Two sides of the same runner! The association between biomechanical and physiological markers of endurance performance in distance runners

Abstract

Background: The number of people who run to achieve competitive performance has increased, encouraging the scientific community to analyze the association of factors that can affect a runner performance. **Research Question:** Is there association between running spatiotemporal and angular kinematics with the physiological markers of endurance performance during a cardiorespiratory exercise test? **Methods:** This was an observational cross-sectional study with 40 distance runners simultaneously submitted to a running biomechanical analysis and cardiorespiratory exercise test on a treadmill. Mixed models were developed to verify the association between angular kinematic data obtained by the Movement Deviation Profile and the running spatiotemporal data with oxygen consumption and ventilatory thresholds. **Results:** Spatiotemporal variables [.e., step frequency Odds Ratio 0.09 [0.06 to 0.12 95% Confidence Interval], center of mass vertical displacement Odds Ratio 0.10 [0.07 to 0.14 95% Confidence Interval], and step length [Odds Ratio -0.01 [-0.01 to -0.00 95% Confidence Interval]] were associated with VO_2. Also, step frequency Odds Ratio 1.03 [1.01 to 1.05 95% Confidence Interval] was associated with the first ventilatory threshold, and angular running kinematics [Movement Deviation Profile analysis] Odds Ratio 1.47 [1.13 to 1.91 95% Confidence Interval] was associated with peak of exercise during the cardiorespiratory exercise test. **Significance:** Our findings demonstrated that: both higher step frequency and center of mass vertical displacement are associated with the increase of oxygen demand; step frequency is associated with the first ventilatory threshold, due to the entrainment mechanism and angular kinematic parameters are associated with peak aerobic speed. Future studies could also compare the biomechanical and physiological characteristics of different groups of distance runners. This could help identify the factors that contribute to oxygen demands during running and performance across different ages, genders, and levels of competition.

Keywords: Biomechanical Phenomena; Exercise Test; Oxygen Consumption; Running.

INTRODUCTION

Distance running became a social phenomenon in the last decades due to the increasing number of individuals running for conditioning or competitive performance [1]. This phenomenon encouraged the scientific community to analyze variables affecting performance, such as biomechanics, and the so-called physiological markers of endurance (i.e., maximum oxygen consumption (VO_2 max) [2], running economy and ventilatory thresholds (VT_1 and VT_2), which can be identified using laboratory tests (i.e., cardiorespiratory exercise test and running kinematics).

Among the physiological markers of endurance performance, running economy is characterized as the relationship between VO_2 and the applied workload as a marker of mechanical efficiency [3]. In addition, ventilatory thresholds are important parameters of the intensity level applied during running. Where both thresholds are transition points of tolerated exercise intensity [4], where the first ventilatory threshold is the transition point between the light to moderate intensity and the second ventilatory threshold refers the transition from moderate to vigorous intensity.

Recently, previous studies [5-7] demonstrated in distance runners the impact of biomechanics on oxygen cost during exercise (i.e., body center of mass (COM), ground contact time, and step length and frequency). Although biomechanical and physiological markers of endurance performance have a plausible relationship, there is no consensus on it [6-7], and most evidence focus on professional athletes [8]. Furthermore, there is a lacking information about the association between physiological markers of endurance performance and kinematic variables of running.

This study aimed to investigate the association of spatiotemporal and angular running kinematic variables with the physiological markers of endurance performance in distance runners during a cardiorespiratory exercise test. We hypothesized that biomechanical variables can influence physiological markers of endurance performance in distance runners during the cardiorespiratory exercise test with three-dimensional biomechanical assessment.

METHODS

This was a cross-sectional study conducted at Human Movement Laboratory between April and July 2022. The study was approved by the local research ethics committee and followed the Declaration of Helsinki. All participants read and signed the informed consent form.

