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Comparison of electromyographic signal features of the hamstring and quadriceps muscles before and after isotonic fatigue in female basketball players

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Abstract

Background: Muscle fatigue is a major factor contributing to impaired function and reduced performance in basketball players, particularly in maintaining balance during jump shooting. This study aimed to evaluate the effects of isotonic fatigue on the electromyographic (EMG) signals of the quadriceps and hamstring muscles in female basketball players during jump shooting.

Methods: Twelve professional female basketball players participated in this study. EMG signals were recorded from the quadriceps and hamstring muscles following a standardized warm-up and during jump shooting. Fatigue was induced using isotonic contractions. Following the fatigue protocol, EMG signals were recorded again, and the signal features obtained before and after fatigue were compared. Six time-domain features and three frequency-domain features were analyzed. Statistical analysis was performed using SPSS version 20, with the significance level set at 0.05.

Results: Analysis of the time-domain features revealed that the most pronounced changes occurred in the quadriceps muscles. The root mean square (RMS) and mean absolute value (MAV) increased significantly, whereas zero crossing (ZC) decreased significantly after fatigue compared with the pre-fatigue condition. Analysis of the frequency-domain features demonstrated a significant decrease in median frequency (MDF) across all muscles following fatigue.

Conclusion: The findings suggest that fatigue of the knee muscles may alter the activation patterns of the muscles surrounding the knee joint, thereby impairing balance during jump shooting. These findings may contribute to the development of rehabilitation and training programs aimed at minimizing fatigue-induced neuromuscular alterations and improving performance in basketball players.

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Highlights

What is current knowledge?

- Knee muscle fatigue can alter neuromuscular control and impair postural stability during sports activities.
- Surface EMG time- and frequency-domain features are widely used to evaluate muscle fatigue and activation patterns.

What is new here?

- The quadriceps muscles exhibited the most pronounced fatigue-related EMG changes during basketball shooting, characterized by increased RMS and MAV and decreased ZC.
- Median frequency (MDF) decreased significantly in all examined knee muscles following fatigue, indicating reduced muscle performance.
- Knee muscle fatigue may impair balance during shooting, highlighting the importance of fatigue-focused rehabilitation and training programs for basketball players.

Introduction

Muscle fatigue is one of the primary factors contributing to impaired performance in sports. It results in reduced voluntary force production, diminished muscle performance capacity, impaired co-activation of agonist and antagonist muscles, altered movement patterns, and ultimately decreased efficiency of the neuromuscular system (1). Muscle fatigue may develop following either short- or long-duration physical activity and is often accompanied by an unpleasant sensation. Therefore, delaying the onset of fatigue is an important consideration in athletic performance. Muscle fatigue can disrupt the transmission of sensory information to the brain, resulting in impaired balance. It also reduces the transmission speed of afferent and efferent neural signals within the neuromuscular system, thereby negatively affecting the ability to perform effective compensatory movements. Maintaining balance under fatigued conditions plays a crucial role in preventing musculoskeletal injuries during daily activities, particularly in athletic performance. To maintain dynamic knee stability, co-contraction of the hamstring muscles during maximal contraction of the quadriceps is essential (2). These muscle groups are particularly important in basketball players, as they play a key role in maintaining balance during jump shooting (3).

To maintain proper body balance during basketball performance, the feet should be positioned shoulder-width apart, and the knees should be slightly flexed to lower the body's center of gravity in preparation for rapid movements. Because fatigue of the hamstring and quadriceps muscles can readily compromise this balance, it may contribute to reduced athletic performance in basketball players. Therefore, assessing fatigue in these muscle groups is of considerable importance. One approach for investigating the effects of muscle fatigue is the analysis of muscle electrical activity using electromyography (EMG) (4). Electromyographic techniques provide an effective means of evaluating the influence of fatigue on muscle strength and function by identifying and quantifying the neuromuscular adaptations that occur during the fatigue process.

