PHYSICAL EDUCATION OF STUDENTS

ORIGINAL ARTICLE

The impact of a 6000-meter endurance exercise test on acid-base balance parameters

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Abstract

Background and Study Aim Physical exercise disrupts the body's homeostasis, particularly acid-base balance. These changes may influence athletic performance and recovery efficiency. This study aimed to evaluate the changes in acid-base and electrolyte balance parameters in response to a 6000-meter rowing ergometer test. It also examined their dynamics during the first hour of post-exercise recovery in highly trained athletes.

Material and Methods The study included 23 athletes (8 women and 15 men), all members of the Polish Youth National Rowing Team. All participants were university students. Participants completed a 6000-meter test on a Concept2 Model D rowing ergometer. Capillary blood samples were collected from the earlobe at three time points: at rest (T0), immediately after exercise (T1), and 60 minutes post-exercise (T2). Analyses were performed using a portable EPOC analyzer. Parameters assessed included acid-base balance (pH, pCO_2, pO_2, TCO_2, $cHCO_3^-$, BE(ecf), BE(b)), electrolytes (Na^+, K^+, Ca^{2+}, Cl^-), hematological markers (Hct, cHgb), and energy metabolism (glucose, lactate). Renal indicators such as creatinine, urea, and their ratios (BUN/Creatinine, Urea/Creatinine) were also measured. Data were analyzed using repeated measures ANOVA to detect differences across time points and between sexes. Statistical significance was set at $p < 0.05$.

Results The exercise caused significant acid-base disturbances. At T1, pH, TCO_2, and $cHCO_3^-$ levels decreased, with partial recovery at T2. Women showed consistently lower pCO_2 and base excess values than men, indicating sex-related differences in compensatory responses. In men, post-exercise sodium decreased and chloride increased. In women, potassium levels dropped significantly at T1. Calcium remained stable in both groups. Glucose and lactate levels increased after exercise and declined by T2. Lactate levels were higher in men. Creatinine increased after exercise and remained elevated at T2. In men, urea levels also increased during recovery. Hematocrit and hemoglobin rose after exercise and declined afterward, with women showing lower values throughout.

Conclusions Intense physical exertion leads to substantial disturbances in acid–base and electrolyte balance, with compensatory mechanisms failing to restore homeostasis within one hour post-exercise fully. Sex-specific differences in pCO_2, sodium, potassium, and metabolic responses suggest distinct physiological adaptation strategies. These findings highlight the importance of individualized recovery protocols and the consideration of sex-specific factors in training program design to enhance adaptation and accelerate the return to homeostasis. They also provide practical insights for physical education in university settings, supporting the development of evidence-based recovery strategies for student-athletes.

Keywords: acid-base balance, blood gases, physical exertion, athletes, rowers, maximum exertion, intensive exercise

Glossary
ABB – Acid–Base Balance
H^+ – Hydrogen ions
pCO_2 – Partial pressure of carbon dioxide
pO_2 – Partial pressure of oxygen
TCO_2 – Total carbon dioxide content in plasma
Na^+ – Sodium
K^+ – Potassium
Ca^{2+} – Ionized calcium
Cl^- – Chloride
Hct – Hematocrit
Glu – Glucose
Lac – Lactate
Crea – Creatinine
Urea – Urea

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BUN – Blood urea nitrogen
cHgb – Hemoglobin concentration
$cHCO_3^-$ – Bicarbonate level
cSO_2 – Total blood oxygen saturation
$cTCO_2$ – Total CO_2 content in plasma
BE(ecf) – Base excess in extracellular fluid
BE(b) – Base excess in blood
AGap – Anion gap
AGapK – Anion gap including potassium
BUN/Crea – Blood urea nitrogen to creatinine ratio
Urea/Crea – Urea to creatinine ratio

Introduction

High-intensity physical activity is a major factor that disrupts the body's acid-base balance (ABB). The primary disturbance is the accumulation of hydrogen ions (H^+), which causes a reduction in pH in both blood and skeletal muscle. The extent and nature of these changes depend not only on the type and intensity of the exercise but also on the athlete's training status and current training load. These factors influence the body's physiological adaptation mechanisms [1].

Acid-base balance, defined as the dynamic maintenance of the proper ratio of cations to anions in body fluids, is essential for the optimal functioning of the nervous, muscular, and enzymatic systems [2]. Physical exertion increases acidification, which, if inadequately buffered, can limit exercise capacity, enhance the perception of fatigue, and prolong recovery time [3]. The body employs several compensatory mechanisms to counteract acidification, with the bicarbonate buffer system playing a primary role. Under conditions of intense exercise, HCO_3^- is crucial in neutralizing excess H^+. As suggested by Baranauskas et al., a higher baseline concentration of HCO_3^- may enhance buffering capacity and improve anaerobic performance [4].

The kidneys also play a key role in regulating acid-base balance, contributing through both the reabsorption and synthesis of new bicarbonate ions via net acid excretion mechanisms [5]. Acid-base balance is further influenced by non-exercise factors such as diet [6]. A diet high in animal protein, which is typical of the Western diet, increases endogenous acid production and may promote chronic metabolic acidosis [7]. Studies among Lithuanian athletes showed that high-protein diets, comprising 25 to 30 percent of total intake, were associated with acid-base imbalances [4].

