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Post-Exercise Balance Vulnerability in Adults with Sedentary Behavior: Sex Differences in Postural and Metabolic Recovery

Emine Karakaya, Serkan Özgür * and Tuncay Varol

Department of Anatomy, Faculty of Medicine, Manisa Celal Bayar University, Manisa 45030, Turkey; he_mi_ra@hotmail.com (E.K.); tuncay.varol@cbu.edu.tr (T.V.)
* Correspondence: serkan.ozgur@cbu.edu.tr

Abstract

This study examined the post-exercise window of vulnerability in static postural control after submaximal treadmill exercise in adults with sedentary behavior and evaluated sex differences in balance impairment and recovery. Thirty-four adults with sedentary behavior (17 women, 17 men) performed the Modified Bruce Protocol. Postural sway was assessed at baseline (Pre), immediately post-exercise (Post0), and at 5 (Post5) and 10 (Post10) minutes of recovery using center-of-pressure metrics (sway area, total sway distance, anterior–posterior excursion, medial–lateral excursion). Blood lactate and heart rate were recorded concurrently. Postural sway and blood lactate were analyzed with a two-way mixed ANOVA (time × sex): heart rate and RPE, with stage-wise independent-sample *t*-tests. Blood lactate increased markedly post-exercise and remained elevated throughout the 10 min recovery window ($p < 0.001$, $\eta^2_p = 0.797$), with higher levels in men across all time points (main effect of sex, $p = 0.006$, $\eta^2_p = 0.215$). Heart rate was higher in men at rest and throughout recovery (all $p < 0.001$; women higher only at Stage 4), returning near resting level in both sexes by Post10. All four postural sway parameters showed significant main effects of time (all $p < 0.001$, except total sway distance, $p = 0.001$) without statistically significant sex × time interactions, and all remained significantly elevated above baseline at Post10, indicating that postural recovery was incomplete within the 10 min observation window. Submaximal treadmill exercise induces acute postural control impairment in sedentary adults that persists into early recovery along specific CoP axes. Despite higher lactate in men, postural and metabolic recovery did not dissociate within the 10 min observation window, defining a post-exercise vulnerability window of at least 10 min that may warrant heightened attention to postural stability in this population.

Keywords: postural balance; exercise test; lactic acid; sedentary behavior; recovery of function

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1. Introduction

Sedentary behavior is defined as any waking behavior that expends ≤1.5 METs of energy while sitting, reclining, or lying down [1]. Sedentary behavior is not the same concept as "physical inactivity," which refers to the inability to meet recommended physical activity levels; an example of this is adults engaging in less than 150 min of moderate-intensity (or 75 min of vigorous intensity) activity per week [1]. The prevalence of a sedentary lifestyle in modern society may contribute to adverse effects on critical physiological components for postural control, such as decreased muscle strength and changes in motor control of deep trunk muscles [2,3]. Postural control is considered the ability to maintain the body's center of mass within the base of support and to sustain stability by integrating visual, vestibular,

and proprioceptive inputs; its impairment is seen as a significant risk factor for falls and related injuries [4]. Regular physical activity and structured exercise have been reported to support postural stability, muscle strength, and functional ability [2]. However, the effects of acute exercise on balance, especially in sedentary individuals, are a complex process that can vary depending on the type and intensity of the exercise and the individual's fitness level [5].

While long-term exercise training can improve postural stability, acute exercise, particularly after lower-extremity-focused protocols, can lead to temporary postural disturbances due to neuromuscular fatigue [2,6–8]. Fatigue may arise from the combined effects of metabolic stress (such as lactate accumulation), peripheral and central mechanisms, and decreased proprioceptive sensitivity [9]. The duration and intensity of exercise can shape the dominant mechanisms of post-exercise balance impairment; increased ventilation/hyperventilation, muscle fatigue, and temporary impairments in the processing of sensory inputs (visual, vestibular, proprioceptive) are key components involved in this process [5]. Even submaximal efforts can create a temporary period of instability and potential vulnerability following exercise in sedentary individuals lacking training adaptations [2,10]. Although the recovery time of balance parameters after fatigue varies depending on the protocol, it has been reported that in some localized muscle fatigue models, values can return to baseline within 5 min, while in more general aerobic/anaerobic loads, it can extend to 10–15 min [10–12].

It is considered that biological sex may also influence these fatigue and recovery patterns. Anatomical and physiological differences between men and women, such as muscle mass distribution and substrate utilization during exercise, may affect balance control strategies and fatigue resistance [13–15]. However, opinions on the role of sex hormones in balance are controversial. Paillard [9] showed that men may be more sensitive than women to the effects of exercise-induced fatigue on postural control and that estrogen fluctuations throughout the menstrual cycle did not significantly affect postural sway [16]. When these findings are considered together, it is thought that possible sex differences in post-exercise balance recovery may be related to neuromuscular fatigue resistance and muscle-metabolism characteristics rather than hormonal fluctuations.

Although exercise-induced postural perturbations have been documented in athletes, with non-athletes showing greater fatigue-related deterioration than trained populations [17] and in older adults following both maximal and submaximal endurance exercise [18], the early post-exercise recovery trajectory in young-to-middle-aged sedentary adults remains less well characterized despite the clinical relevance of this population, which is disproportionately exposed to clinical exercise testing. The present study addresses this by employing four measurement time points (Pre, immediately post-exercise, Post5, Post10) to resolve the early recovery window and to track the recovery trajectory rather than a single displacement value. Blood lactate clearance is recorded concurrently with center-of-pressure-based postural sway, in line with established methodology for the integrated assessment of post-exercise physiological responses [19], allowing for metabolic and neuromuscular recovery to be compared within the same observation window. These design features (population specificity, early-recovery temporal resolution, and simultaneous metabolic and neuromuscular tracking) position the present work as a contribution to the translational exercise-safety literature.

The study has three specific aims: (1) to determine the extent of balance impairment immediately after exercise, (2) to define the recovery timeline of postural control alongside metabolic parameters (blood lactate and heart rate), and (3) to analyze potential sex differences in these responses. We hypothesized that (H1) acute submaximal treadmill exercise would induce significant deterioration in all measured postural sway parame-

ters immediately after exercise cessation; (H2) metabolic parameters (blood lactate, heart rate) would follow a slower recovery time course than postural parameters, producing a temporal dissociation during the early post-exercise window; and (H3) sex differences would be detectable in metabolic responses but not necessarily in the magnitude or trajectory of post-exercise postural impairment. These hypotheses are evaluated explicitly in the Discussion.

2. Materials and Methods

2.1. Participants

An a priori power analysis was conducted using G*Power software (version 3.1) [20] to determine the sample size required to detect significant differences. A medium effect size (f) of 0.25, an alpha level (α) of 0.05, and a power ($1 - \beta$) of 0.80 were assumed. The analysis indicated that a total sample size of 34 participants would be sufficient. To account for potential dropouts or data exclusion, 40 participants were initially recruited. Of the 40 adults initially enrolled, 6 participants were subsequently excluded through a three-stage attrition pathway: (i) 2 men voluntarily withdrew prior to protocol completion (Stage 1 attrition; remaining n = 38); (ii) 2 women were excluded because of dizziness at the immediate post-exercise time point, which precluded reliable center-of-pressure assessment (Stage 2 attrition; remaining n = 36); and (iii) 2 participants (1 woman and 1 man) were identified as statistical outliers at Post0 (CoP values exceeded $\pm$3 SD from the group mean) and excluded during data screening (Stage 3 attrition; final analytic sample n = 34). The final analytic sample therefore comprised 34 adults with a balanced sex distribution (17 women, 17 men). A CONSORT-style 3-stage attrition flow diagram is provided as Supplementary Figure S1.

