

Muscular Performance and Hemodynamic Responses to Circuit and Traditional Resistance Training at Different Intensities: A Randomized Crossover Study

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ABSTRACT

This study compared the acute effects of circuit and traditional resistance training (RT) performed at different intensities on muscular performance and hemodynamic responses. Ten resistance-trained men (25.8±4.3 years, BMI: 24±2.3 kg/m², RT experience: 4.3±2.5 years) completed four randomized protocols: high-intensity circuit (HC), moderate-intensity circuit (MC), high-intensity traditional (HT), and moderate-intensity traditional (MT). Each protocol was performed twice, once for muscular performance and once for cardiovascular assessment. Sessions involved two sets of bench press and leg press performed at either 80% or 60% one-repetition maximum (1RM). Hemodynamic data were rank-transformed using the aligned rank transform for factorial analysis of main effects and interactions, while muscular and perceptual responses were analyzed using repeated measures ANOVA or Friedman tests, followed by appropriate post-hoc comparisons and effect sizes (ES). Systolic blood pressure ($p<0.001$, large ES), heart rate ($p<0.001$, very large ES), and rate-pressure product

($p<0.001$, very large ES) increased significantly post-exercise across all conditions and remained elevated at 10 min ($p<0.001$, large–very large ES). No post-exercise hypotension was observed. Maximum repetitions and total load lifted were greater at moderate intensity ($p<0.0001$, large ES), accompanied by lower ratings of fatigue ($p<0.0001$, large ES). No significant differences were found between circuit and traditional structures. High-intensity protocols, regardless of structure, elicited greater cardiovascular stress and fatigue, whereas moderate-intensity RT enhanced performance with lower physiological strain. These results highlight exercise intensity as the primary determinant of acute cardiovascular and muscular responses.

Keywords: Strength training; Cardiovascular load; Post-exercise recovery; Muscle endurance; Perceived fatigue.

INTRODUCTION

The regulation of circulation during different types of

exercise is among the most thoroughly researched topics in integrative physiology. In this context, hemodynamic changes in response to acute exercise represent a critical area of investigation, as they reflect the cardiovascular system's ability to meet metabolic demands, guide safe exercise prescription, and inform strategies to optimize performance and recovery [1-3]. Extensive evidence indicates that a single bout of either aerobic or resistance training (RT) can lead to a reduction in blood pressure (BP) during the post-exercise recovery phase [4-7]. This phenomenon, known as post-exercise hypotension (PEH), refers to a condition in which BP decreases below resting levels [7]. A significant decrease in BP can be achieved through a well-structured regular RT program [3, 8]. Importantly, the magnitude of PEH after an acute RT session has been shown to correlate with the long-term reductions in resting BP observed following chronic training [7]. These findings suggest that the cardiovascular benefits associated with regular exercise training may be attributable to the cumulative effects of PEH, establishing RT as a non-pharmacological intervention for hypertension prevention, management, and treatment.

RT has been demonstrated to induce acute BP reductions that are comparable in magnitude to those observed following aerobic exercise bouts [7, 9]. However, various factors influence hemodynamic changes after RT, including exercise order [10, 11], total volume [12], rest intervals between sets [5, 13], exercise intensity [6, 14], and the specific type of protocol employed [15]. The relationship between RT intensity and PEH is particularly nuanced, with conflicting evidence in the literature [6, 14]. Duncan et al. (2014) reported that an acute bout of high-intensity RT, but not low-intensity RT, effectively promoted PEH [6]. Conversely, Rezk et al. (2006) found both low- and high-intensity RT elicited PEH among healthy participants [14].

Furthermore, the type of RT protocol is a factor that has received limited attention regarding its effect on PEH. The circuit RT protocol has been advocated as an alternative to other exercise modalities for the prevention and treatment of hypertension [2, 3, 16]. However, there is currently insufficient information concerning the effect of varying intensities of circuit RE on hemodynamic parameters in trained individuals. This knowledge gap is particularly significant given that different RT protocols have been demonstrated to elicit distinct cardiovascular responses [15], suggesting that manipulation of RT variables could substantially influence post-

exercise cardiovascular outcomes.

Beyond cardiovascular effects, RT protocols are primarily employed to enhance various neuromuscular attributes, including strength, power, and local muscular endurance [17, 18]. Nonetheless, the appropriate design of acute RT variables is essential for maximizing neuromuscular adaptations, with outcomes largely dependent on the exercise volume. Circuit training has traditionally been implemented with lower loads and higher repetition schemes compared to traditional RT. However, Alcaraz et al. (2008) demonstrated that high-load circuit protocols could produce quantitatively similar physical performance outcomes to traditional RT while imposing significantly greater cardiovascular demands [18]. These findings suggest that manipulating loading parameters within circuit RT, compared to traditional protocols, may elicit different cardiovascular responses while achieving comparable muscular performance outcomes.

Despite the growing body of research on RT methodologies, several critical questions remain unanswered regarding the comparative effects of circuit vs. traditional RT protocols when implemented at different intensities. First, the specific impact of RT protocol type (circuit vs. traditional) on post-exercise hemodynamic parameters has received limited attention, particularly when controlling for total training volume. Second, while previous studies have examined intensity-dependent effects on PEH [6, 12, 14, 19, 20], few have systematically compared how intensity modulates the cardiovascular responses across different RT protocol structures [15, 18, 21]. Finally, there is insufficient evidence regarding how these protocol variations affect both muscular performance measures and hemodynamic parameters concurrently in resistance-trained individuals.

The aim of the present investigation was to address the aforementioned knowledge gaps by comparing two RT protocols (circuit vs. traditional) implemented at different intensities (high vs. moderate) while maintaining equivalent training volumes, to determine their distinctive impacts on hemodynamic responses and muscular performance in resistance-trained men. We hypothesized that RT protocols of equal intensity would exert similar impacts on hemodynamic responses and muscular performance, regardless of the protocol structure employed. We prioritized ecological validity and focused on muscle

performance and cardiovascular outcomes that have more direct practical implications for exercise prescription. Such evidence is particularly valuable for exercise professionals working with resistance-trained populations who seek to maximize training efficiency through strategic manipulation of RT variables. Additionally, the results may inform non-pharmacological approaches to cardiovascular health management by clarifying which RT configurations most effectively promote favorable hemodynamic responses while maintaining muscular performance, potentially expanding the application of resistance exercise in clinical contexts where both outcomes are desirable.

