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Abstract: To evaluate the effectiveness of a dual approach involving time-restricted eating (TRE) at different times-of-day combined with physical activity (PA) on functional capacity and metabolic health in overweight or obese women. Random allocation of sixty-one participants into four groups: early time-restricted eating plus physical activity (ETRE-PA, n=15, 31.8±10.56 years, 89.68±10.56 kg, 33.5±5.53 kg/m²), late time-restricted eating with physical activity (LTRE-PA, n=15, 30.60±7.94 years, 94.45±15.36 kg, 34.37±7.09 kg/m²), late time-restricted eating only (LTRE, n=15, 27.93±9.79 years, 88.32±10.36 kg, 32.71±5.15 kg/m²) and a control group (CG, n=15, 36.25±11.52 years, 89.01±11.68 kg, 33.66±6.18 kg/m²). The intervention lasted 12 weeks for all groups. Both ETRE-PA and LTRE-PA groups engaged in a rigorous combined aerobic and resistance-training program. Significant reductions in body weight and body mass index were observed in ETRE-PA and LTRE-PA compared to CG and LTRE groups in post-intervention (p<0.0005). Only ETRE-PA group exhibited a significant decrease in fat mass (p=0.02), low-density lipoprotein cholesterol (p=0.01) and aspartate aminotransferase (p=0.002). Significant reductions in alanine aminotransferase levels were observed in ETRE-PA (p=0.004) and LTRE-PA (p=0.02) groups. These two latter groups achieved higher performances in the 6-min walking test, bench press, 30-second squat, crunch test, vertical jump (p<0.0005 for both) and leg extension (p<0.02 for both) when compared to LTRE and CG groups. In conclusion, the integration of TRE with PA leads to greater improvements in body composition, lipid profile, and physical performance with no significant differences between ETRE-PA and LTRE-PA approaches. This combined strategy offers a promising solution in overweight or obese women.

Keywords: time-restricted eating; circadian rhythms; metabolic health; physical performance

1. Introduction

Obesity is a major public health concern with over 2.5 billion adults classified as overweight (body mass index, BMI ≥25 kg/m²) and 890 million with obesity (BMI >30) [1]. The current rise of obesity prevalence [2] is associated with increased risk for chronic illness [3]. Furthermore, it is established that even a small amount of body weight loss can reduce the risk of cardiovascular disease [4]. Up until now, efforts to treat and prevent overweight and obesity through dietary approaches have been focused on decreasing calorie intake and enhancing the overall quality of the diet [5]. However, maintaining these strategies over time has been challenging, leading to limited success.

Moreover, research has shown that irregular eating patterns can have negative effects on body's circadian rhythms regardless of meal size or macronutrient composition [6]. Notably, dietary approaches that prioritize the timing of eating and length of fasting periods known as chrono-nutrition have been shown to enhance metabolic health irrespective of the kind, quality or quantity of foods consumed without necessarily resulting in weight loss [7]. Indeed, intermittent fasting (IF) has become a popular weight loss strategy that involves refraining from ingesting food and caloric beverages for specified times [8,9]. A specialized IF technique called time-restricted eating (TRE) involves regular fasting and eating windows that fall within a 24-hour cycle is highly recommended for persons living with obesity [10]. Earlier studies looked into how TRE might affect body composition [11] and metabolic health markers [12]. While the timing of daily meals in TRE can range from 4 to 12 hours with food intake periods starting either early (ETRE) or later in the day (LTRE). So far, few studies have compared ETRE and LTRE outcomes on metabolic health and fitness [13]. Despite the potential effects of physical exercise on physical fitness and physiological adaptation during fasting, only few studies investigated the combined effect of physical activity and TRE in metabolic disorders [14]. A review by Albosta et al. [15] concluded that endurance exercise practiced in fasted state induced a greater improvement in insulin sensitivity in type 2 diabetes patients comparatively with exercise in fed state. Furthermore, a meta-analysis conducted by Vieira et al. [16] showed that the combination of TRE and aerobic exercise induced greater body weight loss, a decrease in the liver genes related to lipogenesis and an improvement in fatty acid oxidation compared to control group. However, previous studies have highlighted metabolic differences between early and late TRE schedules [17]. Research indicated variability in how each approach impacts circadian rhythms and glucose metabolism, especially concerning breakfast consumption and the timing of exercise relative to the last meal [18]. Early TRE typically concluding in the afternoon, appeared more aligned with circadian rhythms, potentially enhancing insulin sensitivity and glucose control. While late TRE may be less effective in this area despite supporting overall caloric restriction [19]. Moreover, the timing of exercise has a profound impact on metabolic responses. Exercising in fasted state promotes fat oxidation and enhances metabolic flexibility, while postprandial exercise relies more on carbohydrate stores and may affect glucose dynamics after activity [20]. These aspects highlighted the importance of adapting TRE to individual health objective and chronobiological needs.

Moreover, a study by Wilson et al. [21] showed that 12 weeks of intermittent fasting with or without high intensity interval training (HIIT) exercise prevented weight gain and improved lipid profile in obese rats. To the best of the authors' knowledge, few studies have compared between TRE interventions practiced at different time of day (TOD) combined with PA in overweight or obese women.

Thus, the aim of the present study was to investigate the effect of concurrent (aerobic and resistance) training in combination with ETRE or LTRE on body composition, metabolic profile and functional capacity in overweight or obese women. We hypothesized that exercise intervention associated with ETRE-PA may improve body composition, biomarkers of metabolic profile and functional capacity.

