Original Article

doi: 10.16926/par.2024.12.02

Comparison of energy system contributions in lower body Wingate tests between sexes

Erkan Tortu [1ABCD], **Gökhan Deliceoglu** [2BCD]

[1] Faculty of Sport Sciences, Coaching Training Department, Trabzon University, Trabzon, Turkey
[2] Gazi University, Faculty of Sport Sciences, Ankara, Turkey

Authors' Contribution: A – Study Design, B – Data Collection, C – Statistical Analysis, D – Manuscript Preparation, E – Funds Collection

Abstract: The aim of this study was to compare energy system contributions and examine the relationship between mechanical variables and energy system variables in lower body Wingate tests, with a focus on gender differences. A total of thirty martial artists participated in the study. Participants performed 30-second lower body Wingate tests. Mathematical methods were used to estimate the contributions of the oxidative, glycolytic and ATP-PCr pathways based on lactate levels and oxygen consumption kinetics during rest, exercise and recovery. The main results showed that in men the relative contributions of the oxidative, glycolytic and ATP-PCr pathways were 16%, 37% and 47% respectively. In women the relative contributions for the same pathways were 16%, 38% and 46% respectively. In men the total energy expenditure and the absolute contributions of the oxidative, glycolytic and ATP-PCr pathways were 132 kJ, 22 kJ, 49 kJ and 61 kJ, respectively. In women these values were 106 kJ, 17 kJ, 41 kJ and 49 kJ. Although the relative energy contributions were similar, men had higher total energy expenditure and absolute energy contributions than women. In addition, men had higher absolute and relative power outputs than women, while showing similarities in fatigue index, lactate levels, heart rate and perceived exertion ratings. The ATP-PCr pathway was able to explain the variation in mechanical variables in both male and female participants. The results suggest that the contribution of energy systems, physiological responses and performance variables varies according to gender.

Keywords: anaerobic, aerobic, glycolytic, alactic, combat athletes

Corresponding autor: Erkan Tortu, email: erkantortu@trabzon.edu.tr

Recevied: 27.07.2023; Accepted: 15.08.2023; Published online: 3.01.2024

Citation: Tortu E, Deliceoglu G. Comparison of energy system contributions in lower body Wingate tests between sexes. Phys Act Rev 2024; 12(1): 13-21. doi: 10.16926/par.2024.12.02

INTRODUCTION

Boxing and mixed martial arts are examples of combat sports that require athletes to perform short, high-intensity bursts of activity, making anaerobic power and energy system contribution critical to success. While many factors contribute to an athlete's performance in combat sports, research suggests that sex differences in anaerobic power and energy system contribution may play a role [1,2]. Research has shown that men tend to have higher levels of anaerobic power than women [3,4]. This is likely to be due to a number of factors, including differences in muscle mass, fibre composition and hormonal profiles [5,6]. Men also have higher levels of testosterone, which is associated with increased muscle mass and strength [6].

Combat sports rely heavily on anaerobic energy systems, such as glycolysis, which produce energy rapidly but are limited in their ability to sustain exercise for prolonged periods [2]. However, evidence suggests that there may be sex differences in the relative contribution of different energy systems during martial arts [2,7]. Among martial artists, men relied more on anaerobic metabolism than women during competition, whereas women relied more on aerobic metabolism. The authors of the study suggested that this may be due to differences in muscle mass and aerobic fitness between men and women [8]. The Wingate test (WAnT) is the most commonly used test to assess anaerobic performance on lower body cycle ergometers in athletes. It consists of 30 seconds of full effort against a constant load. Peak power (PP) and mean power (MP) are used in this measurement to determine anaerobic power and capacity. While many studies have looked at the characterisation of energy system contributions using the lower body WAnT [9,10], no data are available on gender comparisons.

Differences in performance and physiological responses may be explained by differences in the number of type II fibres in muscles, muscle size and oxygen extraction capacity between men and women [5,6]. Athletes' results may differ from those of physically active individuals due to the potential influence of their training background. For example, martial artists require a high level of upper body involvement to perform certain athletic tasks, such as grappling [11], and a high level of lower body activation as a result of training exercises [12]. Consequently, these differences may influence the magnitude of the contributions from the energy systems in men and women.