The study included 40 distance runners (20 males and 20 females) aged from 18 to 45 years, with at least 1 year of running experience, and running between 40 and 60 km/week 3 months before data collection. Pregnant women, triathletes, individuals with a history of disabling musculoskeletal injury or infected with COVID-19 in the previous 6 months, with current cardiorespiratory or musculoskeletal complaints, or in continuous use of antiarrhythmic drugs were not included in the study.

Participants answered a sociodemographic questionnaire regarding personal and running practice characteristics. Next, they were simultaneously invited to running kinematic and cardiorespiratory exercise assessments.

Procedures

Cardiorespiratory Exercise Test: The cardiorespiratory exercise test was performed on a motorized treadmill using a stepwise workload each minute. Test started at 6 $km.h^{-1}$ for women and 7 $km.h^{-1}$ for men, increasing 1 kilometer per minute until the participant reached voluntary exhaustion[9]. Ventilatory data and gas exchange measurements were recorded during the test using a breath-by-breath system (MetaLyzer 3B, Cortex). The following criteria were used to define maximal effort: 1) participant demonstrated subjective evidence of exhaustion (perceived exertion, i.e., Borg scale above 17); and either 2) peak heart rate (HR) ≥ 90% age-predicted maximum or 3) maximal respiratory exchange ratio (RER) ≥ 1.10 [9].

The first ventilatory anaerobic threshold (VT_1) was determined at the point at which the VE/VO_2 reached a minimum value and began to rise without a concomitant rise in the VE/VCO_2 [10]. The second ventilatory threshold (VT_2) respiratory compensation point was determined to be the point at which the VE/VCO_2 reached a minimum value and began to rise and the $PeTCO_2$ reached its highest value before its progressive fall [10]. The peak oxygen consumption (peak VO_2) was defined as the maximum VO_2 attained at the end of the exercise period when the subject became exhausted.

Oxygen cost of exercise analysis: was evaluated during cardiorespiratory exercise test by VO_2 as a function of running speed [11].

Running kinematic assessment: Data were collected and processed using the Vicon Nexus® (version 2.12) software. This system is composed of eight infrared cameras in sampling at 240 frames per second. Forty retro-reflective spherical markers were fixed at specific anatomical points as reference for the motion system based on the Vicon Plug-in-Gait® biomechanical model [12]. Biomechanical data were analyzed in synchrony with the recording of the cardiorespiratory exercise test.

The three-dimensional biomechanical model was reconstructed and named using the coordinates captured from the markers. Data processing started by marking the running cycle at each cardiorespiratory test speed [13], resulting in six cycles for lower limbs for each speed of the cardiorespiratory exercise test. An 8 Hz Butterworth filter was used to reduce noise caused by tissue movement. Coordinates data were applied to the Vicon Plug-in-Gait® biomechanical model to estimate the joint centers and reconstruct the body segments [12]. Six cycles of movements were identified from coordinates data in 30 to 45 final seconds of each speed for the following parameters: step frequency; step length; and COM. Mean values of spatiotemporal biomechanical variables were recorded for statistical analysis. Data from 51 angular points of 10 kinematic curves (trunk and pelvis in relation to the laboratory origin in the three planes of motion; hip in relation to the pelvis in the sagittal and frontal planes; leg in relation to the thigh; and foot in relation to the leg in the sagittal plane) for each speed of the cardiorespiratory test were recorded separately and used in the unsupervised neural network Movement Deviation Profile (MDP). MDP is a method based on machine learning to calculate the movement deviation of an individual from a group of similar characteristics, synthesizing and simplifying kinematic data to facilitate interpretation and comparisons [14].

Cardiorespiratory exercise test parameters: heart rate (beats per minute), VO2 (mL/kg/min), and speed at VT were recorded in the same database for statistical analysis. The authors developed an evidence-based theoretical path diagram before the data analysis to represent the hypothetical associations between physiological and biomechanical variables and their confounders to guide the association model building (Fig. 1).

