

Arterial stiffness responsiveness to a 32-week multicomponent exercise program in community-dwelling older adults: associations with physical activity and functional fitness

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Research Article

Keywords: physical training, aging, cardiovascular physiology, vascular function, health

Posted Date: July 10th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10156796/v1>

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Additional Declarations: No competing interests reported.

Abstract

Purpose

The effects of multicomponent exercise training on arterial stiffness in older adults remain equivocal. To investigate the effects of a 32-week multicomponent exercise program on carotid-femoral pulse wave velocity (PWVc-f), functional fitness, and objectively measured physical activity in community-dwelling older adults.

Methods

Fifty-three older adults were allocated to exercise (EG, $n = 33$) or control (CON, $n = 20$) groups; 38 completed the 32-week trial (EG, $n = 26$; CON, $n = 12$). PWVc-f was the primary outcome. Secondary outcomes included global fitness score (GFS), moderate-to-vigorous physical activity (MVPA), and steps/day measured by accelerometry. Exploratory tertile, correlation, and hierarchical regression analyses were performed.

Results

No significant group $\times$ time interactions occurred for PWVc-f, MVPA, or steps/day ($p > 0.05$). GFS improved modestly in EG ($p = 0.015$; $\eta^2p = 0.16$), although the interaction effect was not significant ($p = 0.386$). Participants within the highest PWVc-f tertile exhibited $\sim 10\%$ reductions ($p = 0.012$; $dz = -0.82$); those within the lowest MVPA tertile showed the largest MVPA increases ($\sim 55\%$; $p = 0.03$; $dz = 0.74$). Changes in PWVc-f were associated with changes in MVPA ($r = -0.54$; $p = 0.003$) and steps/day ($r = -0.45$; $p = 0.019$), but not GFS ($r = -0.06$; $p = 0.781$). In hierarchical regression, increases in MVPA remained independently associated with reductions in PWVc-f after adjustment for age, sex, hypertension, and baseline PWVc-f ($\beta = -0.41$; $p = 0.012$). The final model explained 60% of Δ PWVc-f variability ($R^2 = 0.60$; adjusted $R^2 = 0.48$; $p = 0.003$).

Conclusions

The multicomponent exercise program produced modest effects on arterial stiffness. However, participants with elevated baseline PWVc-f and lower physical activity levels exhibited clinically relevant vascular improvements. Increases in habitual MVPA, rather than functional fitness, were independently associated with lower arterial stiffness.

Introduction

Aging is accompanied by progressive alterations in vascular structure and function that contribute to increased cardiovascular risk. Among these changes, arterial stiffening has emerged as a strong and

independent predictor of cardiovascular morbidity and mortality in middle-aged and older adults, regardless of traditional risk factors [1]. Increased arterial stiffness impairs the buffering capacity of large arteries, augments systolic load, and compromises central hemodynamics, thereby contributing to the development and progression of cardiovascular disease [2–4].

Carotid-femoral pulse wave velocity (PWVc-f) is currently regarded as the reference standard for the non-invasive assessment of central arterial stiffness and provides prognostic information beyond conventional cardiovascular risk markers [5, 6]. Elevated PWVc-f has been consistently associated with adverse cardiovascular outcomes, particularly in older populations [3, 4]. Consequently, identifying lifestyle strategies capable of attenuating or reversing arterial stiffening has become a major clinical and public health priority.

Regular physical activity and structured exercise training are recognized as important non-pharmacological approaches for improving vascular health [7, 8]. Exercise-induced adaptations involving endothelial function, shear stress-mediated vascular remodeling, autonomic regulation, and oxidative stress may contribute to reductions in arterial stiffness [9–12]. In this context, higher levels of moderate-to-vigorous physical activity (MVPA) have been associated with lower arterial stiffness in community-dwelling older adults [13], particularly when sedentary time is replaced by higher-intensity activities [14]. Similarly, objectively measured physical activity has been favorably associated with arterial stiffness in adults with obesity, reinforcing the relevance of habitual movement behaviors for vascular health [15]. Exercise-induced adaptations involving endothelial function, shear stress-mediated vascular remodeling, autonomic regulation, and oxidative stress may contribute to these effects [9, 11, 12].

Despite the well-established benefits of exercise for cardiovascular health, exercise-induced reductions in arterial stiffness are not consistently observed across studies involving older adults. Although some interventions have demonstrated favorable effects on PWVc-f, findings remain heterogeneous, likely due to differences in exercise modality, intensity, intervention duration, baseline cardiovascular risk, and habitual physical activity levels [12, 16]. Moreover, older adults exhibit substantial heterogeneity in vascular and behavioral responses to exercise training, including marked variability in daily movement behaviors and sedentary exposure [17]. These observations suggest that overall group-based analyses may underestimate clinically relevant adaptations occurring in specific subgroups of participants.

Multicomponent exercise programs combining aerobic, resistance, balance, and flexibility exercises have been widely recommended for older adults because they simultaneously target several domains of physical function and health [18]. However, although improvements in functional fitness following multicomponent training are well documented, less is known about the extent to which changes in habitual physical activity and functional fitness are associated with vascular adaptations in this population. Understanding these relationships may help explain the heterogeneous effects of exercise interventions on arterial stiffness and contribute to the identification of individuals more likely to benefit from exercise training.

Importantly, older adults exhibit substantial heterogeneity regarding vascular health, physical fitness, and habitual physical activity levels. Individuals with elevated baseline PWVc-f or lower physical activity levels may present greater responsiveness to exercise-induced vascular adaptations, whereas those with preserved vascular function may exhibit limited adaptive margins. Previous studies have independently demonstrated favorable effects of multicomponent exercise on functional fitness and vascular health in older adults [18, 19]. Likewise, accelerometry-based studies have reported associations between habitual MVPA and lower arterial stiffness [13, 15]. However, to our knowledge, no previous studies have simultaneously examined changes in arterial stiffness, objectively measured physical activity, and functional fitness following long-term multicomponent exercise interventions in community-dwelling older adults while also considering potential differences in responsiveness according to baseline vascular and behavioral status.