2. Materials and Methods

2.1. Participants

The required sample size was determined a priori using G*Power software, following the recommended procedures by Beck [22] and based on a previous study employing the same paradigm. Statistical power was estimated at 0.85 with an alpha level of 0.05 [23]. A minimum of 40 participants were deemed necessary. This rigorous approach in determining the sample size helps to ensure that the study has sufficient statistical power to detect meaningful effects and to minimize the risk of incurring a type 2 statistical error. Initially, seventy-seven women volunteered to participate in the present study have been recruited. Before agreeing to participate, each participant was provided with a detailed description of the protocol, as well as an explanation of the potential risks and benefits involved. All the participants gave their written informed consent before participating in the study.

The inclusion criteria required the participants to have a body mass index greater than 25 kg/m2, to be able to attend laboratory assessment and training sessions, free from any known cardiovascular disease, and not pregnant. Despite an attrition rate of 21%, the study successfully enrolled 61 sedentary women who were overweight or obese. Participants body composition was assessed with a bioelectrical impedance (Model TBF-300, Tanita Corp, Tokyo, Japan) [24]. The study design has been approved by the local ethics committee (CPP SUD, n ° 0460/2022, Sfax, Tunisia, approval date: 16 December 2022) and was registered in the Pan African Clinical Trials Registry PACTR202301473691345 and has been conducted in accordance with the Helsinki guidelines.
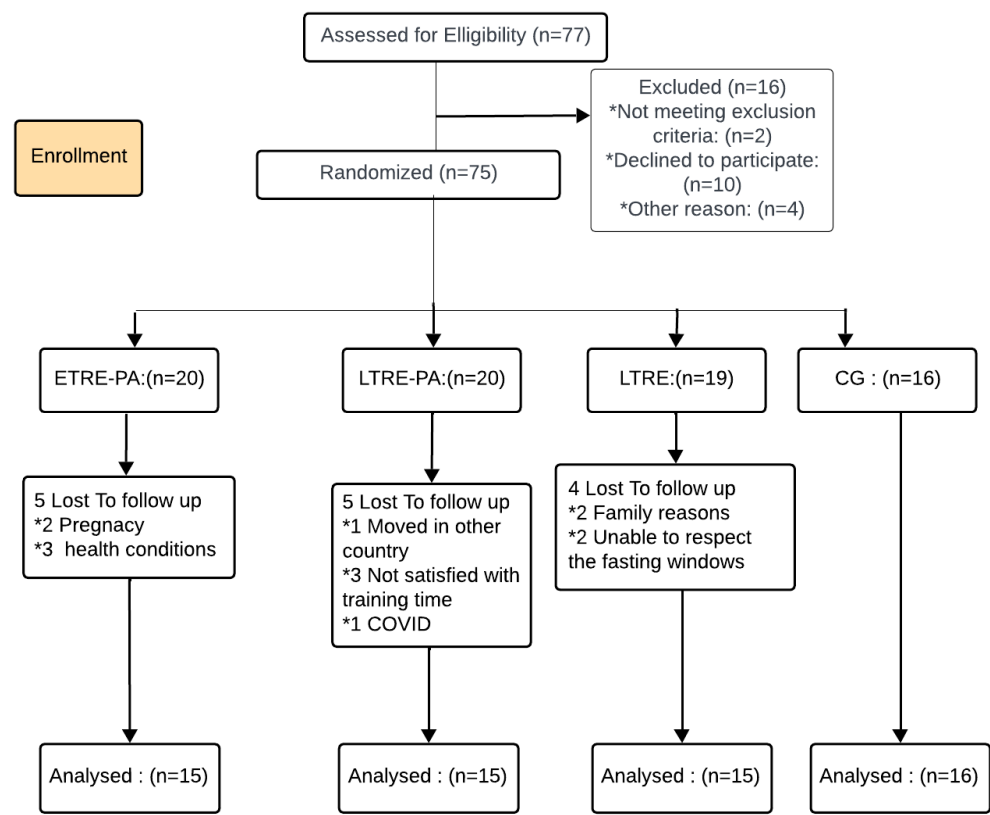

Figure 1. Flow chart of participants' recruitment. ETRE-PA: Early time-restricted eating combined with physical activity group; LTRE-PA: Late time-restricted eating combined with physical activity group, LTRE: Late time-restricted eating group; CG: Control group.

2.2. Study Design

Participants were randomly assigned to one of four groups: ETRE-PA (n=15, 31.8±10.56 years, 89.68±10.56 kg, 33.5±5.53 kg/m²), LTRE-PA (n=15, 30.60±7.94 years, 94.45±15.36 kg, 34.37±7.09 kg/m²), LTRE (n=15, 27.93 ± 9.79 years, 88.32 ± 10.36 kg, 32.71± 5.15 kg/m²) and CG (n=16, 36.25 ±11.52 years, 89.01±11.68 kg, 33.66±6.18 kg/m²). The two experimental groups adhered to a time-restricted eating (TRE) protocol ad libitum and participated in training sessions that combined aerobic exercises with muscle-strengthening activities (Figure 2). The intervention spanned twelve weeks, during which body composition, biochemical and physical performance were measured. The participants of the control group (CG) were advised to maintain their regular daily meal and bedtime routines throughout the study. To ensure consistency, all measurements were taken between 7:00 am and 12:00 pm after a 16-hour fast. The three intervention groups (ETRE-PA, LTRE-PA, and LTRE) received dietary guidelines with specific recommendations on meal timing, daily caloric intake and macronutrient distribution, designed to achieve a total daily intake of 1,200–1,500 kcal. Participants were instructed to consume three daily meals without additional snacks, all within 8-hour period

