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Influence of Fatigue on Selected Kinematic Parameters in High Jump – A Pilot Case Study

Sara Aščić[1], Marin Marinović[1,2], Danijela Kuna[2]

[1]Faculty of Kinesiology, University of Zagreb, 10000 Zagreb, Croatia
[2]Faculty of Kinesiology, University of Osijek, 31000 Osijek, Croatia

ABSTRACT

PURPOSE: High jump, a complex athletic activity, involves distinct phases crucial for success, notably the take-off phase. While previous studies explored kinematic parameters' influence on high jump success, none investigated their fatigue-induced changes. This pilot study aimed to explore fatigue's impact on kinematic parameters in high jump performance. METHODS: A prominent Croatian junior high jumper underwent rested and fatigued jumping sessions. Internal fatigue was assessed via the Wellness questionnaire and session rating of perceived exertion (sRPE). External fatigue parameters were assessed through bilateral and unilateral Countermovement Jump (CMJ) height using Gyko and Optogait devices. Kinematic parameters were recorded via Logitech C920 and Xiaomi Redmi Note 8 Pro cameras, including contact time, take-off place, knee and body angles. RESULTS: Significant differences were observed in knee angle touchdown ($p=0.01$), knee angle take-off ($p=0.05$), body angle touchdown ($p=0.01$), body angle take-off ($p=0.03$), knee amortization start ($p=0.05$), and knee amortization ($p=0.01$). CONCLUSION: Fatigue significantly impacts kinematic parameters in high jump, particularly affecting body inclination during take-off, knee angles, and knee amortization. Coaches should consider fatigue when planning training and competition schedules for optimal performance. Maintaining rested conditions is crucial, and targeted training can enhance muscle groups affected by fatigue during specific jump phases.

Keywords: High jump; Fatigue; Kinematics

INTRODUCTION

Sports training is a complex transformational process defined by organized training systems tailored to athletes' states and goals (Milanović, 2013). To optimize training, a suitable plan is crucial, ensuring intense stimuli for change while allowing recovery (Meeusen et al., 2013; Turner et al., 2015). Monitoring workload volume, defined by informational and energetic components, is vital, progressively increasing for adaptations and elevated training levels (Askow et al., 2021; Milanović, 2013). Adequate dosing of workload volume is crucial for sports form and injury prevention (Bourdon et al., 2017; Thorpe et al., 2017), considering various training operators and sport-specific challenges (Askow et al., 2021). Multiple protocols exist for monitoring workload volume, chosen based on sport requirements (Askow et al., 2021; Bourdon et al., 2017; Meeusen et al., 2013; Milanović, 2013; Thorpe et al., 2017; Turner et al., 2015). Bourdon et al. (2017) categorizes workload assessment tests into those evaluating external and internal indicators, emphasizing the importance of employing both types for a comprehensive understanding of workload. Tests relying on external indicators provide information on performed work, while those utilizing internal indicators assess the athlete's physiological response to specific stimuli.

Among the internal workload assessment tests are heart rate, oxygen uptake, blood lactate levels, Wellness questionnaire, and perceived exertion rating (sRPE) (Bourdon et al., 2017). Thorpe et al. (2017) suggest the use of personalized questionnaires as a non-invasive, accessible, and cost-effective method for obtaining information on workload levels. Heart rate monitoring, frequently used in endurance sports, provides physiological parameter insights (Bourdon et al., 2017). The sRPE method, a brief and practical post-training questionnaire, correlates with training volume, validated by Turner et al. (2015) and Askow et al. (2021). Other studies confirm the validity of sRPE for workload measurement (Mellalieu et al., 2021; Thorpe et al., 2017). The Wellness questionnaire offers a detailed insight into specific aspects of subjective workload, allowing athletes to rate fatigue levels from 1 to 5 (Bourdon et al., 2017; McLean et al., 2010).

For external workload assessment, common practices include monitoring repetitions, duration, total distance covered in running, total weight lifted, and speed (Bourdon et al., 2017). The countermovement jump (CMJ) serves for assessing workload both within individual sessions and between training days. Reliable methods for measuring jump height include force platforms, Optogait, and Gyko (García-Ramos et al., 2017; Pueo et al., 2020; Thorpe et al., 2017). Inadequate workload dosing can lead to negative consequences such as overtraining, fatigue, injuries, and unmet sports goals (Elloumi et al., 2012; Meeusen et al., 2013; Neville et al., 2008). Askow et al. (2021) highlight risks associated with inadequate workload, including the inability to adapt to training, illnesses, injuries, and overtraining.