Participants were enrolled consecutively on the basis of sedentary-behavior eligibility (SBRN criteria); no a priori matching, stratification, or recruitment quota was applied for body-mass index (BMI), cardiorespiratory fitness, body composition, or sex. The observed between-group BMI difference (women: 24.31 $\pm$ 3.36 kg/m^2; men: 25.51 $\pm$ 4.25 kg/m^2) therefore reflects the natural anthropometric distribution of the sedentary adult cohort available for screening rather than a deliberate design choice. None of the enrolled participants had a prior clinical diagnosis of obesity at the cardiological pre-screening evaluation; all had been medically cleared for maximal exercise testing by the screening cardiologist. Mean body-mass index values for both sexes remained within the normal-to-overweight range, and no participant was excluded on the basis of body-mass index or body composition.

Sedentary status was operationalized during a structured face-to-face enrolment interview conducted by a physician, which combined three elements: (i) the Sedentary Behavior Research Network (SBRN) consensus definition of sedentary behavior as any waking activity expending $\leq$ 1.5 METs while sitting, reclining, or lying down [1]; (ii) a structured description of the participant's typical weekday, including occupational activity, commuting, leisure-time behavior, and regular exercise participation; and (iii) a structured question on regular structured exercise participation, with the requirement of no regular structured exercise during the preceding six months. Absolute daily sitting duration was not quantified numerically during the interview. Device-based sedentary-behavior assessment (e.g., accelerometry, activPAL) and validated sedentary-behavior questionnaires (e.g., IPAQ, Sedentary Behavior Questionnaire) were not employed; this is acknowledged as a limitation in Section 4.

Participants were included if they met the following criteria: (1) aged between 18 and 40 years, (2) classified as sedentary based on the Sedentary Behavior Research Network (SBRN) guidelines (energy expenditure $\leq$ 1.5 METs while awake in a sitting, reclining, or lying posture) [1], and (3) no history of regular exercise training in the past six months.

Exclusion criteria were (1) history of musculoskeletal injury (e.g., ankle sprain, fractures) in the lower extremities within the last year, (2) neurological or vestibular disorders affecting balance, (3) cardiovascular or respiratory contraindications to maximal exercise testing, and (4) use of medications that could affect balance or metabolism. Eligible volunteers underwent a pre-participation health screening by a cardiologist.

The descriptive characteristics of the participants were as follows: women (age: 31 ± 6 years, weight: 62.35 ± 8.81 kg, height: 160.2 ± 5.35 cm, BMI: 24.31 ± 3.36 kg/m^2); men (age: 28.93 ± 6.53 years, weight: 77.29 ± 13.56 kg, height: 174.0 ± 6.78 cm, BMI: 25.51 ± 4.25 kg/m^2). The study was conducted in accordance with the Declaration of Helsinki, and ethical approval was obtained from the Local Ethics Committee of Manisa Celal Bayar University Faculty of Medicine (Approval No: 20478486-188). Informed consent was obtained from all individual participants included in the study.

2.2. Research Design and Procedure

This study utilized a repeated-measures design to investigate the acute effects of submaximal exercise on postural control. Participants visited the performance laboratory between 16:00 and 18:00 to control for circadian rhythm effects on balance and physiological variables. Laboratory conditions were maintained at a constant temperature (21 ± 2 °C) and humidity (40–50%). Upon arrival, participants underwent a mandatory 30 min rest period to stabilize baseline physiological values. Following baseline measurements (Pre) (lactate, heart rate, and postural sway), participants performed the Modified Bruce Protocol. Post-exercise assessments were conducted immediately after cessation of exercise (Post0) and at 5 min (Post5) and 10 min (Post10) of recovery, as shown in Figure 1.

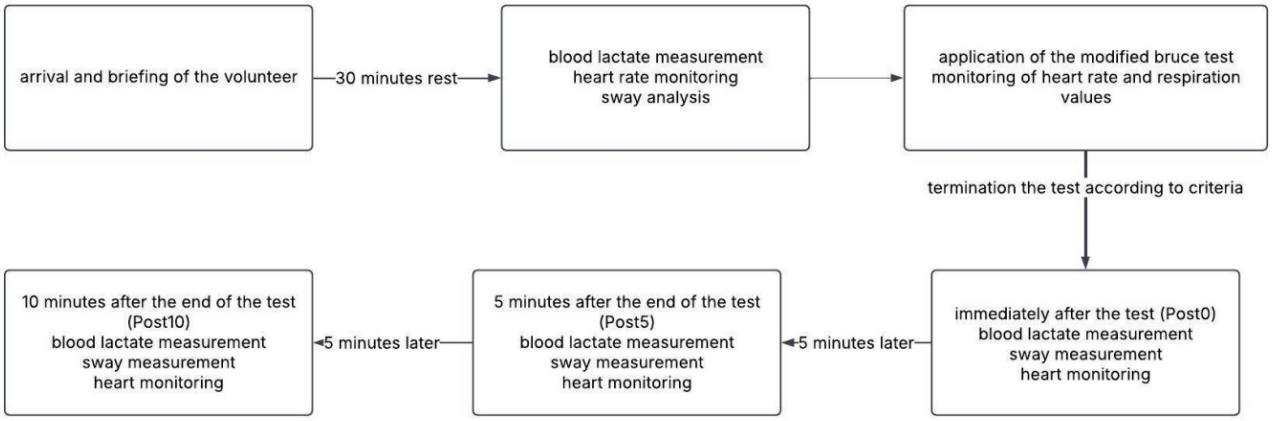


Figure 1. Timeline of the modified Bruce test protocol showing preparation, baseline measurements, test execution, and post-test assessments at three time points.

2.2.1. Physiological Measurements

Blood lactate concentration was measured to objectively quantify metabolic stress and confirm the anaerobic contribution to the exercise bout [11,21]. Capillary blood samples were collected from the fingertip using a YSI 1500 Sport Lactate Analyzer (Yellow Springs Instruments, Yellow Springs, OH, USA). The analyzer was calibrated with 5 mmol/L and 30 mmol/L standard lactate solutions prior to each test. Heart rate (HR) was monitored continuously throughout the protocol using a Polar RS400 heart-rate monitor (Polar Electro Inc., Kempele, Finland).

Respiratory gas analysis: To verify that participants reached the targeted physiological intensity, respiratory gas exchange parameters were monitored breath-by-breath using a portable metabolic system (Cosmed K4b^2, Cosmed, Rome, Italy). Prior to each test, the device was calibrated with a reference gas mixture (5% CO_2, 16% O_2, 79% N_2) and a 3 L

calibration syringe. Maximal oxygen consumption (VO_2max) and respiratory exchange ratio (RER) were recorded to corroborate the criteria for volitional fatigue [22].

2.2.2. Postural Sway Analysis

Static postural sway was assessed using a Tekscan HR Matscan pressure-sensing mat (Tekscan, Inc., Boston, MA, USA). The mat was factory-calibrated prior to the study and was re-zeroed before every recording session following the manufacturer's live-calibration procedure. All participants were tested barefoot and were asked to remove socks as well to eliminate between-subject variability introduced by footwear. Stance was standardized with the feet at shoulder-width, with each foot rotated outward by approximately 15° from the sagittal midline; foot position was marked on the mat for each participant and reproduced across time points to ensure within-participant consistency. A circular fixation target (5 cm in diameter) was mounted on the laboratory wall at a horizontal distance of 2 m from the participant and individually adjusted to eye level to provide a constant visual-vestibular reference. Ambient illumination and room temperature were kept constant across test sessions. Participants were instructed to stand quietly with arms relaxed at the sides, to breathe normally, and to fixate the visual target without speaking or moving the head. One 30 s familiarization trial was completed prior to the experimental recordings; the experimental condition itself consisted of one 30 s recording at each time point (Pre, Post0, Post5, Post10), sampled at 100 Hz. A single recording per time point was used as a deliberate trade-off against the temporal resolution requirements of the post-exercise recovery curve, which would otherwise have been contaminated by intervening rest periods. The mat was positioned immediately adjacent to the treadmill so that the Post0 recording could be initiated within approximately 10–15 s of exercise cessation. Raw center-of-pressure metrics exported by the Tekscan HR Matscan acquisition software (Tekscan HR Mat Research 6.7) were converted to centimeters for analysis and reporting; in particular, total Sway Distance, which the device exports in millimeters, was divided by 10 to express the metric in centimeters consistent with the other CoP variables (Sway Area in cm^2; AP and ML excursions in cm). The following parameters obtained using the device's software were analyzed:

Sway Area (cm^2): The area of the 95% confidence ellipse enclosing the center of pressure (CoP) trajectory, representing the overall magnitude of postural instability.