2.3 Statistical Analysis

Mixed models were developed to analyze the associations of physiological variables with independent biomechanical (i.e., spatiotemporal and angular running kinematics) and other (i.e., confounders) variables. These models were applied due to the repeated measurement design. Thus, an indicator variable of the repeated measurements was included for random effects to generate models with random intercepts for each participant. R (version 4.1.2) [15] was used to fitted the models using the lme4 [16] and lmerTest [17] packages.

A linear mixed model was considered for the dependent variable VO_2. The fixed effects term was composed of biomechanical variables, an ordinal variable representing the VTs, and confounding variables. The distribution was defined as Gaussian with the function link set as identity. The results of the linear mixed model were described using linear regression coefficients (β) and 95% confidence intervals (CI).

Binomial logistic mixed models were considered for the dependent variable VT. A single ordinal or multinomial model could not be fitted because the estimates were implausible, probably due to insufficient data to generate the conditional probabilities of complex models, resulting in matrices of variance and covariance with exorbitant values. Therefore, four dummy variables were defined based on the categories of the VT variable, resulting in four binomial models (i.e., 0: pre-ventilatory threshold; 1: first ventilatory threshold; 2: second ventilatory threshold; e 3: voluntary maximum exhaustion). The fixed effects term of the four binomial models was composed of biomechanical variables, a continuous VO_2 variable, and confounding variables. The distribution was defined as Binomial with the function link set as logit. The results of the binomial logistic mixed models were described using exponentiation of the regression coefficients (exp[β]) representing odds ratios (OR) and their 95% CI.

RESULTS

Forty distance runners, 50% (n=20) man and 50% (n=20) woman, participated in this study. Personal, biomechanical, and physiological data obtained during the cardiorespiratory exercise test were summarized in Table 1.

Table 2 presents the results from the linear mixed models having VO_2 as the dependent variable. Statistically significant associations were found for the following variables: sex, body mass, running speed, ventilatory thresholds [i.e., second ventilatory threshold and maximum voluntary exhaustion], center of mass vertical displacement, step frequency and length. VO_2 increased about 3.65 mL/kg/min [95% CI 3.29 to 4.00] for each additional 1 km/h in speed during the cardiorespiratory exercise test, 0.10 mL/kg/min [95% CI 0.07 to 0.14] for each additional 1 mm vertical displacement in COM, 0.09 mL/kg/min [95% CI 90.06 to 0.12] for each additional 1 step/min in step frequency during running; and decreased about 0.32 mL/kg/min [95% CI -0.57 to -0.08] for each additional 1 kg in body mass, and 0.01 mL/kg/min [95% CI -0.01 to -0.00] for each additional 1 mm in step length during running. Although step length was statistically associated with VO_2, the effect size was small, indicating an irrelevant effect.

Table 3 presents the results from the four binary logistic mixed models having the dummy variables for VT. Two biomechanical variables showed statistically significant associations in at least two of the four models: step frequency [each additional 1 step/min increased the odds of being at the first VT by 1.03-fold [95% CI 1.01 to 1.05] or 3% [95% CI 1% to 5%]] and MDP [each additional 1 angular degree increased the odds of exhaustion by 1.47-fold [95% CI 1.13 to 1.91] or 47% [95% CI 13% to 91%]].

DISCUSSION

This study was aimed to investigating the association between spatiotemporal and angular running kinematic variables with physiological markers of endurance performance in distance runners during the cardiorespiratory exercise test. The main findings of the present study were: 1) the strong association between spatiotemporal variables (i.e., step frequency, COM, and step length) with oxygen cost during running; 2) the strong association between step frequency with VT_1; and 3) angular running kinematics (MDP analysis) was associated with peak aerobic speed during the cardiorespiratory exercise test.