In individual sports like high jump, where performance outcomes hinge on individual execution, maintaining a high level of readiness and performance is crucial. High jump, a complex activity, demands a high level of athlete training to achieve top results (Yang, Pu & Fan, 2013; Akhmetov et al., 2016). Improper workload dosing with high-intensity training operators in high jump can lead to injuries (Roslan & Ahmad, 2020). Researchers continually seek new training methods to maximize performance while minimizing injury risks (Akhmetov et al., 2016). High jump performance is typically divided into three phases: approach, take-off, and flight, with some studies adding a fourth landing phase (Mateos-Padorno et al., 2021). The take-off phase is crucial, and parameters like contact duration, leg positioning, knee angle, and body inclination are essential for success (Aščić, 2021; Čoh and Supej, 2007; Dapena & Chung, 1988; Pavlović, 2017). Optimal performance requires a precise combination of kinematic parameters.

Previous studies have explored influence of kinematic parameters on high jump success, but none have investigated how kinematic parameters change with fatigue. Understanding this could enhance training by targeting specific jump phases affected by fatigue, ultimately improving athletic performance. We hypothesized that there will be significant differences in kinematic parameters when jumping in fatigued state compared to rested jumping session. Therefore, the aim of this pilot case study is to compare jumping in rested and fatigued conditions to see how some kinematic parameters are affected when fatigue is present.

METHOD

Participant

The sample for this pilot case study consisted of a prominent Croatian junior high jumper. The participant is a medalist in various categories at the Croatian National Championships, including younger juniors, juniors, and younger seniors. Additionally, the participant has represented Croatia in senior competitions, such as the Triangular Meet involving Croatia, Slovenia, and Serbia. At the time of the study, the participant's personal record stood at 195 centimeters, equating to 870 points according to the World Athletics scoring tables. During the testing period, the participant was in the competition period and did not have any musculoskeletal injury or illness within three months prior to the commencement of testing. The participant, being a minor at the time of testing, received a comprehensive explanation of the research objectives and potential risks of participation, which was provided to both the participant and their parents who granted consent for participation in the study. The participant had the opportunity to withdraw from the study at any given moment. The results obtained from this research are made available to the participant, coach, and parents. The study was conducted in accordance with the current Helsinki Declaration.

Measuring instruments and variables

Fatigue measurement

The Wellness questionnaire, as outlined by Mendes et al. (2018), Tavares et al. (2018), and Vavassori, Moreno & Ureña Espa (2023), was employed for assessing internal fatigue. Participants rated subjective fatigue, muscle pain, stress, and mood on a Likert scale ranging from 1 to 5. A higher score indicated lower levels for fatigue, muscle pain, stress, and mood. The reliability of the Wellness questionnaire was established by Aben et al. (2020).

For the subjective assessment of training load volume, the sRPE (session rating of perceived exertion) questionnaire was utilized. Participants subjectively rated their perceived fatigue state on a scale from 1 to 10, where a value of 1 represented very, very easy, and 10 represented maximal effort. The reliability of the sRPE questionnaire, as defined by Haddad et al. (2017), was incorporated into the scientific paper by Koyama et al. (2024).

External fatigue parameters were evaluated through CMJ height, measured by Gyko and Optogait devices. Gyko, with accelerometers and magnetometers, wirelessly transmitted data to GykoRePower software, while Optogait, equipped with optical sensors, analyzed spatiotemporal parameters, providing comprehensive CMJ insights. The validity and reliability of the Optoagait photoelectric cell system have been investigated in several studies (Gomez Bernal et al., 2016; Lee et al., 2014). The reliability of the Gyko device was established by Jaworski et al. (2020) and Santospagnuolo et al. (2019). CMJ has been recognized as a reliable test for evaluating neuromuscular status, with jump height identified as a robust parameter (Claudino et al., 2017). Maté-Muñoz et al. (2017) used CMJ as a control for muscle fatigue in various training programs, and Hader et al. (2019) highlighted its frequent use and reliability in indicating muscle fatigue post-performance. Given the unique demands of high jump as a sport and the distinct requirements of the dominant and nondominant legs during performance, a single-leg CMJ was also utilized in this study. Kutáč and Uchytil (2018) demonstrated significant performance differences between the dominant and nondominant legs in athletics jump disciplines, especially in the take-off phase. Therefore, this research examined variables such as CMJH for jump height in unilateral jumps with designations of R for the right leg and L for the left leg.