Sway Distance (cm): The total path length traveled by the CoP during the recording period.

Anterior–Posterior (AP) Excursion (cm): The range of CoP displacement in the sagittal plane.

Medial–Lateral (ML) Excursion (cm): The range of CoP displacement in the frontal plane.

2.2.3. Exercise Protocol

The Modified Bruce Protocol was implemented on a motorized treadmill (Cosmed T150, Cosmed, Rome, Italy) using a six-stage scheme commonly applied in young-adult populations [23,24] and conforming to the American Heart Association's exercise-testing standards [25]. Each stage lasted 3 min, with progressive increases in speed and grade as follows: Stage 1 (2.7 km/h, 0% grade), Stage 2 (2.7 km/h, 5%), Stage 3 (2.7 km/h, 10%), Stage 4 (4.0 km/h, 12%), Stage 5 (5.5 km/h, 14%), and Stage 6 (6.8 km/h, 16%); maximum exercise duration was 18 min. This protocol has previously been shown to elicit measurable changes in postural stability following completion in healthy young adults [26]. All participants had been cleared for exercise testing by a cardiologist prior to entry. Testing was conducted in a climate-controlled laboratory (21 ± 2 °C, 40–50% relative humidity)

with continuous heart-rate monitoring (Polar RS400) and breath-by-breath respiratory gas analysis (Cosmed K4b^2) under the supervision of a sports physician.

To avoid exhaustive effort and to equalize the relative exercise stimulus across participants of differing fitness, the test was terminated at the earliest occurrence of any of the following criteria: (1) Borg Rating of Perceived Exertion $\geq$ 17 ("very hard") [27,28]; (2) heart rate $\geq$ 85% of age-predicted maximum (220 − age); (3) respiratory exchange ratio $\geq$ 1.10; or (4) VO_2 peak (<150 mL·min^{-1} rise over the final stage) or inability to maintain the treadmill speed [22]. This protocol elicited the post-exercise balance perturbation required to test our hypotheses while minimizing exhaustion-related confounds.

Ventilatory variables (VE, VO_2, VCO_2, RER) were recorded continuously during the treadmill protocol by the Cosmed K4b^2 portable breath-by-breath analyzer for the sole purpose of verifying adherence to the pre-specified test-termination criteria. Ventilation was not recorded during the post-exercise recovery period. Blood lactate was sampled at each time point (Pre, Post0, Post5, Post10). This concurrent recording of cardiopulmonary, metabolic and perceptual variables during submaximal exercise follows established methodological practice for characterizing integrated physiological responses to graded- and constant-load exercise protocols [19].

2.3. Statistical Analysis

Statistical analyses were performed using SPSS software (version 15.0, SPSS Inc., Chicago, IL, USA). Prior to inferential testing, all dependent variables (blood lactate, sway area, sway distance, anterior–posterior and medial–lateral excursions, heart rate) were screened for outliers via boxplot inspection; two participants (one woman, one man) exceeded the ± 3 SD threshold on the primary postural sway parameters at Post0 and were excluded from the analytic sample (see Section 2.1). The normality of data distribution was assessed using the Shapiro–Wilk test, and all variables met the normality assumption (all $p > 0.05$). Homogeneity of variances was confirmed via Levene's test (all $p > 0.05$), and homogeneity of covariance matrices was confirmed via Box's M test (all $p > 0.001$).

For postural sway parameters and blood lactate, which were recorded at standardized post-exercise time points (Pre, Post0, Post5, Post10) with complete data in the analytic sample of 34 participants, a 2 × 4 (sex × time) two-way mixed-design analysis of variance (ANOVA) was employed, with sex as the between-subjects factor (male vs. female) and time as the within-subjects factor (Pre, Post0, Post5, Post10). Sphericity of the within-subjects factor was verified using Mauchly's test; when the sphericity assumption was violated, the Greenhouse–Geisser correction was applied, and the corrected degrees of freedom are reported. Significant main effects and interactions were followed by pairwise comparisons with Bonferroni correction. Partial eta-squared (η^2_p) is reported as the effect-size metric for every F-ratio (main effect of sex, main effect of time, and sex × time interaction), with magnitudes interpreted as small ($\eta^2_p = 0.01$), medium ($\eta^2_p = 0.06$), and large ($\eta^2_p = 0.14$). HR and Rating of Perceived Exertion (RPE) were recorded at the end of each Modified Bruce stage; because stage-wise attrition differed systematically between sexes (Stage 6 was reached by $n = 1$ woman and $n = 9$ men), the complete-cell requirement of the factorial mixed-design ANOVA could not be met for these two variables. For HR and RPE, between-sex stage-wise comparisons were therefore performed using independent-sample t-tests with Cohen's d as the effect-size metric.

For variables in which the sex × time interaction did not reach statistical significance, simple-effect decomposition was not performed in order to avoid post hoc inflation of Type I error without any change in the statistical conclusion. Main-effect and within-subject pairwise comparisons are reported, and where relevant, descriptive per-time-point

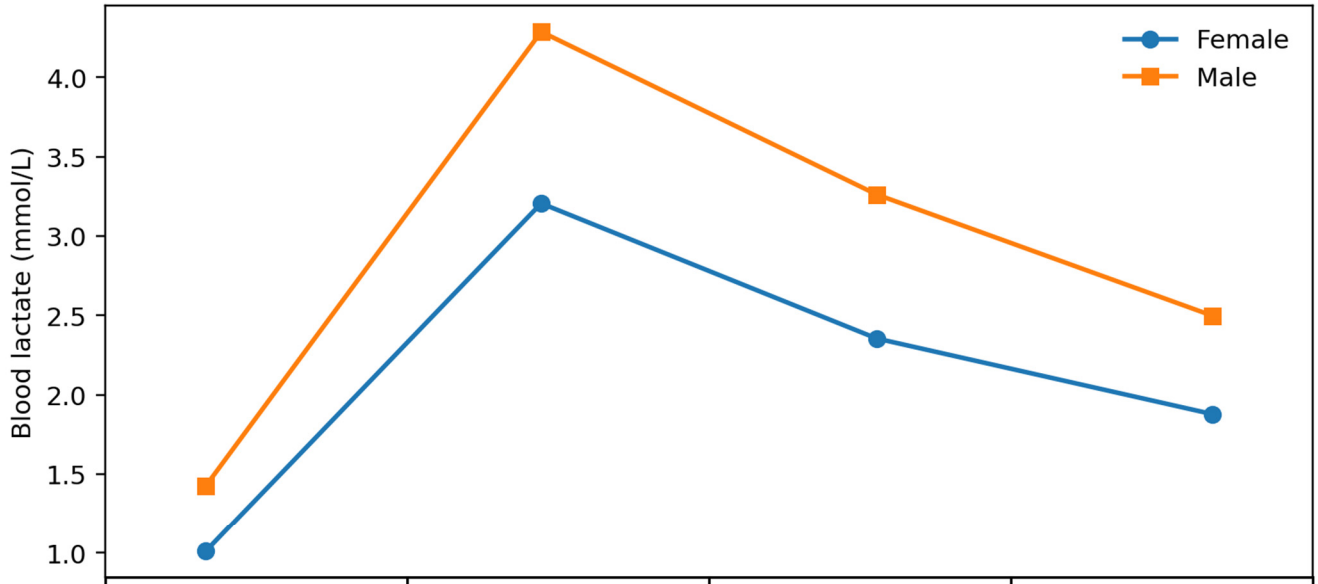
between-sex comparisons are provided. The significance level was set at $p < 0.05$, and data are presented as mean ± standard deviation (SD).