METHODS

Subjects

The sample size was determined using an *a priori* power analysis based on previous research [5, 18] in this field (effect size $f=0.40$, $\alpha=0.05$, power=0.80, and a correlation among repeated measures of 0.5) [22], utilizing G*Power software (version 3.1.9.4; Heinrich Heine University, Düsseldorf, Germany). This analysis revealed that a minimum of ten participants was required for a repeated-measures design, which generally necessitates fewer participants than between-subjects designs. The criteria for inclusion in the study were: age 18 and 30 years, having normal BP (systolic BP<120 mmHg and diastolic BP<80 mmHg), having a minimum of two years of experience in RT, not using any drugs or dietary supplements, and having no injuries or health issues at the point of study enrolment. The study was conducted in line with the Declaration of Helsinki, and the research protocol received approval from the Research Ethics Committees of Shahrood University of Technology (IR.SHAHROODUT.REC.1402.026).

Ten young males (age: 25.8 ± 4.3 years, body mass index: 24 ± 2.3 kg/m², resistance training experience: 4.3 ± 2.5 years) enrolled in the study who possessed a background in regular RT (3-4 times per week for at least two years). All participants engaged in typical training sessions that included both multi-joint and single-joint exercises at moderate to high intensities (70-85% of one-repetition maximum; 1RM). Participants were not competitive athletes yet maintained a consistent training frequency (3.3 ± 0.5 sessions/week) over the six months prior to the study.

Study Procedures

This study employed a within-subjects repeated measures design. All participants were directed to refrain from engaging in vigorous exercise and to maintain their regular dietary routines for 24 hours prior to data collection [23]. Additionally, participants were requested to abstain from the consumption of caffeinated substances after 18:00 on the evening prior to the testing day [23].

One week prior to the study, all participants engaged in a familiarization session. During this session, after providing detailed explanations of the research methodology and obtaining informed consent, all participants performed the following six exercises in a standardized manner: leg press, lat pull down, leg flexion, bench press, leg extension, and shoulder press.

In the first session, body mass and height were measured according to standard protocols [24], and body mass index (BMI) was calculated using the equation body weight/height² (kg/m²). Subsequently, the participants' maximum strength was assessed using the 1RM test, adhering to established guidelines [25]. Five days later, the RT sessions began. Each participant completed four RT protocols: high-intensity circuit (HC), moderate-intensity circuit (MC), high-intensity traditional (HT), and moderate-intensity traditional (MT). Each protocol performed twice in a randomized sequence: once for cardiovascular measurements and once for assessment of muscular performance and fatigue, resulting in a total of eight experimental sessions. A five-day rest period was enforced between sessions. The methods for conducting the sessions and the associated measurements are outlined in Figure 1. BP and HR were measured at rest (baseline), immediately after exercise, and at 10 and 30 min post-exercise.

Muscle Strength Testing

Prior to the 1RM test, participants completed a warm-up consisting of 10 min of cycling on an ergometer, followed by dynamic stretching exercises, an approach shown to minimize potential impairments and enhance subsequent muscle performance [26]. The 1RM determination followed standardized procedures as described by Arazi et al. (2022) [25]. Initially, participants performed a specific warm-up set of 5 repetitions at 50% of their perceived 1RM. This was followed by one to two sets of 2-3 repetitions at 60-80% of estimated 1RM.

Each session was performed with two intensities:

Moderate-intensity: 2 sets of 10 reps with 60% of 1RM
High-intensity: 1 set of 8 reps and 1 set of 7 reps with 80% of 1RM