Kinematic parameters

For kinematic parameters, Logitech C920 (1080p, 30 fps) and Xiaomi Redmi Note 8 Pro (30 fps) cameras were used. Smartphone reliability for Kinovea-based vertical jump analysis was established in previous research (Caseiro-Filho et al., 2023; Harrington, Adeyinka & Burkhart, 2023; Iijima, Shiomi & Hara, 2023; Pueo et al., 2020). Video analysis was conducted using Kinovea (version 0.9.5) on an Acer Aspire laptop. Software calibration was performed using a high jump stand. Additionally, contact time during jumping session was measured with newly constructed Optogait test. The test was designed so that measurements would commence when the participant's foot came on the LED lights and conclude when their foot entirely exited the area of the plates. This construction allows for the measurement of contact time during the jumping session.

For the purposes of this research, nine kinematic parameters of the high jump were selected. CT was measured using the Optogait system, and the result is expressed in milliseconds. Meanwhile, take off place (TP) was measured by determining the smallest distance from the top of the foot to the bar. Knee amortization start (KA1) was measured by selecting the first frame in Kinovea where the participant's entire foot touched the surface. Subsequently, the angle's magnitude was measured in the program, with its vertices being the lateral malleolus, lateral femoral condyle, and trochanter major. Knee amortization end (KA2) was measured by selecting the last frame in Kinovea where the participant's entire foot touched the surface. The angle's magnitude was then measured in the program, using the same vertices. The value of the variable Knee amortization (KA) was obtained by calculating the difference between the variables KA1 and KA2. Knee angle touch down (KATD) was calculated by measuring the angle between the shank and the surface in the Kinovea program. The center of the angle was the tarsus, and the apex was the patella, with the second leg of the angle being parallel to the surface. Knee angle take off (KATO) was calculated similarly in the Kinovea program by measuring the angle between the shank and the surface. The center of the angle was the tarsus, the apex was the patella, and the second leg of the angle was parallel to the surface. Body angle touch down (BATD) was calculated using the angle between the surface and the line connecting the tarsus and nasion in the frame where the foot had its initial contact with the surface. Body angle take off (BATO) was calculated using the angle between the surface and the line connecting the anterior part of the talocrural joint and the nasion at the moment when the foot had its final contact with the surface.

Protocol

The rested jumping session, conducted 10 days before a significant competition, aimed to ensure the participant was in optimal condition and well-rested for the assessment. Upon arrival at the facility, the participant was acquainted with the testing protocol, and a standard warm-up procedure was implemented. After the standard warm-up protocol, the participant completed the Wellness questionnaire to subjectively assess the level of fatigue. Following the jumping session, the Wellness questionnaire was administered again. Additionally, after each jump, the participant filled out a condensed version of the Wellness questionnaire and provided a rating of perceived exertion (sRPE) as immediate feedback on the current fatigue state.

After completing the questionnaire, the participant was familiarized with the CMJ test. Optogait device plates were positioned on the ground with a 1-meter spacing. The participant wore a Gyko device harness on their back, secured to the vest, aligned with the C7 vertebra. The C7 vertebra was chosen as it is identified as a stable body point suitable for jump parameter measurements, with prior studies showing a high correlation with force platform measurements (Brownjohn, Bocian & Hester, 2017). The researcher demonstrated the jumps to the participant, who then stood within the Optogait plates and performed bilateral CMJ on an auditory cue. The test was repeated thrice, allowing sufficient rest between jumps until the participant felt ready for the next maximal jump. Subsequently, the participant executed unilateral CMJs, starting with three jumps with the right leg, followed by the same protocol with the left leg. Brief pauses between unilateral jumps were taken, allowing the participant to prepare for the next maximal effort. Rest intervals between sets lasted around 30 seconds to a minute. The recorded results of jump height were entered into an Excel spreadsheet.

Kinematic parameters were measured in the athletic tunnel of the Gradski vrt arena, specifically on the high jump platform. All equipment, including the mat, bar, and stands, was certified for competitive use. The kinematic parameters were recorded using two cameras and the Kinovea software. Camera 1 was aligned with the right stand, positioned 100 cm to the right, and set at a height of 127 centimeters. Camera 2 was situated 26 centimeters to the left and 490 centimeters behind the right stand, with a height of 130 centimeters. Both cameras were strategically placed to capture the final step of the approach and the take-off. The Optogait device's bars were positioned 60 centimeters away from the mat, allowing for the recording of takeoff without the participant stepping between them on the final step. The bars were spaced 450 centimeters apart from each other.

The participant performed jumps at a height of 180 centimeters. The selection of this height was a result of consultations with the coach, considering it to be sufficiently challenging for the participant yet low enough to allow for a substantial number of jumps even in a fatigued state. Moreover, given that the initial testing took place 10 days before a significant competition, this height ensured that the participant could execute numerous jumps without experiencing excessive fatigue or risking potential injuries that could hinder performance in the upcoming competition. The chosen height was deemed appropriate, as it allowed the participant to continue jumping even after the competition and in a state of significant fatigue without the fear of injury. Jumping ceased when the participant no longer felt comfortable continuing due to fatigue.