3. Results

3.1. Analysis of Physiological Measurements

3.1.1. Blood Lactate Levels

Blood lactate increased sharply from pre-exercise baseline to the immediate post-exercise time point and remained substantially elevated throughout the 10 min recovery window, with consistently higher values in men at every measurement time point; the time course of recovery did not differ statistically between sexes (large main effect of time: $F(1.716, 54.912) = 125.548$, $p < 0.001$, $\eta^2_p = 0.797$, Greenhouse–Geisser corrected; large main effect of sex: $F(1, 32) = 8.787$, $p = 0.006$, $\eta^2_p = 0.215$; non-significant sex × time interaction: $F(1.716, 54.912) = 2.441$, $p = 0.104$, $\eta^2_p = 0.071$; Figure 2). Bonferroni-corrected pairwise comparisons confirmed that Pre differed significantly from all post-exercise time points (Post0, Post5, Post10; all $p < 0.001$) and that Post0 differed significantly from Post5 and Post10 (both $p < 0.001$). Post5 and Post10 did not differ significantly from each other ($p = 0.206$), indicating a plateau in lactate clearance during the second half of the recovery window.



	Pre	Post0	Post5	Post10
Female	1.011 ± 0.34	3.206 ± 0.87	2.355 ± 0.76	1.879 ± 0.67
Male	1.426 ± 0.42	4.287 ± 1.16	3.262 ± 0.91	2.499 ± 0.86

Figure 2. Comparison of blood lactate concentration (mmol/L) between female ($n = 17$) and male ($n = 17$) participants in adults with sedentary behavior at four measurement time points: pre-exercise (Pre), immediately post-exercise (Post0), 5 min post-exercise (Post5), and 10 min post-exercise (Post10), following the Modified Bruce Protocol. Data are presented as mean ± SD.

3.1.2. Heart Rate

Heart rate increased progressively during the Modified Bruce Protocol and then declined during recovery, approaching but not fully returning to baseline by Post10 in either sex (Table 1). Because stage-wise attrition differed between sexes (only 1 woman versus 9 men reached Stage 6), the two-way mixed-design ANOVA was not applied to heart

rate; instead, independent-sample stage-wise comparisons with Cohen's d are reported. Pre-exercise resting values differed significantly between sexes, with higher resting values in men (women: 80.90 ± 3.80 beats/min; men: 86.36 ± 4.20 beats/min; $p < 0.001$; d = 1.36). During the protocol, significant between-sex differences were present at Stage 1 (men higher, $p = 0.010$) and at Stage 4, where women exhibited higher heart rate than men (147.10 ± 7.20 vs. 135.14 ± 6.80 beats/min; $p < 0.001$; Cohen's d = 1.71, large). During recovery, men displayed significantly higher heart rate than women at Post0 (103.86 ± 5.30 vs. 92.65 ± 4.90 beats/min; $p < 0.001$; d = 2.20, large), Post5 (94.29 ± 4.50 vs. 85.40 ± 4.10 beats/min; $p < 0.001$; d = 2.07, large), and Post10 ($p < 0.001$; d = 1.79; Table 1).

Table 1. Heart-rate (beats/min) values (mean ± SD) during the Modified Bruce Protocol application, each stage lasting 3 min, and during the recovery period.

Phase	Stage	Female (n = 17)	Male (n = 17)	p
Baseline	Pre-exercise	80.90 ± 3.80	86.36 ± 4.20	<0.001 *
Exercise	Stage 1	103.55 ± 5.10	108.21 ± 4.80	0.010 *
Exercise	Stage 2	112.35 ± 5.70	109.71 ± 6.10	0.202
Exercise	Stage 3	123.75 ± 6.30	120.07 ± 5.90	0.088
Exercise	Stage 4	147.10 ± 7.20	135.14 ± 6.80	<0.001 *
Exercise	Stage 5 (n = 16 F/13 M)	163.75 ± 7.90	158.38 ± 7.40	0.072
Exercise	Stage 6 (n = 1 F/9 M)	165.00	165.78 ± 7.90	NA
Recovery	Post0	92.65 ± 4.90	103.86 ± 5.30	<0.001 *
Recovery	Post5	85.40 ± 4.10	94.29 ± 4.50	<0.001 *
Recovery	Post10	81.25 ± 3.60	88.14 ± 4.10	<0.001 *

Note. Pre-exercise = resting baseline; Stages 1–6 of the Modified Bruce Protocol, each lasting 3 min; Post0 = immediately after exercise cessation; Post5 = 5 min into recovery; Post10 = 10 min into recovery. Stage-wise sample sizes for Stage 5 and Stage 6 reflect the number of participants who reached each stage prior to volitional fatigue or test-termination criteria (see Section 2.2.3). Between-sex comparisons were performed using independent-sample t-tests. NA, not applicable; statistical comparison was not performed for Stage 6 due to insufficient sample size in the female group (n = 1). * $p < 0.05$.

3.1.3. Respiratory Parameters

Ventilation and oxygen consumption increased markedly from rest to peak exercise in both sexes, with significantly higher peak values in men (Table 2). Peak ventilation was substantially higher in men than in women (VE_{peak}: 72.95 ± 14.94 vs. 47.02 ± 12.19 L/min, $p < 0.001$), as was peak absolute oxygen consumption (VO_{2peak}: 2306.20 ± 744.90 vs. 1536.44 ± 348.46 mL/min, $p < 0.001$) and peak weight-adjusted oxygen consumption (VO_2/kg_{peak}: 32.21 ± 3.60 vs. 27.55 ± 7.86 $mL \cdot kg^{-1} \cdot min^{-1}$, $p = 0.045$). Peak respiratory exchange ratios were comparable between sexes (men: 1.01 ± 0.09; women: 1.00 ± 0.06; $p = 0.693$), confirming that both sexes reached equivalent relative metabolic intensity at test termination. Resting values for all respiratory parameters did not differ significantly between sexes (all $p > 0.05$).

Table 2. Respiratory and metabolic parameters at rest and peak exercise during incremental treadmill testing (mean ± SD).

Parameter	Female (n = 17)	Male (n = 17)	p
Ventilation, rest (VE_{pre}) (L/min)	11.93 ± 6.00	12.74 ± 2.07	0.623
Ventilation, peak (VE_{peak}) (L/min)	47.02 ± 12.19	72.95 ± 14.94	<0.001 *
Oxygen consumption, rest (VO_{2pre}) (mL/min)	387.02 ± 208.59	403.57 ± 87.10	0.779
Oxygen consumption, peak (VO_{2peak}) (mL/min)	1536.44 ± 348.46	2306.20 ± 744.90	<0.001 *
Weight-adjusted VO_2, rest (VO_2/kg_{pre}) (mL/kg/min)	7.99 ± 7.67	5.32 ± 1.29	0.218
Weight-adjusted VO_2, peak (VO_2/kg_{peak}) (mL/kg/min)	27.55 ± 7.86	32.21 ± 3.60	0.045 *

