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EFFECTS OF UPPER EXTREMITY FATIGUE ON SHOOTING ACCURACY, KINEMATICS, AND MUSCLE ACTIVATION IN BASKETBALL PLAYERS

UČINKI UTRUJENOSTI ZGORNJIH OKONČIN NA NATANČNOST META, KINEMATIKO IN AKTIVACIJO MIŠIC PRI KOŠARKARJIH

ABSTRACT

Fatigue is a critical determinant of sports performance, often impairing athletic precision and efficiency. This study investigated the effects of upper extremity fatigue on shooting accuracy, kinematics, and muscle activity in adolescent basketball players. Twelve participants (age: 15 ± 1.1 yrs; sports experience: 6 ± 2.7 yrs) performed free throws under pre- and post-fatigue conditions. Fatigue was induced through a structured protocol utilizing a graphical user interface to monitor exertion levels. Shooting accuracy was qualitatively assessed based on predefined shot outcome categories. Kinematic variables, joint angles, joint angular velocities, and ball trajectory parameters were analyzed alongside muscle activation of key upper extremity muscles. Post-fatigue analysis revealed a significant decrease in elbow angular velocity (−5.08%, $p = 0.041$, effect size = 0.59), indicating impaired joint coordination. Additionally, palmaris longus muscle activation declined (−4.68%, $p = 0.028$, effect size = 0.63), suggesting reduced wrist stability and grip control. Furthermore, shooting accuracy deteriorated, with a significant increase in the frequency of 'Airball' ($p < 0.05$) and 'Short or uncontrolled shot did not score' ($p < 0.05$) outcomes. However, no significant differences were observed in the 'Balanced and controlled shot, but did not score' and 'Successful shot' categories. These findings highlight the negative impact of fatigue on neuromuscular control and biomechanics, underscoring the importance of fatigue management strategies in basketball training to maintain shooting efficiency.

Keywords: basketball, electromyography, muscular fatigue, motion analysis, triceps brachii, free throw

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IZVLEČEK

Utrujenost je ključen dejavnik športne uspešnosti, saj pogosto zmanjšuje natančnost in učinkovitost športnika. Ta študija je preučevala vplive utrujenosti zgornjih okončin na natančnost meta, kinematiko in mišično aktivnost pri mladostnikih košarkarjih. Dvanajst udeležencev (starost: 15 ± 1,1 let; športne izkušnje: 6 ± 2,7 let) je izvajalo proste mete v pogojih pred in po utrujenosti. Utrujenost je bila povzročena s strukturiranim protokolom, ki je z grafičnim vmesnikom omogočal spremljanje ravni napora. Natančnost meta je bila kvalitativno ocenjena na podlagi vnaprej določenih kategorij izida meta. Kinematične spremenljivke, kot so koti v sklepih, kotne hitrosti sklepov in parametri trajektorije žoge, so bili analizirani skupaj z aktivacijo ključnih mišic zgornjih okončin. Analiza po utrujenosti je pokazala pomembno zmanjšanje kotne hitrosti v komolcu (−5,08 %, p = 0,041, velikost učinka = 0,59), kar kaže na oslabljeno koordinacijo sklepa. Poleg tega se je zmanjšala aktivacija mišice palmaris longus (−4,68 %, p = 0,028, velikost učinka = 0,63), kar nakazuje zmanjšano stabilnost zapestja in nadzor prijema. Natančnost meta se je poslabšala, s pomembnim povečanjem pogostosti izidov »Airball« (p < 0,05) in »Prekratek ali nenadzorovan met, ki ni zadel« (p < 0,05). V kategorijah »Uravnotežen in nadzorovan met, ki ni zadel« ter »Uspešen met« ni bilo zaznanih pomembnih razlik. Ti izsledki poudarjajo negativen vpliv utrujenosti na nevromišični nadzor in biomehaniko ter izpostavljajo pomen strategij za obvladovanje utrujenosti v košarkarskem treningu za ohranjanje učinkovitosti metov.

Ključne besede: košarka, elektromiografija, mišična utrujenost, analiza gibanja, triceps brachii, prosti met

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INTRODUCTION

Muscle fatigue is defined as a reduction in force production following repeated or sustained contractions (Gandevia, 2001). In basketball, fatigue plays a crucial role in determining key skills such as coordination, strength, velocity, and shooting accuracy, all of which are essential for optimal performance (Ali et al., 2015; Kellis et al., 2006; Marcolin et al., 2018; Rashid et al., 2020; Slawinski et al., 2015). Among these skills, free throw (FT) shooting holds particular importance, as its accuracy often determines the outcome of games (Miller & Bartlett, 1993). Understanding the impact of fatigue on shooting performance is crucial for enhancing basketball performance and minimizing injury risk (Zhao, 2025).

