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Acute and chronic effects of traditional and high-speed resistance training on blood pressure in older adults: A crossover study and systematic review and meta-analysis

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ABSTRACT

Purpose: The present study included two related investigations that explored the acute and chronic effects of high-speed resistance training (HSRT) on blood pressure (BP) in older adults.
Methods: The first study involved a randomized crossover study that compared the acute effects of traditional resistance exercise (TRT) and high-speed resistance training (HSRT) on hemodynamic parameters in frail older adults. Sixteen institutionalized frail older adults were recruited. BP was recorded before, over 1 h, and 24 h after the end of the experimental session. Participants performed 4 resistance exercises involving 4–8 sets with 4–10 repetitions at moderate intensity. The second study was a systematic review and meta-analysis of experimental studies that investigated the acute and chronic effects of HSRT on BP in older adults. Crossover, quasi-experimental, and randomized controlled trials that examined the effects of HSRT on BP in people aged 60+ years as a primary or secondary outcome were included. Studies were retrieved from MEDLINE, SPORTDiscuss, CINAHL, SCOPUS and AgeLine databases from inception through December 31, 2021. The risk of bias was evaluated using the Newcastle - Ottawa Quality Assessment Scale (NOS). A pooled effect size was calculated based on standard mean differences (SMD).
Results: In study 1, we observed that both TRT and HSRT caused post-exercise hypotension (PEH). However, systolic BP (SBP) was significantly lowered for up to 60 min after TRT, while it was only reduced 30 and 50 min after HSRT. There was no difference in SBP between resistance exercise protocols. A reduction in mean arterial pressure was only observed after TRT. In study 2, 1114 articles were identified, and 8 were included in the meta-analysis. Pooled analyses indicated that HSRT did not cause significant PEH. However, a significant reduction in SBP was observed after HSRT programs in comparison to controls (SMD = 0.61, $P = 0.009$) and baseline values (SMD = 2.03, $P = 0.04$).
Conclusion: In study one, we observed that both TRT and HSRT caused systolic PEH in comparison to baseline in frail older adults. However, specific patterns were observed according to each type of RT. Indeed, a longer PEH in comparison to baseline was observed after TRT, whereas HSRT had greater reductions in comparison to CS. In addition, TRT had exclusive reductions in MAP. These results were not supported by our meta-analysis, given

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that no significant effects of an acute session of HSRT on office and ambulatorial BP were observed. On the other hand, our findings suggest that HSRT might significantly reduce SBP in older adults.

1. Introduction

Aging is an inherent process that involves functional and structural changes of all physiological systems, contributing to the development of geriatric syndromes and degenerative diseases (Franceschi et al., 2018). Chronic elevations in blood pressure (BP) levels are an example of these age-related events and the main feature of hypertension (Lloyd-Sherlock et al., 2014; Mozaffarian et al., 2015; Rigaud and Forette, 2001). This disease is highly prevalent in older people, affecting >75% of the older population (Zhou et al., 2021).

Old age is also associated with increased prevalence of frailty (Coelho-Júnior et al., 2020; Collard et al., 2012; Da Mata et al., 2016; Kojima et al., 2017; Ofori-Asenso et al., 2019), a potentially reversible state of greater vulnerability to negative health-related events (Coelho-Júnior et al., 2020). Although the progression of frailty is commonly associated with physical and cognitive decline (Kojima, 2017), some studies have expanded this view by indicating a significant association between some aspects of frailty (e.g., dynapenia, low mobility, impaired balance) and hemodynamic parameters (Acar et al., 2015; Coelho Junior et al., 2017; Feng et al., 2021; Hausdorff et al., 2003). Furthermore, cardiovascular disease is common in frail people (Kańtoch et al., 2018) and a frequent cause of hospitalization due to inappropriate care (Ahmed and Ekundayo, 2009).

A recent report of the European Society of Hypertension-European Union Geriatric Medicine Society (ESH-EUGMS) Working Group recommended that special attention be given to the antihypertensive treatment of frail older adults (Benetos et al., 2016). However, no specific guidelines or algorithms for the management of cardiovascular disease in this population are available (Kańtoch et al., 2018).

Exercise training is a well-established non-pharmacological tool for the management of BP and hypertension in older adults (MacDonald et al., 2016). Studies have repeatedly observed that different designs of dynamic and isometric resistance training (RT), a type of exercise in which muscles work or hold against an applied force (Kraemer and Ratamess, 2004), might significantly reduce BP in normotensive, pre-hypertensive, and hypertensive older adults (De Sousa et al., 2017; Hansford et al., 2021; Herrod et al., 2018; Igarashi and Nogami, 2018; Kelley and Kelley, 2010, 2000a, 2000b; Loaiza-Betancur et al., 2020; López-Valenciano et al., 2019; MacDonald et al., 2016; Naci et al., 2019; Owen et al., 2010). Particularly, prior pooled analyses (De Sousa et al., 2017; MacDonald et al., 2016) observed that traditional RT (TRT), the type of RT commonly recommend to counteract age-related reduction in neuromuscular function (Mark D. Peterson et al., 2016; Martone et al., 2017), reduced systolic BP by approximately 7 mmHg in pre-hypertensive and hypertensive people. As such, specific exercise recommendations for health professionals have been proposed (Pescatello et al., 2015).

In the last years, high-speed resistance training (HSRT), a type of RT in which muscle contractions are performed as fast as possible, has received increasing attention in geriatrics and related fields (Cadore and Izquierdo, 2018a; Izquierdo and Cadore, 2014). According to experts in the field (American College of Sports Medicine et al., 2009; Fragala et al., 2019), HSRT should be part of RT programs for older adults who aim to improve physical function, given that some aspects of neuromuscular function seem to be more dependent on high-speed muscle actions than on those performed at low speed (Bean et al., 2003; Reid and Fielding, 2012). Indeed, the prescription of HSRT programs for frail older adults have been highly encouraged as an approach to promote gains in physical performance and reduce falls (Fragala et al., 2019), even if its superiority and effectiveness at counteracting frailty have not been clearly demonstrated (Coelho-Júnior and Uchida, 2021) and its feasibility is debated (Coelho-Júnior, 2021).