Table 2. *Cont.*

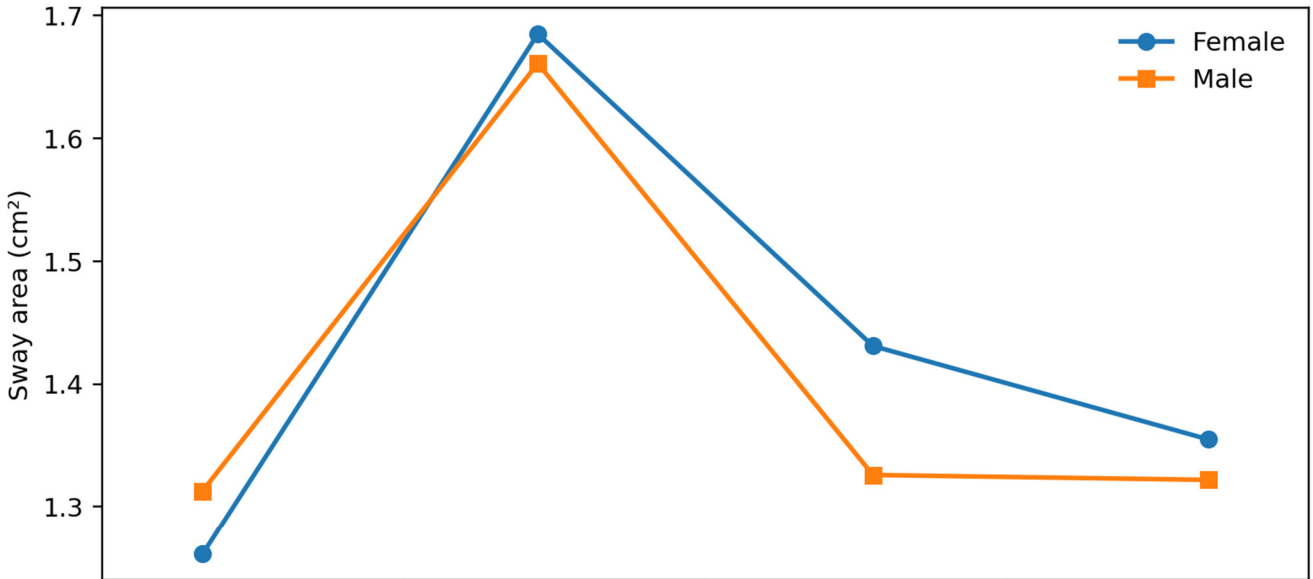
Parameter	Female (n = 17)	Male (n = 17)	p
Respiratory exchange ratio, rest (R_{pre})	0.79 ± 0.08	0.81 ± 0.10	0.475
Respiratory exchange ratio, peak (R_{peak})	1.00 ± 0.06	1.01 ± 0.09	0.693

Abbreviations: R_{peak}, respiratory exchange ratio at peak exercise; R_{pre}, respiratory exchange ratio at rest; SD, standard deviation; VE_{peak}, peak ventilation; VE_{pre}, resting ventilation; VO_{2peak}, peak oxygen consumption; VO_{2pre}, resting oxygen consumption; VO_2/kg_{peak}, weight-adjusted peak oxygen consumption; VO_2/kg_{pre}, weight-adjusted resting oxygen consumption. * $p < 0.05$.

3.2. Postural Sway Outcomes

3.2.1. Sway Area

Sway area increased markedly from pre-exercise baseline to the immediate post-exercise measurement and remained elevated at five minutes of recovery, with only partial return toward baseline by the tenth minute; the overall magnitude and the early-recovery trajectory did not differ statistically between women and men (large main effect of time: $F(2.37, 75.84) = 8.21$, $p < 0.001$, $\eta^2_p = 0.204$, Greenhouse–Geisser corrected; non-significant main effect of sex: $F(1, 32) = 2.60$, $p = 0.117$, $\eta^2_p = 0.075$; non-significant sex × time interaction: $F(2.37, 75.84) = 1.29$, $p = 0.282$, $\eta^2_p = 0.039$; Figure 3). Bonferroni-corrected pairwise comparisons confirmed that Post0, Post5, and Post10 all exceeded the Pre value (Pre vs. Post0 and Pre vs. Post5: $p < 0.001$; Pre vs. Post10: $p < 0.05$). A significant early-recovery reduction was observed between Post0 and Post5 and between Post0 and Post10 (both $p < 0.05$), whereas Post5 and Post10 did not differ significantly from each other ($p = 0.245$).

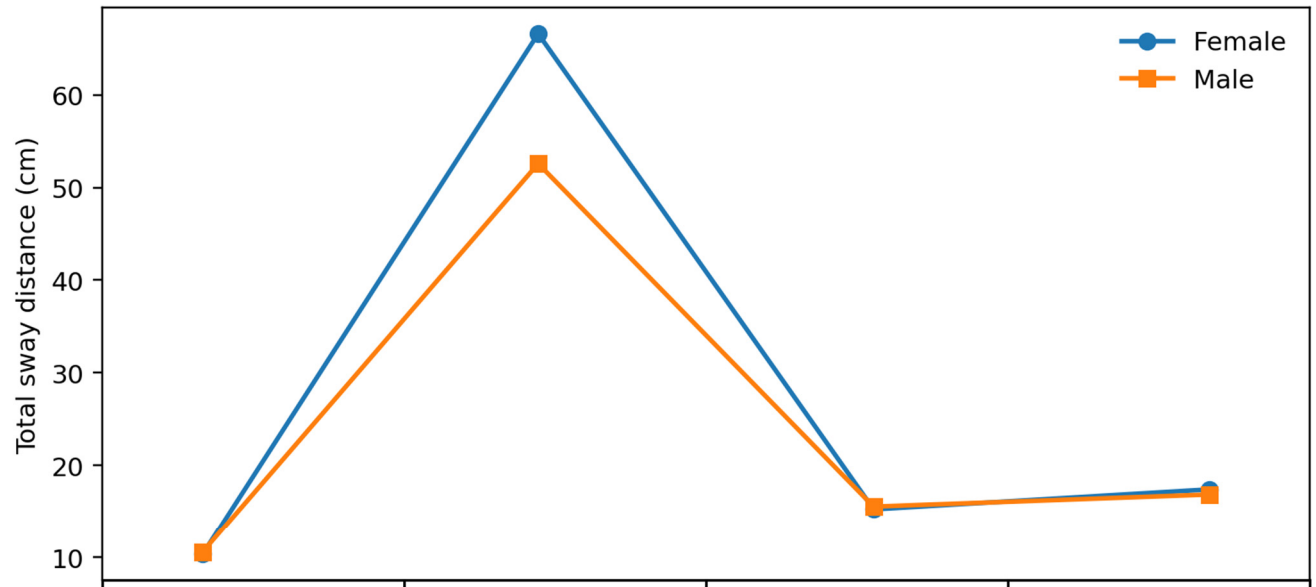


	Pre	Post0	Post5	Post10
Female	1.261 ± 0.31	1.685 ± 0.49	1.431 ± 0.38	1.355 ± 0.33
Male	1.313 ± 0.35	1.661 ± 0.46	1.326 ± 0.34	1.322 ± 0.36

Figure 3. A comparison of sway area (cm^2) between female (n = 17) and male (n = 17) participants in adults with sedentary behavior at four measurement time points: pre-exercise (Pre), immediately post-exercise (Post0), 5 min post-exercise (Post5), and 10 min post-exercise (Post10), following the Modified Bruce Protocol. Data are presented as mean ± SD.

3.2.2. Sway Distance

Total sway distance increased sharply at the immediate post-exercise measurement and then declined rapidly between Post0 and Post5, with partial return toward baseline by Post10 (Figure 4). The main effect of time was large and statistically significant ($F(1.00, 32.00) = 12.25$, $p = 0.001$, $\eta^2_p = 0.277$, Greenhouse–Geisser corrected), while neither the main effect of sex ($F(1, 32) = 0.744$, $p = 0.395$, $\eta^2_p = 0.023$) nor the sex × time interaction ($F(1.00, 32.00) = 0.421$, $p = 0.522$, $\eta^2_p = 0.013$) reached significance, indicating that the early-recovery trajectory did not differ statistically between sexes. Bonferroni-corrected pairwise comparisons confirmed that Post0, Post5, and Post10 all exceeded the Pre value (Pre vs. Post0: $p < 0.001$; Pre vs. Post5: $p < 0.05$; Pre vs. Post10: $p < 0.05$). A significant early-recovery reduction was observed between Post0 and Post5 and between Post0 and Post10 (both $p < 0.001$), whereas Post5 and Post10 did not differ significantly from each other ($p = 0.528$). Values are reported in centimeters throughout, following conversion from the device's raw millimeter output.