Previous studies highlighted the detrimental effects of fatigue on basketball performance (Li, Li, et al., 2021). For instance, upper extremity fatigue has been shown to significantly impair shooting accuracy in basketball, particularly when induced by high-intensity exercises targeting the shoulder or elbow extensors during FTs, as well as two-point and three-point shots (Chen et al., 2005; Rashid et al., 2020). Additionally, fatigue impairs kinematic parameters critical to shooting mechanics, such as joint angular velocity and ball release speed (Erculj & Supej, 2009; Li, Knjaz, et al., 2021). For example, a study demonstrated that basketball-induced fatigue adversely affects three-point shooting accuracy by delaying shot execution, reducing optimal ball trajectory, and decreasing shot success (Bourdas et al., 2024). These findings underscore the need for effective fatigue management strategies to help athletes maintain biomechanical efficiency and shooting accuracy during gameplay.

Muscle activity, as assessed through surface electromyography (EMG), provides further insight into the neuromuscular effects of fatigue (Yasar et al., 2024). Previous research has demonstrated that fatigue can alter EMG signals, reflecting diminished force production and neuromuscular efficiency (Ghasemi et al., 2012; Rashid et al., 2020). For example, a study indicated that basketball-specific fatigue significantly reduces EMG activation in the deltoid anterior muscle during a three-point jump shot (Peterca & Dolenec, 2019). Another study found that in basketball players, an isometric submaximal triceps brachii fatigue protocol led to an increase in RMS values and a decrease in frequency values in MVIC measurements taken before and after fatigue (Rashid et al., 2020).

However, there is limited evidence on how specific muscles involved in basketball shooting, such as the triceps brachii and palmaris longus, respond to fatigue, especially during FT shooting in young basketball players. This study aims to address this gap by investigating the effects of upper extremity fatigue on free-throw accuracy, kinematic parameters, and the muscle activity of the triceps brachii and palmaris longus in adolescent basketball players. These muscles play critical roles in arm extension, torque control, and stability during shooting (Pakosz et al., 2021; Salonikidis et al., 2021). While FT shooting requires coordination across the entire kinetic chain, the release phase of the movement is primarily dependent on upper limb muscles. In particular, the triceps brachii is essential for elbow extension and force application during the shot (Mir et al., 2025). For this reason, the present study concentrated on inducing localized fatigue in the triceps brachii to examine its specific impact on shooting performance. We hypothesize that fatigue in these muscles will disrupt shooting mechanics and accuracy, providing further evidence for the necessity of targeted training interventions to mitigate fatigue's impact on basketball performance.

METHODS

Participants

Twelve right-handed elite male adolescent basketball players participated in this study (mean ± SD: age: 15 ± 1.1 years; height: 182.7 ± 9.3 cm; weight: 68.5 ± 9.8 kg; body mass index: 20 ± 2.3 kg/m²). Participants had an average of 6 ± 2.7 years of sports experience, engaged in training five times per week, and actively competed in the U15–U16 local league. Only healthy athletes without any chronic pain or injury history were included in the study. Participants were instructed to complete their meals at least two hours before testing and to refrain from caffeine consumption. The study received ethical approval from the Sakarya University of Applied Sciences Rectorate Ethics Committee (Approval no: E-26428519-044-37254). Informed consent was obtained from the participants' families prior to data collection.

Procedure

Testing was conducted individually for each participant over approximately 45 minutes. Each participant completed an 11–12 minute warm-up supervised by a strength and conditioning coach. The protocol included 5 minutes of jogging followed by 6–7 minutes of basketball-specific exercises (half-court dribbling, jump shots, layups, and FTs). After warm-up, markers were placed on key joints and surface electrodes were applied to specific muscle groups for data collection. Participants were then instructed to shoot 10 FTs, during which kinematic and EMG data were recorded simultaneously. Shooting accuracy was also assessed. Subsequently, the Maximum Voluntary Isometric Contraction (MVIC) force of the triceps brachii was measured using a load cell (Baykon BT604, 200 kg). Following the fatigue protocol, participants performed another set of 10 FTs using the same protocol as the pre-fatigue measurements. The study design is illustrated in Figure 1.