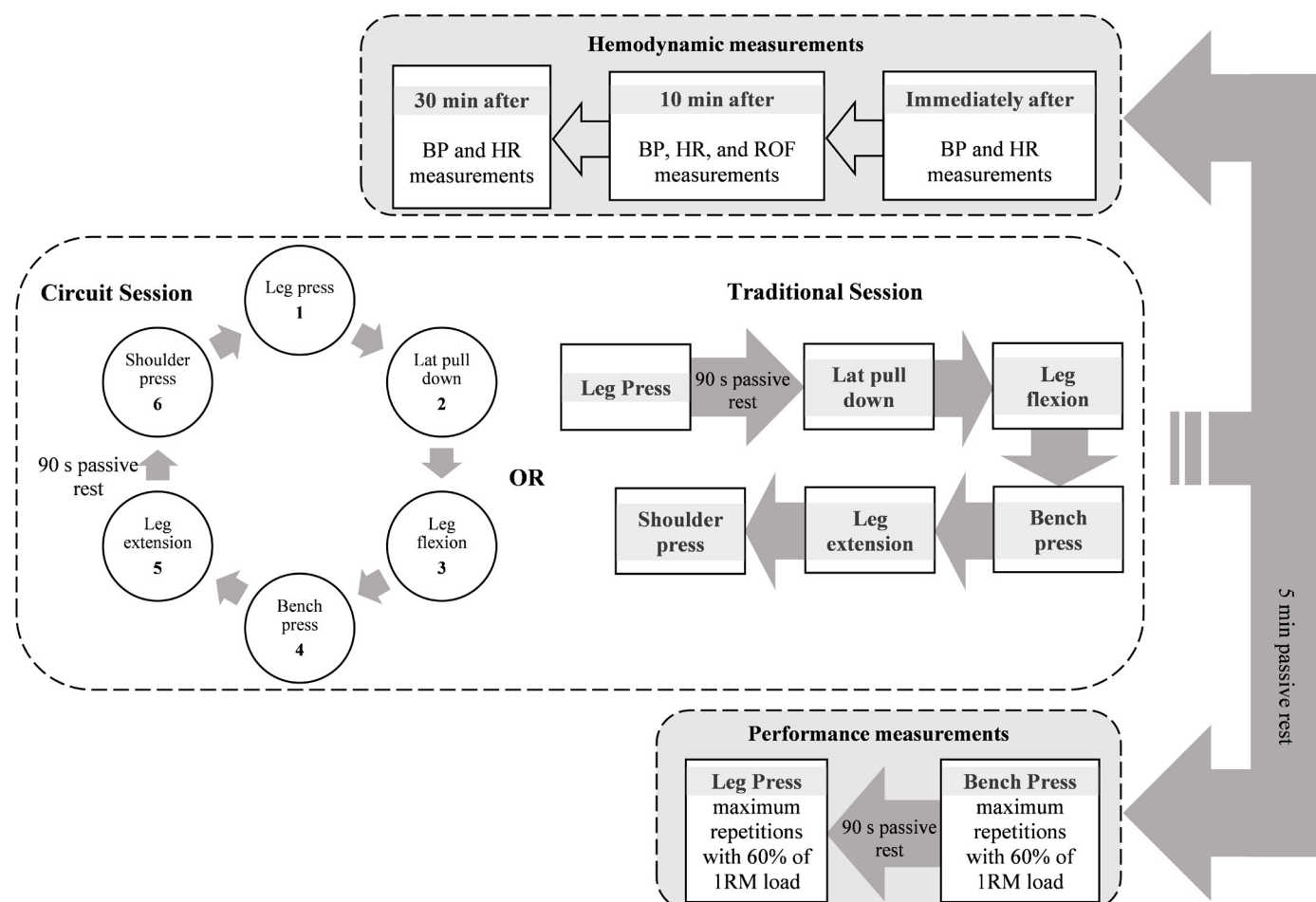


Figure 1. Experimental design of the study. 1RM: one-repetition maximum, reps: repetitions, BP: blood pressure, HR: heart rate, ROF: rating of fatigue.

After these warm-up sets, participants attempted single repetitions with progressively increasing loads to establish their 1RM. Rest periods of at least 3 min were provided between sets to minimize fatigue. The 1RM was typically established within 4 to 5 attempts [25, 27].

Resistance Training Sessions

As shown in Figure 1, each RT session included two sets of three exercises targeting the lower body (leg press, leg flexion, and leg extension) and the upper body (lat pull down, bench press, and shoulder press), performed at high (80% 1RM) and low (60% 1RM) intensities. In the high-intensity RT sessions, participants completed one set of 7 repetitions and one set of 8 repetitions, while in the moderate-intensity sessions, they performed two sets of 10 repetitions. This procedure was adopted to maintain a similar total load volume across sessions (sets $\times$ repetitions $\times$ load). A rest

period of 90-s was enforced between sets. After completing the exercises, participants rested for 5 min before executing a set of bench press and leg press exercises at an intensity of 60% of 1RM. The maximum number of repetitions (MNR) achieved during these 2 sets was recorded and used as a measure of muscular endurance. To standardize the tempo of the repetitions, a metronome was utilized during the familiarization session, with a designated tempo of 2-s for the concentric phase and 2-s for the eccentric phase, resulting in a total of 4-s per repetition [15]. Participants were instructed to maintain this tempo during all RT sessions, although the metronome was not used after the familiarization session [28].

The total load lifted (TLL) for these 2 sets was also calculated by multiplying the number of repetitions by the external load, expressed in kilogram-force (kgf) [29]. Furthermore, the rating of fatigue (ROF) scale, a validated 11-point scale used during exercise and

post-exercise recovery [30], was utilized to assess the level of muscle fatigue 10-min after the sets. No participants experienced any exercise-related injuries or adverse events throughout the exercise sessions. All RT sessions were overseen by the same researcher for consistency. Throughout the exercises, all participants received strong verbal encouragement.

Cardiovascular Measurements

Participants rested comfortably for 10–12 min in a designated chair prior to baseline hemodynamic measurements [15], and all subsequent measurements were performed in the same seated position. Systolic and diastolic BP and HR were recorded using a standard BP monitor (Glamor, model TMB-1112, China) on the upper nondominant bare arm at heart level. To enhance measurement reliability, three consecutive readings were taken at each time point with 1-min intervals between measurements, and the average value was taken forward for analysis. This multiple-reading protocol follows established guidelines for cardiovascular assessment in exercise research [31]. The mean BP was then calculated using the formula: $[(\text{systolic BP} - \text{diastolic BP}) / 3 + \text{diastolic BP}]$ [31]. Additionally, the RPP values were computed using the standardized equation: $[(\text{systolic BP} \times \text{HR}) / 100]$ [3].

Statistical Analysis

Data analysis was conducted using SPSS (v. 22®, Inc. Chicago, IL) and GraphPad Prism (v. 10®, GraphPad Software Inc.; San Diego, CA, USA) at an alpha level of <0.05 . The normality of the distribution for each dependent variable was assessed using the Shapiro-Wilk test. Due to non-normal distributions, cardiovascular data were rank-transformed using the aligned rank transform (ART) via the ARTool package (v. 2.2.2®, R Foundation for Statistical Computing, Vienna, Austria) in R, allowing valid factorial analysis of main effects and interactions [32]. The area under the curve (AUC) for the cardiovascular measurements was further determined, and a one-way ANOVA was conducted to compare the AUC values across different protocols. Differences in muscular performance and perceived fatigue across the conditions were analyzed using the repeated measures ANOVA and Tukey's HSD post-hoc test (for parametric data), or the Friedman test and Dunn's multiple comparisons test (for non-parametric data). Furthermore, effect size statistics were calculated using partial eta

squared (η_p^2), rank-biserial correlation (r), Kendall's W , and Cohen's d [33]. The magnitudes were considered as small (0.01), medium (0.06), and large (0.14) for η_p^2 , small (0.2), moderate (0.6), large (1.2) and very large (2.0) for Cohen's d , and small (0.3), medium (0.5), and large (>0.5) for r and Kendall's W [3, 33].

RESULTS

Displayed in Table 1 are the anthropometric characteristics, baseline cardiovascular measurements, and the 1RM values.

Cardiovascular Parameters

No significant time $\times$ condition interactions were observed for cardiovascular parameters (Table 2). However, a main effect for time was significant for systolic BP ($F=35.9$, $p<0.001$, $\eta_p^2=0.409$ [large]), mean BP ($F=11.3$, $p<0.001$, $\eta_p^2=0.179$ [large]), HR ($F=136.9$, $p<0.001$, $\eta_p^2=0.725$ [large]), and RPP ($F=166.9$, $p<0.001$, $\eta_p^2=0.762$ [large]). Post-hoc comparisons revealed that the systolic BP increased significantly immediately post-exercise in all protocols (HC: $p<0.001$, $d=1.1$ [large]; HT: $p=0.003$, $d=1.1$ [large]; MC: $p<0.001$, $d=1.1$ [large]; MT: $p=0.004$, $d=1.1$ [large]), and 10 min post-exercise only in the HC ($p=0.03$, $d=1.1$ [large]) and MC ($p=0.036$, $d=1.1$ [large]) protocols. Diastolic BP showed no significant time-dependent differences ($p>0.05$), but mean BP decreased significantly at 30 min following the HC ($p=0.032$, $d=1.1$ [large]) and MT ($p=0.038$, $d=1.1$ [large]) protocols.