Mechanical variables (PP and MP) may also influence energy system contributions, with athletes outperforming physically active individuals and males outperforming females. The limited research on gender differences in energy system contributions during the WAnT suggests that men and women may differ in their reliance on anaerobic and aerobic energy systems during this type of high-intensity exercise. Previous research has mainly focused on performance factors, fatigue, recovery mechanisms and sex differences during the Wingate test [5,13,14]. However, there is a lack of data on sex differences in the contribution of energy systems to the 30-second WAnT exercise.

The aim of the current study was to investigate whether there are sex differences in energy metabolism after lower body WAnT. The contributions of the energy systems to the 30 s WAnT may be different in male and female martial artists.

MATERIAL AND METHODS

Participants

Thirty (15 female, 15 male) highly trained martial artists voluntarily participated in this study. The sample size was calculated using G*Power. The effect size of the study was determined to be 0.30 (medium), power 0.80 and alpha value 0.05. Accordingly, the study group consisted of 15 male and 15 female athletes. Participants had at least seven years of training, had competed in official national tournaments, and were not undergoing weight loss, supplementation, or medical treatment. The day before the performance tests, the participants were instructed to continue eating as usual and to refrain from strenuous activity. They were given information about the aims, steps, risks and benefits of the study and asked to sign an informed consent form. This study adhered to the tenets of the Declaration of Helsinki and all procedures were approved by the Ethics Committee for Non-Interventional Clinical Research (E-81614018-000-2300011183).

Experimental protocol

The 30-s WAnT test was used to examine energy pathway contributions, performance and physiological responses in the current study, which had a descriptive design. On two occasions, 48-72 hours apart, the participants simultaneously visited the laboratory of the Sports Performance Analysis and Talent Centre of Trabzon University (±1 hour). Prior to the experimental testing session, the participants were trained on the testing instruments and procedures. A graded exercise test to exhaustion was used in the first session to calculate VO_2max. After the exercise session, VO_2 was recorded for 15 minutes and peak lactate was measured 5-7 minutes later. Menstruation was not taken into account for female participants, as repeated sprinting and anaerobic performance are not affected by menstruation [15]. Laboratory conditions of 20-22°C and 38-40% relative humidity were used for testing.

Physical and physiological measurements

Anthropometric measurements were taken while the participants were fasting (12 h). A portable stadiometer was used to measure height to the nearest 0.1 cm, and a multifrequency bioelectrical impedance analyzer (MF-BIA) (TANITA MC-780, Japan; 0.1 kg accuracy) was used to measure body mass, body fat (%), fat mass (FM), and fat-free mass (FFM) (Holtain, London, United Kingdom). VO_2 was measured using a mobile cardiopulmonary exercise testing device (Cosmed K5, Italy) capable of automatic gas analysis from each expiratory breath, with a ramp procedure on a cycle ergometer to determine the athletes' VO_2max, VO_2 and HR (Polar 810i, Polar Electro, Kempele, Finland) were monitored continuously throughout the Wingate tests. In addition, VO_2 was measured for 15 min after the tests to observe the fast and slow phases of post-exercise oxygen uptake, and for 10 min before the tests to determine resting VO_2 (the last 5 min were used for analysis) (EPOC). Lactate was measured using a portable handheld analyser (Lactate Pro, Arkray, Japan) from capillary blood samples taken from a fingertip on the left hand before the tests and in the first, third, fifth and seventh minutes after exercise. Before each measurement, the portable metabolic gas analyser was calibrated according to the manufacturer's recommendations. RPE was graded using Borg's 15-point scale (6-20), and RPE was recorded immediately after each test.

Lower body Wingate tests

Before each test session, each participant warmed up for 3-5 minutes at their own pace, interspersed with short (2-5 s) maximal sprints with an unloaded weight cradle of 50 W. Warm-up and WAnT were performed on a lower body cycle ergometer (894E, Monark Lower Body Ergometer, Vansbro, Sweden) with 0.075 $kg \cdot kg^{-1}$ of the participant's body mass. Each participant was instructed to crank as fast as possible from the command "GO!" and to sprint for the full 30 seconds of each test. The test was started with the dominant leg and the saddle height was adjusted to the height of the participant to produce 5 to 10 degrees of knee flexion with the foot in the low position of the central cavity. As previously reported by La Monica et al, Monark software (Monark ATS, Vansbro, Sweden) was used to record peak power (highest 1 s running average achieved during the 30 s sprint) and mean power (average power achieved over the entire 30 s sprint) and total work done [16].