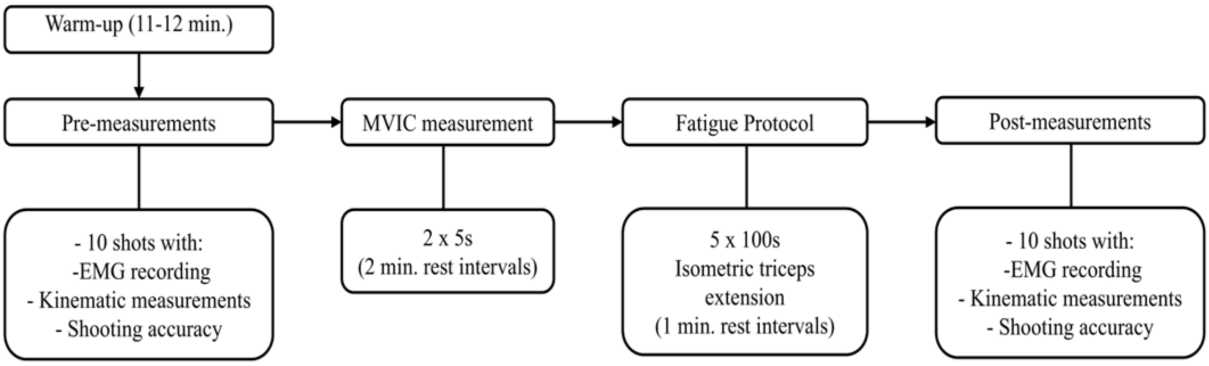

Figure 1. Study design.

MVIC measurements

For the triceps brachii muscle MVIC measurement, participants positioned themselves with their backs against a wall to ensure stability and minimize extraneous movements. The assessment was conducted with participants pulling the load cell downward while maintaining a standardized posture: elbow flexed at 90°, shoulder internally rotated at 45°, and wrist in a neutral position (Konrad, 2005). The load cell was fixed at chest level, and adjusted according to each athlete's height for consistency. Each participant performed two trials, each lasting 5 seconds, with 2-minute intervals between trials to ensure maximal force exertion. A graphical user interface (GUI), developed in MATLAB R2021a, was used to provide real-time visual feedback. The GUI displayed an indicator and a countdown timer, enabling participants to follow the measurement protocol precisely (Figure 2).

Figure 2. MATLAB Graphical User Interface.

Fatigue protocol

A fatigue protocol targeting the triceps brachii was chosen in this study because this muscle plays a key role in basketball shooting by enabling elbow extension—the final and critical movement during ball release. This action is particularly important in free throws, where precision and control are essential. Given that shooting involves coordinated shoulder elevation and elbow extension, understanding the impact of triceps fatigue is crucial for designing training strategies to improve shooting consistency and performance (Mir et al., 2025). The fatigue protocol required participants to maintain the same body position as in the MVIC measurement while performing isometric triceps extensions on the load cell at chest level, with a neutral wrist, 90° elbow flexion, and 45° shoulder internal rotation. The protocol consisted of five sets of 100-second triceps extensions at 40% ±10% of their MVIC (Rashid et al., 2020) with 2–3 minutes of rest between trials to minimize additional fatigue. The protocol was terminated when MVIC force dropped below 30% of its initial value, as monitored in real-time via the GUI.

Shooting accuracy assessment

Shooting accuracy was evaluated qualitatively based on four predefined categories (Table 1). It was divided into these categories to move beyond a simple successful/missed classification and to capture the qualitative characteristics of each attempt, such as control, balance, and shot trajectory (Ozdalyan et al., 2022). This approach allows for a more detailed analysis of shooting performance, particularly when examining the effects of fatigue. An Airball refers to a shot that completely misses both the rim and the backboard. A Short or Uncontrolled Shot (did not score) is an unsuccessful attempt that is visibly off-target, typically falling short or lacking control, and may hit only the backboard or barely graze the rim. A Balanced and Controlled Shot (did not score) is a missed shot that demonstrates proper balance, form, and trajectory, indicating sound shooting mechanics. A Successful Shot is a made basket, regardless of whether it passes cleanly through the hoop or makes contact with the rim. Each participant completed 20 total shots (10 pre-fatigue and 10 post-fatigue), and shooting accuracy was calculated as a percentage for each category. Each participant completed 20 total shots (10 pre-fatigue and 10 post-fatigue), and accuracy was calculated as a percentage for each category.

Table 1. Qualitative evaluation of shooting accuracy.

Scores	Categories
0	Airball
1	Short or uncontrolled shot (did not score)
2	Balanced and controlled shot (did not score)
3	Successful shot

Kinematic measurements

Kinematic data were collected using a high-speed camera (iPhone 13 Pro) operating at 240 frames per second (FPS).This method has been widely adopted in sports biomechanics research and has shown acceptable levels of validity and reliability for capturing joint angles and angular velocities during dynamic movements (Erculj & Supej, 2009). To track joint positions, reflective markers were placed on key anatomical landmarks: the wrist (ulnar styloid process), elbow (lateral epicondyle), shoulder (acromion), hip (greater trochanter), knee (lateral femoral epicondyle), ankle (lateral malleolus), and the base of the fifth metatarsal. A 135 cm calibration stick was used for two-dimensional spatial calibration. Video recordings were analyzed using Tracker Video Analysis Tool version 6.1, an open-source software commonly utilized in sports biomechanics (Brown, 2008; Wee & Lee, 2012). The extracted parameters included joint angles (°), joint angular velocities (°/s), ball velocity components (cm/s), ball release height (cm), and ball release angle (°) (see Table 2).