The effects of HSRT on BP in older adults are poorly understood. Although clinical guidelines are commonly based on the chronic benefits of exercise, a single session of exercise may induce post-exercise hypotension (PEH), a phenomenon characterized by reduced BP values to levels below baseline or a control session (de Brito et al., 2019). PEH may last up to 24 h (Taylor-Tolbert et al., 2000) and might persists during the activities of daily living (Coelho-Júnior et al., 2017a; MacDonald et al., 2001). In addition, evidence has indicated that PEH can help discriminate responders from non-responders to chronic exercise (Moreira et al., 2016).

An increasing number of studies have investigated the acute effects of HSRT on PEH and trials have provided inconsistent results. Studies were conducted in healthy older women (Coelho-Júnior et al., 2017b; Orsano et al., 2018), BP was measured only immediately after the exercise session (Machado et al., 2019), and not equalized exercise protocols were adopted (Coelho-Júnior et al., 2017b), which impedes a clear understanding of post-high speed resistance exercise hypotension in older adults. Noticeably, no studies have been conducted in frail older people.

Since frail older adults are at especially high cardiovascular risk, understanding the acute effects of HSRT may provide information for developing specific recommendations on non-pharmacological therapies in this population. Hence, the first aim of present study was to investigate the acute effects of HSRT and TRT on BP parameters in frail older adults.

Several studies have investigated changes in hemodynamic parameters during (Da Silva et al., 2007; Machado et al., 2021; Richardson et al., 2018) and after (Coelho-Júnior and Uchida, 2021; Kanegusuku et al., 2011; Roberson et al., 2018) HSRT exercise sessions or programs. However, substantial differences exist in sample characteristics, instruments and intervals selected to measure BP, and HSRT protocols. Therefore, important information to guide the choice of exercise variables is presently lacking. A comprehensive appraisal of existing studies might allow filling this gap in knowledge. Hence, we conducted a second study that involved a systematic review and meta-analysis of experimental studies that investigated the acute and chronic effects of HSRT on BP in older adults. Because of the small number of investigations eligible for the meta-analysis, results of our first study were included in the pooled analysis to increase the amount of information on treatment effects in a "real-world" sample of older adults.

2. Material and methods

2.1. Study 1

The first study was a randomized crossover trial that compared the acute effects of HSRT and TRT on BP parameters in a sample of frail older adults. Participants performed three experimental sessions (i.e., TRT, HSRT, and a control session [CS]) in a random order and separated from one another by seven days (standard deviation [±] 1 day). Food consumption was maintained constant during 48 h prior to the exercise session and a standard breakfast was offered 60–90 min before the beginning of the experimental sessions. The pharmacological therapy was kept constant during the whole study, and participants took their anti-hypertensive medication at the same time in all experimental days as prescribed by their physician. The study protocol was approved by the Research Ethics Committee of the University of Campinas (Campinas - SP, Brazil; ID number: 20021919.7.0000.5404). All study procedures were conducted in compliance with the Declaration of Helsinki and the Resolution 196/96 of the National Health Council. All participants gave

their written informed consent before participation. The study adheres to the Consolidated Standards of Reporting Trials guidelines (CONSORT): Extension to Randomized Crossover Trials (Dwan et al., 2019). The study was retrospectively registered at ClinicalTrials.gov (20021919).

2.1.1. Participants

Institutionalized older adults (aged 72 to 99 years) without prior experience in resistance training were recruited by convenience from a public nursing home located in the eastern region of São Paulo State, in southern Brazil. Candidate participants were eligible if they were: a) aged ≥60 years; b) frail according to Fried's criteria (2001); c) possessed sufficient physical and cognitive abilities to perform all exercises required by the protocol; and d) had a physician authorization to participate. Exclusion criteria were: participation in a structured physical exercise training program in the past six months, prescription of hormone replacement therapy and/or psychotropic drugs, and presence of any acute cardiovascular event (e.g., myocardial infarction) or complication in the past six months.

Participants were randomized into TRT, HSRT, and CS sessions by an independent researcher using a computer-generated list of random numbers TRT.

2.1.2. 10-repetition maximum test (10RM)

Participants were familiarized with resistance exercises used in the present study before the ten-repetition maximum test (10RM). 10RM tests were performed for the following three exercises: squat on the chair, seated unilateral hip flexion, and seated unilateral knee extension. Before the tests, participants performed a brief specific warm-up using light loads. Afterward, the 10RM load was determined in up to three attempts, with a 3-min rest interval between the attempts. The resistance was increased according to the participant capacity to perform more than one successful RM with the proper technique. The test was completed when participants were unable to perform >10 repetitions using proper technique (Simão et al., 2012). All trials were performed using the full range of motion. Subsequently, the one-maximum repetition (1RM) was calculated based on the following formula:

a) $1RM = (10RM / (1.0278 - [0.0278 \times 10]))$ (Brzycki, 1993).