Therefore, the present study investigated the effects of a 32-week multicomponent exercise program on central arterial stiffness, functional fitness, and objectively measured physical activity in community-dwelling older adults. Additionally, we explored potential associations between changes in PWVc-f and changes in functional fitness and physical activity. We further explored whether responsiveness to exercise differed according to baseline vascular and behavioral status. We hypothesized that participants with poorer baseline vascular and physical function would exhibit greater responsiveness to the intervention.

Methods

Participants

Sample size was estimated a priori using G*Power software (University of Düsseldorf, Düsseldorf, Germany) considering a repeated-measures ANOVA (within-between interaction), an effect size of 0.25, $\alpha = 0.05$, and statistical power ($1 - \beta$) of 0.95, resulting in a minimum sample of 34 participants.

Community-dwelling older adults aged ≥ 65 years were recruited from the metropolitan area of Porto, Portugal. Eligibility criteria included the absence of medical conditions contraindicating participation in functional assessments or exercise training. Recruitment was conducted through community-based programs for older adults, including educational and social support initiatives, as well as through public advertisements and informational flyers distributed in areas surrounding the Faculty of Sport of the University of Porto.

Study design

This controlled experimental trial adopted a parallel-group design with non-probabilistic allocation. Eligible participants were assigned to either the exercise (EG) or control (CON) groups. Individuals allocated to CON were instructed to maintain their usual daily activities and exercise habits throughout the study period. Participants attended the research center for face-to-face interviews and baseline

assessments. Evaluations were conducted before and after the 32-week intervention and included anthropometry, body composition, functional fitness, objectively measured physical activity, blood pressure, and carotid-femoral pulse wave velocity (PWVc-f).

All participants provided informed consent, and the study gained approval from the Ethics Committee of the Faculty of Sport at the University of Porto, Portugal (CEFADE 06.2016). This clinical trial was registered at the National Library of Medicine online database (NCT04095962) and followed the Consolidated Standards of Reporting Trials (CONSORT) for the elaboration and description of the study.

Medical history, anthropometry, and body composition

Information regarding medical history, medication use, and health conditions was obtained through structured face-to-face interviews. Body mass and height were measured using a calibrated scale and stadiometer (Tanita™ Scan BC532, Tokyo, Japan), and body mass index (BMI) was calculated as body mass divided by height squared (kg/m^2). Body composition was assessed by dual-energy X-ray absorptiometry (DXA) (QDR 4500A, Hologic™, Bedford, MA, USA). All scans were performed by the same trained technician according to manufacturer guidelines. The following variables were analyzed: fat mass (kg), android fat (%), and gynoid fat (%).

Functional fitness assessment

Functional fitness was evaluated using the Fullerton Functional Fitness Test battery [20, 21], which assesses upper- and lower-body strength, flexibility, aerobic endurance, agility, and dynamic balance. Tests were performed in the morning following a standardized 10-min warm-up and conducted in the following order: arm curl, back scratch, 30-s chair stand, chair sit-and-reach, 8-foot up-and-go, and 6-min walk test. Sex- and age-specific percentile scores were obtained according to the Senior Fitness Test Manual. A global fitness score (GFS) was calculated as the mean percentile across all six tests. Accordingly, a global fitness score derived from sex- and age-adjusted percentile values obtained from the Fullerton battery was used for statistical analyses.

Physical activity assessment

Habitual physical activity and daily step counts were objectively assessed using uniaxial accelerometers (ActiGraph™ GT1M, ActiGraph Corporation, Pensacola, FL, USA). Participants wore the device on the hip for seven consecutive days during waking hours, except while bathing or swimming [22, 23]. A valid recording required at least 10 h/day of wear time, including a minimum of two weekdays and one weekend day. Periods of consecutive zero counts were considered non-wear time. Data were collected at 30 Hz and analyzed in 60-s epochs using ActiLife™ software version 6.11.4 (ActiGraph Corporation, Pensacola, FL, USA).

Physical activity intensity was determined according to previously established accelerometry cut-points [23]: sedentary (0–99 counts/min), light (100–2,019 counts/min), and moderate-to-vigorous (MVPA; $\geq$ 2,020 counts/min). Daily MVPA values were interpreted according to current physical activity recommendations for older adults [24], whereas daily step counts were interpreted using commonly adopted accelerometry-based thresholds proposed by Tudor-Locke et al. [25].

Blood pressure and arterial stiffness assessments

Resting blood pressure was measured after 10 min of seated rest using a semi-automatic device (Colin BP 8800, Critikron™, Tampa, FL, USA). Three measurements were obtained at 1-min intervals by the same trained evaluator (AMPC), and the average value was recorded. Hypertension was defined as systolic blood pressure $\geq$ 140 mmHg, diastolic blood pressure $\geq$ 90 mmHg, or current antihypertensive medication use.

Central arterial stiffness was assessed by carotid-femoral pulse wave velocity (PWVc-f) using applanation tonometry (SphygmoCor™, AtCor Medical, Sydney, Australia). Measurements were obtained with participants in the supine position. A validated transfer function was used to derive central aortic waveforms from radial artery recordings [26]. Doppler waveforms from the carotid and femoral arteries were simultaneously obtained with ECG tracings using a Millar tonometer (Millar™ Instruments, Houston, TX, USA). Pulse transit time was determined from the mean time difference between arterial waveforms and ECG signals over a 10-s recording period.

Carotid-femoral transit distance was calculated as the distance from the femoral artery to the sternal notch via the umbilicus minus the distance from the carotid artery to the sternal notch. PWVc-f was subsequently calculated as transit distance divided by pulse transit time, according to established recommendations [27]. Elevated arterial stiffness was defined as PWVc-f $\geq$ 10 m/s [6].

Exercise intervention

The multicomponent exercise program was designed according to World Health Organization recommendations for older adults [7] and included aerobic, resistance, flexibility, balance, and neuromotor exercises. Training sessions were performed three times per week on non-consecutive days over a 32-week period. Each session consisted of a warm-up involving low-intensity walking and stretching (5–10 min), followed by aerobic exercises such as walking, jogging, or running (30–40 min), resistance exercises targeting upper- and lower-body muscle groups (approximately 10 min), and cool-down activities including proprioceptive exercises, stretching, and relaxation (5–10 min).