followed by 16-hour fasting period. However, a 4-hour difference was established between the meal timing of ETRE-PA group, LTRE-PA and LTRE groups. Participants in ETRE-PA group were required to abstain from consuming any calories between 4:00 pm and 8:00 am the following day throughout the intervention. In contrast, participants in LTRE-PA and LTRE groups were instructed to follow their customary dietary patterns but within a designated eating window from 12:00 pm to 8:00 pm, allowing an 8-hour period for food consumption while restricting intake outside this timeframe.
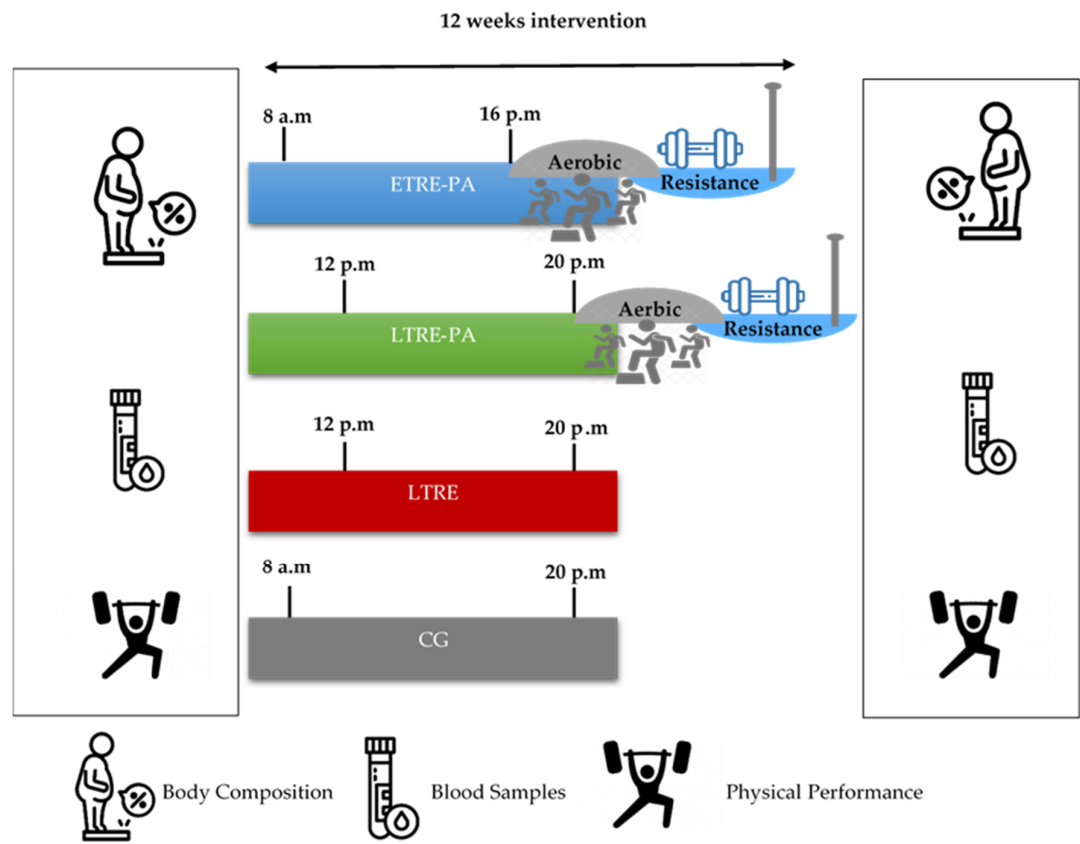

Figure 2. Study Design. ETRE-PA: Early time-restricted eating combined with physical activity; LTRE-PA: Late time-restricted eating combined with physical activity; LTRE: Late time-restricted eating; CG: Control group.

2.3. Training Sessions

ETRE-PA and LTRE-PA participants were required to attend all physical training sessions at the fitness center, where they engaged in a 70-minute workout three times a week. Each training session consisted of a comprehensive routine, including warm-up (5 minutes), aerobic exercise (30 minutes), strength training (30 minutes), and stretching and breathing exercises (5 minutes).

2.3.1. Endurance Training

The training program incorporated auditory stimulation and intensity modulation (tempo). Sessions were scheduled three times per week on Monday, Wednesday, and Friday at the end of the feeding window for each group (i.e., at 4:00 pm for ETRE-PA and 8:00 pm for LTRE-PA). The intervention was divided into four phases with progressive increase of intensity within each phase lasting three weeks (nine training sessions). In the first phase, participants exercised for 30 minutes at 50-60% of their estimated maximum heart rate (HRmax: 220—age) with an auditory tempo of 135-140 beats per minute (BPM). The second phase involved exercising for 30 minutes at 55-65% of

HRmax with the same tempo. In the third phase, participants exercised for 30 minutes at an intensity of 60-70% of HRmax with a faster auditory tempo of 140-152 BPM. Finally, the fourth phase required participants to exercise for 60 minutes at an intensity of 65-75% of HRmax, with the same tempo as phase three.

2.3.2. Strength Training

The training was structured as circuit weight training, incorporating handheld weights, weight machines (Technogym, Italia), and participants' own body weight. Each participant engaged in two preliminary training sessions to become familiarized with the equipment and to master the correct techniques for executing the exercises [25].