Hypoxia is another factor affecting acid-base balance. By increasing minute ventilation, it reduces pCO_2 and induces respiratory alkalosis. When combined with physical exertion, this may result in the coexistence of opposing disturbances, such as metabolic acidosis and respiratory alkalosis, which further complicates the maintenance of acid-base homeostasis [8].

In response to potential disturbances in acid-base balance, various ergogenic support strategies have been employed [9]. For example, sodium bicarbonate supplementation has been used to enhance hydrogen ion buffering capacity. However, as demonstrated by Gurton et al., it does not always lead to significant effects [10]. Drid et al. reported that hydrogen-enriched water may help mitigate exercise-induced acidification by increasing arterial blood pH [3].

Despite a growing body of research on acid-base balance, data on post-exercise acid-base restitution remain limited, especially following prolonged exertion under real-world conditions in highly trained athletes. Furthermore, few studies have considered the effects of preceding training loads or sex-related physiological differences.

The aim of this study was to evaluate changes in selected acid-base balance parameters following an endurance rowing test over 6000 meters in highly trained male and female rowing athletes. The study also assessed the restitution process within one hour post-exercise, taking into account prior training load and potential sex-related differences. It was hypothesized that in trained individuals, all acid-base balance parameters would return to baseline values within one hour and that the physiological response would not differ significantly between women and men.

Materials and Methods

Participants

The study involved rowing athletes, including women (n = 8) and men (n = 15), all of whom were members of the Polish Youth National Rowing Team. All participants were university students. Prior to the ergometric test, anthropometric parameters were assessed using the Tanita MC-980 body composition analyzer and Gmon software. Detailed body composition and participant characteristics are presented in Table 1.

The study was conducted in accordance with the principles of the Declaration of Helsinki. The research protocol was approved by the Local Ethics Committee at the Poznań University of Medical Sciences (Resolution No. 645/24). All participants were fully informed about the study procedures and provided written informed consent prior to participation.

Inclusion Criteria

Participants were included if they met the following conditions: at least five years of training experience, up-to-date medical clearance, active student status, consent to blood sampling, current enrollment at the university, membership in the National Team, and successful completion of the 6000-meter ergometer test.

Exclusion Criteria

Participants were excluded if they had any injuries or reported the use of medications or dietary supplements. As shown in Table 1, male athletes were generally taller, heavier, and had greater fat-free mass compared to their female counterparts. Female participants demonstrated a higher percentage of body fat. These differences reflect typical sex-related physiological characteristics and may influence metabolic and performance responses during exercise and recovery.

An overview of the athletes' training load in the seven days preceding the ergometer test is presented in Table 2. The data include total training time, rowing-specific volume and intensity, strength training, and unspecific activities such as running.

The data indicate a variable training schedule among participants, with notable fluctuations in training volume and intensity across the week. Most rowing-specific and endurance training was performed on days 3, 5, and 6, while force development was concentrated on days 3 and 5. Unspecific training, including activities such as running, was consistently incorporated throughout the week, with the highest volumes on days 2 and 3.

Research Design

All athletes performed a 6000-meter ergometric test on a rowing ergometer (CONCEPT2, USA). Prior to the exercise, each subject completed a 5-minute individual warm-up. Blood samples were collected in the morning under fasting conditions at three time points: at rest (before exercise), immediately after exercise, and one hour after its completion. Capillary blood (90 µl) was obtained from the earlobe to assess acid-base balance.

Measurements were conducted using a portable EPOC blood analysis system (Siemens Healthineers, USA) to evaluate blood gases, electrolytes, and metabolic markers. The following parameters were determined: pH, pCO_2 (partial pressure of carbon dioxide), pO_2 (partial pressure of oxygen), TCO_2 (plasma carbon dioxide content), Na^+ (sodium), K^+ (potassium), Ca^{2+} (ionized calcium), Cl^- (chloride), Hct (hematocrit), Glu (glucose), Lac (lactate), Crea (creatinine), Urea (urea), BUN (blood urea nitrogen), cHgb (hemoglobin), $cHCO_3^-$ (bicarbonate level), $cTCO_2$ (total plasma CO_2 content), BE(ecf) (extracellular fluid base excess), BE(b) (blood base excess), cSO_2 (total blood oxygen saturation), AGap (anion gap), AGapK (anion gap with potassium), BUN/Crea (blood urea nitrogen to creatinine ratio), and Urea/Crea (urea to creatinine ratio).

In addition, the following performance-related parameters were recorded: time [s], power [W], power relative to body weight [W/kg], and lactate concentration [mmol/L]. The characteristics of the participants' effort are presented in Table 3.

The results indicate higher absolute power output and shorter completion times among male athletes. However, relative power output (W/kg) showed smaller differences between sexes. Both groups demonstrated substantial increases in lactate concentration post-exercise, with partial recovery after one hour, indicating comparable anaerobic engagement and recovery kinetics.