Table 2. Parameters of kinematic for pre- and post-fatigue.

Parameters
Joint Angles (°) at ball release (Ankle, Knee, Hip, Shoulder, Elbow)
Joint Angular velocities (°/s) at ball release (Ankle, Knee, Hip, Shoulder, Elbow)
Ball velocity (cm/s) at ball release x-axis (Vx) and y-axis (Vy)
Ball release height (cm)
Ball release angle (°)

Electromyography (EMG) measurements

Muscle activity was assessed using the Delsys Trigno Wireless EMG system (Natick, MA, USA) (Figure 3) a well-validated and widely used tool in biomechanical and neuromuscular research (Jayaraman et al., 2024). Electrodes were placed on the palmaris longus and the lateral and medial heads of the triceps brachii, following the SENIAM guidelines (Hermens et al., 2000). Skin preparation included shaving (if necessary) and cleaning with gel. EMG data were collected at a sampling rate of 1259 Hz. Signals were filtered with a 20–450 Hz bandwidth filter, and root mean square (RMS) values were calculated using MATLAB R2021a. EMG responses were recorded for each FT pre- and post-fatigue.

Statistical analysis

Data analysis was conducted using SPSS v24.0. The Shapiro-Wilk test was performed to assess the normality of the data. Since the data did not follow a normal distribution, the Wilcoxon Signed-Rank Test was used to evaluate differences between pre- and post-fatigue conditions for kinematic and EMG variables. To determine the effect size (r) for the kinematic and EMG parameters, the formula $r = Z / \sqrt{N}$ was applied. Effect sizes were interpreted based on Cohen's (1988) classification, where small effects were defined as ($0.10 \leq r < 0.30$), medium effects as ($0.30 \leq r < 0.50$), and large effects as ($r \geq 0.50$) (Cohen, 1988). Lastly, the shooting accuracy percentage was analyzed using the Wilcoxon Signed-Rank Test. All results are reported as the median and interquartile range (IQR: 25th–75th percentile), with statistical significance set at $p < 0.05$.

RESULTS

The results in Table 3 indicate that fatigue did not significantly affect joint angles (°) (ankle, knee, hip, shoulder, and elbow) during shooting, as all comparisons remained non-significant

($p > 0.05$). Joint angular velocity (°/s) showed mixed responses to fatigue. While ankle, knee, hip, and shoulder angular velocities remained unchanged ($p > 0.05$), elbow angular velocity significantly decreased ($p = 0.041$, effect size = 0.59), suggesting a large effect of fatigue. Regarding ball kinematics, ball velocity (cm/s) in the x-axis (Vx) and y-axis (Vy) and ball release height (cm) did not change significantly. However, the ball release angle showed a moderate effect size (effect size = 0.52) despite not reaching statistical significance ($p = 0.071$), indicating a possible impact of fatigue on shooting mechanics. Muscle activation analysis revealed no significant changes in triceps brachii (medial and lateral heads) (mV) EMG activity ($p > 0.05$), suggesting that triceps function remained stable. However, palmaris longus (mV) EMG amplitude significantly decreased ($p = 0.028$, effect size = 0.63), indicating a notable decline in wrist stability and grip control due to fatigue.

Table 3. Kinematic and electromyographic parameters pre and post fatigue.