2.4. Outcome Measures

The study spanned a period of 14 weeks, with the 12-week intervention starting after one week of baseline measures. Throughout this period, all participants maintained their usual dietary intake. Outcome measures were taken at both baseline and post-intervention. Body composition was assessed by measuring total body mass and composition including lean mass, fat-free mass (FFM), bone mass and total water before and after the intervention period, using bioelectrical impedance analysis (Model TBF-300, Tanita Corp, Tokyo, Japan). Measurements were taken in the morning following an overnight fast, with participants dressed simply and without shoes or socks. A wall-mounted stadiometer was used to measure the participants standing height to the nearest 0.1 cm.

2.5. Blood Samples

Blood samples were obtained from antecubital vein after an overnight fasting 16-hour fasting period, between 7:00 and 10:00 am, both three days before and after the intervention. Participants were advised to maintain their regular diet and avoid vigorous physical activity within 48 hours prior to each blood sampling session. The blood samples were immediately placed in an ice bath to prevent degradation and then centrifuged at 2500 rpm for 10 minutes at 4°C. The resulting plasma was divided into smaller aliquots to avoid multiple freeze-thaw cycles and stored at -80°C for 2 weeks until analysis. All measurements were performed using the Cobas 6000 ™ machine from Roche Diagnostics Manheim. The lipid profile variables, including total cholesterol (TC) and triglycerides (TG), were assessed using an enzymatic colorimetric technique. High-density lipoprotein cholesterol (HDL-c) was determined through a direct enzymatic colorimetric method, while low density lipoprotein (LDL-c) levels were calculated using the Friedewald formula:

$$[LDL] = [TC] - ([HDL] + [TG/2.2]) \ [26]$$

For the glycemic profile, fasting blood glucose was measured using an enzymatic hexokinase assay, and insulin levels were assessed using an electrochemical luminescence-based assay. Insulin resistance was quantified using the homeostatic model assessment (HOMA-IR), calculated as [insulinemia (U/mL) × glycemia (mmol/L)] / 22.5. Aspartat aminotransferase (ASAT) and alanine aminotransferase (ALAT) levels were determined using the UV kinetic assay to assess liver function. Total Bilirubin levels were measured using a colorimetric technique, creatinine, was assessed using an enzymatic method. Alkaline phosphatase levels were assessed using a visible kinetic assay, which measures the enzyme's activity at a wavelength of 405 nm. This method involves monitoring the rate of reaction over time as the substrate is converted into product, allowing for the quantification of alkaline phosphatase activity in the samples. This measurement is crucial for assessing bone and liver health. Finally, C-Reactive protein (CRP), was measured using the immuno-turbidimetric method. All measurements were conducted within a single assay run by the same experienced experimenter.

2.6. Functional Capacity

2.6.1. Six-Minute Walk Test (6MWT)

The 6-minute walk test (6MWT) was conducted to measure functional capacity [27]. During this test, participants were instructed to walk along a 30-meter corridor at their maximum speed for six minutes. The corridor was marked every 5 meters with colored tape to allow for precise measurement of the distance covered (6MWD). Before the test began, participants rested for about 10 minutes on a chair located near the starting point. Blood pressure was measured during this period to establish a baseline value. Once the participants began walking, the stopwatch was started, and each completed lap was recorded when participants returned to the starting point. In addition to the completed laps, any extra distance covered beyond the 30-meter corridor was also recorded using the nearest colored tape marker on the floor. This procedure ensured the collection of accurate and reliable data during the test.

2.6.2. Strength Tests

For strength assessments, we recorded the one repetition maximum (1-RM) for both the bench press and leg press exercises. Each 1-RM assessment was preceded by a specific warm-up routine, which involved performing five repetitions with a weight typically manageable for ten repetitions, following the techniques outlined in previous studies **[28,29]**.The 1-RM measurements were conducted at the beginning of the study and after 12 training sessions for all prescribed exercises. This allowed us to make necessary adjustments to account for any potential increases in strength that may have occurred during the course of the training program. To estimate 1-RM values, we employed the Epley method, which calculates the 1-RM as follows: 1-RM = Weight Lifted × (1 + 0.0333 × Number of Repetitions) [28].

2.6.3. Vertical Jump Test

To assess lower body explosiveness, a Takei Vertical Jump Meter (Takei, Niigata, Japan) was used. Three maximum attempts were measured with a 30-second rest time between jumps. The participants were encouraged throughout the testing process. The highest jump was selected for additional analysis.

2.6.4. 30 s Crunch and Squat Test

The 30-Second Crunch Test is a simple fitness assessment designed to evaluate the strength and endurance of the abdominal muscles. To conduct the test, the participant lies on a mat with knees bent at a 90-degree angle and feet flat on the floor. The arms are either crossed over the chest. The test begins by engaging the core muscles and lifting the shoulder blades off the ground, raising the upper body towards the knees until the elbows touch the thighs or reach a 30-degree angle. The movement is then reversed to return to the starting position. This action is repeated continuously and rhythmically for 30 seconds, with each complete crunch being counted.

The squat test was used to assess lower body strength and endurance either. Participants were instructed to stand with their feet shoulder-width apart, engage their core, bend their knees, and lower their hips towards the ground. It is important to maintain proper form by keeping the back straight and the knees in line with the toes. Once in a seated position, participants must stand back up by pushing through their heels and engaging their glutes and thigh muscles. The test lasts for 30 seconds, during which participants should aim to complete as many correctly executed squats as possible.