The analysis of OR values at the pre-ventilatory threshold shows an adjustment in the biomechanical and respiratory behavior of the runners when starting the cardiorespiratory exercise test, with an association between all variables, but with a small effect size. However, with the increase in running speed, which implies greater energy demand, there is a reduction in VO_2 uptake values related mostly to the angular kinematic change of running that occurs at the peak of the exercise. It is noteworthy that the effect size observed in the associations found during peak exercise makes it possible to evaluate that the biomechanical changes observed during exhaustion occurred due to higher intensity effort applied to distance runners, resulting in increased cardiorespiratory and metabolic stress.

Although spatiotemporal kinematics and oxygen cost of locomotion were associated, the direct interference of one variable with the other still needs to be elucidated [18]. It is estimated that changing the frequency or length of the stride can lead to changes in oxygen consumption at different speeds [19]. However, although there is a plausible relationship between running biomechanics, performance and physiological variables, the literature does not present a consensus regarding a possible association [6,7]. In this sense, our findings suggest that both an increase in step frequency and COM vertical displacement are associated with increase oxygen cost during running. Specifically, our data show to both step frequency and COM an increase in VO2 of 0.09 mL/kg/min and 0.10 mL/kg/min for each additional 1 step/min and 1 mm vertical displacement, respectively. The present results corroborated with studies by observing that increased speed and step frequency increase oxygen demands in distance runners [20]. In contrast, trained runners can self-select the step frequency or step length and reduce oxygen cost of running [20]. Interestingly, the COM directly correlates with VO2 [5] (i.e., an increase in COM vertical displacement increases VO2) where an increase in this vertical displacement indicates decreased energy efficiency, due to an increase in the transfer of impact energy to the body and a reduction in the elastic potential energy absorbed and dissipate during running [21].

Another point observed in the present study was a close relationship between step frequency and ventilatory threshold. In this context, our results suggest that a higher step frequency is associated to lower VT1. The question that arises is what physiological mechanisms are associated with this finding? Noteworthy, there is solid evidence [22] that an increase in cadence during physical exercise promotes an excitatory response from respiratory center to increase pulmonary ventilation. This locomotor-respiratory coupling, also termed entrainment, refers to the phase – locking of locomotor and respiratory frequencies during exercise [23]. Within this context, Takano et al. [24] demonstrated that entrainment can affect the ventilatory threshold during cycle exercise in healthy subjects.

Lastly, regarding angular kinematics to our knowledge this is the first study that evaluated the movement deviation profile method in distance runners. Briefly, MDP is based on an artificial neural network and uses a self-organizing map (SOM) [25]. The SOM employs an unsupervised learning paradigm that calculates the multi-dimensional deviation of movement from a reference distribution. In this context, our results showed an association between the angles formed by the body's joints during the running phases and peak aerobic speed. However, the magnitude of change between these parameters [25] is unclear. Noteworthy, angular running kinematics was not associated with aerobic fitness but only with peak aerobic speed during the cardiorespiratory exercise test.

This study's innovation also lies in using the MDP method, which stands out for its ability to condense the complexity of the kinematic data of the lower limbs into a single representative variable. Although less specific, this approach provides a global view of kinematics, which is more relevant to our aim and analysis. We did not seek to associate isolated variables, such as the maximum hip flexion angle or the minimum knee extension during the flight phase, with the physiological responses of running. Instead, a global metric, derived from a robust tool and considered one of the most advanced for gait analysis [26], may be more appropriate to correlate with variables that represent the behaviour of the cardiovascular system as a whole. However, we recognise that analysing a joint at a specific moment in the running cycle may help understand particular injuries.

Furthermore, our results indicate that the MDP did not show a significant statistical association with VO2. On the other hand, when we analysed the ventilatory thresholds as the outcome variable, we observed that an increase of 1 degree in the MDP, indicative of a kinematic change relative to the expected standard, increases the probability of maintaining exhaustion by 47%. This finding does not allow us to definitively conclude whether kinematic variables influence cardiopulmonary variables or vice versa. However, it creates the opportunity for future research to investigate this relationship more deeply, determining whether specific variables or their combination, as in the MDP, are responsible for the observed results. In addition, it raises the hypothesis that it is possible to manipulate kinematic variables to control performance during exhaustion or even to alter kinematics to delay the onset of exhaustion.

