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Lower Extremity Kinetic and Kinematic Responses During Maximal Anaerobic Power Testing in a Cross-Sectional Experimental Study

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ABSTRACT

Aim: The aim of this study was to examine the changes in time-dependent power outputs of the kinetic and kinematic analysis of the lower extremities during the maximal anaerobic power test and to determine possible differences in these changes according to gender.The study population consisted of a total of 34 individuals, including 16 women and 18 men aged 18-25 who lived in Istanbul and had been exercising regularly for the past 3 months. **Material and Method**: In the study, 30s anaerobic power test was applied as anaerobic exercise protocol and angular motion kinematics of lower extremities (hip, knee, ankle) were taken by a 3D motion analyzer (Qualisys Motion Analyzer) at 120 hz. Statistical analysis of the study was conducted using IBM SPSS Version 27. Data were assessed for normality using the Shapiro-Wilk test. The skewness-kurtosis coefficients were assessed using the t-test (independent samples t-test) for two-group comparisons of parametric data; and the Mann-Whitney U test was used for two-group comparisons of non-parametric data. Two-factor analysis of variance (Two-Way ANOVA for Mixed Measures) tests were used for repeated measurements for 5-second assessments within 30 seconds. The Bonferroni test was also used as a post-hoc test for pairwise comparisons to determine which variables accounted for the differences. Friedman analysis was used for repeated measurements of non-parametric data. Statistical analyses used in the study were conducted at 0.05 error levels with a 95% confidence. **Results**: Men participants demonstrated significantly higher average values than women in mean power (W), max power (W), power average (W), speed average (km/h), and distance (m) ($p = 0.012, 0.009, 0.015, 0.022$, and 0.018, respectively; all $p < 0.05$). Specifically, men produced more power during the 5–20 second intervals and achieved greater speed and distance. However, no statistically significant gender differences were observed in kinematic parameters at any time point ($p > 0.05$; e.g., $p = 0.643, 0.521, 0.487$). Significant time-dependent changes occurred within both groups ($p < 0.001$), confirmed by Bonferroni post-hoc tests. While men generated higher anaerobic performance outputs, movement mechanics remained similar across genders. **Conclusion**: Men participants produced significantly higher power output compared to women across all time intervals. In terms of joint angles, the concentric and eccentric angle values of both the right and left lower extremities decreased significantly over time. However, gender differences were not a determining factor for most of the kinematic parameters.

KEYWORDS: Anaerobic Power, Kinetic, Kinematics, Gender.

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INTRODUCTION

Maximal anaerobic exercise involves short-duration, high-intensity physical activity that produces significant physiological and biomechanical effects on the musculoskeletal system. These exercises primarily engage the anaerobic energy system, including alactic and lactic components, and are crucial for generating rapid energy during intense activity (1). During such exercises, the kinematics of movement occurring in the lower extremity joints (hip, knee, and ankle) and the effect of fatigue on the angles of these joints are critical for understanding athletic performance and injury risks. Identifying these effects, particularly in recreationally active individuals, is an important area of research for optimizing training strategies and preventing injury (2).

Fatigue patterns following anaerobic exercise vary depending on the duration and intensity of the exercise. Fatigue can negatively impact range of motion and stability in lower extremity joints by altering movement patterns during maximal anaerobic exercise. This can lead to a decrease in muscle strength and neuromuscular control mechanisms, leading to decreased performance and potential injury. Because the knee, hip, and ankle joints bear a significant load during anaerobic exercise, a detailed examination of the kinematic changes in these joints allows us to better understand an athlete's biomechanical performance (3).

Studies show that fatigue during exercise affects neurophysiological, technical aspects such as lower extremity angles and velocities etc. and especially ankle range of motion and angular changes. Changes in ankle, knee, and hip joint angles were reported during the stance phase (3). A study involving repetitive jumping examined joint kinematics and energy absorption at the hip, knee, and ankle during fatigue. Similarly, significant changes in joint angles and power were reported during the fall phase. Gender differences in performance create some differences in both joint kinematics and energy efficiency (4).

Lower extremity kinetic and kinematic analysis during maximal anaerobic power testing is essential to understand how force, joint motion, and muscular coordination contribute to peak power output. Anaerobic tests, such as sprint or cycling power assessments, rely heavily on rapid and efficient lower-body movement patterns. Identifying biomechanical factors that influence performance can help optimize training strategies, improve athletic efficiency, and reduce the risk of injury. However, limited studies had reported the potential impact of fatigue on lower extremity movement kinematics during anaerobic cycle ergometer exercise in regularly recreationally active men and women athletes. Therefore, this study aimed to investigate the changes in lower extremity velocity, acceleration, and angular velocity parameters, as well as time-dependent power outputs during a 30-second maximal anaerobic power test, and to determine whether these changes differ by gender. This research will allow deeper insight into how athletes generate and transfer power through the hip, knee, and ankle joints. Understanding these mechanics will supports evidence-based interventions for performance enhancement and rehabilitation planning.