Aerobic exercise intensity during the first two months was maintained between 60–70% of maximum heart rate (HRmax), corresponding to ratings of perceived exertion (RPE) between 5 and 6 on the CR10 Borg scale [28]. Thereafter, intensity was progressively increased to approximately 80% HRmax, corresponding to RPE values between 7 and 8. Resistance exercises were performed using weight-

training machines and included chest press, low back extension, leg extension, seated leg curl, abdominal flexion, biceps curl, and triceps extension. Participants initially performed one set of 10–15 repetitions, progressing to three sets of 10–12 repetitions throughout the intervention. Training loads were adjusted every 12 sessions to maintain target exertion levels corresponding to RPE values of 3–6 during weeks 1–12, 6–7 during weeks 13–20, and 7–8 during weeks 21–32.

Statistical analyses

Data normality and homogeneity of variance were assessed using the Shapiro–Wilk and Levene tests, respectively. Continuous variables are presented as mean $\pm$ standard deviation (SD), and categorical variables as absolute and relative frequencies.

Baseline between-group differences were examined using independent-samples t-tests for continuous variables and chi-square tests for categorical variables. PWVc-f was defined as the primary outcome, whereas GFS, MVPA, and steps/day were considered secondary outcomes. Intervention effects over time were analyzed using repeated-measures ANOVA, including group (exercise vs. control) and time (pre vs. post) as factors. When appropriate, Bonferroni-adjusted post hoc comparisons were performed.

Exploratory subgroup analyses were additionally conducted according to tertiles of baseline PWVc-f, GFS, MVPA, and steps/day to investigate potential differences in responsiveness to the intervention. Changes over time (Δ = post – pre) were calculated for PWVc-f, GFS, MVPA, and steps/day. Pearson correlation coefficients were used to examine associations between changes in PWVc-f and changes in physical activity and functional fitness variables. Correlation magnitudes were interpreted as trivial (< 0.10), small ($0.10–0.29$), moderate ($0.30–0.49$), large ($0.50–0.69$), or very large (≥ 0.70).

Hierarchical multiple linear regression analyses were performed to identify factors associated with changes in PWVc-f. Age, sex, hypertension status, and baseline PWVc-f were entered in the first block, followed by changes in MVPA, steps/day, and GFS in subsequent models. Standardized beta coefficients (β), coefficients of determination (R^2), adjusted R^2 , and 95% confidence intervals (95% CI) were reported.

Effect sizes for repeated-measures ANOVA were estimated using partial eta-squared (η^2p), interpreted as small (0.01), moderate (0.06), or large (≥ 0.14). For exploratory within-tertile comparisons, Cohen's d_z was calculated and interpreted as small (0.20), moderate (0.50), or large (0.80). Statistical significance was set at $p < 0.05$. All analyses were performed using SPSS version 24.0 (IBM SPSS Statistics, Armonk, NY, USA).

Results

Participant flow and baseline characteristics

Figure 1 illustrates participant flow throughout the study. Of the initial 74 volunteers, 53 older adults met the eligibility criteria and were allocated to either EG or CON. Thirty-eight participants (24 women) completed the 32-week follow-up and were included in the final analyses. Participants withdrew for personal, health-related, and logistical reasons.

Baseline characteristics are presented in Table 1. Participants were aged 69 ± 4 years, and most were retired (85%) and married (68%), with approximately 40% reporting at least 12 years of formal education. Hypertension was present in approximately 29% of the sample, whereas overweight status was observed in nearly 74% of participants. Common medications included antihypertensive, lipid-lowering, and antiplatelet agents. Approximately 58% of participants exhibited elevated arterial stiffness at baseline (PWVc-f > 10 m/s). Participants generally presented low-to-moderate functional fitness and low levels of habitual physical activity, with approximately 94% accumulating less than 30 min/day of MVPA and 77% performing fewer than 7,500 steps/day, values below commonly recommended thresholds for older adults.

No significant between-group differences were observed at baseline for demographic characteristics, body composition, hemodynamic variables, arterial stiffness, functional fitness, or objectively measured physical activity (all $p > 0.05$). Nevertheless, considerable interindividual variability was evident for PWVc-f, GFS, MVPA, and steps/day, indicating a broad spectrum of vascular, functional, and behavioral profiles among participants. This heterogeneity supported subsequent exploratory analyses according to baseline tertiles to investigate potential differences in responsiveness to the intervention.

Table 1
Baseline characteristics of exercise (EG) and control (CON) groups.

Variable	EG (n = 26)	CON (n = 12)	p-value
Demographic and anthropometric variables			
Age, years	69 ± 4	69 ± 5	0.778
Body mass, kg	74.1 ± 14.3	72.3 ± 16.6	0.751
BMI, kg/m ²	29.1 ± 4.2	28.0 ± 3.9	0.455
Body composition			
Fat mass, kg	27.9 ± 7.9	25.7 ± 4.2	0.290
Fat-free mass, kg	44.7 ± 9.9	44.1 ± 12.1	0.867
Android fat, %	40.4 ± 6.6	42.6 ± 4.3	0.247
Gynoid fat, %	39.6 ± 8.0	37.1 ± 6.7	0.331
Hemodynamics and arterial stiffness			
SBP, mmHg	132.7 ± 14.0	130.5 ± 13.4	0.644
DBP, mmHg	72.1 ± 7.7	69.6 ± 8.0	0.380
Hypertension, n (%)†	7 (26.9)	4 (33.3)	0.984
PWVc-f, m/s	10.5 ± 2.2	11.0 ± 1.7	0.461
Elevated PWVc-f (> 10 m/s), n (%)	14 (53.8)	8 (66.7)	0.165
Functional fitness and physical activity			
Global fitness score (GFS)	52.9 ± 14.2	45.7 ± 16.8	0.189
MVPA, min/day	11.0 ± 8.4	10.6 ± 6.2	0.900
Steps/day	6,454 ± 2,338	6,183 ± 1,494	0.683
Values are mean ± standard deviation or absolute (n) and relative frequency (%).			
† Hypertension defined as SBP > 140 mmHg and/or DBP > 90 mmHg at baseline.			
BMI: body mass index; SBP: systolic blood pressure; DBP: diastolic blood pressure; PWVc-f: carotid-femoral pulse wave velocity; GFS: global fitness score; MVPA: moderate-to-vigorous physical activity.			