The fatigued jumping session was scheduled after the participant's performance in a two-day competition, where they took part in four disciplines. Twelve hours after the conclusion of the competition, a protocol identical to the initial testing was conducted.

Statistical analysis

The data obtained from the software were entered into an Excel spreadsheet. Tibco Statistica Enterprise software (version 14.0.1.25) was utilized for the analysis of the results. Due to the small sample size, descriptive parameters such as median (MED), lower quartile (Q25), and upper quartile (Q75) were employed. Percentages are employed to illustrate the differences in both bilateral and unilateral CMJ heights between the rested and fatigued testing sessions. The Wilcoxon matched pairs test was utilized to determine differences between variables. The effect size (ES) is calculated as Z statistic divided by square root of the sample size (N) ($Z/\sqrt{N}$)) (Cohen, 1988). The statistical significance level was set at $p < 0.05$.

RESULTS AND DISCUSSION

In the rested jumping session, the participant showed a 10% reduction in average CMJ height (from 39.7 cm pre-training to 35.8 cm post-training). In contrast, the fatigued jumping session saw a more pronounced 15% decrease (from 38.1 cm to 32.5 cm). Comparing sessions, the average initial CMJ height in the fatigued session was 4% lower, and the final fatigued session experienced a 9% decline compared to the rested session. Focusing on the right leg during the rested session, a substantial 19.2% reduction occurred (from 26.6 cm to 21.5 cm), and the fatigued session displayed a 13.1% decline in initial height (from 20.6 cm to 17.9 cm). Comparing sessions, the average initial CMJ height with the right leg in the fatigued session was notably 22.6% lower, and the final fatigued session exhibited a 16.7% decrease compared to the rested session. Turning to the left leg during the rested session, participants showed a 12.6% reduction (from 24.7 cm to 21.6 cm). In contrast, the fatigued session displayed a more substantial 25% decrease in initial height (from 21.6 cm to 16.2 cm). Comparing sessions, the average initial CMJ height with the left leg in the fatigued session was 12.6% lower, and the final fatigued session experienced a more pronounced 25.4% decline compared to the rested session.

The acquired data suggests that the jumps executed by the participant during the jumping session induced considerable muscular fatigue. The results also reveal that, during the rested testing, the participant attained higher jump values, indicating a lower overall muscular fatigue compared to the fatigued testing. These findings are consistent with expectations and are in accordance with studies that show lower CMJ heigh results in presence of fatigue (Rabbani et al., 2021; Rebelo et al., 2023).

Table 1 displays the median values with interquartile range (M±25th–75th) for kinematic and fatigue parameters along with differences between rested and fatigued jumping sessions.

Table 1. Basic descriptive parameters and differences between rested and fatigued jumps

		ALL (N=19)	**RESTED (N=11)**	**FATIGUED (N=8)**	**RESTED/ FATIGUED**	
	VAR	MED (Q25–Q75)	MED (Q25–Q75)	MED (Q25–Q75)	p	ES
FATIGUE PARAMETERS	sRPE	7.00 (5.00–10.00)	5.00 (4.00–7.00)	10.00 (10.00–10.00)	**0.00***	**0.58**
	FA	5.00 (4.00–5.00)	4.00 (4.00–5.00)	5.00 (5.00–5.00)	1.00*	0.51
	MP	4.00 (4.00–5.00)	4.00 (3.00–4.00)	5.00 (5.00–5.00)	**0.00***	**0.58**
	SL	4.00 (3.00–5.00)	3.00 (3.00–3.00)	5.00 (5.00–5.00)	**0.00***	**0.58**
	MO	1.00 (1.00–3.00)	1.00 (1.00–1.00)	3.00 (3.00–3.00)	**0.00***	**0.58**
KINEMATIC PARAMETERS	CT	0.20 (0.18-0.21)	0.20 (0.18-0.20)	0.20 (0.18-0.21)	0.48	0.16
	KATD	65.20 (61.60-69.40)	63.40 (61.10-65.20)	69.75 (67.95-72.95)	**0.01**	**0.58**
	KATO	84.60 (82.90-87.30)	83.50 (82.90-85.00)	87.10 (84.65-88.75)	**0.05**	**0.45**
	BATD	69.40 (67.60-73.20)	67.80 (67.10-69.30)	73.60 (72.55-74.55)	**0.01**	**0.58**
	BATO	93.60 (91.10-94.50)	92.90 (90.00-93.60)	95.15 (94.35-96.75)	**0.03**	**0.51**
	TP	90.73 (84.92-94.15)	89.76 (87.16-93.34)	91.96 (81.67-95.01)	0.78	0.06
	KA1	148.70 (146.30-154.20)	146.40 (144.80-149.80)	154.90 (150.30-157.30)	**0.05**	**0.45**
	KA2	134.40 (132.00-137.50)	133.70 (131.00-136.00)	137.15 (134.40-140.40)	0.12	0.35
	KA	15.10 (12.00-21.20)	13.50 (12.40-15.30)	20.00 (11.15-23.40)	**0.01**	**0.35**