Determination of energy system contributions

The contributions of the oxidative, glycolytic and ATP-PCr systems were determined by measuring oxygen consumption, blood lactate concentration and the rapid period of excess oxygen consumption after exercise. Breath-by-breath metabolic gas analysis was used to measure oxygen uptake during rest, exercise and the 15-minute recovery period after exercise. Blood samples were taken from the left fingertip before the WAnT and at 1, 3, 5 and 7 minutes after exercise to determine the peak plasma lactate concentration. The fast component of post-exercise excess oxygen consumption (EPOC) kinetics, body mass, VO2, lactate values and oxidative, glycolytic and ATP-PCr pathway components were calculated using OriginPro 8.0 software (OriginLab Corp., Northampton, USA). Test VO_2 was calculated from the area under the curve to measure the contribution of the oxidative pathway (trapezoidal method). Oxidative pathway contribution was calculated as test VO_2 minus resting VO2 [16,17]. The glycolytic contribution was calculated on the basis that 1 mmol·L-1 of BLa accumulation is equivalent to 3 mL of oxygen per kg of body weight. Bi-exponential models provided parameters to estimate the contribution of ATP-PCr [9,18]. A caloric quotient of 20.92 kJ was used for the three different energy systems. Total energy consumption was represented by the sum of the three energy systems. Furthermore, the contribution of each energy system was expressed as a proportion of the total energy expenditure.

Statistical analysis

All values are expressed as mean standard deviation. To determine the normality of the population for each dependent variable, the Shapiro-Wilk test and tests of homogeneity of variance were conducted. The independent samples t-test was used to evaluate the performance, physiological characteristics and energy contribution between men and women, once the assumption of normality had been validated. A two-way analysis of variance with repeated measures was used to examine the variables related to energy system contributions (energy system - 3 levels x sexes), followed by a least significant difference test for multiple comparisons whenever a significant F value was found. The coefficient of determination for the relationship between mechanical factors and energy system contributions was determined using simple linear regression. The alpha level was set at 0.05 for all tests. Effect sizes for the independent samples t-test were calculated using Cohen's d [19] and classified according to Hopkins [20].

RESULTS

Mechanical and physiological variables

The descriptive characteristics of the participants are shown in Table 1. Significant differences in favour of men were observed for all variables except age and experience. Men had a higher absolute VO2 ($L\cdot min^{-1}$), whereas no significant difference was observed for relative VO2 ($ml\cdot kg\cdot min^{-1}$). With regard to mechanical and physiological variables, higher values for absolute PP (W), relative PP ($W\cdot kg^{-1}$), absolute MP (W) and relative MP ($W\cdot kg^{-1}$) were observed in favour of men, except for fatigue index (%), lactate delta ($mmol\cdot L^{-1}$), peak HR (bpm) and RPE (Table 2).

Energy system contributions

Energy expenditure and estimated energy contributions are shown in Table 3. There were significant differences between sexes for absolute ATP-PCr (kJ), glycolytic (kJ) and oxidative (kJ), TEE, PCr-EPOC fast (kJ) and energy demand (L of O2). Males had higher values than females. Table 3 shows the coefficients of determination for the correlations between energy system contributions and mechanical factors for men and women. Figure 1 shows the estimated relative energy contributions for the lower body Wingate test (males and females).

Table 1. Descriptive characteristics of male (n=15) and female (n=15) athletes.

Variable	Male M ± SD	Female M ± SD	p	d
Age (yrs)	19.36 ± 0.80	20.22 ± 2.72	0.75	0.43
Experience (yrs)	5.06 ± 0.51	6.00 ± 1.10	0.61	1.10
Height (cm)	175.6 ± 2.10	167.82 ± 3.30	0.00	2.82
Body weight (kg)	68.98 ± 6.57	63.16 ± 5.50	0.03	0.96
Body fat (%)	11.41 ± 3.02	16.19 ± 2.45	0.02	1.74
Body Mass Index (kg/m^2)	22.54 ± 1.34	22.63 ± 1.96	0.07	0.05
VO2 (ml·min^{-1})	3840 ± 41.00	3530 ± 30	0.00	2.90
VO2(ml·kg·min^{-1})	56.47 ± 4.93	56.03 ± 4.10	0.66	0.09

M±SD = mean ± standard deviation; p = statistical significance; d = standardized effect size

Table 2. Physiological and performance responses to the Wingate tests.