2.1.3. Experimental sessions

Exercise sessions were performed in the morning (07:00 am–12:00 am) under the supervision of at least two fitness instructors in the rehabilitation unit of the nursing home. After a brief warm-up, participants performed the following exercises using an adjustable weight vest and ankle weights (DOMYOS®, Shangai, China): 1st) squat on the chair, 2nd) seated unilateral hip flexion, 3rd) seated unilateral knee extension, and 4th) bilateral calf raise. The total volume load (sets × repetitions × load = ~800 kg) was equalized among the exercise sessions. A 40–45 s rest interval was provided between exercise sets and a 1-min rest interval was provided between resistance exercises. TRT and HSRT were designed according to the peculiarities of each type of resistance exercise (Chodzko-Zajko et al., 2009). During TRT, participants performed four sets of 8–10 repetitions at 70–75% of 1RM. The concentric and eccentric phases were carried out for 2 s. For HSRT, exercises were performed eight times (sets) with 4–5 repetitions at 70–75% of 1RM. The concentric phase was performed as fast as possible, and the eccentric phase was carried out for 2 s. Bilateral calf raise was performed using the same load as unilateral knee extension. A researcher was responsible for monitoring and ensuring that the velocity of muscle contractions was compliant with the protocol. Particularly, verbal encouragement was provided during the HSRT. For the CS, participants remained seated in a comfortable chair listening to music and/or talking with study investigators for approximately 30 min.

2.1.4. Main outcome: hemodynamic parameters

Hemodynamic parameters were measured by the same investigator accordingly to the recommendations of the VII Joint National Committee of High Blood Pressure (JNC7) (Chobanian et al., 2003). Baseline BP was calculated as the mean value measured during the three consecutive visits. Participants remained seated in a comfortable chair in a room with artificial light for baseline and post-exercise BP measurements. The hemodynamic parameters were blindly measured in the left arm using an automated oscillometric equipment (BP 3BT0A, Microlife AG, Widnau, Switzerland) (Cuckson et al., 2002) and were recorded immediately after (IA) (0 min), and at 10, 20, 30, 50, and 60 min, as well as 24 h after the end of experimental sessions. The same procedures were used to assess hemodynamic parameters across the whole study. At the end of each measurement, the equipment provided systolic BP (SBP), diastolic BP (DBP), and heart rate (HR). Mean arterial pressure (MAP) was determined based on the formula:

b) $SBP + [2 \times DBP]) / 3$.

Mean 1 h hemodynamic parameters were calculated according to the formula:

c) (value IA + value at 10′ + value at 20′ + value at 30′ + value at 50′ + value at 60′) / 6.

2.1.5. Statistical analysis

The researcher responsible for the statistical analysis was not blinded to participant group assignments. The normality of data was tested using the Kolmogorov-Smirnov test. Intra- and inter-session comparisons among the different periods (i.e., baseline, 10′, 20′, 30′, 50′, 60′, and 24 h after the end of each session) for SBP, DBP, HR, and MAP were performed using two-way repeated-measures analysis of variance (2-way ANOVA) followed by Dunnett's post-hoc test. Greenhouse-Geisser corrections were applied for data that violated sphericity assumptions. The area under the curve (AUC) was calculated taken into consideration the space between IA and 60′ and compared using 1-way ANOVA followed by Tukey's post-hoc test. The level of significance was 5% ($P < 0.05$) and all analyses were performed using GraphPad PRISM software 6.0 (CA, USA).

2.2. Study 2

The second study was a systematic review and meta-analysis of experimental studies that investigated the acute and chronic effects of HSRT on hemodynamic parameters of older people. The study was fully performed by investigators and no librarian was part of the team. The study complied with the criteria of the Primary Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) Statement (Dwan et al., 2019) and Cochrane Handbook for Systematic Reviews and Interventions (Green and Higgins, 2005). An a priori protocol was established and registered on PROSPERO [CRD42022298495].

2.2.1. Eligibility criteria

Crossover, quasi-experimental, and randomized controlled trials that examined the effects of HSRT on BP in people aged 60+ years as a primary or secondary outcome were included. No restrictions for sample characteristics were adopted. Additional eligibility criteria consisted of studies that measured hemodynamic parameters during or at least over 30 min after the end of experimental sessions, and/or before and after HSRT programs with a minimum duration of 4 weeks, and published studies in English, Italian, Spanish, or Portuguese language. To be included in the meta-analysis, in addition to the aforementioned criteria, investigations had to include an active (exercise) or non-exercise control group (CG)/CS and provide pre-post mean and standard deviation (SD) of each intervention arm. Baseline BP levels were used as the comparator in studies that investigated PEH. We excluded preclinical and

review studies, and studies that combined HSRT with other interventions.

2.2.2. Search strategy and selection criteria

Studies published on or before December 31, 2021 were retrieved from the following five electronic databases by one investigator: MEDLINE (PubMed interface), Scopus (EBSCO interface), AgeLine (EBSCO interface), CINAHL (EBSCO interface), SPORTDiscus (EBSCO interface). Further eligible articles were identified by checking reference lists of systematic reviews and meta-analyses (De Sousa et al., 2017; Hansford et al., 2021; Herrod et al., 2018; Igarashi and Nogami, 2018; Kelley and Kelley, 2010, 2000a, 2000b; Loaiza-Betancur et al., 2020; López-Valenciano et al., 2019; MacDonald et al., 2016; Naci et al., 2019; Owen et al., 2010) and retrieved articles. In addition, citation searches on key articles were performed in Google Scholar and ResearchGate. Initially, a search strategy was designed using keywords, MeSH terms, and free text words, such as "Power Training", "Blood Pressure", and "Older Adults". Keywords and subject headings were exhaustively combined using Boolean operators. The complete search strategy is detailed in Supplementary Material 1 (SM1).

