24). All measurements for each participant were completed in 1 session to control for daily variations. Participants were free to rest between experiments. After the data was recorded and stored, the Cortex software (version 2.5.0.1160-64 bit) was used for data filtering, marker labeling, and removing gaps between recorded marker paths. The required information was extracted from the recorded video of 3 consecutive selected gait cycles. Then, the desired parameters, including the ROM of the lower limb joints in the sagittal plane, were calculated. In this study, Excel software (Microsoft Office 2016; Microsoft Corp., Redmond, WA, USA) and SPSS software (Version 22; IBM Corp., Armonk, NY, USA) were used for data analysis. Descriptive statistics such as mean and standard deviation were used to describe the data, and the Shapiro-Wilk test was used to assess the data distribution. If the data followed a normal distribution, repeated measures analysis of variance (ANOVA) with paired sample t-tests as post-hoc tests were conducted. If the data did not follow a normal distribution, the Wilcoxon test was used for significant level ($\alpha = 0.05$) analysis.

Results

The Shapiro-Wilk test results indicated that the data in this study followed a normal distribution. Therefore, parametric statistical methods were used for data analysis.

The demographic information of the participants in this study is presented in table 1.

The results of the ROM in the lower limbs on zero and -15 degree slopes with and without a backpack are presented in table 2.

Table 1. Demographic information of the participants

Variable	Value (mean ± SD)
Number of participants	14
Age (year)	49.23 ± 2.20
Weight (kg)	74.9 ± 3.83
Height (cm)	176.71 ± 4.16
Body index mass (kg/cm^2)	22.40 ± 1.16
Climbing history (years)	9.03 ± 4.02

BMI: Body mass index; SD: Standard deviation

The results of the comparison of the investigated situations in the correlated t-test are presented in table 3.

The paired sample t-test results indicated no significant difference in the ROM of the hip and ankle joints between walking with and without a backpack at zero-degree incline (P = 0.586 and P = 0.077, respectively). However, on the -15-degree incline slope, the ROM was significantly lower with a backpack than without a backpack (P = 0.044 for the hip joint and P = 0.007 for the ankle joint). Additionally, when using a backpack, the ROM of the knee joint was significantly lower than the condition without a backpack at both zero-degree incline (P = 0.038) and -15-degree incline (P = 0.029).

According to the results of the paired sample t-test, there was no significant difference in the ROM of the ankle joint between the two slope degrees in the condition without a backpack at 25% of the body weight (P = 0.067). However, a significant difference was observed in the state with a backpack at 25% of the body weight (P = 0.032).

Table 2. Comparison of range of motion in the lower limbs on 0 and -15 slopes with and without a backpack

Joint	Slope	Having a backpack weighing 25% of body weight	Range of motion (degrees)	P-value comparison of two backpack modes	P-value comparison of two slopes
Ankle	Zero	Yes	25.85 ± 2.04	0.270	0.001
		No	24.06 ± 2.12		0.100
	-15	Yes	16.7 ± 1.19	0.012	
		No	23.25 ± 2.00		
P-value of the variance test with repeated data between the 4 investigated conditions				0.002	
Knee	Zero	Yes	57.2 ± 5.07	0.030	< 0.001
		No	64.8 ± 7.26		0.001
	-15	Yes	46.82 ± 3.72	0.001	
		No	55.9 ± 5.20		
P-value of the variance test with repeated data between the 4 investigated conditions				< 0.001	
Hip	Zero	Yes	6.11±38.16	0.170	0.052
		No	4.18±40.29		0.035
	-15	Yes	7.57±28.7	0.014	
		No	2.36±34.3		
P-value of the variance test with repeated data between the 4 investigated conditions				0.024	

Data are presented as mean ± standard deviation (SD)

Table 3. Correlated t-test results of the range of motion of the lower limb joints at a zero degree slope with -15 degree slope with and without a backpack weighing 25% of the body weight