Table 1. Body Composition and Participant Characteristics

Parameter	Female ($\bar{x}$ ± SD)	Male ($\bar{x}$ ± SD)
Age [years]	18.75 ± 1.30	19.33 ± 1.14
Body mass [kg]	66.35 ± 5.98	86.50 ± 7.97
Height [cm]	171.88 ± 3.10	191.80 ± 4.53
Body fat [%]	18.60 ± 4.76	9.99 ± 2.97
Fat-free mass [kg]	53.95 ± 5.28	77.67 ± 5.53

Table 2. Training loads

Training Variables	Days before the 6000m test						
	1	2	3	4	5	6	7
Total training time, min/day	115	90	210	100	205	110	95
Time rowed, min/day	60	-	30	80	40	60	-
Distance rowed, km/day	12	-	6	18	8	10	-
Training for force development, min/day	-	-	85	-	105	-	-
Moderate endurance rowing training time, min/day	40	-	30	40	40	10	-
High intensity endurance rowing training time, min/day	20	-	-	40	-	50	-
Unspecific training (running, etc.), min/day	55	90	95	20	60	50	95

Statistical Analysis

Statistical analyses and data visualization were performed using GraphPad Prism 9 (GraphPad Software, Boston, USA). Descriptive statistics, including mean and standard deviation (SD), were calculated to illustrate trends across three time points. The Shapiro–Wilk test was used to assess the normality of distribution. To verify the assumption of equal variances between groups, Levene's test was applied. Group differences across time (Baseline, Post, and 1-hour recovery) were analyzed using a two-way repeated measures analysis of variance (ANOVA), followed by Tukey's post hoc test. When the assumption of sphericity was violated, Greenhouse–Geisser correction was applied. A p-value of $\leqslant 0.05$ was considered statistically significant.

Results

Acid–Base Balance (Fig. 1)

In all participants, the 6000-meter ergometer test induced a statistically significant decrease in pH (Fig. 1A), TCO_2 (Fig. 1B), and bicarbonate ($cHCO_3^-$) (Fig. 1C). During the recovery phase, these parameters increased significantly but remained below baseline, indicating partial restitution of acid–base balance. A

Table 3. Exercise Characteristics of the Participants – 6000 m Ergometer Test

Parameter	Female ($\bar{x}$ ± SD)	Male ($\bar{x}$ ± SD)
Exercise duration [s]	1457 ± 29.30	1252 ± 43.97
Power [W]	195.86 ± 11.48	309.47 ± 27.30
Power/body weight [W/kg]	3.00 ± 1.01	3.37 ± 0.91
Lactate [mmol/L] T1	1.23 ± 0.33	1.05 ± 0.23
Lactate [mmol/L] T2	12.40 ± 2.01	11.87 ± 2.58
Lactate [mmol/L] T3	3.19 ± 1.06	3.00 ± 1.47

Note. T1 – resting value (before exercise); T2 – immediately after exercise; T3 – 60 minutes post-exercise.