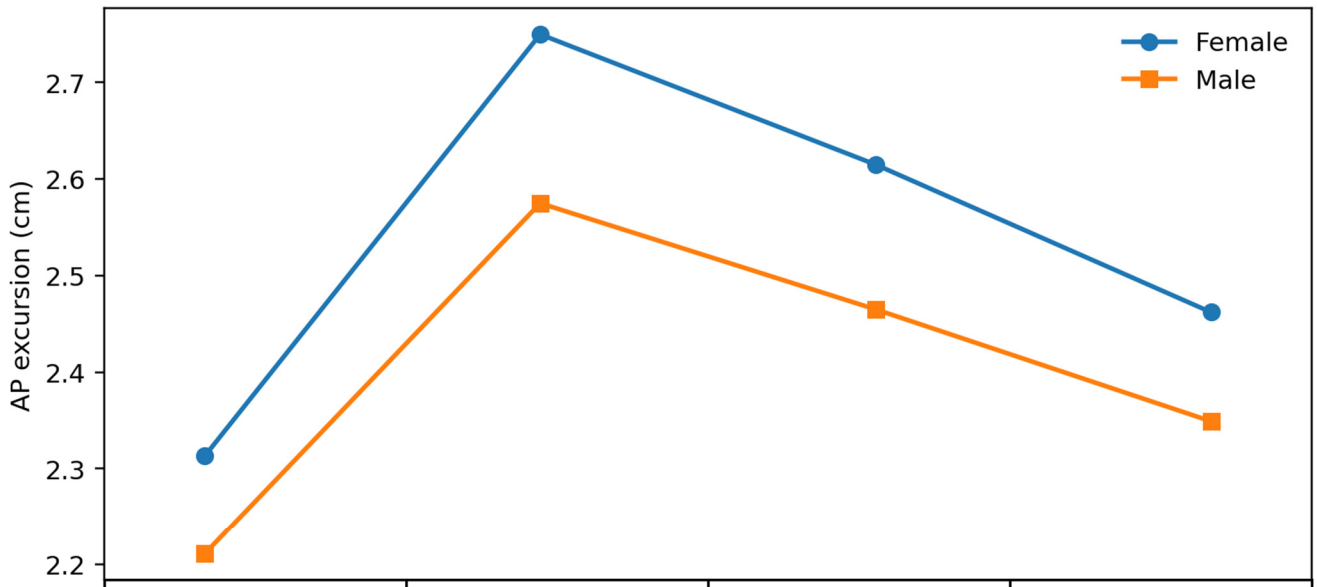
	Pre	Post0	Post5	Post10
Female	10.36 ± 5.24	66.59 ± 28.65	15.27 ± 8.46	17.42 ± 9.68
Male	10.61 ± 5.87	52.58 ± 26.48	15.56 ± 9.13	16.87 ± 8.85

Figure 4. A comparison of total sway distance (cm) between female (n = 17) and male (n = 17) participants in adults with sedentary behavior at four measurement time points: pre-exercise (Pre), immediately post-exercise (Post0), 5 min post-exercise (Post5), and 10 min post-exercise (Post10), following the Modified Bruce Protocol. Data are presented as mean ± SD.

3.2.3. Anterior–Posterior (AP) Excursion

Anterior–posterior excursion increased substantially after exercise and remained significantly elevated above baseline throughout the 10-min recovery window; the between-sex comparison of the recovery trajectory was statistically null (large main effect of time: $F(1.51, 48.17) = 24.54$, $p < 0.001$, $\eta^2_p = 0.434$, Greenhouse–Geisser corrected; non-significant main effect of sex: $F(1, 32) = 1.16$, $p = 0.290$, $\eta^2_p = 0.035$; non-significant sex × time interaction: $F(1.51, 48.17) = 0.221$, $p = 0.739$, $\eta^2_p = 0.007$; Figure 5). Bonferroni-corrected pairwise comparisons indicated significant differences between Pre and Post0, Pre and Post5, Pre and Post10, Post0 and Post5, and Post0 and Post10 (all $p < 0.001$); Post5 and

Post10 did not differ significantly ($p = 0.206$), indicating that AP excursion had not returned to baseline by the tenth minute of recovery.



	Pre	Post0	Post5	Post10
Female	2.313 ± 0.43	2.750 ± 0.50	2.615 ± 0.48	2.462 ± 0.36
Male	2.211 ± 0.29	2.575 ± 0.41	2.465 ± 0.43	2.349 ± 0.33

Figure 5. A comparison of anterior–posterior (AP) excursion (cm) between female ($n = 17$) and male ($n = 17$) participants in adults with sedentary behavior at four measurement time points: pre-exercise (Pre), immediately post-exercise (Post0), 5 min post-exercise (Post5), and 10 min post-exercise (Post10), following the Modified Bruce Protocol. Data are presented as mean ± SD.

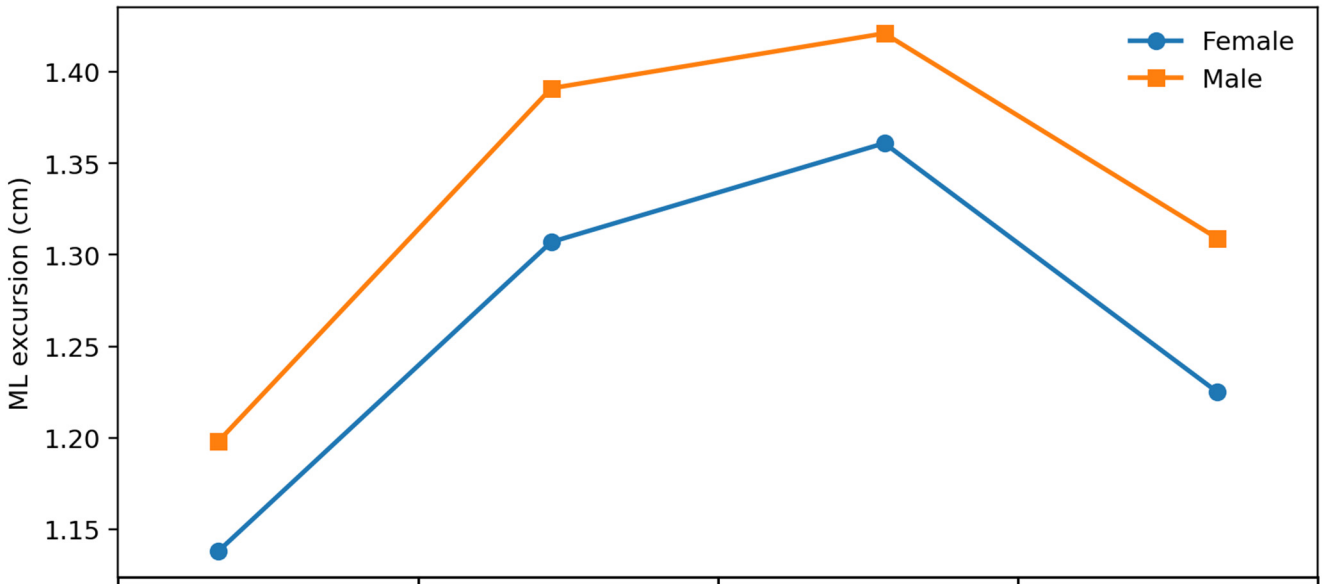
3.2.4. Medial–Lateral (ML) Excursion

Medial–lateral excursion increased substantially after exercise (a large main effect of time: $F(1.19, 38.14) = 40.19$, $p < 0.001$, $\eta^2_p = 0.557$, Greenhouse–Geisser corrected; non-significant main effect of sex: $F(1, 32) = 0.325$, $p = 0.573$, $\eta^2_p = 0.010$; non-significant sex × time interaction: $F(1.19, 38.14) = 0.198$, $p = 0.703$, $\eta^2_p = 0.006$; Figure 6). Bonferroni-corrected pairwise comparisons confirmed that Post0, Post5, and Post10 all exceeded the Pre value (Pre vs. Post0, Pre vs. Post5, Pre vs. Post10: all $p < 0.001$). A significant increase from Post0 to Post5 was observed ($p < 0.001$), followed by a significant decrease from Post5 to Post10 ($p < 0.001$) and from Post0 to Post10 ($p < 0.001$).