Demographic variables may also influence running performance and timing for reaching VT [27]. For example, older athletes more experienced with running reached the second VT later than younger runners with less running experience [28]. Also, increased step frequency in women [7] may increase energy expenditure and lead to exhaustion faster than in men. Increased energy expenditure was also associated with increased body mass [29].

The association between physiological markers of endurance performance and biomechanical variables may be explained by the sum of several factors. The study design did not allow causality inference; however, the associations may guide future interventions involving distance runners for improved performance. This cross-sectional study had limitations since it was conducted in a controlled environment (laboratory) with a homogeneous sample, not allowing generalizations to runners with different characteristics and environments. Thus, future studies should be conducted to reiterate or refute the present findings and enhance clinical and practical relevance. The present study demonstrated in distance runners that: 1) both higher step frequency and center of mass vertical displacement are associated with the increase of oxygen demands during running; 2) step frequency is associated with the VT_1, due to the entrainment mechanism and 3) angular kinematics (MDP analysis) increases the probability of maintaining exhaustion by 47%. Future studies could compare the biomechanical and physiological characteristics of different groups of distance runners, such as young vs. master runners, elite vs. recreational runners [26,28]. This could help identify the factors that contribute to improve performance across different ages, genders, and levels of competition.

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Figure 1

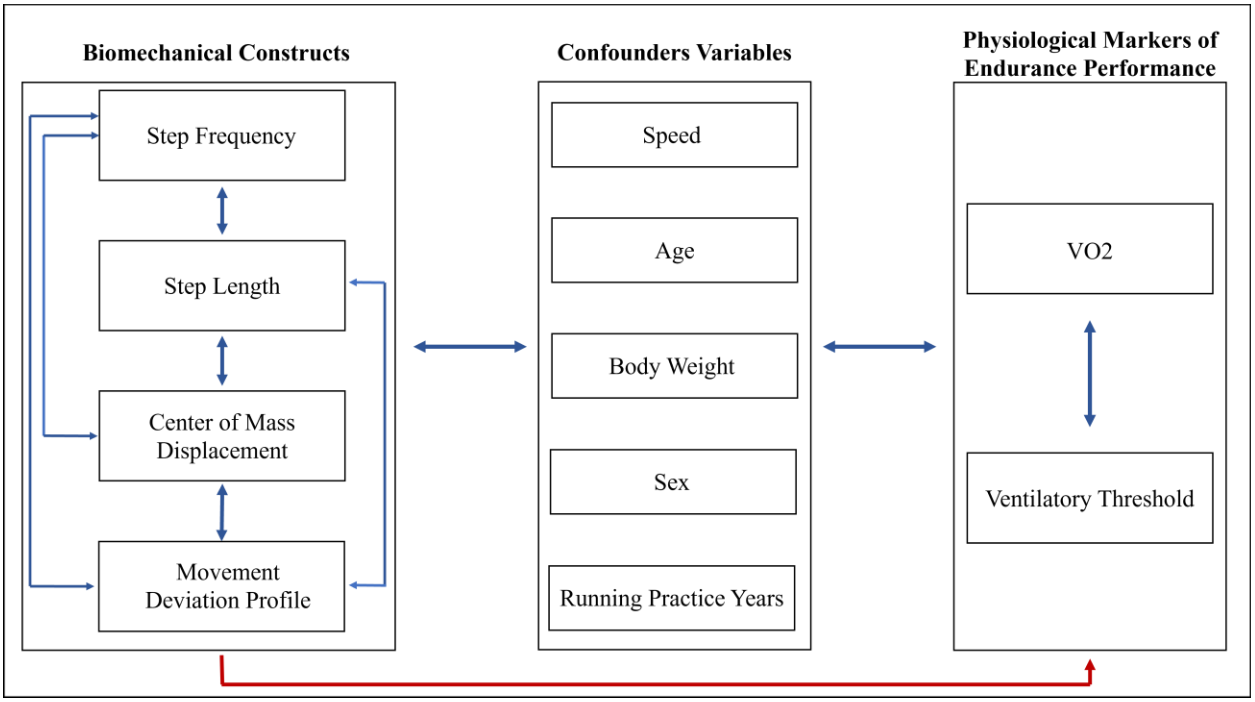

Figure 1: Theoretical path diagram representing the hypothetical associations of interest between the physiological markers of endurance performance, biomechanical constructs and possible confounders. Where the red arrow shows the influence between the biomechanical constructs on the physiological markers of endurance performance, and the blue arrow show the bidirectional influence among the variables.