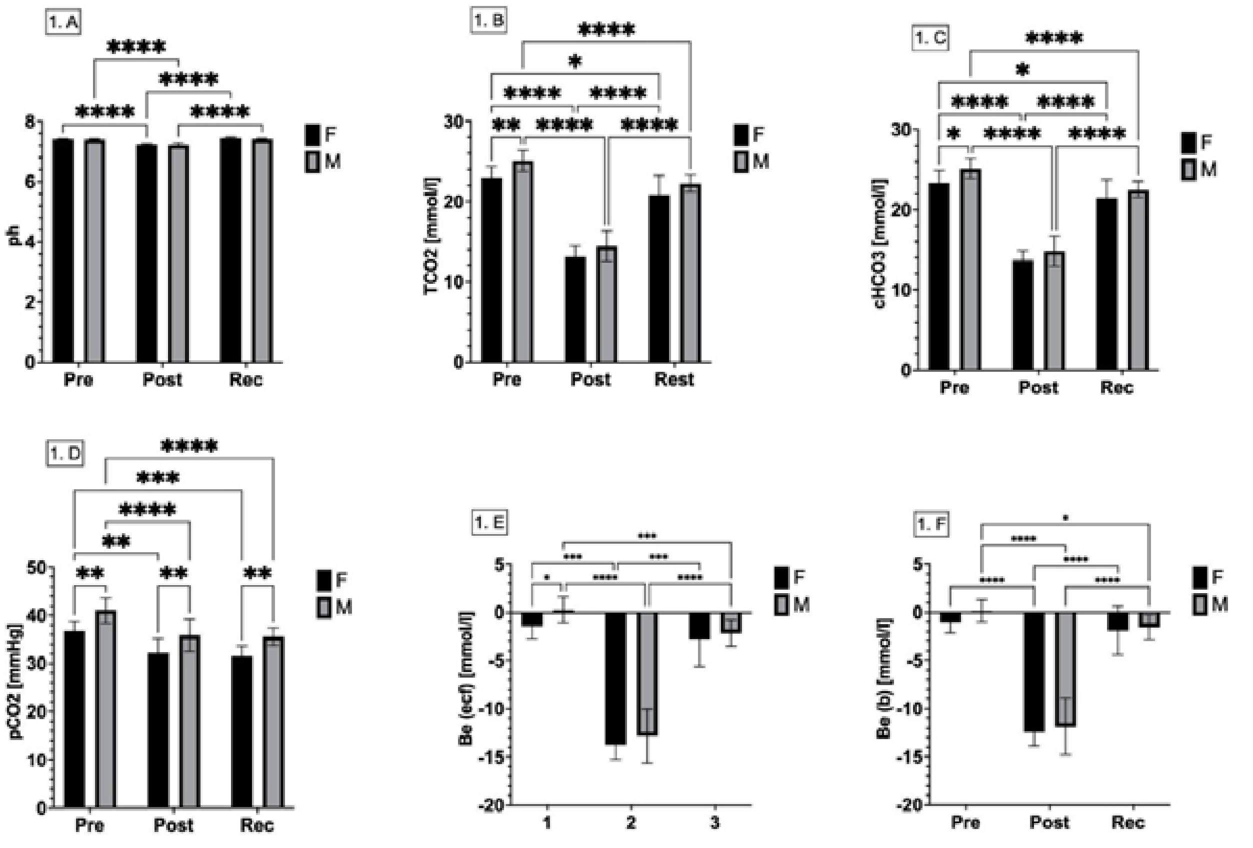

Figure 1. Levels of acid–base balance parameters before exercise, immediately after, and one hour following the 6000-meter ergometer test: 1A – pH, 1B – plasma carbon dioxide (TCO_2), 1C – bicarbonate ($cHCO_3^-$), 1D – partial pressure of carbon dioxide (pCO_2), 1E – base excess in extracellular fluid (BE(ecf)), and 1F – base excess in blood (BE(b)). Values are presented as mean ± standard deviation. Statistical significance: $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$, $^{****}p < 0.0001$.

significant post-exercise decrease in pCO_2 was also observed (Fig. 1D), with consistently lower values in women at all time points compared to men. Base excess in both extracellular fluid (BE(ecf), Fig. 1E) and blood (BE(b), Fig. 1F) declined after exercise and showed partial recovery during the restitution phase.

Electrolyte Balance and Water–Electrolyte Status (Fig. 2)

Sodium levels (Na^+, Fig. 2A) did not differ significantly between sexes. However, a statistically significant post-exercise decrease in sodium concentration was observed in men, which was not present in women. Potassium levels (K^+, Fig. 2B) showed a significant sex-related difference. In women, exercise caused a marked reduction in potassium, and values during the recovery phase remained below baseline. In men, baseline potassium levels were higher, with a slight decrease observed after exercise.

Chloride concentrations (Cl^-, Fig. 2C) remained stable in women across all time points. In contrast, men exhibited an increase in chloride levels immediately after exercise, followed by a decline during restitution. Calcium concentrations (Ca^{2+}, Fig. 2D) showed no significant changes in response to exercise in either group.

Energy Metabolism and Metabolite Elimination (Fig. 3)

In both women and men, the 6000-meter exercise test led to a significant increase in blood glucose concentration (Fig. 3A). During the restitution phase, glucose levels decreased significantly compared to the post-exercise peak. A similar dynamic was observed for lactate (Fig. 3B), with a pronounced increase immediately after exercise, followed by a significant reduction during recovery. In men, lactate concentration remained elevated even one hour post-exercise and was significantly higher at this point compared to baseline.

Renal Filtration and Metabolite Elimination Rates (Fig. 4)

In both groups, the 6000-meter exercise test led to a significant increase in creatinine concentration