Furthermore, HR and RPP increased significantly following exercise across all protocols ($p<0.001$, $d>2.0$ [very large]) and remained elevated at 10 min post-exercise ($p<0.001$, $d>1.2$ [large to very large]). Although no statistically significant differences were observed between protocols ($p>0.05$), RPP at 30 min post-MT was significantly lower than at 30 min post-HT ($p=0.048$, $d=0.9$ [moderate]).

Figure 2 illustrates the comparison of cardiovascular AUC values among the different RT protocols. No significant differences were found in systolic BP ($F_{(3, 36)} = 0.71$, $p = 0.55$, $\eta_p^2 = 0.06$ [medium]), diastolic BP ($F_{(3, 36)} = 0.22$, $p = 0.88$, $\eta_p^2 = 0.02$ [small]) and mean BP ($F_{(3, 36)} = 0.11$, $p = 0.952$, $\eta_p^2 = 0.05$ [small]), as well as HR ($F_{(3, 36)} = 0.72$, $p = 0.56$, $\eta_p^2 = 0.06$ [medium]) and RPP ($F_{(3, 36)} = 1.2$, $p = 0.33$, $\eta_p^2 = 0.09$ [medium]).

Table 1. Descriptive characteristics of the participants (n = 10).

Variable	Mean ± Standard Deviation	Range
Age (years)	25.8 ± 4.3	18-30
Height (cm)	179 ± 8.5	165-194
Body mass (kg)	77.7 ± 12.4	60-97
Body mass index (kg/m ²)	24 ± 2.3	21.4-27.4
Training experience (years)	4.3 ± 2.5	2-8
Resting systolic BP (mmHg)	111 ± 8.6	98-125
Resting diastolic BP (mmHg)	62.2 ± 5.2	55-73
Resting mean BP (mmHg)	78.4 ± 4.6	70-84.7
Resting heart rate (beats.min ⁻¹)	79 ± 4.5	74-90
Resting RPP (mmHg.beats.min ⁻¹)	87.7 ± 10.8	72.5-113
1RM values (kg)		
Leg press	168 ± 71	116-348
Leg flexion	37 ± 9.5	23-52
Leg extension	79 ± 28.4	41-122
Lat pull down	66 ± 16.4	41-93
Bench press	85 ± 23	52-116
Shoulder press	47 ± 16	29-70

BP: blood pressure, RPP: rate-pressure product, 1RM: one-repetition maximum

Table 2. Mean ± standard deviation for the cardiovascular changes among different protocols.

Variable	Protocol	Baseline	Post-exercise	10 min post	30 min post	Time x Condition
Systolic BP (mmHg)	HC	107.1±16	123±8.7 ^{aaa}	114.4±8.6 ^a	102.3±6.4 ^{bbb}	F=0.801 p=0.615 η _p ² =0.048 (small effect)
	HT	102.1±8	123±10.7 ^{aa}	114±9.1	103.9±4.7 ^{bbb}	
	MC	98.3±8.7	115.9±8.9 ^{aaa}	106.5±6.9 ^a	99.4±8.6 ^{bbb}	
	MT	102.2±8.7	113.8±12.3 ^{aa}	110±9	102.8±4 ^{bbb c}	
Diastolic BP (mmHg)	HC	59.3±7.7	60.7±8.1	62.8±8.6	57.5±3	F=0.653 p=0.75 η _p ² =0.039 (small effect)
	HT	54.9±9.5	62.8±13	59.9±6.6	60.1±5.6	
	MC	57±7.1	57.7±7.6	55.8±7.7	57.1±6.1	
	MT	59.4±7	59.5±8.5	58.2±7.6	58.5±2.8	
Mean BP (mmHg)	HC	75.2±8.2	81.5±5.1	80±7.7	72.4±3.9 ^b	F=0.715 p=0.695 η _p ² =0.043 (small effect)
	HT	70.6±6.6	82.9±11.8	77.9±5.7	74.7±3.9	
	MC	70.8±6.6	77.1±5.6	72.7±6.8	71.2±5.7	
	MT	73.7±5	77.6±7.4	75.5±5.5	73.3±1.4 ^b	
Heart rate (bpm)	HC	75.2±7.8	108.2±8.9 ^{aaa}	95.6±6.5 ^{aaa bb}	81.3±7.2 ^{bbb ccc}	F=0.551 p=0.835 η _p ² =0.033 (small effect)
	HT	77.9±9.7	115±11.6 ^{aaa}	102.5±7.6 ^{aaa b}	86.6±9.3 ^{bbb cc}	
	MC	71.1±5.2	113.1±10.6 ^{aaa}	93.8±8.6 ^{aaa b}	81±9.5 ^{bbb cc}	
	MT	71±6.6	107.1±15 ^{aaa}	91.1±10.9 ^{aaa}	83.4±8.1 ^{bbb c}	
RPP (mmHg·bpm/100)	HC	80.8±16.2	133.1±14.4 ^{aaa}	109.4±11.2 ^{aaa b}	83.2±9 ^{bbb ccc}	F=0.983 p=0.457 η _p ² =0.058 (small effect)
	HT	80.2±15.6	141.4±18.5 ^{aaa}	117±14.4 ^{aaa b}	90±10.6 ^{bbb ccc}	
	MC	70±9.5	130.6±9.9 ^{aaa}	99.7±9.7 ^{aaa bbb}	80.4±10.4 ^{a bbb ccc}	
	MT	72.4±7.7	121.6±20.9 ^{aaa}	100.4±16.3 ^{aaa bb}	85.7±8.6 ^{bbb ccc ht}	

BP = blood pressure; RPP = rate-pressure product; HC = high-intensity circuit; MC = moderate-intensity circuit; HT = high-intensity traditional; MT = moderate-intensity traditional. Significant differences from baseline (^ap<0.05, ^{aa}p<0.01, ^{aaa}p<0.001), immediately post-exercise (^bp<0.05, ^{bb}p<0.01, ^{bbb}p<0.001), and 10 min post-exercise (^cp<0.05, ^{cc}p<0.01, ^{ccc}p<0.001). Significant difference from HT (^{ht}p<0.05).