2.2.3. Data extraction, quality assessment, and risk of bias

Titles and abstracts of retrieved articles were independently screened for eligibility by two researchers (HJCJ, SSA). The full text was consulted if the abstract did not provide enough information for final evaluation. Two reviewers (HJCJ, SSA) extracted coded variables (i.e., methodological quality, risk of bias, and characteristics of the studies) using a standardized coding form. A third researcher was consulted to solve disagreements (EM), if necessary. The quality of reporting for each study was independently performed by two researchers (HJCJ, SSA) using the Quality Assessment Tool for Before-After (Pre-Post) Studies With No Control Group and the Quality Assessment of Controlled Intervention Studies (National Heart, Lung, and Blood Institute [NHLBI], n.d.). The maximum scores for crossover, quasi-experimental, and randomized controlled studies were 10, 12, and 14, respectively. The agreement rate for quality assessment between reviewers was 99%. The risk of bias was assessed using the Newcastle - Ottawa Quality Assessment Scale (NOS): Randomized Controlled Trial (Modesti et al., 2016; Wells et al., 2011). NOS examines potential bias on selection, comparability, and exposure.

2.2.4. Statistical analysis

The meta-analysis was conducted using Revman 5.4.1 (Cochrane Collaboration, Copenhagen, Denmark). Effect sizes (ESs) were measured using mean, SD, and sample size. A single pairwise comparison was created when studies had multiple intervention groups using the formulas proposed by the Cochrane group (Green and Higgins, 2005):

a) Sample size = $N_1 + N_2$
b) Mean = $(N_1 M_1 + N_2 + M_2) / N_1 + N_2$
c)

$$SD = \sqrt{\frac{[N1 - 1]SD12 + [N2 - 1]SD22 + \frac{N1N2}{N1+N2}[M12 + M22–2M1M2]}{N1 + N2 - 1}}$$

Pooled ESs were calculated based on standard mean difference (SMD) of PEH and office BP. PEH was ascertained based on changes in SBP and DBP 15, 30, 45, and 60 min after the end of HSRT sessions in comparison to baseline values and TRT. The SMD of office BP was calculated based on values obtained before and after HSRT and CG interventions. Due to the different characteristics of the included studies, a random-effect model was used to calculate the pooled ES. Heterogeneity across studies was tested using the Q statistics, whereas the I^2 index was used to assess inconsistency (Green and Higgins, 2005). In addition, the I^2 index was classified as might not be important (0–40%), may represent moderate heterogeneity (30–60%), may represent substantial heterogeneity (50–90%), and represents considerable heterogeneity (75–100%) (Green and Higgins, 2005). Forest plots were used to illustrate summary statistics and the variation across studies.

3. Results

3.1. Study 1

Twenty-two older adults were invited to participate and 20 accepted to be evaluated for inclusion criteria (Fig. 1). Of these, two were excluded for having a clinical diagnosis of psychiatric diseases, while two declined for personal reasons. Hence, 16 older adults were included in the study. No participants were lost to follow-up in any experimental sessions. A flowchart is presented in Fig. 1.

3.1.1. Participant characteristics

The main characteristics of participants are shown in Table 1. All participants were disabled and required assistance to perform basic activities of daily living. Their daily activities involved walking three to four times from the bed to the dining room of the institute. Those who could not walk well and safely were accompanied using a wheelchair. Movie sessions, visits to theatres and open markets, and socializing activities took place once a week, but only some participants joined these activities. Regarding frailty criteria, exhaustion and low physical activity levels were observed in the whole sample, while weakness and slow walking speed were observed in 87.5% of the participants. Eleven older adults reported involuntary weight loss in the past six months. A mean number of two medications were took by each participant. Pharmacological therapy was highly heterogeneous: one participant took six medications, two participants took three, eight participants took two, four participants took one, and one participant did not take any medication. Participants completed all experimental sessions.

3.1.2. Hemodynamic responses to HSRT and TRT

Delta and raw values of hemodynamic parameters are shown in Fig. 2 and Table 2, respectively. ANOVA revealed a significant main effect of time ($P < 0.0001$) and interaction ($P < 0.0009$), but not treatment ($P = 0.6686$) on SBP. Both TRT and HSRT caused systolic PEH (Fig. 2a), but different patterns were observed among the exercise sessions. SBP was significantly lowered 30 and 50 min after HSRT and over the entire period after TRT relative to baseline. When compared with CS, HSRT reduced SBP at 10, 30, and 50 min, while it was only decreased at 20 min by TRT. ANOVA revealed a significant main effect of time ($P = 0.02$) and interaction ($P < 0.0006$), but not treatment ($P = 0.5695$) on MAP. Exclusive reductions in MAP at 10, 20, and 30 min were observed after TRT (Fig. 2c). Lower MAP values at 20 min were found for TRT relative to CS. Similar results were observed for the 1-h mean of post-exercise hemodynamic parameters, given that SBP were significantly reduced after both TRT and HSRT, whereas only TRT reduced MAP. In contrast, DBP and MAP were significantly increased after CS. No further within- and between-session significant differences were observed (Fig. 2b and d).

Hemodynamic responses according to frailty parameters are shown in SM2. Significant reductions in SBP were observed after both TRT and HSRT in people with weakness ($n = 14$), slowness ($n = 14$), and unintentional weight loss ($n = 11$). In people with slowness and unintentional weight loss, DBP and MAP were significantly increased after CS. Furthermore, 1-mean SBP was significantly lower after TRT in comparison to HSRT in participants with unintentional weight loss.

AUC analysis is shown in Table SM3. Greater AUC for SPB was observed in HSRT and TRT in comparison to CS. In addition, TRT had greater AUC for MAP than HSRT and CS.