3. Statistical Analysis

Statistical analyses were conducted using SPSS software (v.23, IBM, New York, USA). All data were presented as mean ± standard deviation (SD). Parametric tests were performed after confirming the assumption of normality using the Kolmogorov-Smirnov test. A two-way ANOVA for repeated

measures was used to evaluate differences across groups (4 groups (ETRE-PA, LTRE-PA, LTRE, CG) x Two measurement points (before and after the intervention)). This analysis was applied to assess changes in body composition parameters (body weight, BMI, FM, FFM, MM and TBW), cardiometabolic parameters (Glycemic profile (Fasting Glycemia, Fasting insulin, Insulin Resistance), hepatic profile ASAT, ALAT, Gamma GT, TB, creatinine) lipid profile (LDL-c, HDL-c, TC) and TG. CRP and Cortisol levels), 6MW distance (6MWD), 1-RM for extension leg (1-RM EL), 1-RMfor bench press (1-RM BP), squat performance, and crunch performance. ANOVA effect sizes were calculated using partial eta squared (ηp^2) to assess the magnitude of the observed effects. When significant main or interaction effects were observed, pairwise comparisons were performed using the Bonferroni post-hoc test. The significance level for all statistical procedures was set at $p<0.05$.

4. Results

4.1. Body Composition

Two way ANOVA for repeated measures showed significant changes over time for body weight ($F_{(1, 57)}=127.41$, $p<0.0005$, $\eta p^2=0.69$), BMI ($F_{(1, 57)}=76.61$, $p<0.0005$, $\eta p^2=0.57$) , FM ($F_{(1, 57)}= 8.16$, $p=0.006$, $\eta p^2=0.12$) and LM ($F_{(1,57)}=4.29$, $p=0.04$, $\eta p^2= 0.07$). A group effect was observed only for FM ($F_{(3, 57)}=3.01$, $p=0.03$, $\eta p^2=0.13$). A (Group x Time) interaction was identified for weight ($F_{(3, 57)}=30.88$, $p<0.0005$, $\eta p^2=0.61$), BMI ($F_{(3, 57)}=15.62$, $p<0.0005$, $\eta p^2=0.57$) and LM ($F_{(3, 57)}=3.08$, $p=0.03$, $\eta p^2=0.14$). The Bonferroni post hoc analysis revealed a significant decrease in body weight for both ETRE-PA ($p<0.0005$, Δ (%) = -10.98) and LTRE-PA ($p<0.0005$, Δ (%) = -7.99) groups after the intervention compared to before the intervention. Furthermore, during the post-intervention these decreases were also significant in ETRE-PA and LTRE-PA when compared to CG and LTRE groups ($p<0.0005$). Additionally, a significant reduction in BMI was observed in both the ETRE-PA ($p<0.0005$, Δ (%) = -12.06) and LTRE-PA ($p<0.0005$, Δ (%) = -8.39) groups after the intervention. However, during post-intervention only ETRE-PA group showed a significant lower BMI compared to CG group ($p=0.02$). Significant decrease of FM ($p=0.02$, Δ (%) = -7.44) and LM ($p=0.01$, Δ (%) = -7.32) was observed in ETRE-PA only after the intervention. No significant difference was observed between the groups concerning TBW.

4.2. Metabolic Parameters

ANOVA for repeated measures showed a significant time effect in TC, LDL-c and ALAT, ASAT, and Alkaline Phosphatase (Table 1). Furthermore, group effect was observed only in Alkaline Phosphatase ($F_{(3, 57)}=7.33$, $p<0.0005$, $\eta p^2=0.27$). However, interaction effect (Group x Time) was observed only in TC ($F_{(3, 57)}=3.16$, $p<0.0005$, $\eta p^2=0.14$). When comparing before to after the intervention, the Bonferroni post hoc analysis showed a significant reduction in ALAT levels in both the ETRE-PA ($p=0.004$, Δ (%) = -47.75) and LTRE-PA ($p=0.02$, Δ (%) = -37.58) groups. Additionally, only the ETRE-PA group showed a higher decrease in TC ($p=0.001$, Δ (%) = -14.58) and LDL-c ($p=0.01$, Δ (%) = -14.29). Conversely, only the LTRE-PA group exhibited a reduction in ASAT levels ($p=0.02$, Δ (%) = -24.61). Furthermore, when comparing between groups, a significant difference was observed in Alkaline Phosphatase between ETRE-PA and CG groups ($p=0.002$) and LTRE-PA and CG ($p<0.005$) groups. Glucoregulatory factors, HDL-c, Gamma GT, cortisol, bilirubin, creatinine, CRP, and TSH levels remained unaffected by either intervention ($p>0.05$).

Table 1. Biochemical parameters before and after the intervention.

Biomarkers	ETRE-PA		LTRE-PA		LTRE		CG		ANOVA		
	Pre	Post	Pre	Post	Pre	Post	Pre	Post	$F_{(1, 57)}$	P (Time)	ηp^2 (Time)
LDL-c (mmol/L)	2.75±0.76	**2.32**±0.54	2.65±0.76	2.46±0.95	2.38±0.72	2.12±0.54	3.17±1.08	2.39±0.63	24.27	0.000	0.29
TC (mmol/L)	4.47±0.90	**3.76***±0.64	4.29±0.96	3.98.96±1.38	4.13±0.91	**3.69***±0.69	4.96±1.24	3.87±0.85	43.07	0.000	0.43
ALAT (UI/L)	14.73±10	**6.38***±2.14	13.60 ±7.28	**7.04*** ±3.34	12.66 ±10.8	7.80±2.27	19.07±15.66	11.31±7.69	24.97	0.000	0.30
ASAT (UI/L)	18.13±6.45	12.53 ±2.16	20.20 ±14.10	**12.60***±5.69	19.86±10.09	15.33±8.98	21.31±15.41	15.68±7.94	12.85	0.001	0.18