Variable	Male M ± SD	Female M ± SD	t	p	d
Absolute PP (W)	928.55 ± 141.2	599.87± 88.8	5.917	0.000	2.79
Relative PP (W·kg^{-1})	12.77 ± 1.7	10.26± 1.4	3.314	0.005	1.61
Absolute MP (W)	754.68 ± 107.1	506.73± 89.3	5.199	0.000	2.51
Relative MP (W·kg^{-1})	10.37 ± 1.26	8.65± 1.4	2.595	0.020	1.29
Fatigue index (%)	34.43 ± 8.5	34.73± 10.5	0.031	0.975	0.03
Lactate delta (mmol·L^{-1})	11.81 ± 2.2	12.08± 1.7	-0.281	0.782	0.13
HR peak (bpm)	173.86 ± 17.3	176.80± 7.3	-0.484	0.635	0.22
RPE	15.80 ± 1.3	17.21± 0.3	-0.563	0.848	1.49
TEE (kJ)	131.79 ± 12.5	105.98±15.6	3.632	0.002	1.83
$PCr_{EPOCfast}$ (kJ)	61.32 ± 7.1	48.56± 7.7	3.408	0.004	1.72
Energy Demand (L of O_2)	6.30 ± 0.6	5.07±0.7	3.623	0.003	1.89

M±SD = mean ± standard deviation; PP = peak power, MP = mean power; HR = heart rate; RPE = perceived exertion rating; TEE = total energy expenditure; $PCr_{EPOCfast}$ = estimated PCr consumption during the fast phase of EPOC (kJ); t = result of t-test; p = statistical significance; d = standardized effect size

Table 3. Coefficient to determine the relationship between energy system contribution and mechanical variables for the Wingate tests.

Energy system contribution (kJ)	Absolute peak power (W)				Absolute mean power (W)				Fatigue index			
	Male		Female		Male		Female		Male		Female	
	R^2	p	R^2	p	R^2	p	R^2	p	R^2	p	R^2	p
ATP-PCr	0.78	0.001	00.65	0.005	0.45	0.030	00.39	0.037	-0.44	0.029	-0.39	0.038
Glycolytic	0.50	0.019	00.44	0.026	0.65	0.001	00.55	0.005	-0.78	0.000	-0.64	0.005
Oxidative	0.33	0.078	00.35	0.081	0.39	0.051	00.33	0.053	-0.21	0.314	-0.17	0.428