Overall intervention effects

Figure 2 presents individual and mean changes in PWVc-f (Panels A and B), GFS (Panels C and D), MVPA (Panels E and F), and steps/day (Panels G and H) following the 32-week intervention in EG and CON.

Repeated-measures ANOVA revealed no significant group $\times$ time interactions for PWVc-f, MVPA, or steps/day ($p > 0.05$).

GFS showed a modest numerical improvement in EG ($p = 0.015$, $\eta^2p = 0.16$), although the overall interaction effect was not significant ($F(1,34) = 0.77$; $p = 0.386$; $\eta^2p = 0.022$). Objectively measured physical activity remained low throughout the intervention period, with average MVPA remaining close to 10–12 min/day in both groups. Despite the modest overall effects, substantial interindividual variability was observed for PWVc-f and MVPA responses, supporting subsequent exploratory analyses according to baseline vascular and behavioral status.

Exploratory analyses according to baseline status

Exploratory analyses according to tertiles of baseline PWVc-f, GFS, MVPA, and steps/day are presented in Fig. 3. Individuals within the highest baseline tertile of PWVc-f exhibited reductions of approximately 9–10% following the intervention ($p = 0.012$; $dz = -0.82$), representing a large effect size, whereas no meaningful changes were observed in the remaining tertiles (Panel A). Regarding functional fitness, the largest improvement in GFS was observed within the second tertile of baseline values in EG ($p = 0.0007$; $dz = 1.05$), indicating a large effect size, while a smaller increase was observed in the third tertile ($p = 0.04$; $dz = 0.64$), corresponding to a moderate effect (Panel B). In CON, moderate changes were also observed across tertiles ($dz \approx 0.58$ – 0.71).

Those classified within the lowest tertile of baseline MVPA showed the greatest increases in daily MVPA following the intervention (approximately 55%; $p = 0.03$; $dz = 0.74$), representing a moderate effect size, whereas little or no change was observed in the higher tertiles (Panel C). Daily step counts remained relatively stable across tertiles in EG. In CON, increases were observed within the lowest tertile ($p = 0.03$; $dz = 0.62$), whereas reductions occurred within the second tertile ($p = 0.013$; $dz = -0.77$), both corresponding to moderate effect sizes (Panel D).

These exploratory findings suggest that responsiveness to multicomponent exercise training may depend on baseline vascular and behavioral status, with more pronounced adaptations occurring among individuals with poorer initial profiles.

Associations between changes in arterial stiffness vs. physical activity and global fitness

Pearson correlation analyses revealed moderate inverse associations between changes in PWVc-f and changes in MVPA ($r = -0.54$; $p = 0.003$) and steps/day ($r = -0.45$; $p = 0.019$) (Fig. 4). These findings indicate that individuals exhibiting greater increases in habitual physical activity also tended to present larger reductions in arterial stiffness following the intervention. In contrast, changes in GFS were not significantly associated with changes in PWVc-f ($r = -0.06$; $p = 0.781$), suggesting that vascular adaptations were more closely related to behavioral changes in daily physical activity than to improvements in overall functional fitness. Visual inspection of the scatterplots suggested

approximately linear associations between changes in PWVc-f and physical activity variables, without evidence of substantial clustering or marked nonlinearity. Although some interindividual variability and isolated extreme responses were observed, the overall pattern remained consistent across participants.

Hierarchical multiple regression analyses are presented in Table 2. Age, sex, hypertension status, and baseline PWVc-f were initially included in the models because these variables are recognized determinants of arterial stiffness and vascular responsiveness to exercise interventions. In the baseline-adjusted model, only baseline PWVc-f was independently associated with changes in PWVc-f ($\beta = -0.31$; $p = 0.025$), indicating greater reductions among individuals with higher initial arterial stiffness.

Table 2

Hierarchical multiple regression models for changes in carotid-femoral pulse wave velocity (Δ PWVc-f) (n = 38)

Variable	Standardized β	p-value
Model 1		
Age	-0.11	0.481
Sex	0.18	0.267
Hypertension	0.09	0.562
Baseline PWVc-f	-0.31	0.025
<i>Model $R^2 = 0.31$; adjusted $R^2 = 0.18$</i>		<i>0.073</i>
Model 2		
Age	-0.10	0.503
Sex	0.17	0.291
Hypertension	0.08	0.601
Baseline PWVc-f	-0.30	0.027
Δ MVPA	-0.41	0.012
<i>Model $R^2 = 0.52$; adjusted $R^2 = 0.40$</i>		<i>0.006</i>
Model 3		
Age	-0.09	0.544
Sex	0.15	0.322
Hypertension	0.08	0.618
Baseline PWVc-f	-0.31	0.025
Δ MVPA	-0.36	0.049
Δ steps/day	-0.12	0.175
<i>Model $R^2 = 0.58$; adjusted $R^2 = 0.46$</i>		<i>0.004</i>
Model 4		
Age	-0.08	0.612
Sex	0.14	0.341
PWVc-f: carotid-femoral pulse wave velocity; MVPA: moderate-to-vigorous physical activity; GFS: global fitness score.		

Variable	Standardized β	p-value
Model 1		
Hypertension	0.07	0.641
Baseline PWVc-f	-0.31	0.025
Δ MVPA	-0.17	0.049
Δ steps/day	-0.12	0.175
Δ GFS	-0.05	0.592
<i>Model $R^2 = 0.60$; adjusted $R^2 = 0.48$</i>		<i>0.003</i>
PWVc-f: carotid-femoral pulse wave velocity; MVPA: moderate-to-vigorous physical activity; GFS: global fitness score.		