MATERIAL AND METHOD

Participants

The study included 34 healthy volunteers aged 18–25 residing in Istanbul, consisting of 16 women and 18 men. All participants had been engaged in regular exercise for at least the previous three months, ensuring a consistent physical activity level prior to testing. Individuals were informed about study procedures and provided consent before participation. The sample was selected to compare gender-related differences in lower extremity angular motion during anaerobic power testing under controlled conditions. No participant reported recent injuries or medical conditions that could affect lower-extremity performance. All participants were in good health and reported no history of upper or lower extremity injuries, nor any current or prior neuromuscular, musculoskeletal, or cardiometabolic disorders that might compromise their ability to participate in the study.

Study Design, Location, Duration, and Ethical Approval

This study followed a cross-sectional experimental design. Data collection was conducted in the Sports Hall of the Department of Exercise and Sports Sciences, University of Health Sciences. Ethical approval was obtained from the The University of Health Sciences Scientific Research Ethics Committee approved the study as compliant with the Helsinki Declaration of Ethical Principles in Medical Research on Human Subjects (2025/13-13/49). Institutional Ethics Committee and written informed consent was collected from all participants prior to participation.

Inclusion Criteria

- Individuals aged 18–25 years
- Physically active and engaged in regular exercise for at least three months
- No history of musculoskeletal injury in the previous six months

Exclusion Criteria

- Presence of cardiovascular, neurological, or orthopedic disorders
- Use of medications affecting balance, coordination, or performance
- Inability to complete anaerobic testing procedures

Sample Size Calculation

The sample size was determined based on mean power output differences between genders using the formula for comparing two independent means:

$$n = \frac{2\sigma^2(Z_{\alpha/2} + Z_\beta)^2}{(\mu_1 - \mu_2)^2}$$

The effect size and standard deviation were taken from previous literature [27], establishing a minimum required sample of 34 participants, comprising 16 women and 18 men.

Procedures / Methodology

All participants completed a standardized warm-up followed by a maximal anaerobic power test on a cycle ergometer. Power output, speed, and distance were recorded at 5-second intervals. Kinematic data, including right and left lower extremity joint angles in concentric and eccentric phases, were obtained using a 3-D motion capture system positioned at 120 fps. Joint angles were analyzed at predefined time intervals throughout the test.

Statistical Analysis

Data analysis was performed using IBM SPSS Version 27. Descriptive statistics (mean ± standard deviation) were calculated. Between-group differences were assessed using an Independent Samples t-test. Repeated measures ANOVA with Bonferroni post-hoc correction was applied to examine time-dependent changes within each group. The level of significance was set at $p < 0.05$.

Data collection tool

Data collection was carried out at the Sports Hall of the Department of Exercise and Sports Sciences, University of Health Sciences (5). The instruments used for data collection included anthropometric measurement devices, a bicycle ergometer, and a three-dimensional kinematic analysis system. All equipment was located in the faculty laboratory and calibrated prior to testing to ensure measurement accuracy.

The heights of the participants were measured using a Holtain stadiometer with a precision of ±1 mm, and their body weights were measured and recorded using with Tanita (BC 418 MA) digital scale with a precision of ±0.1 kg.

The Wattbike cycle ergometer (Wattbike Ltd, Nottingham, UK), which was a valid and reliable and calibrated during manufacture, was used for anaerobic power test (Figure 1). The corresponding data was downloaded using the Wattbike Expert software package, which recorded actual cadence, power, force, and torque output data from the Wattbike for every pedal stroke.

The 3D motion capture system, Qualisys Track Manager (QTM^{TM}) (Qualisys Medical Ltd, Sweden) was used for cycling performance analysis (6). The system was consist of 8 high speed Miqus cameras (500hz; Sizes: 14.0x8.7x8.4cm; weight: 700g); wand calibration kit (T stick size: 60.3cm); reflector markers (sizes, 14mm) and QTM^{TM} software, version 2023.1.

Upon arrival at the sports hall, participants completed a personal information form documenting demographic details prior to the marker setup procedure. Six reflective markers were placed bilaterally on the participants' lower bodies at the following anatomical landmarks: the greater trochanter hip joint, lateral epicondyle knee joint, and lateral malleolus ankle joint. Following this, participants completed a 5-minute warm-up on a cycle ergometer at a self-s elected intensity.