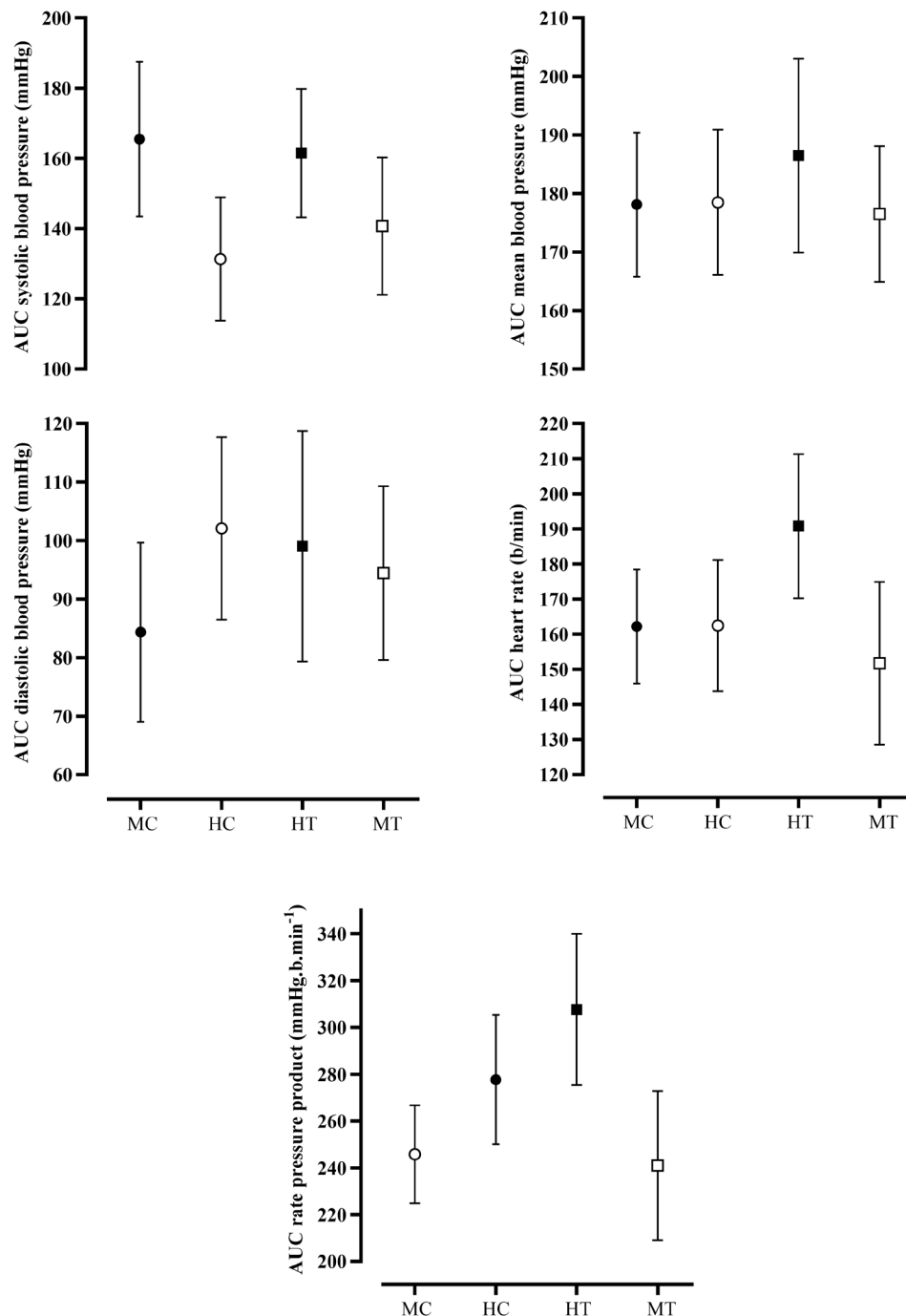


Figure 2. Mean and standard deviation (errors bars) for cardiovascular area under the curve (AUC) values for the high-intensity circuit (HC), moderate-intensity circuit (MC), high-intensity traditional (HT), and moderate-intensity traditional (MT) protocols.

Muscular Performance

A significant difference between the RT protocols was found for MNR ($X^2_{(3)}=26$, $p<0.0001$, $W=0.87$ [*large*]) and TLL ($F_{(1.6, 14.3)}=38.1$, $p<0.0001$, $\eta_p^2=0.81$ [*large*]) during the bench press exercise. A more comprehensive overview of the differences can be found in Figure 3.

The findings indicated a statistically significant difference in the conditions for MNR ($F_{(2, 19)}=31.1$, $p<0.0001$, $\eta_p^2=0.78$ [*large*]) and TLL ($X^2_{(3)}=22.6$,

$p<0.0001$, $W=0.75$ [*large*]) during the leg press exercise. The differences between the conditions are shown in Figure 4.

Fatigue Score

The analysis showed a statistically significant difference between the conditions for the ROF scale ($X^2_{(3)}=24.8$, $p<0.0001$, $W=0.83$ [*large*]). As shown in Figure 5, multiple comparisons indicated that there were significant differences between the conditions ($p<0.05$).