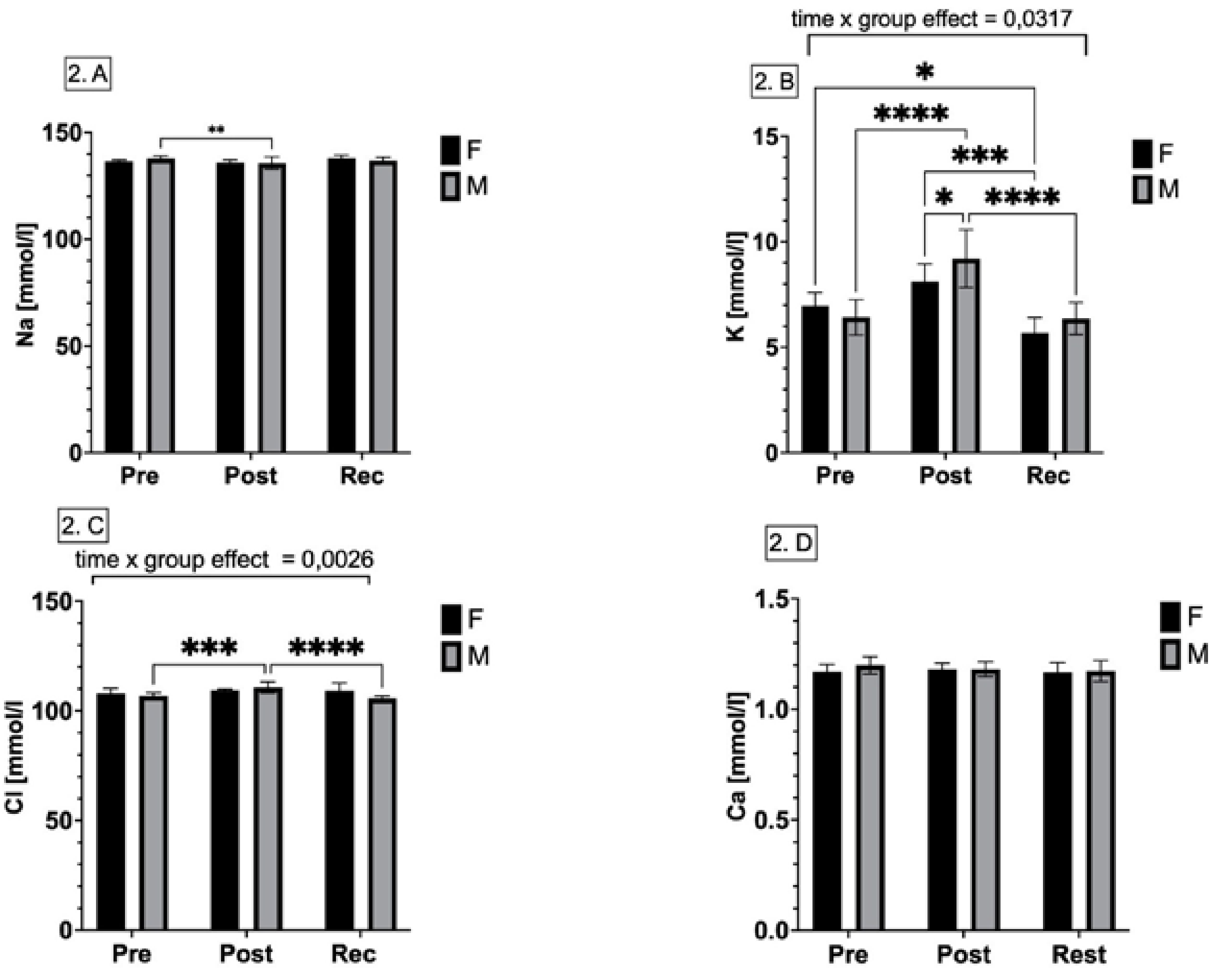

Figure 2. Electrolyte concentrations measured before exercise, immediately after, and one hour following the 6000-meter ergometer test: 2A – sodium (Na^+), 2B – potassium (K^+), 2C – chloride (Cl^-), and 2D – calcium (Ca^{2+}). Values are presented as mean ± standard deviation. Statistical significance: *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$, ****$p < 0.0001$.

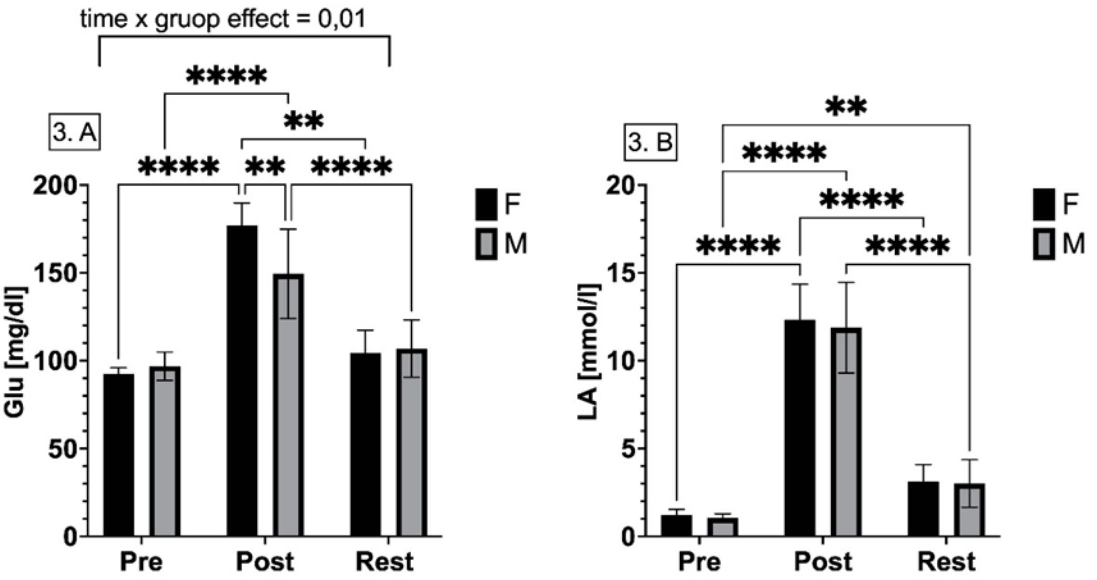

Figure 3. Energy metabolism parameters measured before exercise, immediately after, and one hour following the 6000-meter ergometer test: 3A – glucose concentration (Glu), 3B – lactate concentration (Lac). Values are presented as mean ± standard deviation. Statistical significance: *p < 0.05, **p < 0.01, ***p < 0.001, ****p < 0.0001.