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The EMG signal is a biological signal that reflects the electrical potentials generated by muscles during contraction (5). Because muscle activity is continuously regulated by the nervous system, the EMG signal is influenced by both the anatomical and physiological characteristics of the muscles. Numerous biomechanical variables are associated with EMG signals. During isometric contractions, a positive relationship has been reported between muscle tension and the amplitude of the recorded EMG signal (6). However, with the onset of muscle fatigue, muscle tension generally decreases, whereas EMG amplitude often remains constant or increases. In addition, the high-frequency components of the EMG signal decrease during fatigue, leading to a reduction in the median frequency of the signal (7). Because the quadriceps and hamstring muscles play a fundamental role in maintaining stability during basketball jump shooting, understanding their neuromuscular responses to fatigue is essential for optimizing performance. Therefore, this study aimed to investigate the effects of isotonic fatigue on the electromyographic activity of the quadriceps and hamstring muscles in female basketball players by recording and comparing EMG signals before and after fatigue during jump shooting.

Methods

Study design

This quasi-experimental study included 12 professional female basketball players from the North Khorasan Zarbam Part Team, who competed in the First Division of the Iranian Women's Basketball League. A census sampling method with purposive participant selection was employed. The study was approved by the Ethics Committee of North Khorasan University of Medical Sciences, Bojnurd, Iran (IR.NKUMS.REC.1403.061). Written informed consent was obtained from all participants, and their privacy was protected throughout the study. Twelve professional female basketball players (Weight = 65.77 ± 6.08 kg, Age = 20.87 ± 4.06 years, Height = 172.15 ± 3.47 cm) participated in the study. The dominant foot of all athletes was the right foot.

Data collection

The data collection protocol followed the block diagram illustrated in Figure 1. EMG signals were recorded after the warm-up phase while the participants performed jump shots. Fatigue was induced through isotonic functional contractions, during which the players performed squat exercises until exhaustion. Following the fatigue protocol, EMG signals were recorded again, and the signal features obtained before and after fatigue were compared. Before signal acquisition, researcher-developed questionnaires containing demographic information were distributed to all participants for completion. The medical histories of the selected participants revealed no underlying medical disorders or history of medication use. Subsequently, written informed consent was obtained from all participants. After a standardized team warm-up, the athletes received detailed instructions regarding the testing procedure. EMG signals were then recorded on three consecutive occasions from the hamstring and quadriceps muscles using bipolar adhesive electrodes (Ambu Neuroline, conductive area 28 mm²) during jump shooting while maintaining balance. Figure 2 illustrates the electrode placement and the recording protocol used during shooting and balance assessment in one of the athletes.

The same procedure was repeated after completion of the fatigue protocol. Before electrode placement, hair over the quadriceps and hamstring muscles was shaved, and the skin was cleaned with a specialized preparation gel to reduce skin impedance. Two pairs of bipolar electrodes were then positioned over the distal portion of the quadriceps muscles (Approximately above the tendon), specifically on the vastus lateralis (VL) and vastus medialis (VM). Similarly, two pairs of bipolar electrodes were placed over the hamstring muscles, including the biceps femoris (BF) and semitendinosus (ST). The Borg Rating of Perceived Exertion (RPE) scale is commonly used to identify muscular fatigue (8). In most studies, a scale ranging from 6 to 20 is used to assess the individual's perceived level of exertion and workload, where a score of 6 indicates no fatigue and scores between 17 and 20 indicate exhaustion (9). The same scale was used in the present study to assess fatigue. EMG signals were recorded using a four-channel EMG system (AD Instrument Co.). The recorded signals were transferred to a computer in TXT format and subsequently converted to MAT format for processing in MATLAB software. Surface bipolar EMG signals obtained from the quadriceps and hamstring muscles before and after fatigue were segmented into time windows corresponding to 10% of the total contraction duration. EMG parameters were then averaged within each 10%-time window. Accordingly, temporal and frequency-related changes in the signals were calculated from the beginning to the end of the contraction. In the time domain, root mean square (RMS), mean absolute value (MAV), standard deviation (SD), zero crossing (ZC), mean peak value (MPV), and integral absolute value (IAV) were extracted. In the frequency domain, the power spectral density (PSD), representing the power at each frequency, was calculated. The Welch algorithm with a Hamming window was used to compute the Fast Fourier Transform (FFT), from which median frequency (MDF), mean frequency (MNF), and frequency ratio (FR) were extracted from the power spectrum (10).