Parameters	**Percentiles**		**Z**	**p**	**Effect size**
	Pre-fatigue Median (25th - 75th)	**Post-fatigue Median (25th - 75th)**			
Ankle Angle (°)	123.1 (116.7 - 134.8)	125.5 (117.7 - 133.2)	-0.235	0.814	0.07
Knee Angle (°)	164.8 (156.6 - 169.2)	164.3 (157.7 - 171.3)	-0.471	0.638	0.14
Hip Angle (°)	171.9 (165.8 - 175.8)	173.5 (171.7 - 174.7)	-1.218	0.223	0.35
Shoulder Angle (°)	105.4 (97.8 - 109.2)	106.4 (93.8 - 108.9)	-0.133	0.894	0.04
Elbow Angle (°)	110.5 (105.3 - 113.9)	111.6 (101.3 - 117.9)	-0.314	0.754	0.09
Ankle Angular Velocity (°/s)	194.5 (117.8 - 235.7)	196.1 (125.7 - 231.6)	-0.471	0.638	0.14
Knee Angular Velocity (°/s)	112.6 (92.0 - 138.3)	123.4 (106.6 - 142.3)	-1.452	0.147	0.42
Hip Angular Velocity (°/s)	69.9 (39.5 - 108.1)	78.4 (56.3 - 97.8)	-0.392	0.695	0.11
Shoulder Angular Velocity (°/s)	273.6 (247.7 - 385.7)	280.8 (231.6 - 441.0)	-0.549	0.583	0.16
Elbow Angular Velocity (°/s)	806.6 (712.1 - 890.0)	765.6 (683.0 - 853.1)	-2.04	*0.041**	0.59
Ball Velocity Vx (cm/s)	329.2 (308.8 - 357.2)	330.0 (306.8 - 359.8)	-0.471	0.638	0.14
Ball Velocity Vy (cm/s)	474.2 (432.0 - 492.9)	465.7 (445.5 - 492.4)	-0.392	0.695	0.11
Ball release height (cm)	235.1 (224.7 - 242.7)	236.2 (228.0 - 243.5)	-1.245	0.213	0.36
Ball release angle (°)	44.0 (41.5 - 47.6)	42.1 (40.4 - 46.1)	-1.804	0.071	0.52
Triceps Medial (mV)	0.17835 (0.11653 - 0.28105)	0.16035 (0.13843 - 0.21225)	-0.863	0.388	0.25
Triceps Lateral (mV)	0.10820 (0.06768 - 0.13425)	0.09970 (0.06688 - 0.12880)	-1.098	0.272	0.32
Palmaris Longus (mV)	0.09825 (0.07623 - 0.16633)	0.09365 (0.05160 - 0.12608)	-2.197	*0.028**	0.63

* $p < 0.05$

The analysis in Table 4 revealed a significant difference in the 'Airball' ($p = 0.041$) and 'Short or uncontrolled shot did not score' ($p = 0.023$) categories between pre- and post-fatigue conditions ($p < 0.05$). However, no significant differences were observed in the 'Balanced and controlled shot, but did not score' and 'Successful shot' categories ($p > 0.05$). These findings indicate that fatigue negatively impacts uncontrolled and inaccurate shooting outcomes but does not significantly influence the execution of balanced or successful shots.

Table 4. Comparison of shooting accuracy.

Category	Percentiles: Pre-fatigue Median (25th - 75th)	Percentiles: Post-fatigue Median (25th - 75th)	Z	p
Airball	0.00 (0.00-0.00)	0.00 (0.00-17.50)	-2.041	0.041*
Short or uncontrolled shot (did not score)	10.00 (0.00-27.50)	30.00 (20.00-47.50)	-2.270	0.023*
Balanced and controlled shot (did not score)	35.00 (10.00-40.00)	20.00 (10.00-30.00)	-1.223	0.221
Successful shoot	50.00 (32.50-77.50)	35.00 (22.50-57.50)	-1.393	0.164

Notes. * $p < 0.05$

DISCUSSION

This study investigated the effects of upper extremity fatigue on FT shooting accuracy, kinematic variables, and muscle activation in adolescent basketball players. The findings indicate that fatigue selectively impacted elbow angular velocity and palmaris longus activation, while other kinematic and neuromuscular parameters remained largely unaffected. Additionally, fatigue impaired shooting accuracy, particularly in 'Airball' and 'Short or uncontrolled shot did not score' categories. These results suggest that fatigue disrupts technical execution and fine motor control, while the fundamental biomechanics of shooting remain stable.

Previous research demonstrated that fatigue can impair motor skills and accuracy, particularly in less experienced athletes (Knicker et al., 2011; Lyons et al., 2006; Mulazimoglu, 2014). More skilled players tend to maintain their performance under fatigue, likely due to greater motor control efficiency and refined movement strategies (Knicker et al., 2011; Lyons et al., 2006; Mulazimoglu, 2014). Similar findings have been reported in tennis, where fatigue-related declines in stroke accuracy were more pronounced in non-expert players than in skilled athletes, except under extreme fatigue conditions (Rupcic et al., 2020). In the present study, fatigue was induced in a controlled manner, targeting the triceps muscle at 40% MVIC, rather than engaging the entire upper body. Given that the participants were not elite-level players, the observed decline in shooting accuracy aligns with the idea that moderate fatigue is sufficient to impair precision in less experienced athletes. Based on previous findings, we anticipate that higher-intensity fatigue protocols will lead to significant decreases in EMG median frequency and overall reductions in EMG amplitude across multiple muscle groups (Ali et al., 2015; Apriantono et al., 2006; Hill et al., 2016). Furthermore, such protocols are expected to produce broader and more pronounced impairments in whole-body posture, alterations in movement patterns, and changes in joint angles affecting both the upper and lower extremities (Henderson et al., 2003; McDonald et al., 2019; Minning et al., 2007; Murdock & Hubley-Kozey, 2012).