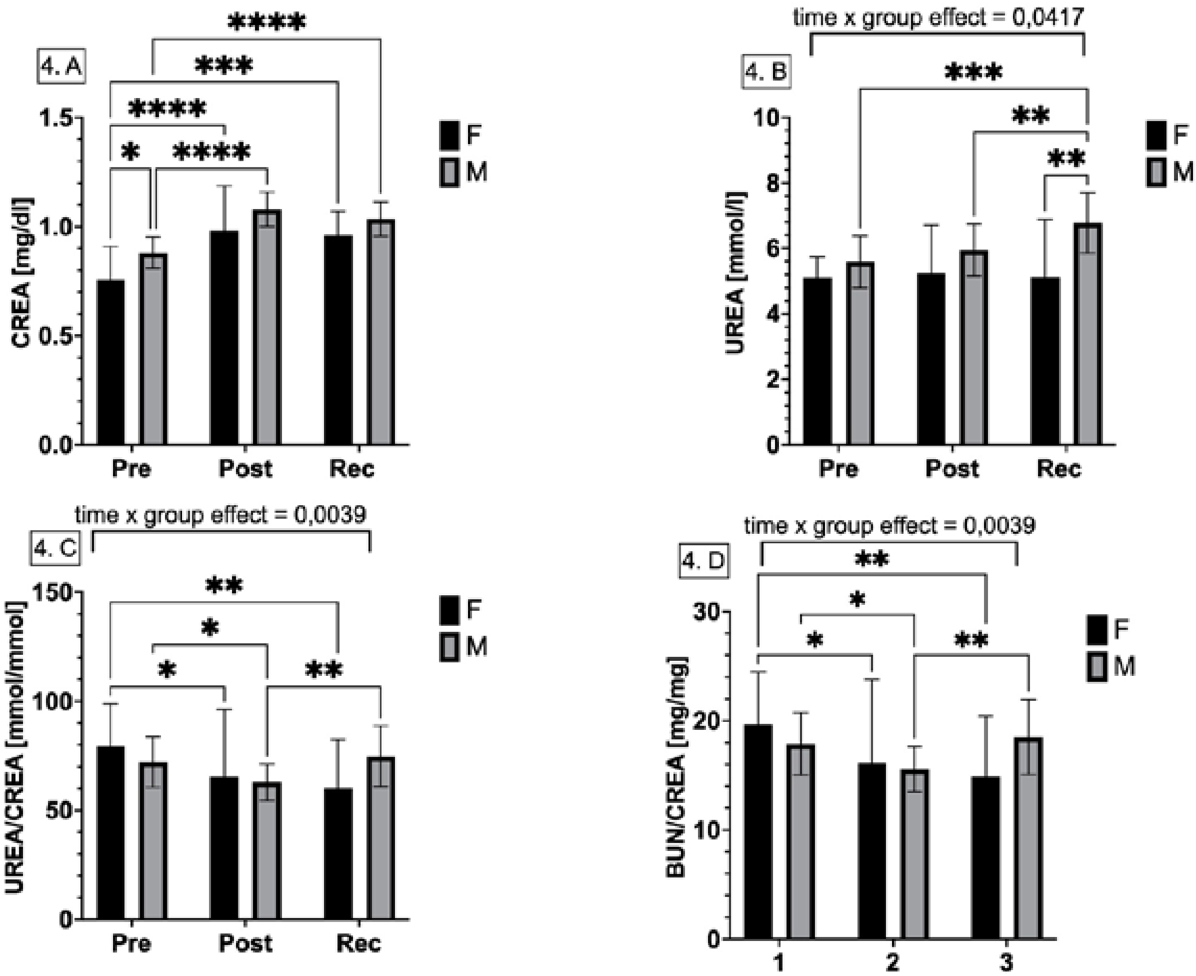

Figure 4. Renal and metabolic elimination parameters measured before exercise, immediately after, and one hour following the 6000-meter ergometer test: 4A – creatinine concentration (Crea), 4B – urea concentration (UREA), 4C – urea to creatinine ratio (Urea/CREA), 4D – blood urea nitrogen to creatinine ratio (BUN/CREA). Values are presented as mean ± standard deviation. Statistical significance: *p < 0.05, **p < 0.01, ***p < 0.001, ****p < 0.0001.

(Fig. 4A). During the restitution phase, creatinine levels remained elevated and were not significantly different from post-exercise values. However, compared to baseline, creatinine levels at one hour post-exercise were still significantly higher. In men, a significant increase in urea concentration was observed during the restitution phase (Fig. 4B), whereas no significant changes occurred in women.

The ratios of urea to creatinine (Urea/CREA, Fig. 4C) and blood urea nitrogen to creatinine (BUN/CREA, Fig. 4D) did not differ significantly between sexes. Nevertheless, both ratios tended to decrease after exercise and to rise during the restitution phase in both groups.

Discussion

The aim of this study was to evaluate the dynamics of selected acid–base and electrolyte balance parameters following a 6000-meter rowing ergometer test and to assess the restitution process within one hour post-exercise in trained male and female athletes. The results demonstrated that intensive physical exertion led to significant shifts in acid–base status across all participant groups.