In 3D motion capture system, 8 Miqus cameras (Qualisys Motion Capture Systems, Qualisys Medical Ltd, Sweden) were placed 3-4 meters distance from each other and were captured reflective marker trajectories at 120 Hz (7). The system was calibrated according to the manufacturer's instructions with a time of 45sec. After calibration, reflection artifact from the sports hall were masked using “Auto-Mask” feature to increase quality of marker trajectory recordings. A wand calibration trial was completed. Marker trajectories were recorded, labeled, and digitized via the system’s supplied software (Qualisys Track Manager, Qualisys Medical Ltd, Sweden). Marker trajectories were low pass filtered at cutoff frequency of 9hz using Butterworth filter.

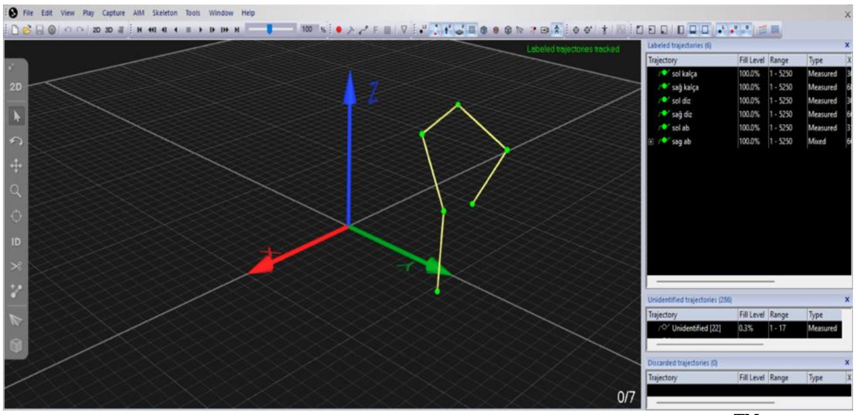

Figure 3. 3d Motion Capture System Screen from the QTM^{TM}.

All participants completed a 30-second maximal sprint cycling test on a Wattbike cycle ergometer following a standardized warm-up session (8) The handlebar and saddle heights were adjusted individually to replicate each participant’s normal racing position. Tests were initiated from a stationary start, and participants were instructed to remain seated throughout the test. Strong verbal encouragement was provided in a standardized manner across all testing occasions to ensure consistency in motivation.

Power output data were recorded using the Wattbike’s onboard performance computer, with pedal revolutions counted at 5-second intervals. The resistance load was automatically calculated based on each participant’s body weight, and the test was conducted using this individualized resistance. This protocol was designed to elicit anaerobic fatigue, as supported by previous literature. Kinematic data were collected using the QTM™ 3D motion capture system during the sprint (9). The 30-second performance was segmented into three phases: beginning (5–10 seconds), middle (15–20 seconds), and end (25–30 seconds). Kinetic variables obtained from the ergometer included maximum power (W), average power (W), and relative power output (W/kg). Maximum power represented the highest watt value recorded during the test, average power reflected the mean watt output over the total test duration, and relative power output was calculated by dividing average power by body mass *(W ÷ kg)*. Additional kinematic data included average speed (km/h), automatically computed by the ergometer based on pedal rotation, and total distance covered (m), calculated from the cumulative wheel revolution count during the test.

Lower extremity kinematic variables were derived from 3-D motion capture by calculating joint angles from marker coordinates, and determining velocity, acceleration, and angular velocity from positional changes over time.

RESULTS

Performance evaluations of all participants were calculated and presented in tables below. The statistical results of all gender-related 30s anaerobic power test data from the cycling performance were given in Table 1.

Tablo 1. The descriptive statistics and the comparison between men and women's 30s anaerobic cycling test results.

Variable	Gender	n	Mean ± SD	t	df	p-value
Avg. Power (5–10s) (W)	Men	18	616.84 ± 131.95	7.523	32	0.001*
	Women	16	350.00 ± 54.78			
Avg. Power (15–20s) (W)	Men	18	474.56 ± 97.61	8.046	32	0.001*
	Women	16	260.63 ± 44.46			
Avg. Power (25–30s) (W)	Men	18	345.39 ± 91.35	6.212	32	0.001*
	Women	16	191.94 ± 39.65			
Max Power (5s) (W)	Men	18	675.50 ± 139.58	6.670	32	0.001*
	Women	16	421.50 ± 64.15			
Max Power / Body Mass (5s) (W/kg)	Men	18	9.20 ± 1.71	4.080	32	0.001

**p<0,05; d= Chen's d*; *Independent sample t-test.*

A comparison of power measurements between genders indicated that men participants consistently demonstrated higher average values than women participants ($p < 0.05$) (Table 1). ($p<0.05$) (Table 1). In particular, in short-term power production, the average power of men was 616.83±131.95W for the 5-10s interval, while the average power of women was 350.00±54.77W. This difference continued over time; in the 15-20s intervals, they produced 474.56±97.61W and 260.63±44.46W, respectively.
In terms of speed and distance, men also had a higher average speed of 51.81±3.96 km/h than women (42.41±2.36 km/h), and their average distance covered was 432.39±33.41m, higher than the women's average of 350.81±21.70m. These findings indicated that men participants generally has higher values than women participants in terms of short-term power production, speed and distance performance as well.