Phosphatase Alcalin (UI/L)	77.06±34.77	79.6±21.56	61.60±13.08	56.93±16.69	79.60±21.56	72.00±20.72	59.37±14.54	45.37±15.51	5.62	0.02	0.09

Values are means ± SD. ETRE-PA: Early time-restricted eating combined with physical exercise group; LTRE-PA: Late time-restricted eating combined with physical exercise group; LTRE: Late time-restricted eating group; CG: Control group; LDL-c: Low Density lipoprotein; TC: Total Cholesterol; ALAT: Alanine aminotransferase; ASAT: Aspartate aminotransferase.* : $p < 0.05$; ** : $p < 0.01$; ***: $p < 0.001$. 4.3. Functional Capacity.

4.3.1. 6 MWT

Two way ANOVA for repeated measure revealed a significant effect of time ($F_{(1, 57)}$=76.29, $p < 0.0005$, ηp^2= 0.57), group ($F_{(3, 57)}$=22.29, $p < 0.0005$, ηp^2=0.54) and (Group x Time) interaction ($F_{(3, 57)}$=23.43, $p < 0.0005$, ηp^2=0.55). Bonferroni post hoc analysis showed higher performances in both ETRE-PA and LTRE-PA when comparing after-intervention to before-intervention (Figure 3). When comparing between groups, a significantly higher 6MWD performance was observed in ETRE-PA and LTRE-PA groups compared to CG group ($p < 0.0005$).

4.3.2. LE and BP 1-RM

Two way ANOVA showed significant effects of time on both LE 1-RM ($F_{(1, 57)}$=29.67, $p < 0.0005$, ηp^2=0.31) and BP 1-RM ($F_{(1, 57)}$= 12.94, p=0.001, ηp^2=0.18). Additionally, group effect ($F_{(3, 57)}$= 14.67, $p < 0.0005$, ηp^2=0.43 ; $F_{(3, 57)}$=11.02, $p < 0,0005$, ηp^2= 0.99, respectively) were observed for the same parameters. However, interaction effects were revealed only in LE 1-RM ($F_{(3, 57)}$=9.68, $p < 0.0005$, ηp^2=0.33). The Bonferroni post hoc analysis showed significantly greater improvements in LE 1-RM in ETRE-PA and LTRE-PA groups compared to LTRE (p=0.001, $p < 0.0005$, respectively) and CG groups ($p < 0.0005$). Moreover, when comparing before- to post-intervention, both ETRE-PA and LTRE-PA demonstrated enhanced performance in LE 1-RM ($p < 0.0005$) and BP 1-RM ($p < 0.005$).

4.3.3. Explosiveness and Endurance Strength

Two way ANOVA for repeated measures revealed significant effect of time in the vertical jump test ($F_{(1, 57)}$=91.19, p=0.001, ηp^2=0.61), 30-second squat test ($F_{(1, 57)}$=45.24, $p < 0.0005$, ηp^2=0.44) and 30-second crunch test ($F_{(1, 57)}$=24.54, $p < 0.0005$, ηp^2=0.30). A group effect was observed in the vertical jump test ($F_{(3, 57)}$=9.95, $p < 0.0005$, ηp^2=0.34), 30-second squat test ($F_{(3, 57)}$=19.05, $p < 0.0005$, ηp^2=0.50) and 30-second crunch test ($F_{(3, 57)}$=7.12, $p < 0.0005$, ηp^2=0.27 Furthermore, an interaction (Group x time) effect was observed for these parameters ($F_{(3, 57)}$=16.28, $p < 0.0005$, ηp^2= 0.46; $F_{(3, 57)}$=8.57, $p < 0.0005$, ηp^2=0.31; $F_{(3, 57)}$=14.45, $p < 0.0005$; ηp^2=0.43, respectively). The Bonferroni post hoc analysis showed a higher performance in the vertical jump test, 30-second squat test and 30-second crunch and when comparing before- to after-intervention (Figure 3 a and b). Both ETRE-PA and LTRE-PA groups exhibited improvements in the vertical jump test when compared to CG ($p < 0.0005$) and LTRE ($p < 0.0005$). In the squat test, both ETRE-PA and LTRE-PA groups exhibited higher improvements in squat test when compared to CG ($p < 0.0005$) and LTRE groups. ($p < 0.0005$, p=0.008, respectively) Additionally, in crunch test both the ETRE-PA and LTRE-PA groups exhibited greater improvements compared to CG ($p < 0.0005$) and LTRE (p=0.01, p=0.003, respectively). (Figure 3 c).
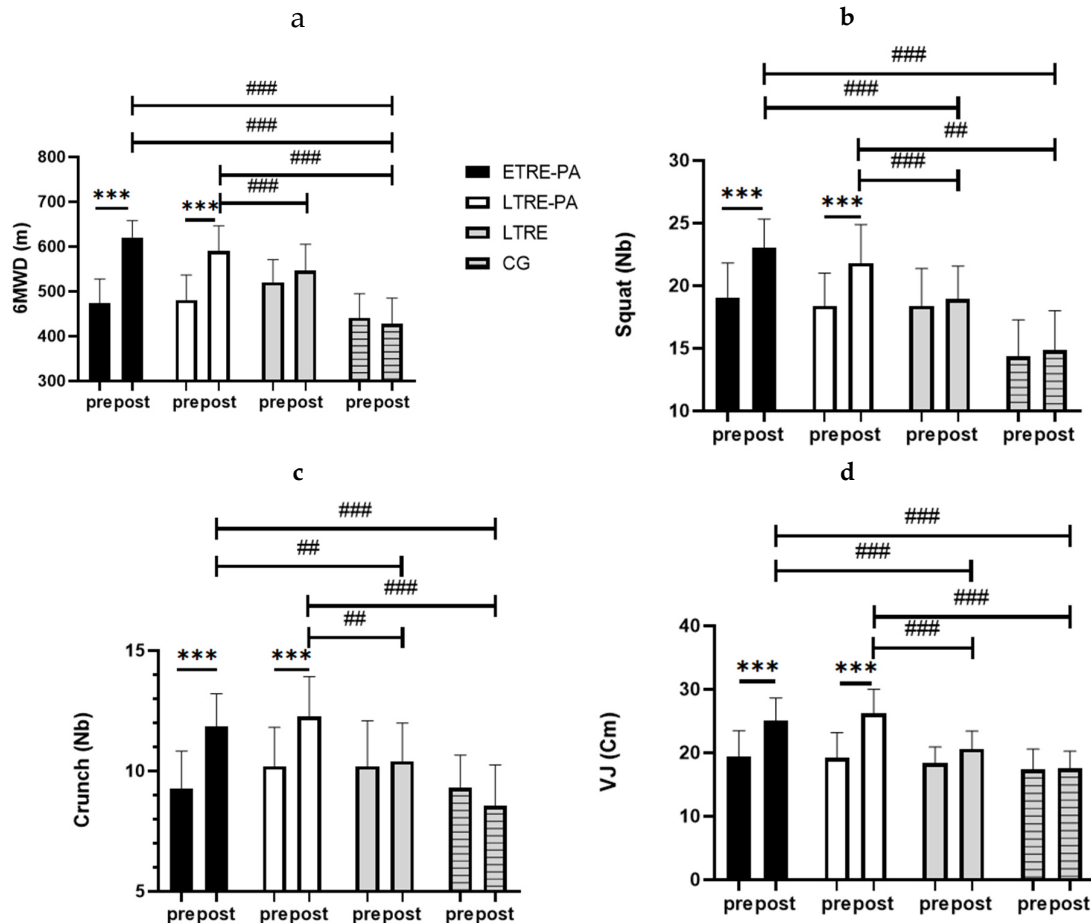
Figure 3. Physical performance indices between groups. ETRE-PA: Early time-restricted eating combined with physical activity; LTRE-PA: Late time-restricted eating combined with physical activity; LTRE: Late-time restricted eating; CG: Control Group; PRE: Before the intervention; POST: After the intervention; VJ: Vertical jump test. ***p<0.0005; ## p<0.01; ### p<0.0005.