In particular, a marked decrease in pH (Fig. 1A), TCO_2 (Fig. 1B), and bicarbonate (HCO_3^-, Fig. 1C) was observed immediately after exercise, indicating the development of exercise-induced metabolic acidosis. During the recovery period, these parameters showed partial restoration but did not return to baseline levels, suggesting a persistent buffer deficit.

The decrease in pCO_2 (Fig. 1D), especially pronounced in women, likely reflects exercise-induced hyperventilation as a compensatory mechanism aimed at mitigating systemic acidification. Similarly, base excess values in extracellular fluid and blood (Fig. 1E, 1F) declined significantly post-exercise and then partially normalized during recovery. These findings point to the activation of physiological buffering systems involved in maintaining acid–base homeostasis.

Similar findings have been reported in previous studies involving rowers. Intensive exercise on a rowing ergometer over a distance of 6000 meters has been shown to significantly reduce blood pH, confirming the development of metabolic acidosis. This physiological response is attributed to the accumulation of hydrogen ions (H^+) and increased lactate production [11], both of which exceed the body's intrinsic buffering capacity.

Nielsen et al. [12] examined the dynamics of pH changes in male athletes following rowing competitions. Their study demonstrated that maximal effort over a 2000-meter rowing distance resulted in a reduction of hemoglobin oxygen saturation (SaO_2) to 93%. The authors suggested that decreased pH diminishes hemoglobin's affinity for oxygen, thereby potentially limiting oxygen delivery to peripheral tissues during and after exertion.

Lühkera et al. [8] further investigated acid–base changes under normoxic and hypoxic conditions. They concluded that acidosis during exercise is primarily driven by lactate accumulation in active muscle tissue. Lactate is exported from muscle cells via monocarboxylate transporters, and the efficiency of this transport system plays a crucial role in preserving intramuscular acid–base equilibrium, even under conditions of elevated H^+ and lactate concentrations.

Additionally, sodium (Na^+), potassium (K^+), and calcium (Ca^{2+}) ions (Fig. 2A, 2B, 2D) play essential roles in maintaining electrolyte balance and regulating cellular excitability. These ions directly influence the function of the sodium–potassium pump and the sodium–calcium exchanger, which are critical for the propagation of action potentials and neuromuscular coordination. Fluctuations in their concentrations during and after exercise may impair muscle fiber responsiveness and reduce contraction efficiency.

Furthermore, the central role of lactate (Fig. 3B) is emphasized as one of the key contributors to the development of exercise-induced metabolic acidosis. Elevated lactate levels reflect increased anaerobic metabolism and correspond with a rise in hydrogen ion concentration, both of which exceed the buffering capacity of the body during high-intensity exertion.

Analysis of electrolyte concentrations, including sodium (Na^+), potassium (K^+), chloride (Cl^-), and calcium (Ca^{2+}) (Fig. 2A, 2B, 2C, 2D), allows for the assessment of ionic homeostasis in response to physical exertion both before and after the exercise test. The results indicate sex-related variations in the regulation of these ions.

There were no significant differences in sodium concentrations between women and men, which suggests that sodium-regulating mechanisms were similarly effective in both groups. However, a significant decrease in Na^+ levels was observed in men following exercise (Fig. 2A). This finding may be attributed to sodium loss through sweating or to shifts in water distribution between intracellular and extracellular compartments. Similar observations have been reported in endurance athletes, where intense physical exertion led to exercise-induced hyponatremia as a result of combined sodium depletion and fluid overload [13].

In contrast, potassium levels (Fig. 2B) decreased significantly in women after exercise and remained below baseline during the recovery phase. In men, higher baseline K^+ concentrations followed by a post-exercise decline may reflect sex-related differences in muscle mass and potassium efflux during muscular contraction. Previous studies have shown that intense physical effort leads to transient hyperkalemia as a result of potassium release from active muscle cells. This condition is typically short-lived and is rapidly corrected by physiological compensatory mechanisms responsible for maintaining ionic equilibrium [14].

Chloride levels (Fig. 2C) remained stable in women, which indicates consistent regulation of this ion throughout the testing period. In men, chloride concentrations increased after exercise and then declined during the recovery phase. These fluctuations may be associated with acid–base compensation processes, particularly the role of chloride in maintaining pH balance through ion exchange mechanisms [15].

Intense physical activity appears to influence electrolyte balance in a sex-specific manner. Variations in sodium, potassium, and chloride concentrations likely reflect physiological differences in adaptive responses as well as distinctions in body composition. In contrast, calcium levels (Fig. 2D) remained stable at all time points in both groups. This suggests that homeostatic mechanisms regulating calcium were effective during and after exertion. The maintenance of calcium balance is especially important given its essential role in neuromuscular transmission and muscle contraction [16].

Analysis of kidney function parameters, including creatinine (Crea, Fig. 4A), urea (BUN and Urea, Fig. 4B), and the BUN to creatinine (BUN/Crea, Fig. 4D) and urea to creatinine (Urea/Crea, Fig. 4C) ratios, provides important insight into the physiological adaptation to intense physical exertion and the associated metabolic demands.