The addition of Δ MVPA substantially improved model fit ($R^2 = 0.52$), and increases in MVPA remained independently associated with reductions in PWVc-f ($\beta = -0.41$; $p = 0.012$). Inclusion of Δ steps/day slightly increased the explained variance but did not significantly improve the model ($p = 0.175$). Likewise, Δ GFS minimally affected model fit and was unrelated to changes in PWVc-f ($p = 0.592$). The final model explained approximately 60% of the variance in Δ PWVc-f ($R^2 = 0.60$; adjusted $R^2 = 0.48$; $p = 0.003$), suggesting that vascular adaptations following multicomponent exercise were more closely associated with increases in habitual MVPA than with improvements in global functional fitness.

Discussion

This controlled trial investigated the effects of a 32-week multicomponent exercise program on arterial stiffness, functional fitness, and objectively measured physical activity in community-dwelling older adults. The main findings were threefold. First, overall intervention effects on PWVc-f were modest, although individuals with elevated arterial stiffness at baseline exhibited clinically meaningful reductions following training. Second, improvements in MVPA were more pronounced among participants with lower baseline activity levels, suggesting greater responsiveness among the least active individuals. Third, and most importantly, reductions in arterial stiffness were independently associated with increases in habitual MVPA, whereas changes in global functional fitness were not. Altogether, these findings suggest that vascular adaptations following multicomponent exercise may be more strongly related to behavioral changes in daily physical activity than to improvements in overall functional fitness.

The overall effects of the intervention on PWVc-f were relatively modest, which is not unexpected considering the marked interindividual variability observed in vascular responses to exercise training in older adults. However, exploratory analyses according to baseline status demonstrated that participants within the highest tertile of PWVc-f experienced reductions of approximately 9–10%, with a large effect size. This finding is clinically relevant because PWVc-f values above 10 m/s are widely recognized as

markers of increased cardiovascular risk and target-organ damage [1, 29]. Our results therefore suggest that multicomponent exercise may be particularly effective among older adults exhibiting unfavorable vascular profiles at baseline. This interpretation aligns with previous studies showing that exercise-induced reductions in arterial stiffness are generally more pronounced in individuals with elevated cardiovascular risk, hypertension, or low baseline fitness levels [16, 19]. More broadly, these findings reinforce the growing recognition that responsiveness to exercise interventions is highly heterogeneous and may depend substantially on baseline physiological status.

An important aspect of the present study is that improvements in PWVc-f were accompanied by increases in habitual MVPA, particularly among the least active participants at baseline. Individuals within the lowest MVPA tertile increased daily MVPA by approximately 55%, whereas changes were minimal among participants with higher baseline activity levels. This pattern strongly suggests the presence of a ceiling effect, whereby individuals already physically active at baseline have less room for behavioral adaptation. Similar findings have been reported in interventions targeting sedentary older adults, in whom the greatest behavioral changes typically occur among those with the poorest initial activity profiles [17, 30]. Thus, analyses based exclusively on overall group means may obscure clinically relevant responses occurring in more vulnerable or less active subgroups.

The association between changes in arterial stiffness and changes in MVPA represents one of the most relevant findings of this study. Moderate inverse correlations were observed between Δ PWVc-f and both Δ MVPA and Δ steps/day, indicating that participants who increased their habitual physical activity to a greater extent also tended to exhibit larger reductions in arterial stiffness. These findings are consistent with previous observational evidence demonstrating lower arterial stiffness among older adults with higher habitual MVPA levels [13]. More importantly, hierarchical regression analyses demonstrated that Δ MVPA remained independently associated with reductions in PWVc-f even after adjustment for age, sex, hypertension status, and baseline arterial stiffness. In contrast, changes in GFS did not independently contribute to the model. Collectively, these findings suggest that vascular adaptations following multicomponent exercise were more closely related to behavioral changes in habitual physical activity than to improvements in global functional fitness.

This observation partially contrasts with the traditional interpretation that improvements in physical fitness are the main mediators of exercise-induced cardiovascular protection. Although functional fitness remains strongly associated with health, mobility, and independence in older adults [18, 31], our data suggest that vascular responsiveness may depend more directly on the accumulated exposure to MVPA performed during daily life. Recent studies using accelerometry-based physical activity assessment support this interpretation. Königstein et al. [15], for example, reported that each additional 10 min/day of MVPA was associated with lower arterial stiffness in adults with obesity, whereas Collings et al. [14] observed favorable associations between MVPA and PWVc-f when time was reallocated from sedentary behavior or sleep to higher-intensity activities. Together with our findings, these data reinforce the concept that activity intensity may be more relevant than total movement volume for vascular health.

in older adults. Accordingly, improvements in objectively measured physical activity were more consistently associated with vascular adaptations than changes in functional performance measures.

Several physiological mechanisms may explain the observed associations between MVPA and arterial stiffness. Repeated exposure to MVPA increases pulsatile blood flow and endothelial shear stress, promoting favorable vascular adaptations such as enhanced nitric oxide bioavailability and improved endothelial function [9, 32]. Additionally, regular MVPA may reduce oxidative stress, sympathetic overactivity, and low-grade inflammation, all of which contribute to arterial stiffening during aging [11, 33]. These mechanisms may help explain why behavioral adaptations in physical activity were more strongly associated with vascular responses than changes in global functional fitness.

Interestingly, changes in daily steps did not remain independently associated with PWVc-f after inclusion of MVPA in the regression models. This finding reinforces the growing recognition that the intensity of physical activity may be more important than step accumulation alone for cardiovascular adaptations [34]. In the present study, daily step counts remained relatively stable in the exercise group despite increases in MVPA, suggesting that participants may have replaced lower-intensity activities with more vigorous activities rather than substantially increasing total ambulatory volume.

The improvements observed in functional fitness are consistent with previous studies demonstrating that multicomponent exercise interventions improve physical function, mobility, and muscular performance in older adults [18, 35, 36]. However, the lack of association between changes in GFS and PWVc-f suggests that improvements in functional performance and vascular function may not necessarily occur in parallel. Functional fitness tests integrate multiple physiological domains, including neuromuscular coordination, balance, flexibility, and muscular endurance, which may not directly reflect vascular adaptations. Thus, although multicomponent exercise appears beneficial for both functional and cardiovascular health, the mechanisms underlying these adaptations may differ.