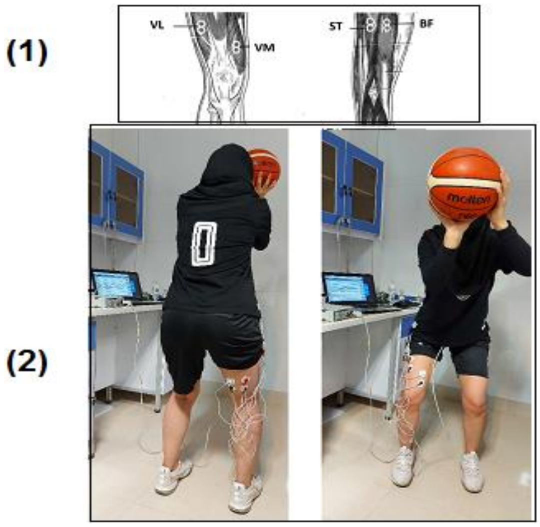

Figure 2. (1) Shows the location of the electrodes for Vastus Lateralis (VL), Vastus Medialis (VM), Biceps Femoris (BF) and Semitendinosus (ST) EMG recording, and (2) Shows the collection protocol during the shoot and balance for one of the athletes.

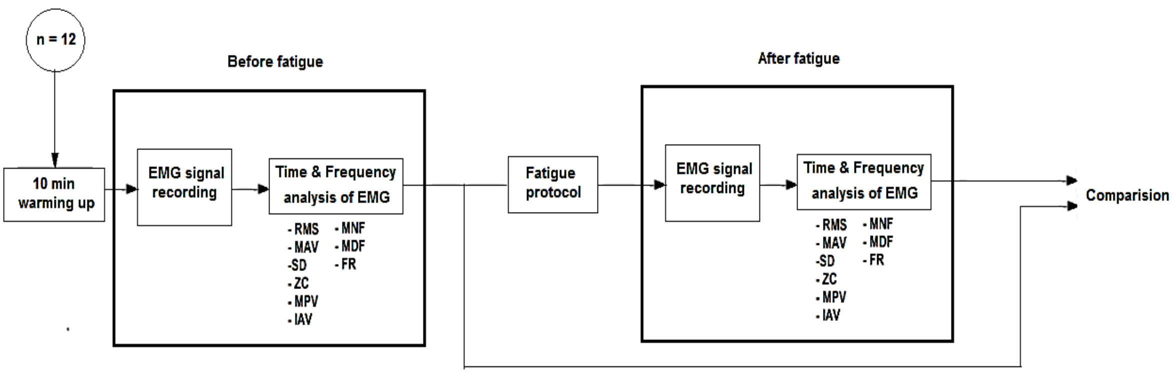

Figure 1. Block diagram of the data recording protocol. In Time and Frequency analysis block, Root Mean Square (RMS), Mean Absolute Value (MAV), Standard Deviation (SD), Zero Cross (ZC), Mean of Peak Value (MPV), Integral Absolute Value (IAV) is extracted in the Time Domain and Median Frequency (MDF), Mean Frequency (MNF), and Frequency Ratio (FR) are extracted from the power spectrum in frequency domain.

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Data analysis

Data analysis was performed using MATLAB software version 2018a. Time- and frequency-domain features were extracted from the recorded EMG signals using the Signal Processing Toolbox. After feature extraction, descriptive statistics, including the mean and standard deviation, were calculated. Data normality was assessed using the Kolmogorov–Smirnov test. Depending on whether the data were normally distributed, either paired t-tests or Wilcoxon signed-rank tests were performed. Statistical analyses were conducted using SPSS version 20, with the significance level set at 0.05. next

Results

Following the fatigue protocol, the mean fatigue test score was 18.31 ± 1.22. After extracting six time-domain features before and after fatigue, a comparative analysis was performed. The time-domain features were analyzed using 500-millisecond intervals. Figure 3 presents a representative 500-millisecond window of the EMG signals recorded before and after muscular fatigue. The results of the time-domain features of the electromyographic signals obtained from the quadriceps and hamstring muscles before and after fatigue are presented in Table 1. Figure 4 illustrates the changes in the time-domain features before and after muscular fatigue using bar charts.