Legend: FA-fatigue, MP-muscle pain, SL- stress level, MO-mood, CT-contact time, KATD-knee angle touch down, KATO-knee angle take off, BATD-body angle touch down, BATO-body angle take off, TP-take off place, KA1-knee amortization start, KA2-knee amortization end, KA-knee amortization

Results from this study indicate that wellness parameters are significantly lower in fatigued stated. Those results are in accordance with previous studies done on other sports. Gallo et al (2017) established that average wellness values were lower day after the football game. Moreover, Gastin, Meyer and Robinson (2013) found that one day after the game, athletes showed significantly lower values in wellness questionnaire when compared with usual values.

By comparing the results between the rested and fatigued testing sessions, statistically significant differences were found in knee angle parameters both at touch down and take off, body angle at the start and end of the take-off, and knee amortization 1, as well as knee amortization. Considering that control tests assessing fatigue were conducted before the rested and fatigued testing sessions, demonstrating differences in fatigue levels between the two testing sessions, it can be presumed that the mentioned parameters are more susceptible to changes during the onset of fatigue.

The knee angle at touchdown was larger in the fatigued session compared to the rested session. This suggests that as fatigue levels increased, the knee angle at the beginning of the take-off also increased. Although it is desirable for athletes to have a more extended leg during take-off (Greig and Yeadon, 2000), considering individual athlete characteristics, it can be assumed that changes in this angle during competition may negatively impact performance. A possible reason for the increased angle could be slower approach running and uncertainty, leading the athlete not to lower the body's center of mass before take-off, which is reflected in the knee angle.

The body inclination angle increased during fatigued jumping in comparison with rested session. The results indicate that as the participant became more fatigued, there was an increasing inclination toward the bar at the start of the take-off. Such a change can undoubtedly have a negative impact on performance, given that the body angle is a crucial component of the take-off in the high jump. If the athlete does not have sufficient clearance from the bar at the beginning of the take-off, it may lead to rushing toward the bar after the take-off, resulting in knocking down the bar and an unsuccessful jump. Additionally, due to fatigue, the athlete may struggle to withstand the forces acting on them during the take-off, causing them to lean more toward the bar. Here, the centrifugal force plays a significant role, as the athlete should aim to utilize it to clear the bar but simultaneously resist it to prevent it from happening too soon.

This study is not without limitations. Firstly, the cameras employed operated at a frame rate of 30 frames per second, which, while functional, may present limitations in achieving optimal precision for video analysis. A higher frame rate would enhance the accuracy of the analysis. Secondly, the study utilized Kinovea for 2D kinematic analysis, which, despite its validity and reliability for angle measurements, may fall short for more intricate high jump analysis that demands 3D analysis software. Thirdly, the results are derived from a single participant, introducing the potential for variations among different high jumpers or specific jumper profiles. As a recommendation for future studies, employing 3D kinematic software with a larger participant pool would provide insights into the impact of fatigue on kinematic parameters in high jump performance. Such insights would enable coaches to strategically target segments of the jump that are predominantly influenced by fatigue.

CONCLUSION

The findings of this study affirm the hypothesis that fatigue exerts an influence on kinematic parameters in high jump. Fatigue specifically impacts body inclination during take-off, directly influencing the success of the performance and potentially resulting in the dislodgment of the bar. Additionally, fatigue affects knee angle and knee amortization, both critical parameters for the success of high jump performance. The insights derived from this research are of considerable importance in the realms of training and competition planning and programming. A key revelation underscores the paramount significance of athletes being well-rested for high jump training or competition; otherwise, alterations in performance may ensue, detrimentally impacting the success of the high jump. The identification of specific segments in the jump where these changes occur proves valuable for coaches, enabling them to focus attentively on these parameters during jump training. It is advisable to ascertain the muscle groups activated during each phase, facilitating targeted efforts to enhance the strength of these muscle groups.

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Contact Information:

Sara Aščić (ascic.sara@gmail.com)