Table 2

Table 2. Results from the linear mixed models having VO_2 as the dependent variable

Dependent Variable: VO_2 (ml/kg/min)		
Parameter	**β**	**95% CI**
Intercept	34.95	31.57 to 38.33
Personal		
Sex		
Male	Reference	–
Female*	4.73	0.12 to 9.34
Age (years)	0.08	-0.22 to 0.38
Body mass (kg)*	-0.32	-0.57 to -0.08
Running practice (years)	-0.09	-0.41 to 0.22
Running speed (km/h)*	3.65	3.29 to 4.00
Biomechanics		
Step frequency (steps/minute)*	0.09	0.06 to 0.12
Step length (mm)*	-0.01	-0.01 to -0.00
Center of mass vertical displacement (mm)*	0.10	0.07 to 0.14
Movement deviation profile (MDP) (º)	0.16	-0.03 to 0.34
Ventilatory thresholds		
Pre-ventilatory threshold (km/h)	Reference	–
VT_1 (km/h)	-0.60	-1.50 to 0.29
VT_2 (km/h)*	-2.41	-3.83 to -0.99
Peak of Exercise (km/h)*	-4.87	-6.73 to -3.01

Estimated R^2 of the model: 0.947 (IC 95% 0.955 to 0.940).

Legend: "β": regression coefficient; "CI": confidence interval; "OR": odds ratio; VO_2: oxygen consumption; "*": statistically significant.

Table 3

Table 3. Results from the binary logistic mixed models having the "dummy" variables corresponding to the ventilatory thresholds as dependent variables

Dependent Variable	**Pre-ventilatory Threshold**		**First Ventilatory Threshold**		**Second Ventilatory Threshold**		**Peak of Exercise**	
Parameter	**OR**	**95% CI**	**OR**	**95% CI**	**OR**	**95% CI**	**OR**	**95% CI**
Intercept	0.13	0.13 to 0.13	0.40	0.24 to 0.67	0.17	0.08 to 0.34	0.00	0.00 to 0.00
Sex								
Male	*Reference*	–	*Reference*	–	*Reference*	–	*Reference*	–
Female	0.00	0.00 to 0.00*	1.17	0.55 to 2.49	1.22	0.46 to 3.24	9.87	1.30 to 74.80*
Age (years)	0.55	0.54 to 0.55*	0.98	0.93 to 1.03	1.06	1.00 to 1.12*	1.04	0.93 to 1.17
Body mass (kg)	0.87	0.87 to 0.88*	1.03	0.99 to 1.07	0.97	0.92 to 1.03	1.16	1.05 to 1.29*
Running practice (years)	1.25	1.25 to 1.26*	1.03	0.99 to 1.08	0.97	0.92 to 1.03	0.90	0.80 to 1.01
Running speed (km/h)	0.00	0.00 to 0.00*	0.61	0.45 to 0.81*	1.46	1.06 to 2.01*	8.00	3.62 to 17.67*
Step frequency (steps/minute)	0.95	0.95 to 0.96*	1.03	1.01 to 1.05*	1.02	0.99 to 1.05	1.00	0.95 to 1.05
Step length (mm)	0.99	0.99 to 1.00*	1.00	1.00 to 1.01	1.00	1.00 to 1.00	1.00	0.99 to 1.00