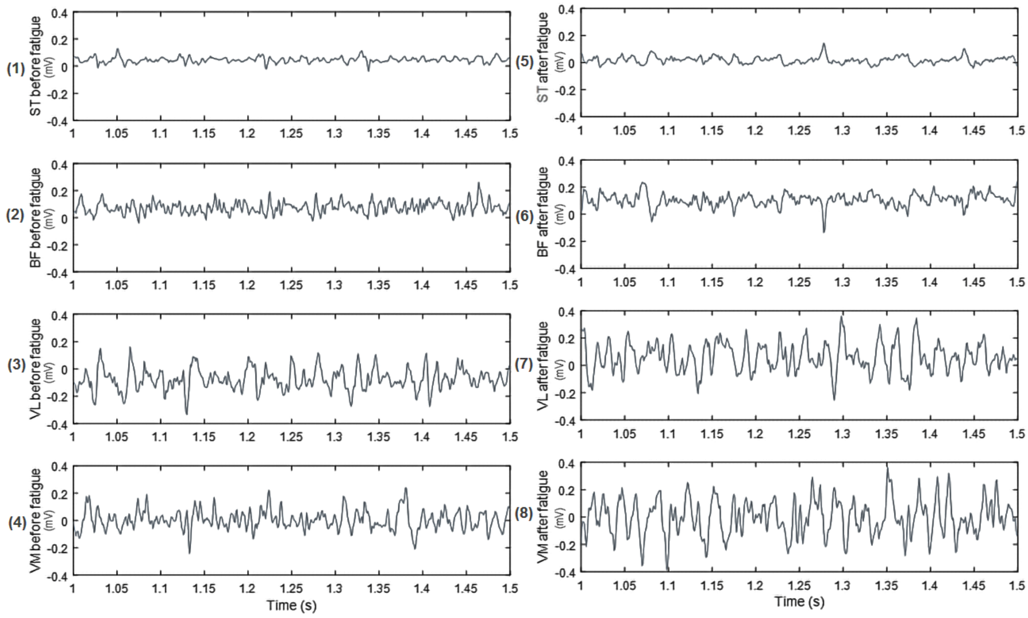

Figure 3. Examples of EMG signals of the hamstring and quadriceps muscles in the time domain for 500 milliseconds before and after fatigue (10% of the 5 sec total contraction time). (1) EMG for Semitendinosus (ST) before fatigue, (2) EMG for Biceps Femoris (BF) before fatigue, (3) EMG for Vastus Lateralis (VL) before fatigue, (4) EMG for Vastus Medialis (VM) before fatigue, (5) EMG for Semitendinosus (ST) after fatigue, (6) EMG for Biceps Femoris (BF) after fatigue, (7) EMG for Vastus Lateralis (VL) after fatigue, (8) EMG for Vastus Medialis (VM) after fatigue.

Table 1. Time feature values of electromyography signals of quadriceps and hamstring muscles before and after fatigue

Time features	Type of muscle	Before fatigue	After fatigue	P-value
Root Mean Square (RMS) , (mV)	Semi Tendinosus	2.08 ± 0.8	2.13 ± 0.75	0.61
	Biceps Femoris	2.22 ± 0.76	2.29 ± 0.92	0.68
	Vastus Lateralis	2.38 ± 0.84	3.11 ± 0.94	0.018*
	Vastus Medialis	2.67 ± 0.63	5.07 ± 0.85	0.001*
Mean Absolute Value (mV)	Semi Tendinosus	0.66 ± 0.13	0.73 ± 0.18	0.224
	Biceps Femoris	0.65 ± 0.15	0.78 ± 0.13	0.043*
	Vastus Lateralis	0.69 ± 0.13	0.91 ± 0.16	0.003*
	Vastus Medialis	0.76 ± 0.16	0.97 ± 0.14	0.001*
Standard Deviation (mV)	Semi Tendinosus	0.11 ± 0.05	0.12 ± 0.06	0.658
	Biceps Femoris	0.13 ± 0.07	0.12 ± 0.05	0.691
	Vastus Lateralis	0.15 ± 0.08	0.18 ± 0.05	0.482
	Vastus Medialis	0.16 ± 0.07	0.19 ± 0.05	0.383
Zero Cross	Semi Tendinosus	1821.33 ± 456.12	1772.11 ± 439.18	0.809
	Biceps Femoris	1726.36 ± 409.85	1619.61 ± 447.12	0.531
	Vastus Lateralis	2418.48 ± 511.66	1893.33 ± 473.36	0.028*
	Vastus Medialis	2203.52 ± 505.11	1789.22 ± 518.25	0.031*
Mean of Peak Value	Semi Tendinosus	0.16 ± 0.06	0.18 ± 0.08	0.542
	Biceps Femoris	0.19 ± 0.07	0.21 ± 0.09	0.418
	Vastus Lateralis	0.22 ± 0.08	0.26 ± 0.08	0.091
	Vastus Medialis	0.21 ± 0.06	0.28 ± 0.09	0.048*
Integral Absolute Value (mV)	Semi Tendinosus	14.16 ± 5.11	12.74 ± 5.35	0.382
	Biceps Femoris	15.17 ± 4.13	18.66 ± 5.72	0.195
	Vastus Lateralis	18.55 ± 3.93	15.38 ± 4.87	0.186
	Vastus Medialis	20.02 ± 3.66	21.25 ± 4.53	0.182