R^2 = Coefficient of determination; p = statistical significance

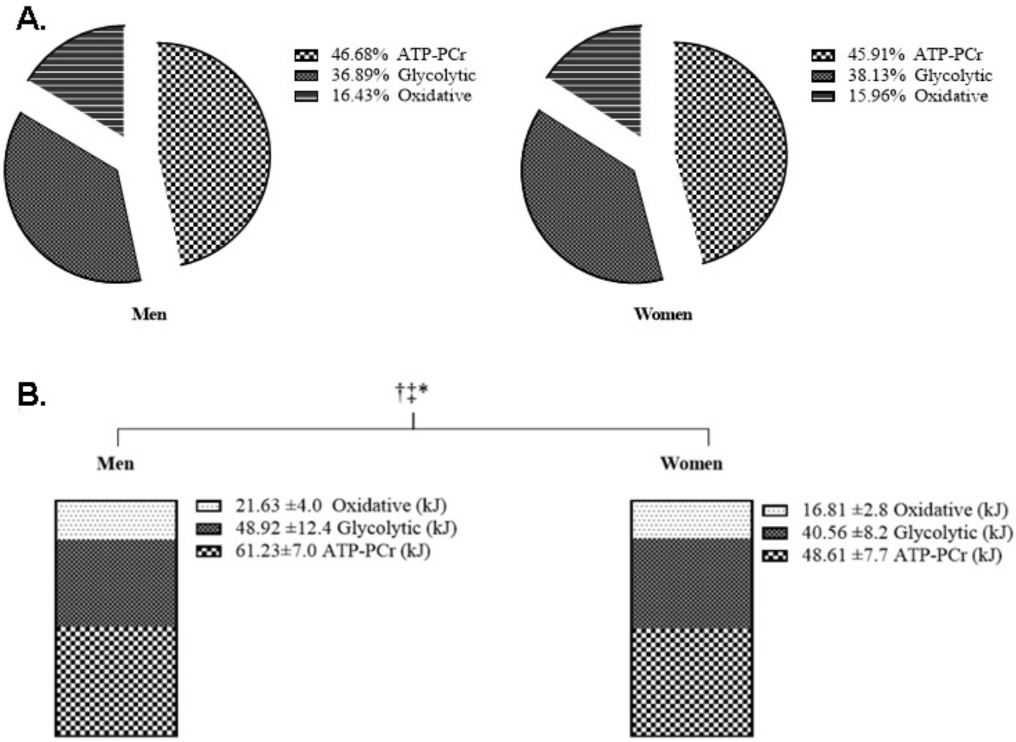

Figure 1. Estimated relative (panel A) and absolute (panel B) energy contribution in the lower body Wingate test (mean ± standard deviation). Note: † = ATP-PCr different from glycolitic and oxidative; ‡ = glycolitic different from oxidative; * = males different from females.

DISCUSSION

This is the first study to assess energy system contributions and physiological and performance responses to the WAnT in martial artists based on gender. Our hypothesis that variations in sex would affect the amount of energy contributed by bioenergetic pathways in the WAnT was supported by the preliminary results. Given the characteristics of the WAnT and evidence that martial artists have well-developed anaerobic fitness in the lower limbs [21], it was determined that the absolute contribution of the three systems to the WAnT would differ in the bodies of men and women. This hypothesis was supported as the results showed that men contributed more absolute ATP-PCr (approximately 61 kJ vs. 48 kJ), glycolytic (approximately 48 kJ vs. 40 kJ) and oxidative (approximately 21 kJ vs. 16 kJ) than women. The contribution of the ATP-PCr system was higher in both sexes.

Men had higher performance and physiological responses than women, with higher relative and absolute power output. There was no difference in fatigue index between the sexes. These results are consistent with previous studies [3,22] suggesting that women may have lower anaerobic thresholds than men during the WAnT. However, there was no significant difference in oxygen uptake between men and women, suggesting that the proportion of aerobic metabolism may have played a similar role in both groups. Previous studies have shown that maximal cycle sprints activate many type II muscle fibres. In both protocols, men tend to have higher power values than women, which may be explained by the fact that women have a smaller cross-sectional area for type II fibres [23]. However, other factors such as muscle size, body composition and hormonal profiles may also contribute to these differences [2,24,25]. Differences in neuromuscular activity between men and women, and the lower mechanical change in women during the WAnT, may contribute to the observed differences in power losses.

During a 30-second cycle sprint, women were more effective than men at removing ammonia from the blood [26]. Furthermore, the small difference in peak power decrement (PD) between men and women in the WAnT is consistent with previous studies [14]. The performance and physiological factors produced results consistent with the literature [27,28]. Due to its practicality, the WAnT, a single maximal cycling exercise of 30 seconds, has become a popular option for assessing energy system contributions [6,16,29-31]. Total energy requirements for men and women were 6.30-5.07 L O2 and there was no gender difference in the percentage of energy system contributions. The results of the mechanical variables supported these findings, with higher absolute and relative MP in men than women, which had a higher contribution from the TEE and ATP-PCr pathways. The glycolytic system is estimated to provide approximately 45-52% of lower body work during WAnT [32,33]. In this study, the glycolytic contribution to WAnT was 36.89% for men and 38.13% for women. Although these percentages appear to be lower than in previous studies, the data suggest that the contribution of the glycolytic pathway decreases as the duration of exercise during maximal activities increases. Similarly, another study showed that the glycolytic contribution during a 10 × 6 second repeated lower body Wingate exercise was 40% in the first sprint and 9% in the tenth sprint [34]. Studies have reported that the aerobic contribution to lower body WAnT ranges from 18-29% [9,33]. In this study, men and women had a 16% contribution from the oxidative system. It has been suggested that increasing sprint duration or distance increases the energy contribution from the aerobic system but decreases power output [13,34].