Despite the decline in shooting accuracy, joint angles (ankle, knee, hip, shoulder, and elbow) and most joint angular velocities remained unchanged, suggesting that fundamental shooting mechanics were preserved. However, elbow angular velocity showed a significant reduction (−5.08%), indicating that fatigue may compromise rapid elbow extension, a critical movement in the shooting sequence. This aligns with previous findings demonstrating that fatigue-induced changes in kinematics often manifest in specific movement components rather than across entire movement patterns (Erculj & Supej, 2009; Tsia et al., 2006). Interestingly, ball release variables, including velocity (Vx, Vy), ball release height, and ball release angle, did not significantly change post-fatigue. While prior research has shown that fatigue can alter ball velocity in sports such as soccer and basketball, those studies typically employed higher-intensity fatigue protocols involving whole-body exertion (Apriantono et al., 2006). The moderate fatigue level in this study, focused solely on the upper extremity, may explain why larger-scale kinematic disruptions were not observed.

EMG analysis revealed that triceps brachii (both medial and lateral heads) activity remained stable, suggesting that triceps function was not significantly affected by the applied fatigue protocol. Consistent with our results, previous research also indicates that basketball-specific fatigue does not impact Triceps Brachii EMG activation in the shooting arm during a three-point jump shot in adolescent athletes, emphasizing its stability and consistent role in the shooting motion despite fatigue (Peterca & Dolenec, 2019). However, palmaris longus activation significantly declined (−4.68%), indicating reduced wrist stability and grip control, which could contribute to altered shot release mechanics. Similar reductions in wrist muscle activation have been reported following localized upper extremity fatigue protocols (Balestra et al., 2001; Peterca & Dolenec, 2019). Considering the function of the palmaris longus in stabilizing wrist flexion, its fatigue-related decline may have contributed to less controlled ball release, leading to more frequent airballs and missed shots.

While prior studies have reported significant reductions in muscle activation following fatigue (Ali et al., 2015; Rashid et al., 2020), these effects are often observed under more intense conditions. The moderate intensity of the 40% MVIC fatigue protocol may explain why major EMG alterations were limited to the palmaris longus rather than affecting the entire upper limb.

Strengths and limitations

This study provides a detailed analysis of fatigue's impact on basketball shooting by integrating kinematic, neuromuscular, and performance-related parameters. It examines the triceps brachii and palmaris longus, key muscles in elbow extension and wrist flexion, to offer deeper insights into their roles in shooting mechanics under fatigue-induced conditions. These muscles have not been extensively explored in previous research on basketball-related fatigue, and their inclusion brings a fresh perspective on their contribution to shooting mechanics. The study also enhances its practical relevance by assessing free throw performance, a fundamental basketball skill, under both pre-fatigue and post-fatigue conditions.

However, some limitations should be acknowledged. The controlled testing environment may not fully reflect in-game conditions, where psychological factors, defensive pressure, and reactive decision-making can influence shooting mechanics. Additionally, the lack of physiological measures (e.g., heart rate, blood lactate) limits the ability to quantify overall systemic fatigue levels. Another limitation of this study is the lack of detailed information regarding participants' individual strength training histories, which may have influenced their neuromuscular responses to the fatigue protocol. Future research should consider incorporating game-like scenarios and higher-intensity fatigue protocols to explore whether more pronounced kinematic disruptions occur under realistic competitive conditions.

CONCLUSION

This study demonstrated that fatigue negatively impacts elbow kinematics, palmaris longus neuromuscular function, and shooting accuracy in adolescent basketball players. Specifically, elbow angular velocity decreased, and palmaris longus activation declined, suggesting impairments in wrist stability and grip control, both crucial for consistent shot release. To mitigate fatigue-related declines in shooting accuracy, basketball training programs should incorporate fatigue-resistant exercises targeting wrist stabilizers and upper limb endurance. Players may also need to adjust their release mechanics to compensate for fatigue-induced changes in elbow velocity and grip stability, ensuring consistent shooting performance throughout a game. By implementing these evidence-based training strategies, coaches and athletes can enhance fatigue resilience, ultimately improving game-time shooting accuracy and overall performance.

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REFERENCES

Ali, M. A., Sundaraj, K., Ahmad, R. B., Ahamed, N. U., Islam, M. A., & Sundaraj, S. (2015). Muscle fatigue in the three heads of the triceps brachii during a controlled forceful hand grip task with full elbow extension using surface electromyography. *Journal of Human Kinetics, 46*(1), 69–76. https://doi.org/10.1515/hukin-2015-0035

Apriantono, T., Nunome, H., Ikegami, Y., & Sano, S. (2006). The effect of muscle fatigue on instep kicking kinetics and kinematics in association football. *Journal of Sports Sciences, 24*(9), 951–960. https://doi.org/10.1080/02640410500386050