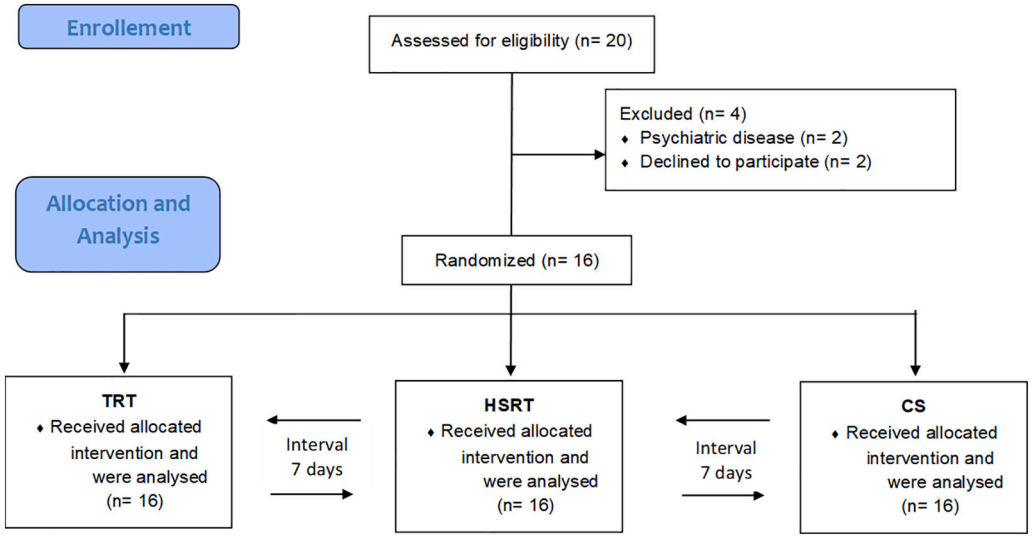

Fig. 1. Flowchart of the crossover study. CS = control session; HSRT = high-speed resistance training; TRT = traditional resistance training.

Table 1
Main characteristics of study participants.

Variables	$n = 16$
Age, years	81.0 ± 9.2
BMI, kg/m^2	23.2 ± 2.1
Men, n (%)	6 (37.5)
Length of institutionalization, years	2.2 ± 3.4
Frailty phenotype, n (%)	
Weakness	14 (87.5)
Slow walking speed	14 (87.5)
Unintentional weight loss	11 (68.0)
Exhaustion	16 (100)
Low activity level	16 (100)
Hemodynamic parameters	
SBP, mmHg	128.8 ± 19.8
DBP, mmHg	77.4 ± 12.2
MAP, mmHg	77.4 ± 12.2
HR, bpm	76.8 ± 12.1
Comorbidities, n (%)	
Hypertension	14 (87.5)
Osteoarthritis	6 (37.5)
Previous stroke	6 (37.5)
Diabetes	10 (62.5)
Low-back pain	1 (6.3)
Parkinson's disease	1 (6.3)
Medications, n (%)	
ACE inhibitors	12 (75)
Diuretics	5 (31.3)
ANG II receptor antagonists	6 (37.5)
Proton-pump inhibitors	5 (31.3)
Antidiabetics	2 (12.5)
Beta-blockers	1 (6.3)
Nonsteroidal anti-inflammatory drugs	1 (6.3)
Mean number of medications	2.0 ± 1.3

Data of continuous variables are presented as mean ± standard deviation. BMI = body mass index; SBP = systolic blood pressure; DBP = diastolic blood pressure; MAP = mean arterial pressure; HR = Heart rate; ACE = angiotensin converting enzyme; ANG = angiotensin.

3.1.3. Harms

No major adverse events were recorded during or after exercise interventions. Some participants of both groups complained of muscle fatigue and minimal joint pain during exercise sessions. One participant reported epigastric discomfort and nausea during squat exercise.

3.2. Study 2

3.2.1. Literature search

One-thousand one-hundred fourteen records were identified through database and hand searching. Of these, 455 records were excluded based on duplicate data. Six-hundred forty-nine were analyzed for title and abstract and 18 studies were fully assessed for eligibility. Four articles did not meet eligibility criteria and were excluded (SM4), leaving 14 articles for the systematic review, Finally, 8 articles were included in the meta-analysis. The flowchart of study 2 is shown in Fig. 3.

3.2.2. Characteristics of the included studies

The main characteristics of the included studies are shown in Table 3. Ten studies involved a crossover randomized design (Coelho-Júnior et al., 2017b; Da Silva et al., 2007; de Oliveira Carpes et al., 2021; Filho et al., 2020; Machado et al., 2021; Oliveira-Dantas et al., 2021; Orsano et al., 2018; Richardson et al., 2018; Schimitt et al., 2020), three investigations were randomized controlled trials (Coelho-Júnior and Uchida, 2021; Kanegusuku et al., 2011; Roberson et al., 2018), and one study was based on a quasi-experimental design (Machado et al., 2019). Two studies included the same cohort (de Oliveira Carpes et al., 2021; Schimitt et al., 2020). Crossover randomized studies included 136 community-dwelling and institutionalized normotensive and hypertensive older adults. The mean age of participants was 68.6 years, ranging from 62.6 to 81 years. Acute sessions of HSRT involved 3–8 sets of 3–10 repetitions at 40–75% of 1RM using one, four, five, six, eight, nine, or 10 exercises. One study involved a fixed number of RM. Concentric contractions were performed as fast as possible, as per protocol, while eccentric contractions lasted from two to three s. Rest intervals between sets and exercises were 2 and 3 min, respectively. CSs were based on exercise and nonexercised groups. Five CS involved acute sessions of TRT, which ranged from 3 to 4 sets of 7–10 repetitions at 60–80% of 1RM using one, four, eight, nine, or 10 exercises. One CS was based on two discontinuous acute sessions of HSRT with pauses of five and 15 s between the fifth and sixth repetitions, respectively. Five investigations compared exercise protocols with equalized total volume. Hemodynamic parameters included office SBP, DBP, MAP, HR, rate pressure