5. Discussion

The present study investigated for the first time the impact of ETRE and LTRE combined with physical activity compared to LTRE and CG on body composition, cardiometabolic health and physical performance among women with overweight or obesity. The main findings revealed significant reductions in body weight and body mass index (BMI) in both ETRE-PA and LTRE-PA groups. Specifically, ETRE-PA group showed reductions in FM, FFM, LDL-c, and ALAT levels. Conversely, LTRE-PA group showed reductions in ALAT and ASAT levels. However, glycemic profile, cortisol, bilirubin, creatinine, CRP and TSH levels were not affected by either intervention. Regarding physical performance, ETRE-PA and LTRE-PA groups showed higher significant improvements in all tests compared to LTRE and CG. Previous studies have established TRE as an effective lifestyle intervention to improve body composition and overall health [6,11,30,31]. The impact of the timing of food intake ETRE vs. LTRE on body composition has gained considerable interest in recent years [32]. Few studies have compared the effects of ETRE vs. LTRE combined with physical exercise on body composition and health parameters. The existing literature presents mixed results mostly without notable differences [33], which aligns with our study.

Queiroz et al. [34] compared the effects of ETRE (8:00 a.m. to 4:00 p.m.), LTRE (12:00 p.m. to 8:00 p.m.) and a control condition (8:00 a.m. to 8:00 p.m.) in overweight and obese adults. Significant decreases in FFM and fat mass were observed in all three groups without notable differences between them. Additionally, a 14-week study by Jamshed et al. [35] compared ETRE (7:00 a.m. to 3:00 p.m.) to