Tablo 2. Descriptive statistics and gender-based comparisons of kinematic variables across the 5–10s, 15–20s, and 25–30s time intervals are presented

	Men (n=18)($\bar{X}$±Ss)	Women (n=16)($\bar{X}$±Ss)	Test value	p (by gender)
5-10s Avg. Power (W) (a)	616.84±131.95	350.00±54.78	7.523	**0.001***
15-20s Avg. Power (W) (b)	474.56±97.61	260.63±44.46	8.046	**0.001***
25-30s Avg. Power (W) (c)	345.39±91.35	191.94±39.65	6.212	**0.001***
	p=0.001* (a>b,c)	***p=0.001* (a>b,c)***		
5-10s RT Velocity (mm/s) (a)	1575104.17±189307.31	1552279.13±219566.1	-0.932	***0.352***
15-20s RT Velocity (mm/s) (b)	1433356.78±370440.21	1489002.07±188137.72	-0.518	***0.605***
25-30s RT Velocity (mm/s) (c)	1298085.06±315924.16	1350361.5±138693.69	-0.242	***0.809***
	p=0.001* (a>b,c; b>c)	***p=0.001* (a>b,c; b>c)***		
5-10s LT Velocity (mm/s) (a)	1557541.73±182426.04	1503058.19±218999.07	-1.587	***0.112***
15-20s LT Velocity (mm/s) (b)	1426775.56±354396.32	1450463.57±167727.46	-1.208	***0.227***
25-30s LT Velocity (mm/s) (c)	128359284±304588.91	1314760.82±123780.08	-0.828	***0.408***
	p=0.001* (a>b,c; b>c)	***p=0.001* (a>b,c; b>c)***		
5-10s RT Acceration (mm/s^2) (a)	4906826.62±7670348.96	7607982.94±10765918.61	-0.85	***0.402***
15-20s RT Acceration (mm/s^2) (b)	4239130.78±6720057.51	7194855.44±9250280.82	-1.074	***0.291***
25-30s RT Acceration (mm/s^2) (c)	3428988.28±5576258.64	5704085.0±7402709.13	-1.019	***0.316***
	p=0.020* (a>c)	***p=0.009* (b>c)***		
5-10s LT Acceration (mm/s^2) (a)	5073567.89±7472648.41	7560528.94±10100258.3	-0.822	***0.417***
15-20s LT Acceration (mm/s^2) (b)	4185246.23±6663658.97	6980306.75±8790695.01	-1.052	***0.301***
25-30s LT Acceration (mm/s^2) (c)	3175709.12±5507744.93	5610654.69±7231231.48	-1.112	***0.274***
	p=0.002* (a>b,c; b>c)	***p=0.020* (a,b>c)***		
5-10s RT Angular Velocity (°/s) (a)	267867.45±47583.27	270926.07±42722.78	-0.196	***0.846***
15-20s RT Angular Velocity (°/s) (b)	260257.06±39462.57	245406.19±26397.44	1.272	***0.212***