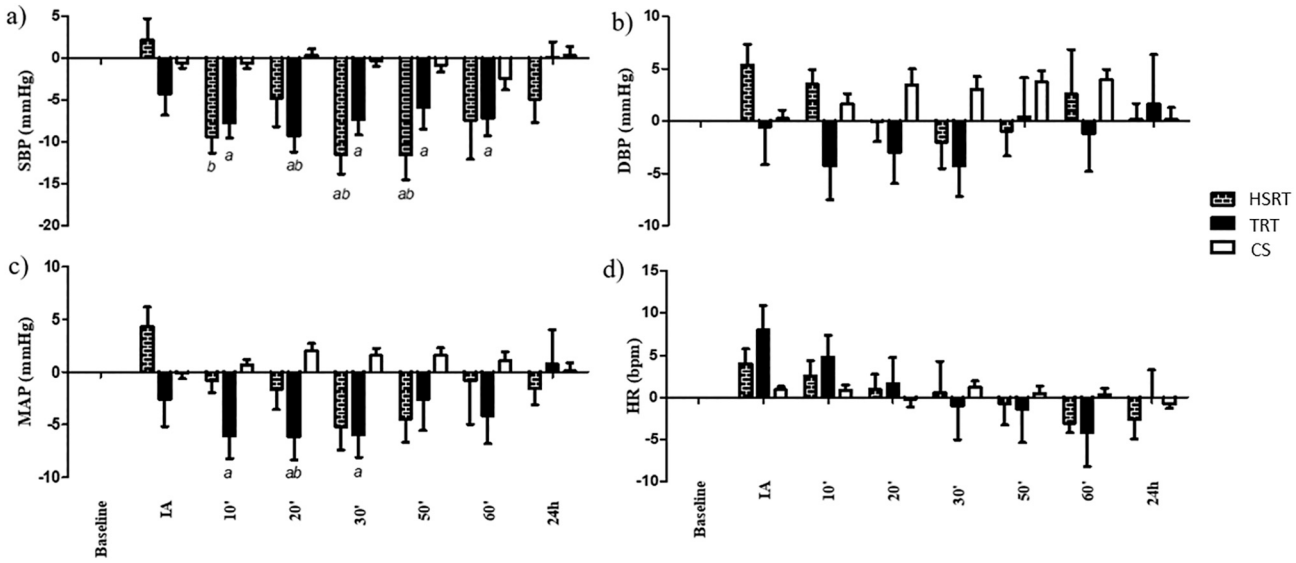

Fig. 2. Hemodynamic parameters in experimental sessions. CS = control session; DBP = diastolic blood pressure; HR = heart rate; HSRT = high-speed resistance training; TRT = traditional resistance training; MAP = mean arterial pressure; SBP = systolic blood pressure.

product (RPP), and 24-h BP. Oscilometric BP and ambulatory BP monitors (ABPMs) were used in most studies, while one study used a mercury column sphygmomanometer.

Three randomized controlled trials that investigated 129 prefrail, frail, normotensive and older adults with increased cardiovascular risk with a mean age of 67.6 years were included. Interventions lasted from 12 to 16 weeks. Two studies involved traditional HSRT programs, while one study was based on a circuit HSRT program. Exercise sessions used 3–8 sets of 3–10 repetitions performed at 30–75% of 1RM. Concentric contractions were performed as fast as possible, while eccentric contractions lasted approximately two s. The circuit HSRT program was based on 1–3 rotations with 12 repetitions at 50–70%1RM in 11 exercises. CG involved exercise and nonexercised groups. One exercise CG program was based on 35 min of treadmill exercise performed at low-to-moderate intensity. The other exercised CG programs included 2–4 sets of 6–10 repetitions at 70–90% 1RM in 4–7 exercises. Eccentric contractions lasted approximately 2 s. Hemodynamic parameters included office SBP, DBP, HR, and RPP.

One study used a quasi-experimental design. Machado et al. (2019) examined 12 older adults with type II diabetes (mean age: 68.7 years), who performed a 12-week HSRT protocol based on 3 sets of 4–10 repetitions at submaximal intensity in eight exercises. The main outcome was office BP assessed using an oscilometric BP monitor.

3.2.3. Quality assessment and risk of bias

Overall quality assessment scores are shown in SM5. All crossover randomized studies described the interventions as randomized trials (item 1), avoided that study participants took part in other interventions (item 10), used valid and reliable instruments to assess BP (item 11), and reported prespecified outcomes (item 13). Treatment allocation was concealed in probably all investigations (item 3). In addition, 80% of the studies used a sample size sufficiently large to detect differences in the main outcome between groups with a power of 0.8 (item 12), 70% used an adequate method of randomization (item 2), and 50% were randomized by a blinded researcher (item 4). Study outcomes were assessed by a blinded investigator in only one study (item 5). All randomized controlled trials described the interventions as randomized trials (item 1), investigated groups with similar important characteristics at baseline (item 6), avoided that study participants took part in other interventions (item 10), used valid and reliable instruments to assess BP (item 11), and conducted an intention-to-treat analysis. Moreover, 66% of the studies showed an adequate method of randomization (item 2), treatment allocation concealed (item 3), a drop-out rate $\leq$ 20% (item 7), a between-group difference in drop-out rate $\leq$ 15% (item 8), a high adherence to intervention protocols (item 9), a sample size sufficiently large to detect a difference in the main outcome between groups with a power of 0.8 (item 12), and reported prespecified outcomes (item 13). In one study, participants were randomized by a blinded investigator (item 4). In all studies, outcomes were assessed by a blinded investigator (item 5). The quasi-experimental study clearly stated its design (item 1) and the eligibility criteria (item 2), examined participants who represented a general clinical population (item 3) that met the inclusion criteria (item 4), described the exercise intervention (item 6), used valid and reliable instruments to assess study outcomes (item 7), had a loss of follow-up rate lower than 20% (item 9), used adequate statistical analysis to identify changes (item 10), and used individual-level data to determine effects at the group level (item 12).