Joint	The slope of the investigated surface	Average range of motion difference (degrees) (mean ± SD)	t-statistic	Degrees of freedom	P-value
Ankle	0	2.34 ± 1.11	1.90	11	0.077
	-15	2.04 ± 1.59	3.11	11	0.007*
Knee	0	4.07 ± 2.19	2.15	11	0.038*
	-15	3.26 ± 4.45	2.40	11	0.029*
Hip	0	4.38 ± 2.00	1.51	11	0.586
	-15	4.29 ± 0.72	5.62	11	0.044*

SD: Standard deviation
*P < 0.05

Regarding the knee and hip joints, the results showed a significant difference in the ROM between the two slope degrees in both conditions with and without a backpack at 25% of the body weight. For the knee joint, the significance level was reported as P = 0.012 with the backpack and P = 0.025 without the backpack. Similarly, for the hip joint, the significance level was reported as P = 0.006 with the backpack and P = 0.015 without the backpack.

Discussion

Numerous studies have attempted to investigate the effects of carrying backpacks with different weights on the kinematics of lower limb joints on level surfaces (21-23). However, the impacts of backpack load on joint ROM in mountain climbers on inclined surfaces have not been comprehensively examined. Nevertheless, it is essential to understand that carrying a backpack on an inclined surface is more challenging and demanding than on a flat surface. Inclined terrains can affect the joint ROM more than flat surfaces (8). Therefore, the main objective of this study was to compare the ROM of lower limb joints on flat and inclined surfaces in middle-aged mountain climbers with and without a backpack.

According to the statistical results evaluated, no significant changes were observed in the ROM of the ankle joint with and without a backpack on a zero-degree negative incline. These findings are consistent with that of previous studies (26-28). It can be concluded that carrying a backpack may not significantly affect the ankle joint's ROM under these conditions. Although previous studies have shown that increasing load during a complete gait cycle can significantly increase ankle joint ROM, these results were inconsistent with that of the present study (5, 24). Possible differences in study methodology, sampling, test conditions, and evaluation parameters can contribute to discrepancies in the results. Therefore, further research and consideration of other variable factors are needed for a more accurate investigation of the impact of carrying a backpack on the ROM of the ankle joint on a zero-degree negative incline.

The ROM of the ankle joint on a negative 15-degree incline was significantly lower when carrying a backpack than without a backpack. In other words, having a backpack on a negative slope (downhill) decreases the dorsiflexion range and increases the plantar flexion ROM in the ankle joint.

Previous studies have shown that carrying a backpack on an incline can induce changes in the kinematics of the ankle joint. In uphill walking conditions, the dorsiflexion ROM of the ankle joint significantly increases when carrying a backpack, which is consistent with the decrease in ankle joint ROM on the negative 15-degree incline observed in our study (5, 24).

Table 4. Correlated t-test results of the range of motion of the lower limb joints with and without a backpack weighing 25% of the body weight at a zero degree slope with a -15 slope

Joint	Having a backpack	Average range of motion difference (degrees) (mean ± SD)	t-statistic	Degrees of freedom	P-value
Ankle	With a backpack weighing 25% of body weight	1.20±2.05	1.25	11	0.032*
	No backpack weighing 25% of body weight	5.11 ± 3.17	2.20	11	0.067
Knee	With a backpack weighing 25% of body weight	2.35 ± 4.81	0.28	11	0.012*
	No backpack weighing 25% of body weight	5.25 ± 2.60	2.95	11	0.025*
Hip	With a backpack weighing 25% of body weight	4.46 ± 3.12	0.69	11	0.006*
	No backpack weighing 25% of body weight	9.42 ± 7.92	0.89	11	0.015*

SD: Standard deviation
*P < 0.05

It should be noted that a reduction in the ankle joint ROM may require altered movement patterns, which can potentially compromise balance and functional performance (25). Therefore, maintaining a healthy ROM in the ankle joint is essential for injury prevention and preservation of helpful ability.