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Analysis of the time-domain features of the quadriceps muscles demonstrated a significant increase in RMS and MAV, along with a significant decrease in ZC following muscular fatigue. In addition, the mean peak value (MPV) showed a significant increase in the vastus medialis (VM) muscle. In contrast, the remaining features, including SD and IAV, did not show significant changes. Analysis of the hamstring muscles revealed no significant differences in any of the extracted time-domain features before and after muscular fatigue, except for MAV, which showed a significant increase in the biceps femoris (BF) muscle following fatigue.

The results further indicated that the vastus medialis (VM) muscle exhibited the greatest changes among the extracted time-domain features after fatigue. Specifically, MAV demonstrated the largest change following fatigue. In addition, a comparison of the frequency-domain characteristics was performed by extracting three frequency-domain features from the power spectra of the EMG signals obtained before and after fatigue. Figure 5 presents representative power spectra of the EMG signals recorded during balance in the shooting position before and after fatigue, providing a visual comparison of the spectral changes. The frequency-domain results of the EMG signals from the quadriceps and hamstring muscles before and after fatigue are summarized in Table 2. Figure 6 also presents bar charts illustrating the changes in the frequency-domain features before and after fatigue.

The MDF decreased significantly after fatigue in both muscle groups. The MNF also showed a significant decrease in the vastus lateralis (VL) muscle during shooting following fatigue. In addition, the FR increased significantly after fatigue compared with the pre-fatigue condition. Analysis of the frequency-domain features of the hamstring muscles demonstrated that MDF decreased significantly after fatigue, whereas the frequency ratio increased significantly in the EMG signals recorded from the biceps femoris (BF) muscle. Among all extracted features, the VM muscle exhibited the greatest fatigue-induced changes, whereas MNF demonstrated the greatest change among the frequency-domain features.