Risk of bias is showed in SM6a and b and the point-by-point analysis is available in SM7 and SM8. Crossover and randomized controlled trials were classified as having a low risk of bias.

3.2.4. Hemodynamic parameters during HSRT

Four studies investigated BP behavior in response to an acute session of HSRT. da Silva et al. (2007) observed a similar increase in BP and RPP throughout three sets of bench exercise at 50% of 1RM during continuous and discontinuous acute sessions of HSRT. Richardson et al. (2018) compared HR kinetics during HSRT and TRT in recreationally active older adults. Resistance exercise programs were based on different exercise intensities, but similar total volume. The authors observed that HSRT caused significantly greater elevations in HR during chest press and leg extension, whereas TRT produced greater increases in HR during leg press and seated row. No significant differences were observed during leg curl, calf raise, triceps extension, or biceps curl. Schimitt et al. (2020) expanded these findings by indicating that RPP, an index of myocardial oxygen demand, was significantly higher during HSRT composed of 3 sets of 8–10 repetitions of 5 exercises performed at 50% of 1RM, in comparison to a CS. More recently, Machado et al. (2021) reported that SBP and DBP increased significantly during HSRT and TRT, based on submaximal knee extensions performed at 60% of 1RM, relative to baseline and a CS in older adults with hypertension. However, the authors observed that TRT tended to cause greater increases in BP as the exercise session progressed to the end.

Table 2
Hemodynamic parameters across time-points in experimental sessions.

Variable		CS	TRT	HSRT
SBP	Baseline	124.4 ± 17.8	126.3 ± 19.1	126.1 ± 17.9
	IA	123.6 ± 17.7 (−0.5, −0.7)	120.8 ± 21.8 (−4.2, −5.5)a	128.3 ± 21.5 (1.5, 2.1)
	10′	123.6 ± 17.8 (−0.5, −0.7)	116.3 ± 17.6 (−7.6, −10.0)a	116.8 ± 17.8 (−7.3, −9.3)b
	20′	124.8 ± 17.7 (0.3, 0.3)	113.7 ± 12.5 (−9.2, −12.6)ab	121.4 ± 17.6 (−3.2, −4.7)
	30′	123.9 ± 16.7 (−0.2, −0.5)	116.1 ± 13.3 (−7.3, −10.1)a	114.6 ± 16.4 (−8.8, −11.5)ab
	50′	123.3 ± 17.2 (−0.8, −1.1)	117.7 ± 13.7 (−5.8, −8.6)a	114.6 ± 16.4 (−8.5, −11.5)ab
	60′	121.9 ± 20.7 (−2.3, −2.5)	116.4 ± 15.0 (−7.1, −9.8)a	118.8 ± 12.8 (−4.3, −7.3)
	24 h	124.9 ± 19.0 (0.3, 0.5)	125.4 ± 13.0 (0.1, −0.9)	121.3 ± 14.2 (−3.3, −4.8)
	1-h mean	123.5 ± 17. 8	116.8 ± 13.9a	119.1 ± 14.0a
DBP	Baseline	78.1 ± 20.8	77.7 ± 18.7	74.7 ± 11.1
	IA	78.2 ± 20.7 (0.2, 0.1)	75.5 ± 11.9 (−0.5, −2.1)	80.1 ± 11.8 (7.7, 5.3)
	10′	79.7 ± 22.9 (1.6, 1.6)	72.5 ± 9.8 (−4.2, −5.1)	78.2 ± 10.1 (5.2, 3.5)
	20′	81.1 ± 23.4 (3.4, 3.0)	73.6 ± 9.8 (−3.0, −4.1)	74.6 ± 9.4 (0.6, −0.0)
	30′	80.7 ± 23.1 (3.0, 2.6)	72.6 ± 9.6 (−4.2, −5.1)	72.7 ± 8.7 (−1.5, 2.0)
	50′	81.2 ± 22.8 (3.7, 3.1)	76.1 ± 12.7 (0.3, −1.6)	73.8 ± 11.2 (−0.5, −0.9)
	60′	81.5 ± 23.2 (3.9, 3.3)	74.6 ± 8.9 (−1.1, −3.1)	77.3 ± 15.6 (4.9, 2.5)
	24 h	78.3 ± 21.6 (0.1, 0.2)	76.7 ± 11.5 (1.6, 3.0)	74.8 ± 12.7 (0.1, 0.1)
	1-h mean	80.4 ± 22.6a	74.1 ± 9.7	76.1 ± 8.5
MAP	Baseline	93.5 ± 17.4	93.9 ± 17.7	91.8 ± 12.5
	IA	93.3 ± 17.1 (−0.1, −0.1)	90.6 ± 14.0 (−2.5, −3.3)	96.1 ± 14.1 (4.7, 4.2)
	10′	94.3 ± 19.1 (0.6, 0.8)	87.1 ± 10.6 (−6.0, −6.8)a	91.0 ± 11.5 (−0.6, −0.7)
	20′	95.6 ± 19.6 (2.0, 2.1)	86.9 ± 9.9 (−6.1, −6.9)ab	90.2 ± 10.8 (−1.2, −1.6)
	30′	95.1 ± 18.9 (1.5, 1.5)	87.1 ± 10.2 (−5.9, −6.8)a	86.7 ± 9.5 (−4.9, −5.1)
	50′	95.2 ± 19.2 (1.6, 1.7)	89.9 ± 11.1 (−2.5, −3.9)	87.4 ± 10.5 (−4.2, −4.4)
	60′	94.9 ± 20.4 (1.0, 1.4)	88.5 ± 9.6 (−4.1, −5.3)	91.1 ± 13.3 (0.7, −0.7)
	24 h	93.8 ± 19.2 (0.0, 0.3)	92.9 ± 10.4 (0.7, −0.9)	90.3 ± 11.7 (−1.4, −1.5)
	1-h mean	94.7 ± 19.0a	88.4 ± 10.0a	90.4 ± 9.2
HR	Baseline	77.5 ± 13.6	73.6 ± 13.3	75.2 ± 12.7
	IA	78.1 ± 13.1 (0.9, 0.6)	79.5 ± 16.9 (7.9, 5.8)	79.2 ± 12.1 (5.9, 4.0)
	10′	78.2 ± 14.3 (0.8, 0.7)	77.0 ± 14.9 (4.7, 3.3)	77.8 ± 12.3 (3.9, 2.5)
	20′	77.5 ± 14.5 (−0.1, 0.0)	74.9 ± 16.5 (1.6, 1.2)	76.1 ± 11.5 (1.8, 0.9)
	30′	78.5 ± 14.2 (1.1, 1.0)	72.2 ± 14.8 (−0.9, −1.4)	75.8 ± 14.1 (2.4, 0.5)
	50′	77.8 ± 13.5 (0.4, 0.3)	72.0 ± 14.8 (−1.3, −1.6)	74.5 ± 15.2 (−0.7, −0.6)
	60′	77.8 ± 14.3 (0.3, 0.3)	69.9 ± 13.9 (−4.1, −3.7)	72.1 ± 10.9 (−3.7, 3.0)
	24 h	77.0 ± 14.3 (−0.7, −0.5)	72.9 ± 12.9 (0.0, −0.7)	72.6 ± 10.8 (−2.5, −2.6)
	1-h mean	78.0 ± 13.9	74.3 ± 13.9	75.9 ± 11.0