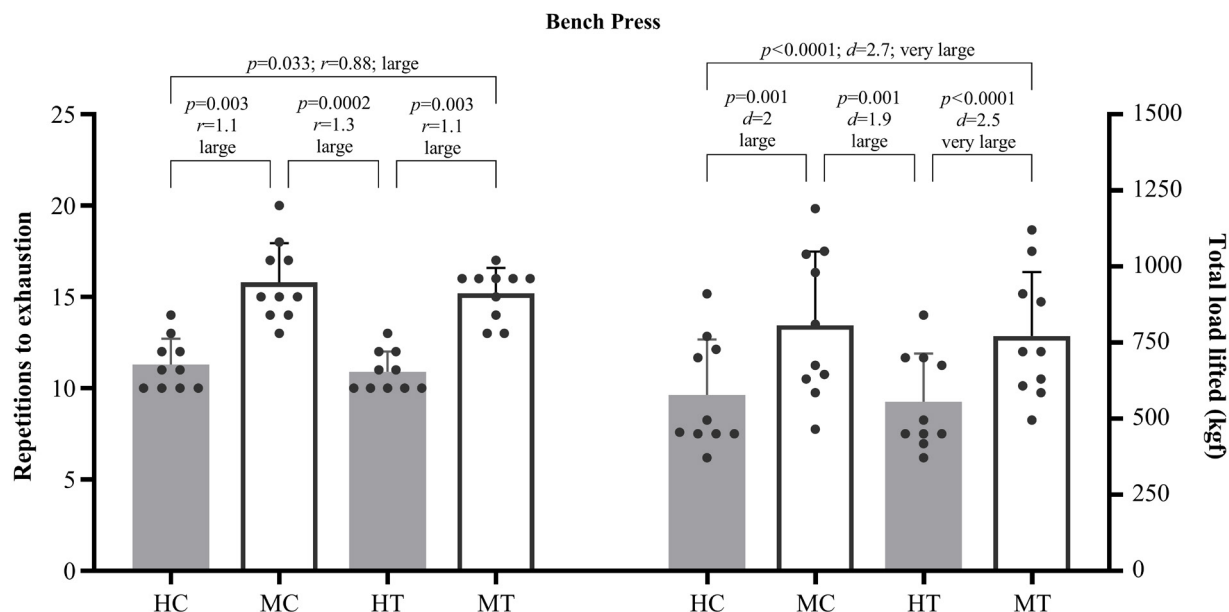


Figure 3. Mean, standard deviation (errors bars) and individual data points for the repetitions to exhaustion (the 4 bars at the left) and the total load lifted (the 4 bars at the right) for bench press between the high-intensity circuit (HC), moderate-intensity circuit (MC), high-intensity traditional (HT), and moderate-intensity traditional (MT) protocols. For each significant comparison, effect sizes (r and d) with their qualitative interpretations are presented.

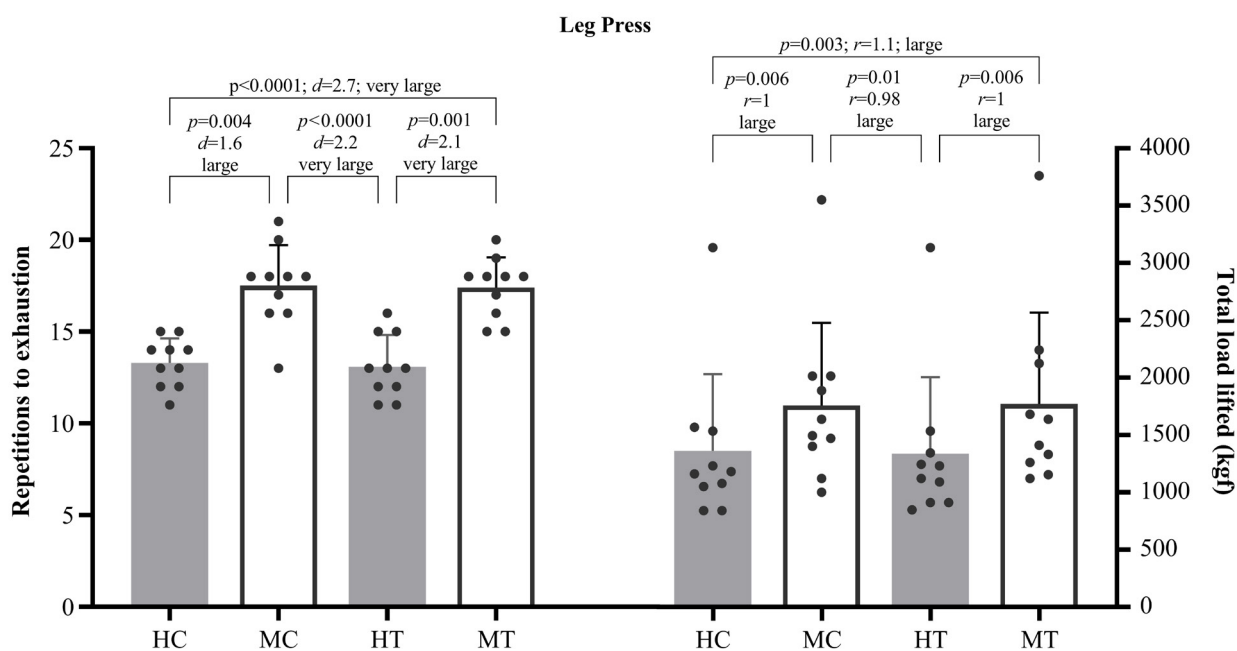


Figure 4. Mean, standard deviation (errors bars) and individual data points for the repetitions to exhaustion (the 4 bars at the left) and the total load lifted (the 4 bars at the right) for leg press between the high-intensity circuit (HC), moderate-intensity circuit (MC), high-intensity traditional (HT), and moderate-intensity traditional (MT) protocols. For each significant comparison, effect sizes (r and d) with their qualitative interpretations are presented.

DISCUSSION

This study compared the acute effects of circuit versus traditional RT protocols at high and moderate intensities on cardiovascular responses in resistance-trained men. The main findings showed that cardiovascular changes were primarily time-dependent rather than protocol-dependent, as no significant time $\times$ condition interactions

were observed. Systolic BP increased immediately after all protocols, with elevations persisting for 10 min in the HC and MC sessions. Mean BP decreased 30 min post-exercise following the HC and MT protocols, whereas diastolic BP remained unchanged across conditions. HR and RPP rose markedly after all training sessions and remained elevated for at least 10 min. Importantly, RPP at 30 min was lower following the MT protocol compared