Studies have shown that martial artists have well-developed anaerobic characteristics [17,31,35,36]. Therefore, the relative contribution of the three energy systems during 30 seconds of exercise is likely to differ between men and women. High intensity exercise, such as sparring or pad work, is mainly determined by the balance between phosphocreatine (PCr) storage and resynthesis [6,13,34]. PCr storage and resynthesis are essential for the success of martial artists at crucial times of the fight, as explosive actions depend on the ATP-PCr energy contribution. PCr concentrations can drop by up to 55% after 10 seconds or 83% after 30 seconds of lower body cycling [34,37], and pH levels can be reduced after additional sprints, which could further inhibit glycolytic enzymes [13,38].

PCr_EPOCfast was higher in men than in women. This may be due to differences in exercise intensity, as exercise intensity and EPOC magnitude and duration are known to be correlated [39,40]. Men showed greater absolute and relative power output than women during each Wingate session, with large effect sizes indicating that exercise intensity was also greater. Although influenced by sex and hormonal variability, no differences were found in peak HR and lactate, which can also be used as indicators of exercise intensity [41]. There was no difference in FI in physically active individuals [10]. The contribution of ATP-PCr was shown to explain the variance in mechanical characteristics in both sexes. However, the glycolytic and oxidative systems showed different coefficients of dependence on WAnT mechanical factors, which could be explained by differences between martial artists.

CONCLUSION

The results of this study may have significant implications for understanding the physiological and metabolic differences between men and women during high-intensity exercise, as well as informing training techniques for both sexes. Performance in martial arts is determined by physiological and technical ability, energy production and efficiency. It is important to note that the study had a limited sample size, which may limit the generalisability of the findings. Furthermore, the study only looked at lower body WAnT and did not examine the contributions of the energy system during other forms of exercise. Future research should replicate these findings in larger and more diverse populations, and examine the effects of different types of exercise on energy system contributions between men and women. Overall, the study provides valuable insights into the differences in energy system contributions between men and women during lower body WAnT and highlights the need for further research in this area to better understand the underlying physiological mechanisms. Understanding the metabolic responses in these circumstances is essential to improve the energy systems targeted in high-intensity exercise training programmes for both sexes. In conclusion, our findings can be used to inform and improve these energy systems to enhance the performance of combat athletes.

Funding: Researcher grant from Physical Activity Review.

Conflict of interest statement: All authors declare that they have no conflicts of interest.

Acknowledgements: The authors would like to thank all the athletes for their participation in the study.