3.3. Rating of Perceived Exertion

The Rating of Perceived Exertion (RPE) increased progressively during the exercise stages and declined rapidly during recovery in both sexes, returning to near-baseline values by Post10 (Table 3). Because stage-wise attrition differed between sexes (only one woman versus nine men reached Stage 6), the two-way mixed-design ANOVA was not applied to RPE; instead, independent-sample stage-wise comparisons with Cohen's d are reported. Pre-exercise and recovery-phase RPE values did not differ significantly between sexes (all $p > 0.20$). A significant between-sex difference emerged at Stage 4, where women reported higher perceived exertion than men (13.60 ± 1.85 vs. 11.93 ± 2.02; $p = 0.018$; Cohen's d = 0.86, large). No other stage-wise comparison reached statistical significance. The per-

stage sample sizes reflecting Modified Bruce Protocol attrition are reported explicitly in Table 3.



	Pre	Post0	Post5	Post10
Female	1.138 ± 0.337	1.307 ± 0.427	1.361 ± 0.416	1.225 ± 0.373
Male	1.198 ± 0.344	1.391 ± 0.342	1.421 ± 0.351	1.309 ± 0.372

Figure 6. A comparison of medial–lateral (ML) excursion (cm) between female (n = 17) and male (n = 17) participants in adults with sedentary behavior at four measurement time points: pre-exercise (Pre), immediately post-exercise (Post0), 5 min post-exercise (Post5), and 10 min post-exercise (Post10), following the Modified Bruce Protocol. Data are presented as mean ± SD.

Table 3. Rate of Perceived Exertion values (Borg Scale) obtained from participants pre-exercise, during protocol stages, at exercise termination, and throughout the recovery period (mean ± SD).

Phase	Measurement Time	Female (n = 17)	Male (n = 17)	p
Baseline	Pre-exercise	8.55 ± 2.06	8.43 ± 2.14	0.870
Exercise	Stage 1	8.70 ± 1.98	8.43 ± 1.65	0.677
Exercise	Stage 2	10.55 ± 1.61	9.57 ± 1.99	0.140
Exercise	Stage 3	12.05 ± 1.70	10.86 ± 2.41	0.126
Exercise	Stage 4	13.60 ± 1.85	11.93 ± 2.02	0.018 *
Exercise	Stage 5 (n = 16 F/13 M)	14.75 ± 1.95	13.85 ± 1.14	0.152
Exercise	Stage 6 (n = 1 F/9 M)	13.00	14.78 ± 1.56	NA
Recovery	Post0	10.95 ± 2.31	10.29 ± 2.67	0.444
Recovery	Post5	9.15 ± 1.79	8.43 ± 1.65	0.241
Recovery	Post10	8.65 ± 2.23	8.14 ± 1.88	0.492

Note. RPE was rated using the Borg 6–20 scale at each measurement time point. Stage-wise sample sizes for Stage 5 and Stage 6 reflect the number of participants who reached each stage prior to volitional fatigue or test-termination criteria. Pre-exercise = resting baseline; Post0 = immediately after exercise cessation; Post5 = 5 min into recovery; Post10 = 10 min into recovery. Between-sex comparisons were performed using independent-sample t-tests. NA, not applicable; statistical comparison was not performed for Stage 6 due to insufficient sample size in the female group (n = 1). * $p < 0.05$.

4. Discussion

This study examined the early post-exercise recovery trajectory of static postural control in adults with sedentary behavior following a Modified Bruce Protocol. Three

principal findings emerged. First, all four center-of-pressure parameters (sway area, total sway distance, anterior–posterior excursion, medial–lateral excursion) were significantly perturbed immediately after exercise (all main effects of time $p \leq 0.001$, with total sway distance $p = 0.001$), confirming that submaximal aerobic exercise produces an acute, statistically robust impairment of static postural control in this population. Second, all four postural sway parameters remained significantly elevated above baseline at Post10, indicating that postural recovery within the 10 min observation window was incomplete for every measured parameter (sway area and total sway distance: $p < 0.05$; anterior–posterior and medial–lateral excursions: $p < 0.001$). Third, no statistically significant sex × time interaction was observed for any postural sway parameter (area $p = 0.282$, distance $p = 0.522$, AP $p = 0.739$, ML $p = 0.703$), indicating that despite a significant between-sex offset in blood lactate (main effect of sex, $p = 0.006$, $\eta^2_p = 0.215$) and in peak ventilatory and metabolic indices, the trajectory of acute postural impairment and subsequent recovery was statistically comparable between women and men in this sedentary cohort. In the present sedentary cohort, postural and metabolic recovery did not dissociate within the 10 min observation window, contrasting with prior reports in healthy young males where exercise-induced increases in sway velocity recovered earlier than physiological parameters [29]. This difference may reflect the lower fatigue resistance of sedentary participants compared with the healthy active samples examined in earlier studies.

The magnitude of postural impairment observed immediately after exercise should be understood in the context of the exercise dose delivered. Whereas low-intensity submaximal protocols such as the 6 min walk test do not adversely affect static postural control in older sedentary adults [30,31], incremental treadmill protocols of the Bruce family—which elicit progressive cardiorespiratory strain and have been shown to acutely impair postural sway in young healthy adults and to produce measurable balance loss with recovery trajectories on the order of 10 min in trained female athletes [11,26]—impose a qualitatively different physiological load that is consistent with the substantial post-exercise CoP perturbations observed in the present sedentary cohort. The Bruce protocol retains well-established prognostic validity for cardiorespiratory function across diverse populations [32], further supporting its relevance as an appropriate exercise stimulus in this context.

The present study measured static center-of-pressure parameters, ventilatory and metabolic variables during exercise, and blood lactate. Lower-extremity neuromuscular fatigue is a plausible primary contributor: exercises confined to the lower limbs have been shown to disrupt balance, whereas upper-body exercises do not produce a comparable effect [7], and even fatigue confined to the foot and ankle musculature can be sufficient to alter quiet-stance postural sway [33]. Lumbar muscle fatigue affecting spinal posture is another candidate factor [3], and increased antagonist co-contraction may compromise fine postural adjustments through elevated joint stiffness [34]. Acute hyperventilation associated with high-intensity exercise has also been proposed as a mechanism for the post-exercise increase in postural sway, with increased respiratory work potentially competing with spinal-stabilization function [21]. Finally, central motor control may be transiently impaired by fatigue, as evidenced by disruptions in locomotor regularity [35], and the visual–proprioceptive sensory conflict generated during treadmill exercise may also contribute to short-term instability after exercise cessation [36]. None of these mechanisms was directly measured in the present design; their consistency with our findings is therefore hypothesis-generating rather than confirmatory.

The diaphragm and the deep abdominal and paraspinal musculature serve a dual physiological role: they generate and regulate the pressure gradients required for pulmonary ventilation, and they simultaneously contribute to intra-abdominal pressure regulation and to trunk/spinal stabilization [37]. Under conditions of increased ventilatory demand, the

priorities assigned to ventilation and to the stabilization role may compete for the same respiratory musculature, and the interaction between respiratory and postural demands has been addressed in studies of respiratory-muscle training [38]. Consistent with this framing, an 8-week randomized double-blind placebo-controlled trial of inspiratory muscle training has been shown to improve balance performance in healthy older adults, providing indirect support for the hypothesis that respiratory-muscle function contributes to postural control [39]. In a sedentary adult cohort, respiratory and postural musculature would be expected to have lower mechanical reserves than in trained individuals, which would plausibly amplify the effect of an acute respiratory load on postural control during the early post-exercise period. As respiratory-muscle fatigue, diaphragmatic function, and intra-abdominal pressure were not directly assessed in this design, this mechanistic interpretation is tentative and would require direct experimental testing in future work.

The magnitude of post-exercise postural impairment observed in the present cohort is consistent with evidence that non-habitually exercising populations are more susceptible to acute exercise-induced balance perturbation. In young non-athletic women undergoing a whole-body fatigue protocol, dynamic postural control deteriorated in multiple reach directions, whereas age-matched athletes showed no comparable impairment [17]. Habitual fatigue resistance therefore appears to be a protective factor. In healthy older adults, exhaustive treadmill exercise produces large increases in center-of-pressure path length (Cohen's d $\approx$ 1.0–1.2), consistent with a transient fall-risk elevation. Submaximal 2 km walking produces only small effects [18]. This dose–response pattern points to an intensity-dependent exercise effect. Although postural and metabolic recovery did not dissociate in our cohort, postural sway parameters remained significantly elevated above baseline at Post10, defining a post-exercise vulnerability window of at least 10 min that may be relevant to clinical exercise testing. Because postural sway parameters had not returned to baseline by the tenth minute, dismissing a sedentary participant in the conventional post-exercise period could overlap with a period of residual postural impairment. This pattern is consistent with prior reports that high-intensity interval training induces a transient post-exercise impairment of postural control, which Donath et al. termed an "open-fall-window" [10]. Our findings are aligned with this observation in the context of submaximal aerobic exercise in sedentary adults, a population disproportionately represented in clinical exercise testing. Post-exercise recovery protocols such as seated recovery, brief active-recovery interventions, or pre-discharge balance screening warrant formal evaluation in future studies.