The most significant measured difference in the lower limbs between zero incline and negative incline with and without a backpack was observed in the knee joint. Carrying a backpack on a flat surface and a negative incline decreased knee joint ROM during walking compared to the condition without a backpack. Specifically, the degree of knee flexion significantly increased with an increase in backpack weight, which is consistent with the findings of other researchers (20, 33, 37, 38). It is suggested that immediate knee flexion after the initial foot-ground contact in each step helps absorb shock forces, and knee flexion in a midstance position with a lower center of mass helps maintain stability (39). Additionally, an increased knee flexion angle may be a compensatory strategy to mitigate the impaired dorsiflexor function of the ankle in reducing impact forces (39). However, the relationship between meniscal injury and the degree of knee flexion should be considered. Many researchers have reported that the medial and lateral menisci bear 50 to 70% of the body weight when the knee is extended, while this amount reaches 85 to 90% in knee flexion (33). Therefore, as the knee flexion angle increases, more pressure is exerted on the menisci (40). In the case of disrupted balance, a decrease in knee ROM in steeper inclines and an increase in maximum knee flexion angle in downhill walking reduce the ability to restore balance quickly (26).

The range of knee flexion motion increases when walking on a steep downhill slope (27). It is said that the knee joint controls the movements of the ankle and hip joints during walking, concurrently maintaining balance, aiding foot clearance, and absorbing impact (42). Considering that the most considerable measured difference in the lower limbs between zero incline and negative incline with and without a backpack was observed in the knee joint, it appears that carrying a backpack while walking on an incline significantly impacts the knee joint. These impacts may include a decrease in knee ROM, an increase in knee flexion angle, a reduction of static balance, and an increase in pressure and impact forces.

The maximum knee flexion during walking with a load differs from the condition without a limitation because the knee may attempt to modify its potential (such as angle, force, or pressure) to reduce the shock and load effects on other body areas (20). When carrying a load weighing 25% of the body weight, the knee loading rate decreases compared to the unloaded condition, and this may be due to considering the knee flexion angle with higher weights (28).

In a study, knee flexion during the stance phase increased by 19% on a negative slope and compensated for the effects of the slope on the stance compared to the ankle and hip (29). Increasing knee flexion angle during midstance compared to walking on a level surface seems to be an appropriate strategy that allows individuals to continue walking with a load on inclined surfaces uniformly and experience less physical stress (29, 30).

However, mountaineers often walk for several hours on downhill paths with backpacks, and there is a possibility of excessive strain and various pathological conditions (8). In other words, the observed kinematic changes in the knee and ankle joints during walking with a backpack can indicate compensatory mechanisms for maintaining body stability (29, 33). These kinematic changes may have adverse effects on the performance of climbers. Various injuries such as osteoarthritis, anterior knee pain, anterior cruciate ligament deficiency, weakness, and muscular soreness in the ankle, knee, and leg joints may be associated with walking on slopes (31, 32), especially considering the effect of weight (33). However, in the present study, the relationship between carrying a backpack and musculoskeletal pain or the prevalence of various abnormalities was not investigated, and further studies in this area are necessary.

In the hip joint, like the ankle joint, carrying a backpack only significantly reduced the ROM on a -15° incline. In other words, having a backpack decreased the ROM in the hip joint while walking on a downhill slope. This finding is consistent with that of previous studies. The reduced ROM in the hip joint on downhill slopes may be due to increased knee flexion and reduced step length (30).

The reduced ROM in the lower limbs, particularly in the hip and knee joints, is one of the leading causes of falls due to the impact of hip stiffness on lower limb dynamics during walking (40). It is a consequence of muscle-tendon unit stiffness and stiffness of the tissues surrounding the joints, which positively correlates with the prevalence of falls (34). The reduced ROM in the hip and ankle joints can be a strategy to maintain balance and the center of gravity on the support surface (35).