The present study has important strengths. Physical activity was objectively assessed using accelerometry, while arterial stiffness was measured using carotid-femoral PWV, considered the reference standard for noninvasive assessment of central arterial stiffness. Additionally, the integration of vascular, behavioral, and functional outcomes allowed a more comprehensive evaluation of responsiveness to exercise training in older adults. The relatively long intervention period (32 weeks), which exceeds the duration commonly adopted in multicomponent exercise trials involving older adults, may have enhanced the ability to detect behavioral and vascular adaptations over time. The exploratory analyses according to baseline tertiles also provided clinically relevant insights regarding differential responsiveness to exercise interventions.

Some limitations should be acknowledged. Group allocation was non-randomized and based on participant availability, which may have introduced selection bias despite efforts to minimize baseline differences between groups. The relatively small sample size and exploratory subgroup analyses increase the risk of type I error and limit generalizability. Moreover, although accelerometry provides objective assessment of physical activity, the study design does not allow determination of whether

increases in MVPA occurred exclusively during supervised exercise sessions or also reflected broader behavioral changes in daily life. Finally, the observational nature of the association analyses precludes causal inference regarding the relationship between changes in physical activity and arterial stiffness. Future studies using larger samples, randomized designs, and longitudinal behavioral monitoring are warranted to clarify how changes in habitual physical activity mediate vascular adaptations to multicomponent exercise in older adults.

Conclusion

The 32-week multicomponent exercise program produced modest overall effects on arterial stiffness in community-dwelling older adults. However, clinically meaningful reductions in PWVc-f were observed among individuals with elevated arterial stiffness and lower habitual physical activity levels at baseline. Increases in MVPA were independently associated with reductions in PWVc-f, whereas improvements in global functional fitness were not. These findings suggest that vascular responsiveness to multicomponent exercise may depend more strongly on behavioral adaptations in habitual MVPA than on changes in overall functional fitness. Such results reinforce the importance of promoting sustained engagement in higher-intensity daily physical activity to optimize cardiovascular health in older adults.

Declarations

Conflicts of Interest

The authors have no competing interests to declare.

Ethics Approval

Approval was obtained from the Ethics Committee of the Faculty of Sport at the University of Porto, Portugal (CEFADE 06.2016). The procedures used in this study adhere to the tenets of the Declaration of Helsinki. This clinical trial was registered at the National Library of Medicine online database (NCT04095962) and followed the Consolidated Standards of Reporting Trials (CONSORT) for the elaboration and description of the study.

Informed consent

Informed consent was obtained from all individual participants included in the study.

Funding

This research was supported by grants from the 'Fundação para a Ciência e a Tecnologia' (FCT, grant UIDB/00617/2020, doi:10.54499/UIDB/00617/2020), 'Fundação de Amparo à Pesquisa no Estado de Minas Gerais' (FAPEMIG, grant APQ-05247- 23), 'Conselho Nacional de Desenvolvimento Científico e

Tecnológico' (CNPq, grant 305262/2023-8), and 'Fundação Carlos Chagas Filho de Apoio à Pesquisa no Estado do Rio de Janeiro' (FAPERJ, grant E-26/204.102/2024).

Author Contribution

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Data Availability

The raw data are available on reasonable request from the corresponding authors to preserve individuals' privacy under the European General Data Protection Regulation.