25-30s RT Angular Velocity (°/s) [(c)]	213754.06±32823.7	217227.69±35514.36	-0.296	***0.769***
	p=0.001* (a,b>c; b>c)	***p=0.001* (a>b,c; b>c)***		
5-10s LT Angular Velocity (°/s) [(a)]	263480.34±43977.34	267225.57±33613.62	-0.276	***0.784***
15-20s LT Angular Velocity (°/s) [(b)]	260574.95±40199.35	245434.63±27150.02	1.27	***0.213***
25-30s LT Angular Velocity (°/s) [(c)]	214503.28±30150.89	219162.38±28463.56	-0.462	***0.647***
	p=0.001* (a,b>c)	***p=0.001* (a,b>c)***		
5-10s RK CP Angle (°) [(a)]	67.35±3.58	66.76±7.14	0.309	***0.759***
15-20s RK CP Angle (°) [(b)]	66.39±4.07	67.29±10.02	-0.351	***0.728***
25-30s RK CP Angle (°) [(c)]	65.87±5.51	66.82±7.72	-0.419	***0.678***
	p=0.184	***p=0.833***		
5-10s LK CP Angle (°) [(a)]	70.27±3.17	68.39±8.28	0.892	***0.379***
15-20s LK CP Angle (°) [(b)]	69.11±4.13	68.09±7.77	0.489	***0.628***
25-30s LK CP Angle (°) [(c)]	67.97±4.80	66.64±7.76	0.611	***0.546***
	p=0.018* (a>c)	***p=0.113***		
5-10s RK EP Angle (°) [(a)]	129.81±6.93	131.98±12.16	-0.648	***0.521***
15-20s RK EP Angle (°) [(b)]	128.09±7.83	129.76±11.42	-0.503	***0.618***
25-30s RK EP Angle (°) [(c)]	123.9±8.68	127.62±11.86	-1.052	***0.301***
	p=0.001* (a,b>c)	***p=0.009* (a>c)***		
5-10s LK EP Angle (°) [(a)]	133.16±9.81	135.21±8.90	-0.636	***0.529***
15-20s LK EP Angle (°) [(b)]	131.36±9.46	132.4±10.63	-0.301	***0.765***
25-30s LK EP Angle (°) [(c)]	126.41±7.76	129.81±10.60	-1.078	***0.289***
	p=0.001* (a,b>c)	***p=0.001* (a,b>c)***		

***P<0.05;** RT: Right Thigh; LT: Left Thigh; RK: Right Knee; LK: Left Knee; CP: Concentric Phase; EP: Eccentric Phase.*

In Table 2, the descriptive statistics of the kinematic parameters are presented, along with their comparisons across time intervals and between men and women participants. The values for kinematic measurements of men and women participants at the 5-10s, 15-20s, and 25-30s time intervals were compared by gender using an independent samples t-test, and it was determined that there was no statistically significant difference between men and women at all time intervals in all parameters (p>0.05). This result indicates that kinematic data did not vary significantly by gender (Table 2 (p=by gender)).

Additionally, repeated measures analyses were conducted to assess changes in participants' kinematic values over time, revealing significant time-dependent differences in both men and women groups ($p < 0.05$). The results of the Bonferroni multiple comparison test, which was performed to identify the specific time intervals where these differences occurred, are presented in Table 2 (12). The differences are showed by the letters a, b, and c for both genders.

DISCUSSION

The main findings of the study revealed that men participants produced higher power than women participants across all time intervals. One study reported that men athletes were less powerful and strong compared to men trained to the same level, and that women's muscle strength was generally between 40% and 75% of men's (13).

In the literature, it has been reported that men exhibit higher anaerobic performance due to greater muscle mass, higher hemoglobin levels, and hormonal differences, particularly testosterone levels (14). Other studies have also found that men demonstrate higher absolute values in peak power, average power, and anaerobic capacity in tests such as cycling sprints (15). These findings are consistent with the results of the present study.

The higher performance of men, particularly in terms of maximum power achieved in the first 5 seconds of the test (5s Max Power) and power values relative to body weight (W/kg), suggests a more efficient phosphagen system in men (16). The creatine phosphate system-based energy supply in the early stages of anaerobic energy production is directly related to muscle mass (17). The greater muscle volume and higher proportion of fast-twitch (Type II) fibers in men may explain this difference (18).

The study also demonstrates that men participants maintained higher power outputs throughout the test duration, with a smaller performance decline compared to women participants (Table 1). This suggests that men have an advantage in anaerobic capacity not only in terms of peak power but also in sustaining power production. However, some studies have reported that despite producing lower absolute power, women tend to be more resistant to fatigue (19).

A similar gender difference has been observed in performance indicators such as distance covered and average speed. Various studies have demonstrated that men have higher pedaling frequency, force production, and pedal torque in tests conducted with ergometer systems (20). This supports the difference in men's average speed and distance in our study.

During the 30-second anaerobic test, it was found that participants' average power outputs decreased over time intervals (21). For both men and women participants, the power outputs recorded during the first 10 seconds were significantly higher compared to those in the subsequent 20 seconds. This finding indicates the effect of fatigue associated with anaerobic performance. In short-duration, high-intensity tests (such as 30 seconds), energy production primarily relies on the phosphagen system (ATP-PCr), the capacity of which is typically depleted within the first 6–10 seconds (22). According to the results of the Bonferroni multiple comparison test, the 0–10 second interval demonstrated significantly higher power output than all other intervals in both genders. This suggests that the efficiency of anaerobic energy systems declines over time, and that fatigue becomes more pronounced as the glycolytic system takes over. Additionally, the 15–20 second interval also showed significantly higher power output compared to the subsequent time interval, highlighting the impact of the transition between energy systems on performance.