An increase in creatinine concentration was observed after exercise, and elevated levels persisted during the recovery phase when compared to baseline (Fig. 4A). This response may reflect greater creatinine release from active skeletal muscle due to increased metabolic turnover. Previous studies involving triathletes have documented a post-race increase in creatinine by 17.25 percent, which was interpreted as a transient reduction in glomerular filtration rate (eGFR) in response to high-intensity exertion [17]. Similar findings have been reported in endurance athletes, where creatinine elevation was associated with exercise intensity and the degree of dehydration [18].

Changes in urea concentration (Fig. 4B) may serve as an indicator of catabolic activity and the body's adaptive metabolic response to physical exertion. A significant increase in urea levels was observed in men during the recovery phase, which may be attributed to enhanced muscle protein breakdown and a reduction in plasma volume. In women, no significant changes were recorded, potentially reflecting lower metabolic stress or differences in lean muscle mass.

In the previously cited study on triathlon athletes, no significant post-race changes in urea concentration were reported, suggesting that the metabolic response to exercise may vary depending on the type, duration, and intensity of physical activity [17]. These findings are consistent with earlier research, which demonstrated that blood urea nitrogen accumulation correlates with the extent of skeletal muscle protein catabolism during prolonged exertion [19].

The BUN to creatinine (BUN/Crea, Fig. 4D) and urea to creatinine (Urea/Crea, Fig. 4C) ratios remained relatively stable between sexes, despite significant fluctuations in the individual parameters. This stability suggests a complex interplay between catabolic activity and renal excretory function. The transient decrease in these ratios immediately following exercise, followed by an increase during the recovery phase, may reflect compensatory mechanisms aimed at regulating the elimination of metabolic by-products.

In addition, previous studies in triathletes have reported an exercise-induced increase in uric acid concentration, which has been linked to elevated oxidative stress and enhanced purine metabolism. These factors may further influence renal function following intense physical effort [20].

Overall, the analysis of renal function parameters in response to strenuous exercise emphasizes the importance of monitoring these indicators to assess physiological adaptation and to support the early detection of potential renal impairment in athletes. While elevations in creatinine (Fig. 4A) and urea (Fig. 4B) may result from transient reductions in glomerular filtration rate and increased protein catabolism, the relative constancy of BUN/Crea and Urea/Crea ratios suggests the involvement of effective regulatory mechanisms that maintain metabolic balance.

The findings of this study demonstrate that intensive endurance exercise, such as a 6000-meter rowing ergometer test, induces significant disturbances in acid–base equilibrium, electrolyte composition, and renal filtration markers in highly trained athletes. These responses are partially sex-dependent and reflect the complex physiological adaptations involved in metabolic regulation, ventilation, ion transport, and renal function. The observed dynamics highlight the importance of individualized recovery strategies and underline the relevance of monitoring biochemical responses to optimize training and minimize physiological stress.

Practical Implications for Physical Education

These findings carry important practical implications for physical education and sport among university students. The observed physiological responses to intense exertion, particularly the incomplete restitution of acid–base and electrolyte balance within one hour, emphasize the need for tailored recovery protocols in student-athlete populations. Integrating post-exercise monitoring of biochemical markers, such as pH, bicarbonate, and electrolytes, may support more individualized and effective training adjustments. This approach is especially relevant in academic environments, where time constraints and cumulative stress may impair recovery. Applying these findings in educational and training settings can enhance students' performance, prevent overtraining, and support long-term physiological adaptation.

Study Limitations and Future Directions

This study has several limitations that should be taken into account. The sample size was relatively small, and all participants were elite university-level rowers, which limits the generalizability of the findings. The study did not control for hydration status, previous day training loads, or dietary composition, all of which may influence acid–base and electrolyte parameters. Future research should involve larger and more diverse athletic populations and explore additional physiological mechanisms of adaptation, including hormonal regulation, intracellular buffering systems, and lactate transport efficiency under various training loads.

Conclusions

The physical exercise protocol applied in this study led to disruptions in acid–base and electrolyte balance in both female and male athletes. Although compensatory mechanisms were activated during the recovery phase, not all parameters returned to baseline levels within one hour. This finding underscores the importance of extending the recovery period to achieve complete physiological restoration and has practical implications for designing effective regeneration strategies in competitive athletes.

The observed changes in electrolyte concentrations, particularly sodium and potassium, may be influenced by individual supplementation habits. These factors should be taken into account when developing personalized exercise and recovery programs. Post-exercise assessment of acid–base balance offers valuable information regarding athletes' functional status, physical capacity, and current stage of physiological adaptation.

The results of this study may provide a basis for optimizing training and recovery protocols and for improving monitoring of athletes' physical condition. Future research should explore longer recovery periods and systematically evaluate the impact of supplementation, hydration status, and training load variability. These findings highlight the importance of internal balance monitoring as a fundamental component of athlete assessment and performance management.

Conflict of interests

The authors declare that there is no conflict of interests.

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