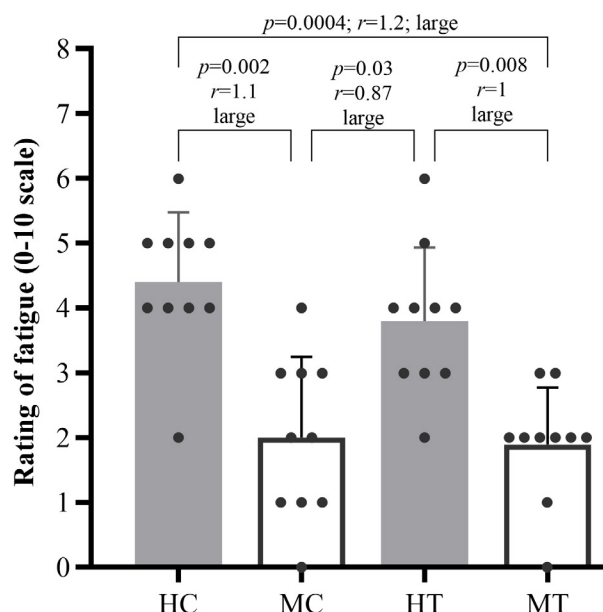


Figure 5. Mean, standard deviation (error bars) and individual data points for the rating of fatigue scale in the high-intensity circuit (HC), moderate-intensity circuit (MC), high-intensity traditional (HT), and moderate-intensity traditional (MT) protocols. For each significant comparison, effect size (r) and qualitative interpretation are presented.

to its high-intensity counterpart, highlighting that intensity influences myocardial oxygen demand even beyond the immediate post-exercise phase.

These results indicate that both circuit and traditional RT protocols elicit similar acute hemodynamic responses, and exercise intensity alone did not consistently predict BP behavior across sessions. The transient post-exercise decreases in mean BP after HC and MT suggest that PEH may occur selectively, but within the first 30 min of recovery, it was neither robust nor consistent across all conditions. This finding is in agreement with Corrêa et al. (2022), who found no significant differences in BP, HR, or RPP across traditional RT protocols and similarly reported an absence of PEH within 30 min following high-intensity RT [15]. Together, these findings suggest that in young, resistance-trained men, acute cardiovascular responses to RT are relatively homogeneous across different modalities and intensities, with only subtle variations in recovery dynamics.

The physiological mechanisms underlying the observed cardiovascular responses likely involve increased intramuscular pressure during contraction, leading to transient elevations in vascular resistance, sympathetic activation, and increased cardiac output [34-36]. During high-intensity RT, significant impedance to blood flow occurs due to increased intramuscular pressure, resulting in metabolite accumulation that triggers

the metabolic reflex and activates the sympathetic nervous system [34]. This activation leads to systemic vasoconstriction and increased peripheral vascular resistance. Additionally, HR increases in conjunction with elevated stroke volume during contraction releases, contributing to heightened cardiac output [34].

The lack of consistent BP reductions in moderate-intensity protocols contrasts with studies reporting acute PEH [15, 34]. This discrepancy may be explained by the use of resistance-trained men in this study, a population with enhanced vascular function and autonomic regulation, who may exhibit blunted BP responses to moderate-intensity exercise compared to untrained or hypertensive individuals [37].

Furthermore, the absence of a consistent PEH effect contrasts with studies reporting delayed BP reductions beyond 30 min post-exercise [6, 15]. It is possible that in trained, normotensive young men, the vascular and autonomic adjustments necessary to induce PEH require longer recovery periods to manifest. Moreover, our volume-equated design, while methodologically rigorous, may have attenuated potential differences, as exercise volume is known to influence the magnitude of PEH [38]. Participant characteristics likely also played a role, as previous research indicates that older and hypertensive populations exhibit more pronounced BP reductions due to greater vascular

responsiveness and altered autonomic control [39]. It is well documented that hypertensive individuals experience more substantial PEH due to altered vascular function and autonomic regulation [40], and aging further modifies cardiovascular responses to RT through changes in arterial stiffness and endothelial function [41]. Thus, the lack of PEH in the present study may reflect the cardiovascular health and training status of the participants.

Regarding the cardiovascular workload, the elevated HR and RPP immediately post-exercise across all protocols confirm the acute cardiovascular stress induced by RT. Notably, the higher RPP at 10 min post-exercise in HT compared to HC suggests that traditional high-intensity RT imposes a greater myocardial workload than circuit-based training at the same intensity. This finding is supported by previous research demonstrating that heavy-resistance circuit training (HRC) elicits higher HR responses during exercise but may result in lower post-exercise myocardial workload compared to traditional RT due to differences in rest intervals and exercise sequencing [18, 42]. For example, Alcaraz et al. (2008) found that although HRC and traditional RT produced similar strength outputs, HRC elicited significantly greater HR during exercise (~71% HR_{max} vs. ~62% HR_{max}) [18], indicating higher cardiovascular demand during the session but potentially more efficient recovery dynamics. Similarly, Marín-Pagán et al. (2020) reported higher oxygen consumption, blood lactate, and HR during HRC compared to traditional RT [42], reflecting greater metabolic and cardiorespiratory stress during circuit training but without sustained increases in myocardial workload post-exercise.

The circuit training format, which typically distributes work across different muscle groups in sequence, may facilitate more effective peripheral blood redistribution between exercises compared to the traditional format where multiple sets of the same exercise are performed consecutively. This improved blood flow distribution during circuit RT potentially reduces overall cardiovascular strain, particularly during recovery periods. de Matos et al. (2013) similarly noted differences in hemodynamic responses based on exercise structure [43], although their focus was on different intensities rather than circuit versus traditional formats.

Moreover, the comparable cardiovascular AUC values across all protocols further suggest that total cardiovascular load over the recovery period does not differ significantly between circuit and traditional

RT when volume and rest intervals are equated. This reinforces the conclusion that RT intensity, rather than RT structure, is the primary determinant of acute hemodynamic responses in resistance-trained men.

Our study demonstrated that muscular performance, assessed via MNR and TLL during bench press and leg press exercises at 60% 1RM, was significantly greater following moderate-intensity protocols compared to high-intensity sessions, with large effect sizes. Additionally, the ROF scale measured 10 min post-exercise were lower after moderate-intensity sessions than after high-intensity ones. These findings suggest that high-intensity RT, irrespective of whether performed in circuit or traditional format, induces greater acute muscular fatigue and diminishes performance capacity.

The superior MNR and TLL observed during moderate-intensity RT protocols likely reflect the greater capacity to sustain repeated muscular contractions at lower loads. At 60% 1RM, participants could perform more repetitions before volitional fatigue, resulting in higher total volume lifted. This aligns with established exercise physiology principles indicating that moderate loads permit higher repetition ranges and greater total work output per set [29]. In contrast, high-intensity sessions (typically >80% 1RM) restrict the number of repetitions due to the greater mechanical demand per contraction, leading to earlier onset of fatigue and reduced total repetitions and load lifted [44]. Our findings corroborate this well-documented inverse relationship between load intensity and repetition capacity in RT sessions.