REFERENCES

1. Andreato LV, Lara FJD, Andrade A, Branco BHM. Physical and physiological profiles of Brazilian jiu-jitsu athletes: a systematic review. Sports Med. 2017; 3: 1-17. doi: 10.1186/s40798-016-0069-5
2. Franchini E. Energy System Contributions during Olympic Combat Sports: A Narrative Review. Metabolites. 2023; 13(2): 297. doi: 10.3390/metabo13020297
3. Billaut F, Giacomoni M, Falgairette G. Maximal intermittent cycling exercise: effects of recovery duration and gender. J Appl Physiol. 2003; 95(4): 1632-1637. doi: 10.1152/japplphysiol.00983.2002
4. Julio UF, Panissa VL, Cury RL, Agostinho MF, Esteves JV, Franchini E. Energy system contributions in upper and lower body wingate tests in highly trained athletes Res Q Exerc Sport. 2019; 90(2): 244-250. doi: 10.1080/02701367.2019.1576839
5. Bogdanis G, Nevill M, Lakomy H, Boobis L. Power output and muscle metabolism during and following recovery from 10 and 20 s of maximal sprint exercise in humans. Acta Physiol Scand. 1998; 163(3): 261-272. doi: 10.1046/j.1365-201x.1998.00378.x
6. Gaitanos, Williams C, Boobis LH, Brooks S. Human muscle metabolism during intermittent maximal exercise. J Appl Physiol. 1993; 75(2): 712-719. doi: 10.1152/jappl.1993.75.2.712
7. Franchini E, Herrera-Valenzuela T. Special issue-strength and conditioning for combat sports athletes. Rev Art Marc Asi. 2021; 16: 1-203. doi: 10.18002/rama.v16i1s.7005
8. Bridge CA, Ferreira da Silva Santos J, Chaabene H, Pieter W, Franchini E. Physical and physiological profiles of taekwondo athletes. Sports Med. 2014; 44: 713-733. doi: 10.1007/s40279-014-0159-9
9. Beneke R, Pollmann C, Bleif I, Leithäuser R, Hütler M. How anaerobic is the Wingate Anaerobic Test for humans? Eur. J. Appl. Physiol. 2002; 87: 388-392. doi: 10.1007/s00421-002-0622-4
10. Price M, Beckford C, Dorricott A, Hill C, Kershaw M, Singh M, et al. Oxygen uptake during upper body and lower body Wingate anaerobic tests. Appl. Physiol. Nutr. Metab. 2014; 39(12): 1345-1351. doi: 10.1139/apnm-2013-0405
11. Franchini E, Artioli GG, Brito CJ. Judo combat: time-motion analysis and physiology. J Perform Anal Sport. 2013; 13(3): 624-641. doi: 10.1080/24748668.2013.11868676
12. Franchini E, Brito CJ, Fukuda DH, Artioli GG. The physiology of judo-specific training modalities. J Strength Cond Res. 2014; 28(5): 1474-1481. doi: 10.1519/JSC.0000000000000281
13. Bogdanis GC, Nevill ME, Boobis LH, Lakomy H. Contribution of phosphocreatine and aerobic metabolism to energy supply during repeated sprint exercise. J Appl Physiol. 1996; 80(3): 876-884. doi: 10.1152/jappl.1996.80.3.876
14. Soydan TA, Hazir T, Ozkan A, Kin-Isler A. Gender differences in repeated sprint ability. Isokinet Exerc Sci. 2018; 26(1): 73-80. doi: 10.3233/IES-180171191
15. Wiecek M, Szymura J, Maciejczyk M, Cempla J, Szygula Z. Effect of sex and menstrual cycle in women on starting speed, anaerobic endurance and muscle power. Acta Physiol Hung. 2016; 103(1): 127-132. doi: 10.1556/036.103.2016.1.13
16. La Monica MB, Fukuda DH, Starling-Smith TM, Clark NW, Panissa VL. Alterations in energy system contribution following upper body sprint interval training. Eur. J. Appl. Physiol. 2020; 120: 643-651. doi: 10.1007/s00421-020-04304-w
17. Julio UF, Panissa VL, Esteves JV, Cury RL, Agostinho MF, Franchini E. Energy-system contributions to simulated judo matches. Int J Sports Physiol Perform. 2017; 12(5): 676-683. doi: 10.1123/ijspp.2015-0750