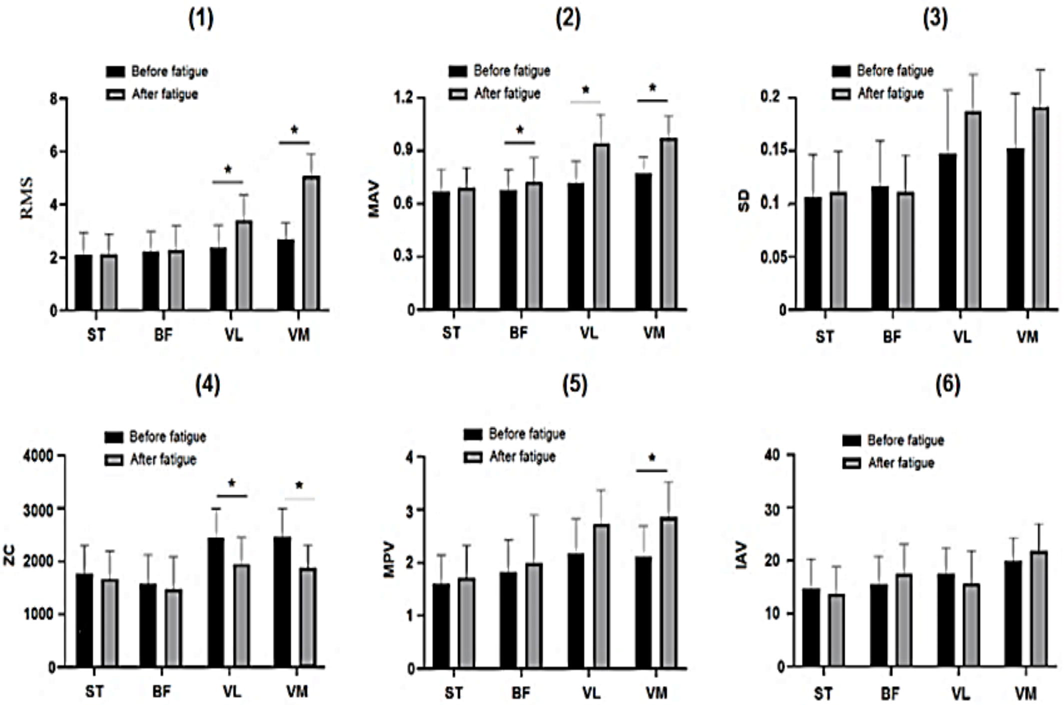

Figure 4. A bar chart of time features changes before and after fatigue for different muscles. (1) Root Mean Square (RMS), (2) Mean Absolute Value (MAV), (3) Standard Deviation (SD), (4) Zero Cross (ZC), (5) Mean of Peak Value (MPV), and (6) Integral Absolute Value (IAV).

Table 2. Frequency feature values of electromyography signals of quadriceps and hamstring muscles before and after fatigue

Frequency features	Type of muscle	Before fatigue	After fatigue	P-value
Median frequency (Hz)	Semi Tendinosus	80.44 ± 3.54	76.21 ± 5.72	0.029*
	Biceps Femoris	75.32 ± 3.63	68.89 ± 4.94	0.003*
	Vastus Lateralis	81.85 ± 5.77	66.91 ± 5.58	0.001*
	Vastus Medialis	80.39 ± 4.81	57.67 ± 3.89	0.001*
Mean frequency (Hz)	Semi Tendinosus	5.36 ± 1.23	5.29 ± 1.16	0.608
	Biceps Femoris	5.54 ± 1.18	4.78 ± 1.02	0.441
	Vastus Lateralis	6.18 ± 0.88	3.31 ± 1.22	0.003*
	Vastus Medialis	5.72 ± 1.12	4.08 ± 0.98	0.056
Frequency ratio	Semi Tendinosus	3.66 ± 1.53	3.99 ± 1.75	0.085
	Biceps Femoris	3.82 ± 1.81	5.69 ± 1.35	0.016*
	Vastus Lateralis	4.17 ± 1.68	6.97 ± 1.33	0.009*
	Vastus Medialis	3.93 ± 1.29	7.69 ± 1.55	0.006*

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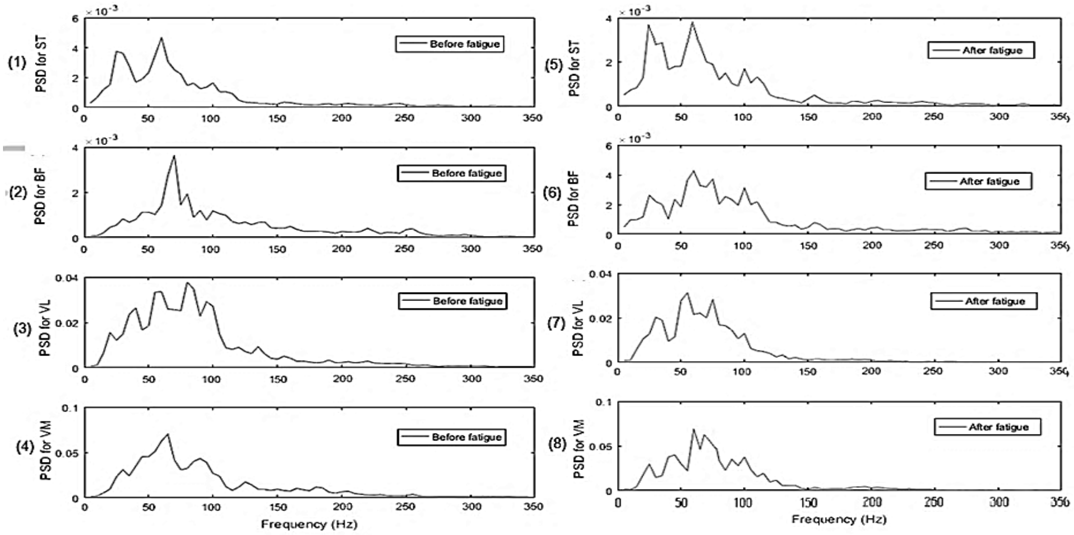