Furthermore, according to the statistical evaluation, in the unloaded condition with a load of

25% of the body weight, there was no significant difference in the ROM at the ankle joint between the two slopes. However, a significant difference was observed in the loaded condition with a backpack weighing 25% of the body weight.

These findings contradict the findings of a previous study on the effects of backpack load on walking motion in healthy adolescent girls, which showed no significant impact on the ROM at the ankle joint (36). Additionally, other studies have shown that carrying a backpack can significantly affect the kinematics and kinetics of the ankle joint during walking and alter the ROM in specific directions (37). Moreover, asymmetric loading of the backpack has been observed to increase the peak dorsiflexion of the ankle joint (38). Furthermore, joint loading during daily activities and sports can induce changes in the ROM of the ankle joint. These findings are consistent with our study (39, 40).

Regarding the knee and hip joints, the results showed that in both conditions, with and without a backpack weighing 25% of the body weight, there was a significant difference in the ROM between the two states on 0° and -15° slopes (21, 41). These findings are consistent with the results of previous studies. Thus, it can be concluded that carrying a backpack may significantly affect the ROM in the knee and hip joints under these conditions.

Based on the results of the paired t-test, the effect of slope on the ROM of the knee and hip joints appears to be more important. Additionally, the results indicate that the backpack's weight also significantly affects the ROM of the ankle joint. However, overall, the effect of the slope seems to be more significant than the backpack's weight on the changes in the ROM in the knee and hip joints. Therefore, in future research, attention should be paid to both these factors (slope and backpack weight).

Limitations

This study was the first step in investigating the effect of an inclined surface on the traction and kinematics of climbers; therefore, a clean, flat surface was used, which would not be the case in real-world hiking outdoors, especially while hiking in the mountains, the ground may be covered with loose stones and dirt, which makes the ground uneven and contaminates the interface of the shoe surface. These factors will affect the required traction, slip potential, and walking kinematics on an incline. There is a solid relationship between heavy and inappropriate backpacks and musculoskeletal injuries, an essential factor in increasing back pain and back pain (thoracic pain) in climbers (10, 42).

Recommendations

It is suggested that inertial measurement unit (IMU) wearable motion analysis systems be used to record motion kinematics outside the laboratory environment in future research. Due to their easy portability, these sensors provide the possibility of recording data outside the laboratory and in the training environment of athletes, which makes the player's performance closer to his/her actual performance during training and competition.

Conclusion

According to the results of the present study, carrying a backpack with 25% of the body weight on a negative slope significantly affects the ROM of the lower limb joints. As a result, they may not be suitable for carrying, especially downhill. The present research results showed that the negative slope has far greater effects than the weight of the load on the ROM of the lower limb joints, especially the ankle joint, in middle-aged climbers. It is generally believed that walking upside down puts less stress on the body. The results of the present study contradict this general idea. The changes in the ROM of the lower limb joints due to carrying a backpack on a negative slope show that this task is more challenging than carrying a backpack on a flat surface. It seems that using backpacks with low weight and modifying how they are carried can be suitable solutions for preventing injuries and improving performance in climbers.

Acknowledgments

The present study was based on the analysis of information extracted from a master's degree thesis of sports biomechanics approved by Shahid Bahonar University of Kerman, so I consider it necessary to thank all the climbers who voluntarily participated in this study.

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Maintaining the integrity of the study process from the beginning to publication and responding to the comments of the referees: Mohammadreza Amirseyfaddini, Mohammadtaghi Amiri-Khorasani, Mohammadbaqher Mahdavikhalilabad, and Hamed Fadaei

Funding

The present study was based on the analysis of a part of the data extracted from the master's thesis in sports biomechanics by Mohammad Bagher Mahdavi Khalilabad (Ethics Code: IR.UK.REC.1401.003), without any financial support from Shahid Bahonar University, Kerman, Iran. The university did not interfered in data collection, analysis and reporting, manuscript preparation, and the final approval of the study for publication.

Conflict of Interest

The authors have no conflicts of interest.

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