a control group (eating window ≥ 12 hours). The ETRE group showed a greater weight loss. A single long-term trial (12 months) presented by Liu et al. [36] compared ETRE (8 a.m. to 4 p.m.) with a CG on a hypocaloric diet (1500-1800 kcal/day for men, 1200-1500 kcal/day for women) in overweight and obese adults. After 12 months, reductions in fat mass (5.9 and 4.5 kg, respectively) and lean mass (1.7 and 1.4 kg, respectively) were statistically significant in both the ETRE and control groups with no notable differences between groups. Similarly, our study showed a significant decrease in lean in ETRE-PA group when comparing pre- and post-intervention values. The decrease in lean mass may be explained by insufficient protein intake [37] . Other mechanisms, such as the disruption of anabolic hormones like growth hormone (GH) may also play a role. An alteration in GH secretion can disrupt protein synthesis, leading to a reduction in lean mass [38]. Additionally, an insufficiency of ketone bodies as an energy source may contribute to the degradation of skeletal muscles [39]. Furthermore, the present study demonstrated that ETRE-PA led to a selective loss of fat mass when comparing pre- and post-intervention results with no significant difference when comparing between groups. These results are consistent with those of Low et al. [40], who also indicated ETRE as an effective intervention to reduce fat mass. This effectiveness could be attributed to the alignment of the body's circadian rhythms with ETRE, which has been shown to improve metabolic processes and reduce the risk of metabolic disorders as reported by Patterson et al. [41]. In the other hand, Kotarsky et al. [42] showed that 8 weeks of TRE combined with training compared to control condition reduce body weight (-3.3% vs. -0.2%) as well as fat mass (-9.0% vs. -3.3%) and increased lean mass percentage (+2.4% vs. +1.2%). According to Boyd et al. [43], these improvements may be attributed to a reduction in energy intake throughout the study. Indeed, it has been shown that the type of diet plays a crucial role in the effects of TRE on health oy. Fasting has been proven to stimulate fat metabolism and promote the metabolic transition from glucose oxidation to fat oxidation when glycogen stores are depleted [42,44]. This can be accompanied by increased lipolysis of adipose tissue and the release of free fatty acids and glycerol into the plasma [45,46]. Mobilization and use of fatty acids in adipocytes increase caloric expenditure, which can prevent obesity [47]. Regarding cardiometabolic health, previous studies [6,48,49] have shown that late eating is associated with poorer cardiometabolic health. The circadian misalignment could explain these results [50]. Additionally, glucose tolerance is better in the biological morning which seems to be related to diurnal variations in β-cell response, peripheral insulin sensitivity, insulin clearance and glucose efficiency [51,52]. Fatty acid oxidation in skeletal muscles and the thermic effect of food are also higher in the morning. This suggests that it is optimal to consume the majority of daily calories earlier in the day, while reserving the late-afternoon and the night for fasting and sleep [53]. In the present study, our results showed that a combination of LTRE and physical exercise had no negative effect on cardiometabolic health. In contrast, we observed that the combination of physical training and LTRE resulted in significant improvements in markers of liver damage (ASAT, ALAT and alkaline phosphatase). Additionally, the ETRE-PA group showed a significant improvement in lipid profile (TC and LDL-c) as well as liver markers (ALAT and alkaline phosphatase), suggesting a synergistic effect of combination between both interventions. These results are consistent with a meta-analysis by Dai et al. [54] that reported a significant improvement in lipid and glycemic profile after combining TRE and physical exercise. Furthermore, another study conducted by Real-Hohn et al. [55] showed a significant decrease in insulin, improved oxidative stress biomarkers, better glucose tolerance and hexokinase activity in the liver, heart and skeletal muscles after intermittent fasting combined with high interval training group compared to the control group. It is important to note that the improvements observed in lipid profiles and liver enzymes in our study were independent of factors regulating blood glucose, cortisol, CRP, and TSH levels, suggesting that TRE may have direct effects on lipid metabolism and liver function. However, we also observed a trend towards reductions in blood glucose regulation parameters, including insulin sensitivity, fasting insulin, and blood glucose levels in the ETRE-PA and LTRE-PA groups after the intervention. Perhaps an increase in exercise intensity could further improve these parameters. Another study by Wei et al. [56] showed no change in glycemic profile during similar intermittent fasting. The same researchers explained this stagnation by the fact that the baseline levels of participants were below 9.9 mmol/l. Therefore, they suggested that an

improvement in fasting blood glucose might be observable beyond these values. One of the main objectives of the present study was to highlight the effectiveness of TRE and physical activity in improving various aspects of physical performance. To our knowledge, this study is the first to examine the combined effects of different TRE times during the day and physical activity on physical performance in overweight and obese women by evaluating the exercise capacity in various intervention groups and compared them to a control group. Our results showed that a 16/8 TRE regimen followed for 12 weeks resulted in a significant improvement in the walking distance during a 6MWT in the ETRE-PA and LTRE-PA groups. Most of previous studies [57–62] have evaluated the effect of fasting combined with physical exercise on athletes, and produced mixed results. During Ramadan (14/10), negative effects on performance appear likely due to factors such as disrupted sleep and hydration. These effects were more pronounced in elite athletes, but among amateur athletes, the difference is minimal [59,60,62]. Conversely, no significant differences were observed after TRE (16/8) in aerobic [63–66], anaerobic [60,64,67], as well as strength and power [57,62,64,66,68,69]. However, a meta-analysis by Zouhal et al. [70] mentioned that fasting training in sedentary and untrained subjects could promote muscle physiological adaptations, potentially leading to improved endurance performance.

Limitations:

This study has some limitations. First, it remains unclear whether the metabolic health benefits associated with time-restricted eating (TRE) are due to the shortened eating window, a potential reduction in energy intake, or a combination of both, as neither caloric intake nor protein consumption were assessed across the groups during the intervention. Moreover, the intensity of the muscle-strengthening exercises may have been insufficient to prevent the loss of lean mass. Additionally, menstrual cycle variations were not accounted for due to the longitudinal design of the study, making it difficult to completely exclude their potential influence on the outcomes. Lastly, future studies could consider incorporating an additional group that engages solely in physical activity, to determine whether the observed benefits can be attributed exclusively to the exercise intervention.

6. Conclusion

Our findings suggest that combining TRE and physical activity positively affects body composition, cardiometabolic health, and functional capacity. Both the ETRE-PA and LTRE-PA interventions contributed to improved patient outcomes, with exercise reduced some of the adverse effects of LTRE on body composition and cardiometabolic health in patients reported in the literature. However, no significant effects on some metabolic parameters related to glycemic variables were observed, indicating that maintaining a relatively short eating window may lead to better outcomes. Finally, incorporating calorie restriction during the TRE period could be an additional strategy to enhance results in future research.

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