Figure 5. A sample of power spectra of EMG signals for hamstring and quadriceps muscles in a shooting balanced position. (1) Power Spectral Density (PSD) for Semitendinosus (ST) before fatigue, (2) PSD for Biceps Femoris (BF) before fatigue, (3) PSD for Vastus Lateralis (VL) before fatigue, (4) PSD for Vastus Medialis (VM) before fatigue, (5) PSD for Semitendinosus (ST) after fatigue, (6) PSD for Biceps Femoris (BF) after fatigue, (7) PSD for Vastus Lateralis (VL) after fatigue, (8) PSD for Vastus Medialis (VM) after fatigue.

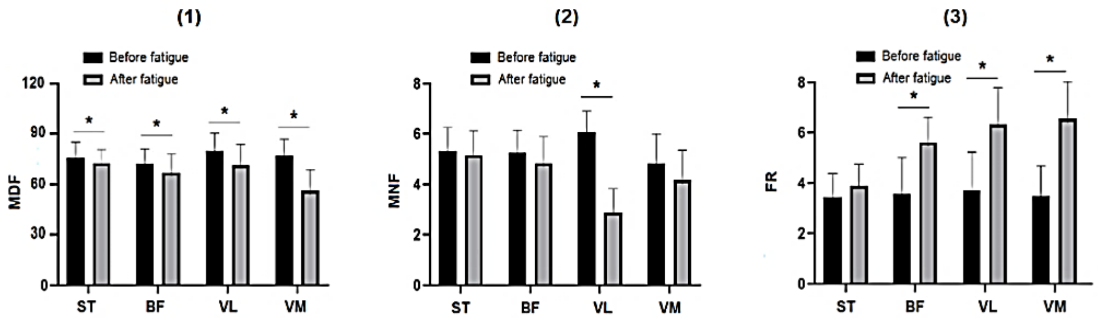

Figure 6. A bar chart of frequency features changes before and after fatigue for different muscles. (1) Median Frequency (MDF), (2) Mean Frequency (MNF), and (3) Frequency Ratio (FR).

Discussion

The present study aimed to evaluate the effects of fatigue on the EMG signals of the hamstring and quadriceps muscles in female basketball players during jump shooting. The results of the time-domain analysis demonstrated that the greatest changes occurred in the quadriceps muscles. Specifically, the RMS and MAV increased significantly, whereas the ZC decreased significantly after fatigue compared with the pre-fatigue condition. The MAV represents the mean absolute value of the EMG signal over a specific time window and reflects the level of muscle contraction (11). Therefore, the observed increase in MAV indicates a significant increase in the level of muscle contraction. Similarly, RMS is an indicator of muscle activation level (12). The increases in RMS and MAV observed in basketball players following muscle fatigue may reflect greater neuromuscular activation required to maintain force production during jump shooting. The more pronounced changes in EMG features observed in the quadriceps muscles may be attributed to the neural mechanisms involved in controlling these muscles during the shooting movement. Numerous studies have investigated the effects of muscle fatigue on EMG signals in athletes from various sports (13-15). Most of these studies have reported a reduction in EMG amplitude following fatigue induced by isometric contractions. These findings are not consistent with those of the present study. During jump shooting, which involves maximal muscle contraction, the EMG amplitude initially remains stable and subsequently increases. This increase in signal amplitude may reflect greater recruitment of motor units to maintain force output and increased activation of cortical motor regions in basketball players. The ZC represents the number of times the EMG signal crosses the zero baseline (16). In the present study, this feature decreased significantly after fatigue. This reduction may be attributed to a decrease in the number of signal sign changes, indicating a reduction in the high-frequency components of the EMG signal as a consequence of muscle fatigue.