Center of mass vertical displacement (mm)	0.95	0.94 to 0.95*	1.00	0.99 to 1.01	1.01	1.00 to 1.02	0.99	0.97 to 1.00
Movement deviation profile MDP (º)	1.01	1.01 to 1.02*	0.98	0.87 to 1.09	0.99	0.85 to 1.14	1.47	1.13 to 1.91*
VO_2 (ml/kg/min)	1.56	1.55 to 1.56*	1.10	1.04 to 1.16*	1.02	0.96 to 1.09	0.91	0.81 to 1.03

Estimated R^2 of the “pre-ventilatory threshold” model: 0.895.

Estimated R^2 of the “first ventilatory threshold” model: 0.220.

Estimated R^2 of the “second ventilatory threshold” model: 0.776.

Estimated R^2 of the “voluntary maximum exhaustion” model: 0.966.

Legend: “β”: regression coefficient; “CI”: confidence interval; “OR”: odds ratio; VO_2: oxygen consumption; “*”: statistically significant.

Table 1(Editable version)

Table 1. Personal, biomechanical, and physiological variables of distance runners obtained during the cardiorespiratory exercise test (all speeds)

Variables	Overall mean (95% CI) n=40	Man mean (95% CI) n=20	Woman mean (95% CI) n=20
Personal			
Age (years)	34.72 (32.81 to 36.64)	36.00 (33.42 to 38.58)	34.05 (30.86 to 37.24)
Body mass (kg)	65.80 (62.66 to 68.94)	73.11 (69.53 to 76.49)	58.50 (55.78 to 61.21)
Height (m)	1.70 (1.68 to 1.73)	1.76 (1.73 to 1.78)	1.65 (1.62 to 1.68)
Running practice (years)	8.43 (7.91 to 14.59)	9.17 (6.05 to 12.29)	11.75 (6.05 to 17.44)
Biomechanics			
Step frequency (steps/min.)	170.35 (168.77 to 171.06)	170.95 (170.87 to 171.02)	169.75 (169.67 to 169.82)
Step length (mm)	96.47 (94.35 to 98.60)	101.82 (101.826 to 101.83)	91.05 (91.04 to 91.06)
Center of mass vertical displacement (mm)	96.49 (96.04 to 96.95)	99.56 (99.56 to 99.57)	93.38 (93.37 to 93.38)
Movement deviation profile (MDP) (º)	8.97 (8.75 to 9.18)	8.11 (8.03 to 8.18)	9.84 (9.76 to 9.91)
CPET			
Maximum heart rate (%)	98.94 (98.23 to 99.55)	98.65 (96.93 to 100.33)	98.86 (97.45 to 100.27)
VO_2 second threshold relative maximum (%)	88.15 (87.68 to 87.83)	86.19 (82.75 to 89.63)	89.70 (86.34 to 93.06)
VT_1			
Speed (km/h)	10.45 (10.08 to 10.81)	10.65 (10.12 to 11.18)	10.25 (9.73 to 10.77)

VO_2 (ml/kg/min)	34.63 (32.90 to 36.36)	33.63 (31.26 to 35.99)	35.64 (32.97 to 38.30)
VT_2			
Speed (km/h)	13.47 (13.07 to 13.87)	13.70 (13.17 to 14.23)	13.25 (12.61 to 13.89)
VO_2 (ml/kg/min)	43.08 (41.19 to 44.96)	41.88 (39.55 to 44.20)	44.28 (41.18 to 47.37)
Peak of Exercise			
Speed (km/h)	16.27 (15.82 to 16.72)	16.85 (16.30 to 17.40)	15.70 (15.05 to 16.35)
VO_2 (ml/kg/min)	48.87 (46.82 to 50.92)	48.56 (45.57 to 51.55)	49.18 (46.10 to 52.25)