18. Harvey L, Wiegand A, Solomon C, Mclellan C, Lovell D. A comparison of upper and lower body energetics during high-intensity exercise. J Sports Med Phys Fitness. 2015; 55(55): 708-713.
19. Cohen J. Statistical power analysis for the behavioral sciences: Academic press; 2013. doi: 10.4324/9780203771587
20. Hopkins W, Marshall S, Batterham A, Hanin J. Progressive statistics for studies in sports medicine and exercise science. Med Sci Sports Exerc. 2009; 41(1): 3. doi: 10.1249/MSS.0b013e31818cb278
21. Franchini E, Del Vecchio FB, Matsushigue KA, Artioli GG. Physiological profiles of elite judo athletes. Sports Med. 2011; 41: 147-166. doi: 10.2165/11538580-000000000-00000
22. Billaut F, Smith K. Sex alters impact of repeated bouts of sprint exercise on neuromuscular activity in trained athletes. Appl Physiol Nutr Metab. 2009; 34(4): 689-699. doi: 10.1139/H09-058
23. Casey A, Constantin-Teodosiu D, Howell S, Hultman E, Greenhaff P. Metabolic response of type I and II muscle fibers during repeated bouts of maximal exercise in humans. Am J Physiol . 1996; 271(1): E38-E43. doi: 10.1152/ajpendo.1996.271.1.E38
24. Forsyth JJ, Burt D. Sex differences in recovery from sprint interval exercise. J Strength Cond Res. 2022; 36(2): e41-e48. doi: 10.1519/JSC.0000000000003460
25. Lundsgaard A-M, Kiens B. Gender differences in skeletal muscle substrate metabolism-molecular mechanisms and insulin sensitivity. Front Endocrinol. 2014; 5: 195. doi: 10.3389/fendo.2014.00195
26. Esbjornsson M, Bulow J, Norman B, Simonsen L, Nowak J, Rooyackers O, et al. Adipose tissue extracts plasma ammonia after sprint exercise in women and men. J Appl Physiol. 2006; 101(6): 1576-1580. doi: 10.1152/japplphysiol.01119.2004
27. Little T, Williams AG. Effects of sprint duration and exercise: rest ratio on repeated sprint performance and physiological responses in professional soccer players. J Strength Cond Res. 2007; 21(2): 646-648. doi: 10.1519/00124278-200705000-00063
28. Milioni F, Zagatto AM, Barbieri RA, Andrade VL, dos Santos JW, Gobatto CA, et al. Energy systems contribution in the running-based anaerobic sprint test. Int J Sports Med. 2017; 38(03): 226-232. doi: 10.1055/s-0042-117722
29. Bogdanis, Nevill ME, Boobis LH, Lakomy H, Nevill AM. Recovery of power output and muscle metabolites following 30 s of maximal sprint cycling in man. J Physiol. 1995; 482(2): 467-480. doi: 10.1113/jphysiol.1995.sp020533
30. Franchini E, Takito MY, Kiss MAPDM. Performance and energy systems contributions during upper-body sprint interval exercise. J. Exerc. Rehabil. 2016; 12(6): 535. doi: 10.12965/jer.1632786.393
31. Ulupınar S, Özbay S. Energy pathway contributions during 60-second upper-body Wingate test in Greco-Roman wrestlers: intermittent versus single forms. Res. Sports Med. 2022; 30(3): 244-255. doi: 10.1080/15438627.2021.1895784
32. Beneke R, Hütler M, Leithäuser RM. Anaerobic performance and metabolism in boys and male adolescents. Eur. J. Appl. Physiol. 2007; 101: 671-7. doi: 10.1007/s00421-007-0546-0
33. Bogdanis G, Nevill M, Lakomy H. Effects of previous dynamic arm exercise on power output during repeated maximal sprint cycling. J Sports Sci. 1994; 12(4): 363-370. doi: 10.1080/02640419408732182
34. Girard O, Mendez-Villanueva A, Bishop D. Repeated-sprint ability-part I: factors contributing to fatigue. Sports Med.. 2011; 41: 673-694. doi: 10.2165/11590550-000000000-00000
35. Slimani M, Chaabene H, Miarka B, Franchini E, Chamari K, Cheour F. Kickboxing review: anthropometric, psychophysiological and activity profiles and injury epidemiology. Biol. Sport. 2017; 34(2): 185-96. doi: 10.5114/biolsport.2017.65338
36. Apriantono T, Herman I, Winata B, Hasan M, Juniarsyah A, Ihsani S, Hidayat I, Safei I, Hindawan I. Differences of physiological characteristics of taekwondo junior players vs pencak silat junior players. Phys Act Rev 2020; 8(2): 9-15. doi: 10.16926/par.2020.08.16
37. Gastin PB. Energy system interaction and relative contribution during maximal exercise. Sports Med. 2001; 31: 725-741. doi: 10.2165/00007256-200131100-00003
38. Mendez-Villanueva A, Edge J, Suriano R, Hamer P, Bishop D. The recovery of repeated-sprint exercise is associated with PCr resynthesis, while muscle pH and EMG amplitude remain depressed. PloS one. 2012; 7(12): e51977. doi: 10.1371/journal.pone.0051977
39. Laforgia J, Withers RT, Gore CJ. Effects of exercise intensity and duration on the excess post-exercise oxygen consumption. J Sports Sci. 2006; 24(12): 1247-1264. doi: 10.1080/02640410600552064
40. McGarvey W, Jones R, Petersen S. Excess post-exercise oxygen consumption following continuous and interval cycling exercise. Int J Sports Nutr Exerc Metab. 2005; 15(1): 28-37. doi: 10.1123/ijsnem.15.1.28
41. Graja A, Kacem M, Hammouda O, Borji R, Bouzid MA, Souissi N, et al. Physical, biochemical, and neuromuscular responses to repeated sprint exercise in eumenorrheic female handball players: effect of menstrual cycle phases. J Strength Cond. Res. 2022; 36(8): 2268-2276. doi: 10.1519/JSC .0000000000003556