The higher ROF scores following high-intensity RT further support the role of intensity in driving acute fatigue responses. The ROF scale is a validated measure sensitive to fatigue-related sensations during and after exercise [30]. This increased fatigue perception likely contributed to the diminished muscular performance observed. Muscle fatigue can be defined as a temporary reduction in the ability of skeletal muscle to generate force or power during sustained or repeated contractions [45]. It results from complex interactions between central (neural) and peripheral (muscular) factors [46]. Peripheral fatigue mechanisms include metabolic disturbances such as depletion of muscle creatine phosphate stores [47], accumulation of lactate and hydrogen ions causing decreased pH [48], and reductions in muscle glycogen availability [48]. These factors impair excitation-contraction coupling

and cross-bridge cycling efficiency, leading to force decline.

Although our study did not directly measure these metabolic variables, the greater fatigue following high-intensity protocols is consistent with the higher metabolic stress imposed by heavier loads, which accelerate depletion of energy substrates and accumulation of metabolites contributing to peripheral fatigue [44, 47, 48]. Moreover, central fatigue, manifested as reduced motor drive from the central nervous system, may also be more pronounced after high-intensity exercise due to increased afferent feedback from fatigued muscles [45].

Interestingly, despite the structural differences between circuit and traditional RT, no significant differences in MNR, TLL, or ROF were observed between these session formats at matched intensities. This suggests that intensity exerts a dominant influence on acute muscular performance and fatigue, overshadowing any potential influence of training structure. Previous studies have reported mixed findings regarding the impact of circuit versus traditional training on fatigue and performance. Some evidence suggests that circuit training, by alternating muscle groups and reducing localized fatigue, may attenuate fatigue accumulation and enhance performance [49]. However, when total volume and rest intervals are equated, as in this study, these differences appear minimized [18], indicating that load intensity is the critical factor modulating fatigue and performance outcomes.

Although our study examined only acute performance and hemodynamic responses, the fatigue-related measures (e.g., maximal repetitions, ROF) suggest important implications for longer-term adaptation in fatigue tolerance and recovery. Indeed, meta-analytic evidence shows that circuit RT can improve not only muscular strength but also cardiorespiratory fitness and body composition over weeks of training [50]. In line with this, an 8-week randomized study in resistance-trained men found that high-resistance circuit training elicited similar gains in strength and lean mass as traditional RT, despite greater metabolic demand per session [51]. These findings are consistent with a fitness-fatigue framework, where repeated exposure to a higher-fatigue stimulus (i.e., circuit modality) may drive enhanced fatigue resistance and recovery adaptations over time [52]. Thus, future longitudinal studies should investigate how different training intensities and modalities (circuit vs. traditional)

modulate chronic adaptations in neuromuscular fatigue, recovery kinetics, and performance, information that would meaningfully extend the translational relevance of our acute findings.

STRENGTHS AND LIMITATIONS

A major strength of this study is its randomized crossover design, which allowed each participant to serve as their own control, minimizing inter-individual variability and increasing the reliability of comparisons between circuit and traditional RT at different intensities. The inclusion of trained young men enhances the relevance of the findings to resistance-trained populations and provides insight into acute cardiovascular and muscular responses under controlled volume and rest conditions. Additionally, the combined assessment of hemodynamic parameters alongside muscular performance and perceived fatigue offers a comprehensive understanding of the acute physiological impact of RT protocols.

However, the study has several limitations. The exclusively male, resistance-trained sample limits the generalizability of the findings, particularly to women, untrained individuals, older adults, and clinical populations with cardiovascular or metabolic conditions. Additionally, only two sets per exercise were performed due to practical constraints related to facility and equipment availability, which limited the session duration. This limitation may have reduced the sensitivity to detect volume-dependent differences in fatigue or cardiovascular responses. Furthermore, the intensity range in this study (moderate vs. high) was relatively narrow. Using much lighter or heavier loads, while still equating total volume, may yield different cardiovascular or performance responses. Future research should examine whether more extreme loading schemes alter the relative role of RT structure on these outcomes.

PRACTICAL APPLICATIONS

When prescribing RT, practitioners should primarily consider intensity as the key determinant of both cardiovascular strain and muscular fatigue. Moderate-intensity protocols enable greater training volume and reduced fatigue, making them suitable for athletes focusing on muscular endurance or hypertrophy. High-intensity RT, while effective for strength development, imposes greater myocardial

workload and perceived fatigue, which necessitates careful monitoring-particularly in individuals with cardiovascular risk. Employing circuit-based structures at high intensities may attenuate myocardial stress during recovery compared to traditional formats, offering a safer alternative for tactical athletes or those with cardiovascular concerns. Incorporating subjective tools like the ROF scale can aid in individualizing recovery and intensity adjustments. Finally, given the absence of post-exercise hypotension within 30 min in trained males, extended monitoring and recovery are recommended to ensure cardiovascular homeostasis after intense sessions.

CONCLUSION AND FUTURE RECOMMENDATIONS

RT intensity emerged as the primary determinant of acute responses to RT sessions, with moderate-intensity protocols enabling greater repetition capacity, TLL, and lower fatigue, while high-intensity sessions induced greater muscular fatigue and cardiovascular strain. Training structure (circuit vs. traditional) had minimal impact, apart from subtle differences in myocardial workload recovery, and overall cardiovascular load was similar across formats. Future studies should examine these responses in diverse populations, extend recovery monitoring beyond 30 min, explore chronic adaptations, and investigate how repeated exposure to higher-fatigue protocols may influence long-term fatigue tolerance and recovery capacity to better inform training prescriptions for performance and cardiovascular health.

DATA AVAILABILITY STATEMENT

Data are available on reasonable request to the corresponding author.

CONFLICTS OF INTEREST

No potential conflict of interest was reported by the authors.

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ETHICAL APPROVAL

The study was conducted in line with the Declaration of Helsinki, and the research protocol received approval from the Research Ethics Committees of the Shahrood University of Technology (IR.SHAHROODUT.REC.1402.026).

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