Balestra, G., Frassinelli, S., Knaflitz, M., & Molinari, F. (2001). Time-frequency analysis of surface myoelectric signals during athletic movement. *IEEE Engineering in Medicine and Biology Magazine, 20*(6), 106–115. https://doi.org/10.1109/51.982282

Bourdas, D. I., Travlos, A. K., Souglis, A., Gofas, D. C., Stavropoulos, D., & Bakirtzoglou, P. (2024). Basketball fatigue impact on kinematic parameters and 3-point shooting accuracy: Insights across players' positions and cardiorespiratory fitness associations of high-level players. *Sports, 12*(3), 1–17. https://doi.org/10.3390/sports12030063

Chen, W.-C., Lo, S., Lee, Y., Wang, J., & Shiang, T. (2005, August 22–27). Effects of upper extremity fatigue on basketball shooting accuracy. In *Proceedings of the 23rd International Symposium on Biomechanics in Sports* (pp. 633–636). Beijing, China.

Erculj, F., & Supej, M. (2009). Impact of fatigue on the position of the release arm and shoulder girdle over a longer shooting distance for an elite basketball player. *Journal of Strength and Conditioning Research, 23*(3), 1029–1036. https://doi.org/10.1519/JSC.0b013e3181a07a27

Gandevia, S. C. (2001). Spinal and supraspinal factors in human muscle fatigue. *Physiological Reviews, 81*(4), 1725–1789. https://doi.org/10.1152/physrev.2001.81.4.1725

Ghasemi, M., Olyaei, G., Bagheri, H., Talebian, S., Shadmehr, A., & Jalaei, S. (2012). The effects of triceps surae fatigue on the torque and electromyographic parameters in athletes compared with non-athletes. *Journal of Back and Musculoskeletal Rehabilitation, 25*(2), 95–101. https://doi.org/10.3233/BMR-2012-0316

Henderson, Z. J., Wang, S., Cornish, S. M., & Scribbans, T. D. (2003). Exploring the acute muscle fatigue response in resistance trained individuals during eccentric quasi-isometric elbow extensions—A cross-sectional comparison of angular kinetics, kinematics, surface electromyography, and sex. *Sport Rx IV Preprint*, 2003.

Hermens, H. J., Freriks, B., & Disselhorst-Klug, Rau, G. (2000). Development of recommendations for SEMG sensors and sensor placement procedures. *Journal of Electromyography and Kinesiology, 10*, 361–374.

Hill, E. C., Housh, T. J., Smith, C. M., Cochrane, K. C., Jenkins, N. D. M., Cramer, J. T., Schmidt, R. J., & Johnson, G. O. (2016). Effect of sex on torque, recovery, EMG, and MMG responses to fatigue. *Journal of Musculoskeletal Neuronal Interactions, 16*(4), 310–317.

Jayaraman, C., Mummidisetty, C. K., Jayaraman, A., Pfleeger, K., Jacobson, M., Ceruolo, M., Sen-Gupta, E., Caccese, J., & Chen, D. (2024). Validity and reliability study of a novel surface electromyography sensor using a well-consolidated electromyography system in individuals with cervical spinal cord injury. *Spinal Cord, 62*(6), 320–327. https://doi.org/10.1038/s41393-024-00981-y

Kellis, E., Katis, A., & Vrabas, I. S. (2006). Effects of an intermittent exercise fatigue protocol on biomechanics of soccer kick performance. *Scandinavian Journal of Medicine and Science in Sports, 16*(5), 334–344. https://doi.org/10.1111/j.1600-0838.2005.00496.x

Knicker, A. J., Renshaw, I., Oldham, A. R. H., & Cairns, S. P. (2011). Interactive processes link the multiple symptoms of fatigue in sport competition. *Sports Medicine, 41*(4), 307–328. https://doi.org/10.2165/11586070-000000000-00000

Konrad, P. (2005). *The ABC of EMG: A practical introduction to kinesiological electromyography*. Noraxon Inc USA.

Li, F., Knjaz, D., & Rupčić, T. (2021). Influence of fatigue on some kinematic parameters of basketball passing. *International Journal of Environmental Research and Public Health, 18*(2), 1–10. https://doi.org/10.3390/ijerph18020700

Li, F., Li, Z., Borović, I., Rupčić, T., & Knjaz, D. (2021). Does fatigue affect the kinematics of shooting in female basketball? *International Journal of Performance Analysis in Sport, 21*(5), 754–766. https://doi.org/10.1080/24748668.2021.1945878

Lyons, M., Al-Nakeeb, Y., & Nevill, A. (2006). The impact of moderate and high intensity total body fatigue on passing accuracy in expert and novice basketball players. *Journal of Sports Science & Medicine, 5*(2), 215–227.