Although there were significant differences in overall strength levels between men and women participants, the fatigue pattern progressed similarly over time in both groups. This suggests that the fatigue trend is independent of gender but influenced by baseline strength levels. Research shows that women produce lower absolute power than men during various forms of exercise, such as cycling, resistance training, and isometric contractions; this is largely due to differences in muscle mass and strength.

However, women generally demonstrate higher fatigue resistance, meaning they fatigue more slowly or less quickly than men during sustained or repeated muscle contractions, especially when the force or workload is matched to their maximum capacity (23).

One study demonstrated that women, even when matched with men for power output, exhibited slower muscle fatigue and faster recovery rates in certain muscle groups, such as the adductor pollicis . Contrary to these findings, our study observed comparable fatigue trends in both men and women participants.

Another main finding of the study was related to ***speed measurements***. When men and women participants were evaluated separately, a significant time-dependent decrease was observed in the ***speed values of the right lower extremity***. The highest average speed values were recorded during the 5–10 second interval, while significantly lower speeds were found during the 15–20 and 25–30 second intervals. This indicates that fatigue during the anaerobic test affects not only power output but also movement speed. This finding aligns with previous literature suggesting that the voluntary contraction speed of lower extremity muscles during dynamic movement decreases over time.

When gender was taken into consideration, no statistically significant difference was found between men and women participants in terms of right lower extremity speed. This finding is consistent with studies reporting that, although women generally demonstrate lower absolute power levels than men, they may perform similarly in certain motor control parameters, such as speed and angular change (24). Furthermore, this result suggests that speed is influenced not only by muscular strength but also by multiple factors such as neuromuscular coordination, nerve conduction velocity, and movement pattern efficience.

When men and women participants were evaluated separately, a significant time-dependent decrease in ***left lower extremity speed*** was observed. The highest average speed values were recorded during the 5–10 second interval, while significantly lower values were found in the 15–20 and 25–30 second intervals.

When gender was considered, no statistically significant differences were found between men and women participants ($p > 0.05$). This finding is consistent with the right leg speed analysis and suggests that gender-related differences in movement speed are not as pronounced as those observed in power output. Previous studies have proposed that women may have a higher tolerance to neuromuscular fatigue compared to men, particularly during repeated lower extremity movements.

The present study explored how fatigue influences lower-extremity kinematics during a maximal anaerobic cycling test. Unlike previous work that focused mainly on power output, this study uniquely examined acceleration, angular velocity, and joint angle changes within the same anaerobic effort, providing a more comprehensive understanding of neuromuscular fatigue.

A clear reduction in movement speed and angular velocity was observed over time. This decline reflects neuromuscular fatigue affecting motor-unit recruitment and movement coordination rather than just power loss (25). These findings highlight that maintaining movement efficiency during high-intensity effort is as crucial as producing power.

A novel finding is that acceleration decreased significantly across intervals in both sexes but showed no gender-based difference, indicating that acceleration capacity is not influenced by anthropometric or strength differences. Instead, fatigue appears to be the primary determinant, supporting the view that acceleration may serve as an early and objective marker of neuromuscular fatigue (26).

Joint angle findings further revealed that both concentric and eccentric angular ranges reduced over time, demonstrating a fatigue-related restriction in dynamic movement control. Although men showed slight side asymmetry in early intervals, women displayed more consistent bilateral symmetry, suggesting a potentially more stable movement pattern under fatigue.

Taken together, the key message is that anaerobic fatigue alters not only power output but also neuromuscular movement quality. Future research should investigate how training interventions may preserve movement efficiency during maximal exertion, especially in sports requiring repeated high-intensity lower-extremity actions.

LIMITATIONS OF THE STUDY

This study has several limitations. The sample size was relatively small and restricted to young adults aged 18–25 who exercised regularly, limiting generalizability to other age groups or sedentary individuals. Only cycling was used for anaerobic testing, so the findings may not fully represent lower extremity kinetics and kinematics during other anaerobic activities such as sprinting or jumping. The study relied on short-term assessment and did not consider long-term training effects or muscle fatigue recovery patterns. Additionally, factors such as menstrual cycle phases in female participants, nutrition, sleep quality, and motivational variations were not controlled, which may have influenced power output.

CONCLUSION

Men participants produced significantly higher power output than women participant across all time intervals, and this superiority was particularly evident in the first 10 seconds of the test. However, both genders experienced significant decreases in power, speed, acceleration, and angular motion over time.