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Figures

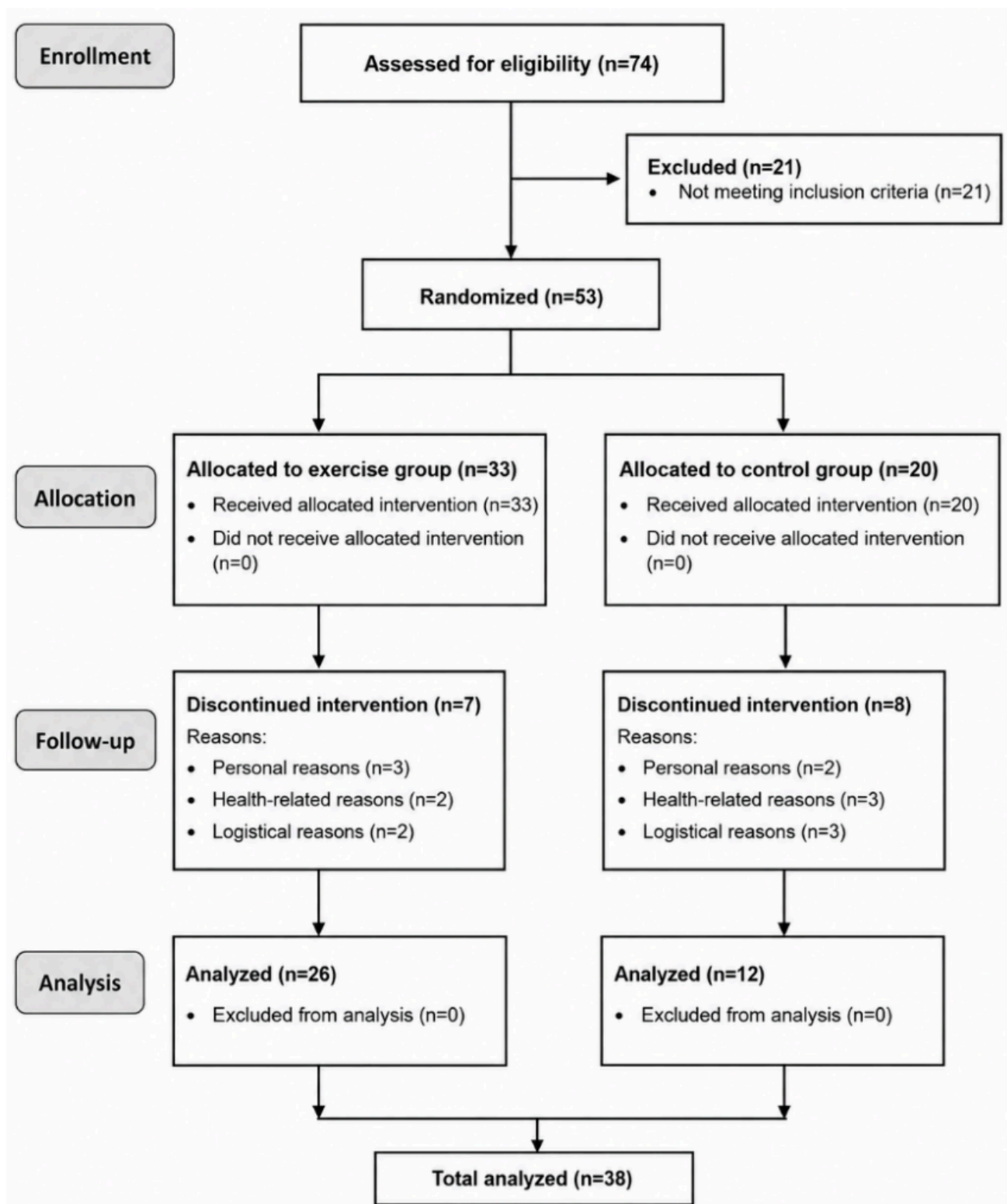


Figure 1

CONSORT flow diagram

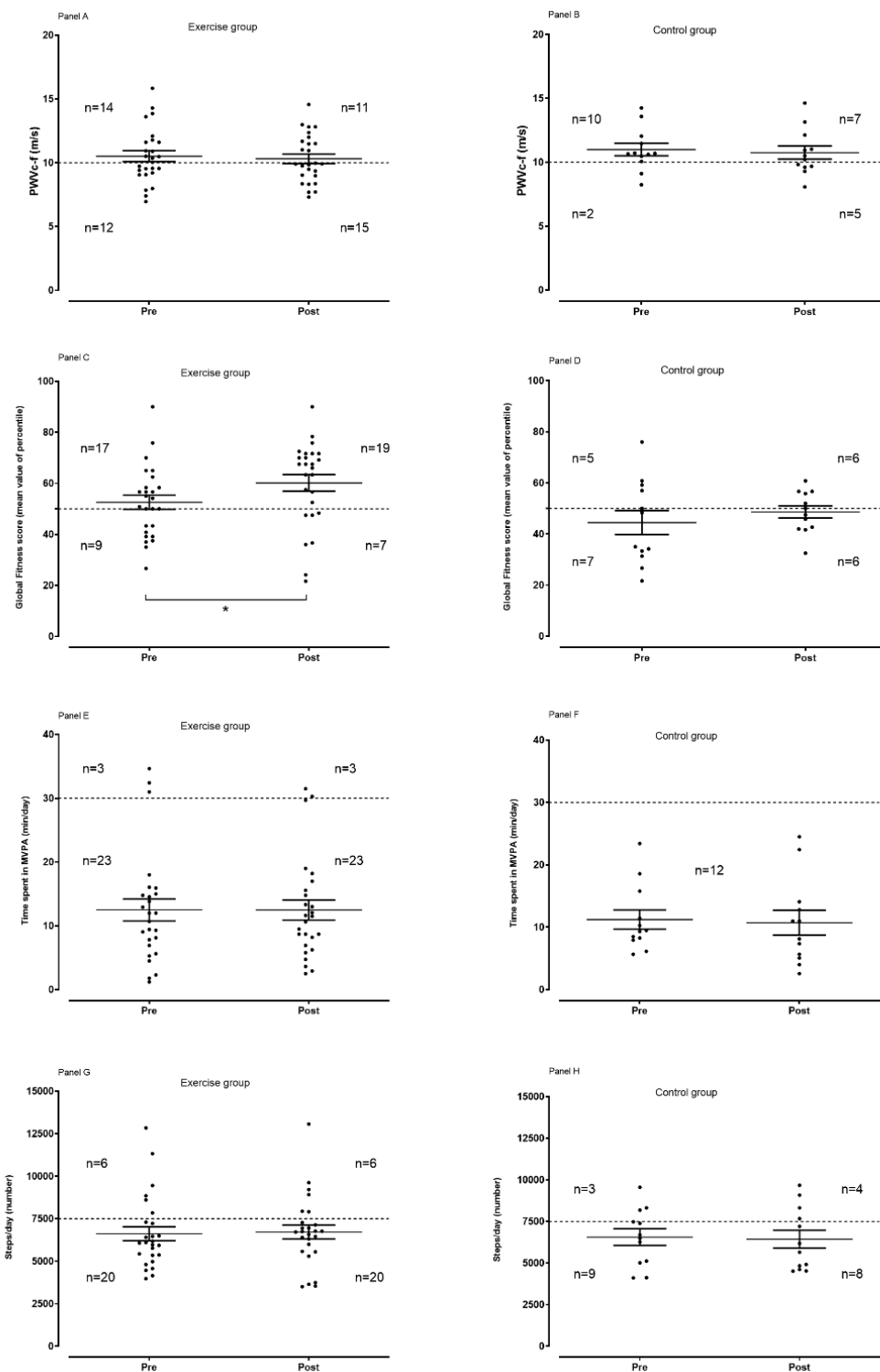


Figure 2

Effects of a 32-week multicomponent exercise program on carotid-femoral pulse wave velocity (PWVc-f; Panels A and B), global fitness score (GFS; Panels C and D), moderate-to-vigorous physical activity (MVPA; Panels E and F), and steps/day (Panels G and H). Data are expressed as mean $\pm$ SEM. Dots represent individual data. Horizontal dashed lines indicate reference thresholds for elevated PWVc-f (>10)

m/s), median for GFS, recommended MVPA (30 min/day), and daily steps (7,500 steps/day). *: Significant pre- to post-intervention difference within group ($p < 0.05$).