Marcolin, G., Camazzola, N., Panizzolo, F. A., Grigoletto, D., & Paoli, A. (2018). Different intensities of basketball drills affect jump shot accuracy of expert and junior players. *PeerJ, 2018*(2), 1–10. https://doi.org/10.7717/peerj.4250

McDonald, A. C., Mulla, D. M., & Keir, P. J. (2019). Muscular and kinematic adaptations to fatiguing repetitive upper extremity work. *Applied Ergonomics, 75*(November 2018), 250–256. https://doi.org/10.1016/j.apergo.2018.11.001

Miller, S., & Bartlett, R. M. (1993). The effects of increased shooting distance in the basketball jump shot. *Journal of Sports Sciences, 11*(4), 285–293. https://doi.org/10.1080/02640419308729998

Minning, S., Eliot, C. A., Uhl, T. L., & Malone, T. R. (2007). EMG analysis of shoulder muscle fatigue during resisted isometric shoulder elevation. *Journal of Electromyography and Kinesiology, 17*(2), 153–159. https://doi.org/10.1016/j.jelekin.2006.01.008

Mir, I. A., Mohd Jamali, M. N. Z., Humayra, S., Chong, K. W., Amalnerkar, T., & Sirajudeen, M. S. (2025). Partial versus full range of motion triceps strength training on shooting accuracy among recreational basketball players: A randomized controlled trial. *BMC Sports Science, Medicine and Rehabilitation, 17*(1). https://doi.org/10.1186/s13102-025-01060-2

Mulazimoglu, O. (2014). An investigation of the effect of fatigue on passing accuracy in soccer players. *International Journal of Academic Research, 6*(2), 259–267. https://doi.org/10.7813/2075-4124.2014/6-2/a.37

Murdock, G. H., & Hubley-Kozey, C. L. (2012). Effect of a high intensity quadriceps fatigue protocol on knee joint mechanics and muscle activation during gait in young adults. *European Journal of Applied Physiology, 112*(2), 439–449. https://doi.org/10.1007/s00421-011-1990-4

Ozdalyan, F., Manci, E., Gencoglu, C., Gumus, H., & Kosova, S. (2022). Comparison of the shooting angles in wheelchair basketball and basketball players: shooting angles in wheelchair basketball. *European Journal of Human Movement*, 48, 35-45. https://doi.org/10.21134/eurjhm.2022.48.4

Pakosz, P., Domaszewski, P., Konieczny, M., & Bączkowicz, D. (2021). Muscle activation time and free-throw effectiveness in basketball. *Scientific Reports, 11*(1), 1–8. https://doi.org/10.1038/s41598-021-87001-8

Peterca, J., Maloney, S., Vučković, G., & Dolenec, A. (2019, November). Influence of basketball-specific fatigue on EMG activation in the shooting arm and ground reaction forces during a basketball three-point jump shot. *BASES Annual Conference 2019*, United Kingdom.

Rashid, D. M. S., Faraj, S. M. S., & Hedayatpour, N. (2020). The effect of triceps brachii fatigue on shot accuracy of male and female basketball players. *International Journal of Performance Analysis in Sport, 20*(2), 206–218. https://doi.org/10.1080/24748668.2020.1736410

Rupcic, T., Feng, L., Matkovic, B. R., Knjaz, D., Dukaric, V., Bakovic, M., Matkovic, A., Svoboda, I., Vavacek, M., & Garafolic, H. (2020). The impact of progressive physiological loads on angular velocities during shooting in basketball - Case study. *Acta Kinesiologica, 14*(2), 102–109.

Salonikidis, K., Mantziou, A., Papageorgiou, K., & Arabatzi, F. (2021). Palmaris longus muscle contribution to maximum torque and steadiness in highly skilled grip and non-grip sport populations. *Journal of Applied Sports Sciences, 1*(2021), 67–79. https://doi.org/10.37393/jass.2021.01.6

Slawinski, J., Poli, J., Karganovic, S., Khazoom, C., & Dinu, D. (2015). Effect of fatigue on basketball three-point shot kinematics. In *Proceedings of the 33rd International Conference on Biomechanics in Sports* (pp. 1209–1211).

Tsia, C. Y., Ho, W. H., Lii, Y. K., & Huang, C. L. (2006, July 14–18). The kinematic analysis of basketball three-point shoot after a high-intensity program. In *Proceedings of the 24th International Symposium on Biomechanics in Sports* (pp. 1–4). Salzburg, Austria.

Yasar, M. N., Sica, M., O'Flynn, B., Tedesco, S., & Menolotto, M. (2024). A dataset for fatigue estimation during shoulder internal and external rotation movements using wearables. *Scientific Data, 11*(1), 1–14. https://doi.org/10.1038/s41597-024-03254-8

Zhao, T. (2025). The impact of fatigue on the jumping mechanics and injury risk of basketball players. *Molecular & Cellular Biomechanics, 22*(2), 1026. https://doi.org/10.62617/mcb1026