The fatigue curves for male and female participants followed a similar temporal decrease in power output throughout the anaerobic cycling test. Men showed higher absolute power values across all time intervals, whereas the rate of decline in power output appeared comparable between genders.

Regarding joint angles, concentric and eccentric angle values for both the right and left lower extremities decreased significantly over time, but gender differences were generally not significant.

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REFERENCES

1. M. Behrens et al., “Fatigue and Human Performance: An Updated Framework,” Sports Medicine, vol. 53, no. 1, Oct. 2022, doi: https://doi.org/10.1007/s40279-022-01748-2.
2. P. Małkowska and M. Sawczuk, “Cytokines as Biomarkers for Evaluating Physical Exercise in Trained and Non-Trained Individuals: A Narrative Review,” International Journal of Molecular Sciences, vol. 24, no. 13, p. 11156, Jan. 2023, Available at: https://doi.org/10.3390/ijms241311156.
3. Q. Hou, “Biomechanics of the Ankle: Exploring Structure, Function, and Injury Mechanisms,” Studies in Sports Science and Physical Education, vol. 1, no. 2, pp. 1–16, 2023, Available: https://www.pioneerpublisher.com/SSSPE/article/view/404
4. B. Kwon and S. Lee, “Joint Swing Energy for Skeleton-Based Gender Classification,” IEEE Access, vol. 9, pp. 28334–28348, 2021, Available at: https://doi.org/10.1109/access.2021.3058745.
5. F. Campbell et al., “Factors That Influence Mental Health of University and College Students in the UK: A Systematic Review,” BMC Public Health, vol. 22, no. 1, pp. 1–22, Sep. 2022, doi: https://doi.org/10.1186/s12889-022-13943-x.
6. T. H. Moe, P. Wongveerakul, V. Saengsirisuwan, N. Charoenpanich, and I. Papadimitriou, “Investigating the Influence of ACTN3 R577X Polymorphism on Performance and Angular Kinematics Using Motion Capture Technology,” The Open Sports Sciences Journal, vol. 15, no. 1, Mar. 2022, Available at: https://doi.org/10.2174/1875399x-v15-e2201030.
7. M. Skublewska-Paszkowska, M. Milosz, P. Powroznik, and E. Lukasik, “3D technologies for intangible cultural heritage preservation—literature review for selected databases,” Heritage Science, vol. 10, no. 1, Jan. 2022, Available at: https://doi.org/10.1186/s40494-021-00633-x.
8. C. Ross, N. Clarke, S. Oxford, M. G. Morris, and C. D. Thake, “The reliability of an intermittent sprint cycling protocol on a Wattbike Pro in hot conditions,” Journal of Science and Cycling, vol. 12, no. 1, pp. 27–34, 2023, Available at: https://doi.org/10.28985/1223.jsc.04.
9. M. E. G. Macias, C. V. Angulo, E. M. A. Millan, and K. R. K. Gonzalez, “Biomechanics Assessment of Kinematic Parameters of Low-Sprint Start in High-Performance Athletes Using Three Dimensional Motion Capture System,” Revista Mexicana de Ingenieria Biomedica, vol. 43, no. 1, pp. 52–64, Apr. 2022, Available at: https://doi.org/10.17488/RMIB.43.1.5.
10. H. I. Okagbue, P. E. Oguntunde, E. C. M. Obasi, and E. M. Akhmetshin, “Trends and usage pattern of SPSS and Minitab Software in Scientific research,” Journal of Physics: Conference Series, vol. 1734, no. 1, p. 012017, Jan. 2021, Available at: https://doi.org/10.1088/1742-6596/1734/1/012017.
11. R. Wilcox, “One-way and two-way anova: Inferences about a robust, heteroscedastic measure of effect size,” Methodology, vol. 18, no. 1, pp. 58–73, Mar. 2022, Available at: https://doi.org/10.5964/meth.7769.
12. S. Greenland, “Analysis goals, error-cost sensitivity, and analysis hacking: Essential considerations in hypothesis testing and multiple comparisons,” Paediatric and Perinatal Epidemiology, vol. 35, no. 1, pp. 8–23, Dec. 2020, Available at: https://doi.org/10.1111/ppe.12711.
13. J. L. Nuzzo and R. O. Deaner, “Men and women differ in their interest and willingness to participate in exercise and sports science research,” Scandinavian Journal of Medicine & Science in Sports, vol. 33, no. 9, pp. 1850–1865, May 2023, Available at: https://doi.org/10.1111/sms.14404.
14. B. N. Chronister et al., “Testosterone, estradiol, DHEA and cortisol in relation to anxiety and depression scores in adolescents,” Journal of Affective Disorders, vol. 294, pp. 838–846, Nov. 2021, Available at: https://doi.org/10.1016/j.jad.2021.07.026.