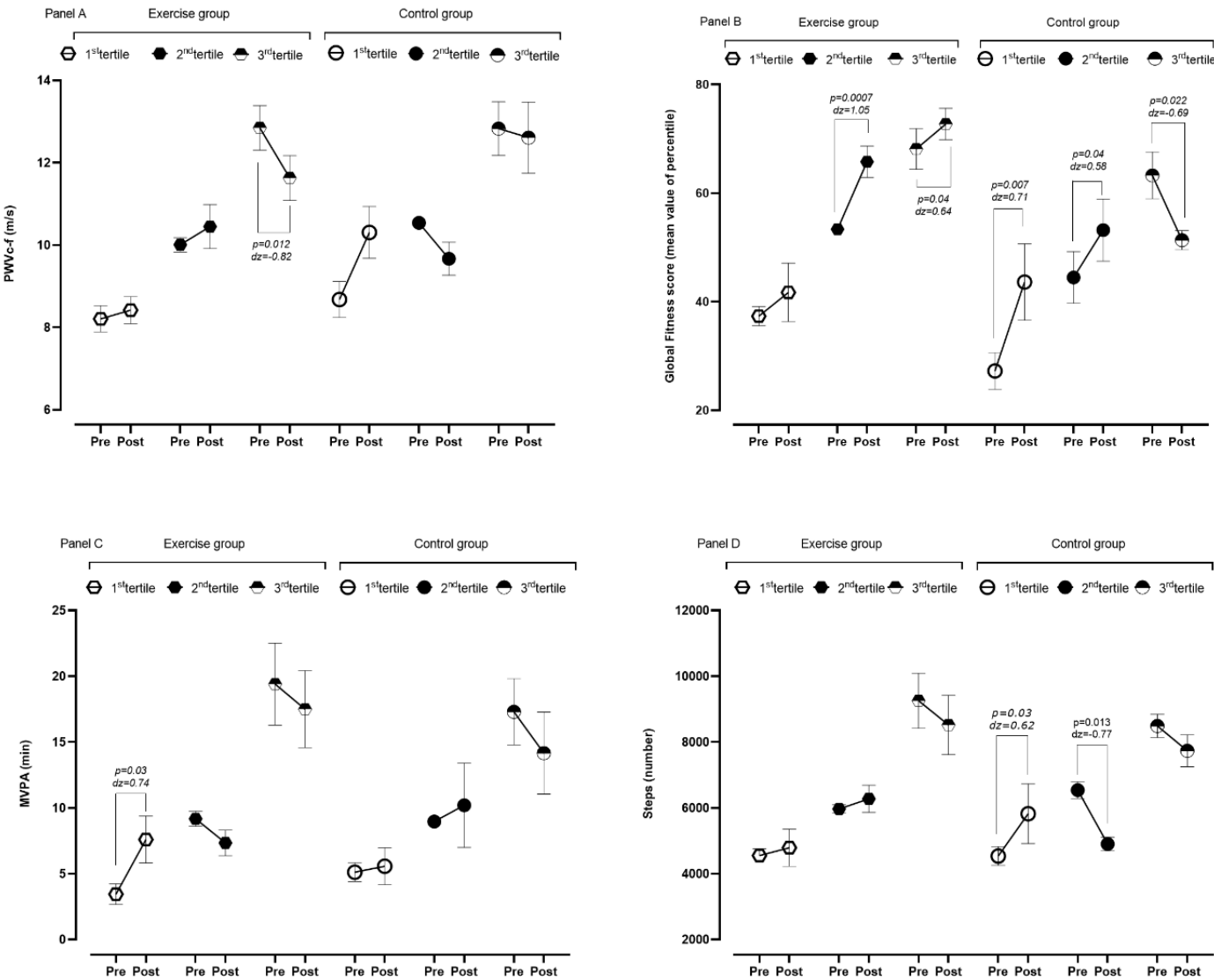


Figure 3

Changes in carotid-femoral pulse wave velocity (PWVc-f; Panel A), global fitness score (GFS; Panel B), moderate-to-vigorous physical activity (MVPA; Panel C), and steps/day (Panel D) according to tertiles of baseline values following the 32-week multicomponent exercise intervention. Data are expressed as mean $\pm$ SEM. p-values and Cohen's dz indicate pre- to post-intervention changes within each tertile and group. Negative dz values indicate reductions over time.

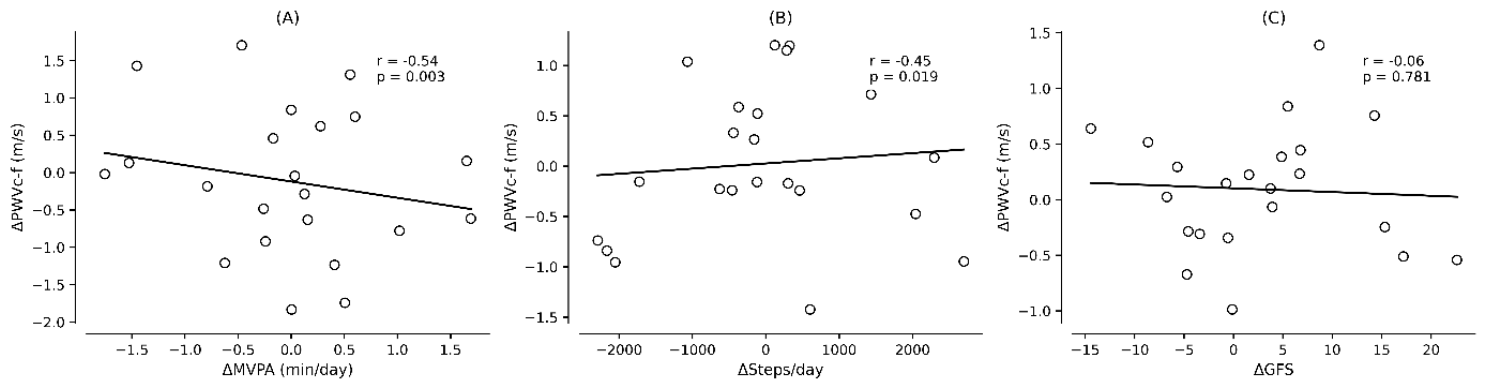


Figure 4

Associations between changes in carotid-femoral pulse wave velocity (ΔPWV_{c-f}) and changes in moderate-to-vigorous physical activity ($\Delta MVPA$; Panel A), steps/day ($\Delta steps/day$; Panel B), and global fitness score (ΔGFS ; Panel C) following the 32-week multicomponent exercise intervention. Lines represent linear regression fits. Pearson correlation coefficients (r) and corresponding p-values are presented within panels.