With respect to the frequency-domain analysis, a significant reduction in MDF was observed across all muscles following fatigue. Notably, the quadriceps muscles exhibited the greatest fatigue-related changes. The reduction in frequency-domain features may be attributed to decreased action potential conduction velocity and a reduced motor unit firing rate. Median frequency divides the EMG power spectrum into two equal halves, whereas mean frequency represents the average frequency of the EMG signal (16). Numerous studies investigating EMG signals have identified median frequency as a more reliable indicator of muscle fatigue because it more accurately reflects fatigue-induced shifts in the frequency spectrum and is less susceptible to noise, thereby providing greater reliability and validity (17). These findings are consistent with those of the present study, in which the median frequency decreased significantly in all recorded muscles following fatigue. Furthermore, studies involving athletes from various sports have demonstrated that muscular fatigue reduces the high-frequency components and increases the low-frequency components of the EMG signal, resulting in an overall decrease in frequency-domain features. This shift in the frequency spectrum toward lower frequencies is primarily attributed to metabolic alterations occurring during fatiguing contractions. The present findings are in agreement with these previous reports. The reduction in EMG frequency features is associated with decreased excitability of muscle fiber membranes, accumulation of potassium ions in the extracellular space, impaired sodium channel function, and accumulation of metabolic by-products such as lactic acid within the muscle. Collectively, these physiological changes reduce action potential conduction velocity and decrease the firing rate of motor units (18-20).

Additionally, comparison of the reductions in frequency-domain features among the investigated muscles indicated that the hamstring muscles exhibited a smaller decrease in median frequency than the quadriceps muscles, suggesting greater resistance to fatigue. This finding may be explained by the fact that the reduction in median

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frequency reflects both a decrease in muscle fiber action potential conduction velocity and an increase in motor unit action potential duration. The primary objective of evaluating frequency-domain features in the present study, as well as in previous investigations, is to verify the occurrence of muscular fatigue. The observed reduction in frequency-domain features across the examined muscles confirms the effectiveness of the fatigue protocol used in this study to induce localized muscular fatigue. Given the variety of protocols available for inducing muscular fatigue, future studies should compare different fatigue-induction protocols to determine their relative effects on neuromuscular function. Furthermore, because simultaneous muscle activation can be enhanced through specific training programs, future research should investigate the effects of such interventions in non-athlete populations. Finally, considering the differences in muscle recruitment patterns and neuromuscular coordination between males and females, further studies are recommended to examine the effects of these exercise protocols on concurrent muscle activity in male athletes.

Conclusion

The findings of this study suggest that fatigue of the knee muscles may reduce the activation of the muscles surrounding the knee joint. This reduction in muscle activity may alter knee muscle activation during shooting, thereby impairing balance. Analysis of the time-domain features revealed that the most pronounced changes occurred in the quadriceps muscles. Specifically, the root mean square (RMS) and mean absolute value (MAV) increased significantly, whereas zero crossing (ZC) decreased significantly after fatigue compared with the pre-fatigue condition. Analysis of the frequency-domain features demonstrated a significant reduction in median frequency (MDF) across all examined muscles following fatigue. These findings have practical implications for the development of rehabilitation and training programs aimed at minimizing fatigue-induced balance impairments during shooting in basketball players.

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Funding Sources

No external funding was received for this study.

Ethical Statement

This study was approved by the Ethics Committee of North Khorasan University of Medical Sciences, Bojnurd, Iran (IR.NKUMS.REC.1403.061).

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Author Contributions

N.H. and M.S. conceived and designed the study. S.J. and M.A.Y.H. were responsible for data collection. S.J. and M.A.Y.H. performed the data analysis. N.H. and M.S. drafted the initial manuscript and contributed to the study conception. All authors reviewed and approved the final version of the manuscript.

Data Availability Statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Use of Artificial Intelligence

The authors declare that no generative AI or AI-assisted technologies were used in the preparation of this manuscript.

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