15. N. W. Almquist, Ø. Sandbakk, B. R. Rønnestad, and D. Noordhof, "The Aerobic and Anaerobic Contribution During Repeated 30-s Sprints in Elite Cyclists," Frontiers in Physiology, vol. 12, May 2021, Available at: https://doi.org/10.3389/fphys.2021.692622.
16. A. D. Mack, "Maximal power in Olympic weightlifters and powerlifters using the inertial load ergometer," Utexas.edu, May 26, 2022. https://repositories.lib.utexas.edu/items/256806b1-02b6-4091-9dc4-36cfe5476701 (accessed Oct. 30, 2025).
17. K.-L. Lee, T.-W. Oh, Y.-C. Gil, and H.-J. Kim, "Correlation between muscle architecture and anaerobic power in athletes involved in different sports," Scientific Reports, vol. 11, no. 1, p. 13332, Jun. 2021, Available at: https://doi.org/10.1038/s41598-021-92831-7.
18. J. P. L. F. Guilherme et al., "The BDNF-Increasing Allele is Associated With Increased Proportion of Fast-Twitch Muscle Fibers, Handgrip Strength, and Power Athlete Status," Journal of Strength and Conditioning Research, vol. 36, no. 7, pp. 1884–1889, Jul. 2022, Available at: https://doi.org/10.1519/JSC.0000000000003756.
19. D. G. Behm et al., "Non-local Muscle Fatigue Effects on Muscle Strength, Power, and Endurance in Healthy Individuals: A Systematic Review with Meta-analysis," Sports Medicine (Auckland, N.Z.), vol. 51, no. 9, pp. 1893–1907, Sep. 2021, Available at: https://doi.org/10.1007/s40279-021-01456-3.
20. [20] L. Burnie, P. Barratt, K. Davids, P. Worsfold, and J. Wheat, "Biomechanical measures of short-term maximal cycling on an ergometer: a test-retest study," Sports Biomechanics, pp. 1–19, Aug. 2020, Available at: https://doi.org/10.1080/14763141.2020.1773916.
21. A. M. Nowak, B. Molik, A. Kosmol, M. Szczepaniak, and J. Marszałek, "Application of the arm-cranking 30-second Wingate Anaerobic Test (the WAnT) to assess power in amputee football players," Acta of Bioengineering and Biomechanics, vol. 23, no. 3, 2021, Available at: https://doi.org/10.37190/abb-01807-2021-02.
22. W.-H. Yang, S.-Y. Park, T. Kim, H.-J. Jeon, O. Heine, and S. Gehlert, "A modified formula using energy system contributions to calculate pure maximal rate of lactate accumulation during a maximal sprint cycling test," Frontiers in Physiology, vol. 14, Apr. 2023, Available at: https://doi.org/10.3389/fphys.2023.1147321.
23. M. Gomes, P. Santos, P. Correia, P. Pezarat-Correia, and G. V. Mendonca, "Sex differences in muscle fatigue following isokinetic muscle contractions," Scientific Reports, vol. 11, no. 1, Apr. 2021, Available at: https://doi.org/10.1038/s41598-021-87443-0.
24. E. N. Hilton and T. R. Lundberg, "Transgender Women in the Female Category of Sport: Perspectives on Testosterone Suppression and Performance Advantage," Sports Medicine, vol. 51, no. 2, pp. 199–214, Dec. 2020, Available at: https://doi.org/10.1007/s40279-020-01389-3.
25. E. Martinez-Valdes, F. Negro, M. Arvanitidis, D. Farina, and D. Falla, "Pain-induced changes in motor unit discharge depend on recruitment threshold and contraction speed," Journal of Applied Physiology, vol. 131, no. 4, pp. 1260–1271, Oct. 2021, Available at: https://doi.org/10.1152/japplphysiol.01011.2020.
26. S. Vial, J. C. Wilkie, M. Turner, M. Scanlan, and A. J. Blazevich, "Does Fatigue Influence Joint-specific Work and Ground Force Production during the First Steps of Maximal acceleration?," Scandinavian Journal of Medicine & Science in Sports, Jan. 2023, Available at: https://doi.org/10.1111/sms.14318.
27. M. Orendurff, T. Kobayashi, K. Tulchin-Francis, A. Tullock, C. Villarosa, C. Chan, E. Kraus, & S Strike. (2018). A little bit faster: Lower extremity joint kinematics and kinetics as recreational runners achieve faster speeds.. Journal of biomechanics, 71, 167-175. https://doi.org/10.1016/j.jbiomech.2018.02.010.