Sex-related differences identified in this study. The variables in which statistically significant between-sex differences were observed are summarized here: (i) blood lactate was significantly higher in men across all measurement time points (main effect of sex, $p = 0.006$, $\eta^2_p = 0.215$); (ii) peak ventilation (VE_{peak}) was significantly higher in men (72.95 $\pm$ 14.94 vs. 47.02 $\pm$ 12.19 L/min, $p < 0.001$); (iii) peak absolute oxygen consumption (VO_{2peak}) was significantly higher in men ($p < 0.001$); (iv) peak weight-adjusted oxygen consumption (VO_2/kg_{peak}) was higher in men (32.21 $\pm$ 3.60 vs. 27.55 $\pm$ 7.86 $mL \cdot kg^{-1} \cdot min^{-1}$, $p = 0.045$); (v) heart rate differed significantly between sexes at multiple time points, where men were higher at rest (Pre: $p < 0.001$, d = 1.36), Stage 1 ($p = 0.010$), Post0 ($p < 0.001$, d = 2.20), Post5 ($p < 0.001$, d = 2.07), and Post10 ($p < 0.001$, d = 1.79), whereas women were higher at Stage 4 ($p < 0.001$, d = 1.71); and (vi) perceived exertion at Stage 4 was significantly higher in women (13.60 $\pm$ 1.85 vs. 11.93 $\pm$ 2.02, $p = 0.018$, Cohen's d = 0.86). No significant main effect of sex or sex $\times$ time interaction was observed for any of the four postural sway parameters, indicating that despite the metabolic and ventilatory differences, the trajectory of acute postural impairment and subsequent recovery was comparable between sexes in this sedentary cohort.

The higher lactate accumulation observed in men across recovery is consistent with evidence that plasma lactate is lower in untrained women than untrained men at all relative intensities between 30 and 100% of VO_2peak [40], whereas studies focused exclusively on peak post-exhaustive values have sometimes reported no sex difference [41], highlighting the timing-dependence of the effect. Of particular relevance, Deschenes and colleagues reported that following submaximal exercise at matched relative intensity, gender-related differences in most physiological parameters were obscured within five minutes of recovery—with plasma lactate the notable exception [42]—a pattern only partially paralleled by the present dataset, in which the between-sex blood-lactate difference likewise persisted, whereas the between-sex heart-rate differences did not resolve within the recovery window. The elevated recovery heart rate observed in men is also consistent with reports of sex differences in cardiac autonomic responses to postural provocations, including larger normalized high-frequency heart-rate variability reductions in women on standing [43]. Baseline sex differences have been documented in ankle-stabilizing muscle co-contraction strategies [44] and in gender-specific EMG responses to postural perturbations [45]. The absence of a sex × time interaction for any postural sway parameter in the present data is consistent with evidence that acute post-exercise balance disturbance diverges by sex only under the most demanding task conditions. For example, males showed prolonged sway-velocity increases when leaning with eyes closed after plantar–flexor fatigue, whereas females did not [46]. Overt sex differences in quiet-standing balance are also most evident in sedentary rather than physically active subgroups [47]. Taken together, in this submaximal aerobic exercise paradigm, the acute postural vulnerability over the first ten minutes of recovery appears sex-independent, even though the underlying metabolic and cardiorespiratory load differs systematically between men and women.

Our three pre-specified hypotheses are addressed as follows. Hypothesis H1, which proposed that acute submaximal exercise would induce significant deterioration in all postural sway parameters, was fully supported. Hypothesis H2, which proposed that metabolic parameters would follow a slower recovery time course than postural parameters, was partially supported: postural sway parameters showed substantial recovery from peak post-exercise values toward Post10 yet remained significantly elevated above baseline, while blood lactate continued to reflect incomplete metabolic recovery, indicating that the trajectories did not dissociate within the 10 min observation window. Hypothesis H3, which proposed that sex differences would be detectable in metabolic responses but not in postural impairment, was supported.

Several methodological constraints should be considered when interpreting the present findings. First, the modest analytic sample size (n = 34; 17 women, 17 men) limits statistical power for detecting small-to-moderate sex × time interaction effects and for subgroup analyses. Second, postural control was assessed exclusively in a static stance condition; dynamic balance, perturbation-based, and dual-task paradigms, which probe partially non-overlapping neuromuscular substrates, were not tested. Third, the mechanistic pathways discussed (respiratory-muscle fatigue, intra-abdominal pressure regulation, proprioceptive input, central motor drive, sensory re-weighting) were not directly measured, and their consistency with the observed CoP trajectory remains hypothesis-generating. Fourth, pulmonary ventilation was recorded only during the treadmill protocol and not during recovery, precluding statistical linkage between ventilatory variables and post-exercise CoP trajectories. Fifth, BMI was not matched between sexes (higher in men), although both groups remained within the normal-to-overweight range with no obesity diagnoses. BMI-related inferences about fall risk require future studies with BMI-stratified subgroups. Sixth, sedentary status was operationalized through a structured self-report enrollment interview rather than a validated questionnaire (e.g., IPAQ) or a device-based monitor,

introducing possible recall and social-desirability bias and precluding quantitative sitting-time estimates. Seventh, one 30 s CoP trial was recorded at each time point rather than the conventional three-trial average in order to preserve the temporal resolution of the early recovery curve; this represents a deliberate trade-off that may reduce single-trial reliability. Eighth, while female participants were not tested on days of active bleeding, cycle phase, cycle-day tracking, and hormonal contraception use were not recorded. Existing evidence on cycle-phase effects on postural control is mixed [48,49], and future studies should schedule testing to a specific cycle phase and record relevant covariates. Ninth, the 10 min post-exercise observation window was selected to preserve temporal resolution of the early recovery trajectory; however, extended recovery observation windows improve model fit for lactate clearance kinetics [50], so the present metabolic trajectory captures only the initial phase and does not resolve the terminal lactate time-course.

5. Conclusions and Recommendations

In sedentary adults, submaximal aerobic exercise produced acute postural perturbations that did not return to baseline within the 10 min post-exercise observation window, alongside an incomplete metabolic recovery. These findings indicate a post-exercise vulnerability window of at least 10 min that may be relevant to clinical exercise testing in sedentary populations. Practical considerations such as seated rather than standing recovery, brief proprioception-focused active-recovery protocols, and pre-discharge balance screening warrant formal evaluation in future studies. Further work in larger BMI- and fitness-stratified samples is required to confirm the present observations and to refine post-exercise recovery strategies for this population.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/app16157366/s1, Figure S1: Participant flow diagram.

Author Contributions: E.K.: Conceptualization, Investigation, Data curation, Formal analysis, Writing—original draft. S.Ö.: Conceptualization, Methodology, Formal analysis, Statistical analysis, Writing—review and editing. T.V.: Supervision, Resources, Writing—review and editing. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement: This study was approved by the Local Ethics Committee of Manisa Celal Bayar University Faculty of Medicine (Approval No. 20478486-188). The study was conducted in accordance with the Declaration of Helsinki.

Informed Consent Statement: Written informed consent was obtained from all subjects involved in the study. All participants received detailed information about the study procedures, potential risks, and expected benefits and provided written informed consent prior to their inclusion in the study.

Data Availability Statement: The data presented in this study are available on reasonable request from the corresponding author. The data are not publicly available due to participant privacy considerations and the conditions of the original ethical approval.

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