Data are presented in mean ± SD (min, max). CS = control session; DBP = diastolic blood pressure; HR = heart rate; HSRT = high-speed resistance training; IA = immediately after; TRT = traditional resistance training; MAP = mean arterial pressure; SBP = systolic blood pressure. a $P < 0.05$ vs. baseline; b $P < 0.05$ vs. CS. Significance was tested using 2-way ANOVA followed by Dunnett's post-hoc test.

3.2.5. Acute effects of HSRT on PEH

Figs. 4 and 5 show the acute effects of HSRT on PEH. BP kinetics were compared to baseline levels in four studies (Fig. 4a–h) and with TRT in three studies (Fig. 5a–h). HSRT had no significant effects.

3.2.6. Acute effects of HSRT on 24-hour BP

Three studies investigated the acute effects of HSRT on 24-hour BP. Oliveira-Dantas et al. (2021) reported a significantly lower ambulatory SBP during the first 4 h after the end of an acute session of HSRT in comparison to a CS. In contrast, Schimitt et al. (2020) did not observe differences between ABPM after experimental and CS. In a recent study, de Oliveira Carpes et al. (2021) investigated if ABPM responses to an acute session of HSRT could be affected by gender. No significant effects of HSRT on 24-h, daytime, or nighttime ABPM were observed.

3.2.7. Chronic effects of HSRT on BP

The chronic effects of HSRT on BP values are shown in Figs. 6 and 7. Office SBP was significantly reduced after HSRT in comparison to the CG (SMD = 0.61, 95% CI = 0.15 to 1.06, $P = 0.009$; $\chi^2 = 1.61$, df = 2, $I^2 = 0\%$, $P = 0.45$; Fig. 6) and baseline values (SMD = 2.03, 95% CI = 0.05 to 4.02, $P = 0.04$; $\chi^2 = 23.37$, df = 2; $I^2 = 91\%$; $P < 0.00001$; Fig. 7). No significant effects of HSRT on DBP were observed. In addition, no significant differences were observed when HSRT was compared with TRT (SM9).

4. Discussion

To the best of our knowledge, this is the first systematic review and meta-analysis that studied the subacute (during), acute, and chronic effects of HSRT on hemodynamic parameters in older adults. The present study involves two related investigations that examined the effects of HSRT on hemodynamic parameters of older adults. In the first study, both TRT and HSRT caused systolic PEH in frail older adults. However, a longer PEH period was observed after an acute session of TRT. Notably, these results were not supported by our meta-analysis, given that no significant acute effects of HSRT on office or ambulatorial BP were observed. On the other hand, our findings suggest that HSRT might significantly reduce SBP in older adults.

4.1. Hemodynamic parameters during HSRT

Two main studies illustrated the behavior of hemodynamic parameters during HSRT in older adults. Richardson et al. (2018) observed that an acute session of HSRT caused significantly larger elevations in HR during chest press and leg extension, whereas TRT produced greater increases in HR during leg press and seated row. No significant differences were observed during leg curl, calf raise, triceps extension, or biceps curl. In addition, Machado et al. (2021) noted smaller increases in SBP and DBP during submaximal leg extension exercise in HSRT when compared with TRT. These results suggest that HSRT produces similar or even lower cardiovascular responses than TRT in older adults.

A possible explanation for these results is based on the activation of muscle metaboreflex, an arm of the exercise pressor reflex (Cristina-Oliveira et al., 2020; Gama et al., 2021). Metaboreflex is a class of receptors originate in the contracting skeletal muscle primarily activated by sensitive group IV unmyelinated afferent nerves that responds to changes in the chemical milieu of the interstitial space (reviewed in (Cristina-Oliveira et al., 2020; Gama et al., 2021)).

Upon exercise conditions, ischemia-induced metabolite accumulation and insufficient oxygen supply to activated muscles stimulate metaboreflex (Delaney et al., 2010; O'Leary, 1993), which relays information to the medulla oblongata area (i.e., nucleus of the solitary tract, caudal and rostral ventrolateral medulla) of the central nervous system (Delaney et al., 2010; Kaufmann et al., 1984; Leal et al., 2008), triggering reflex responses that involve an augmented sympathetic outflow to the periphery thereby increasing HR, BP, and cardiac output

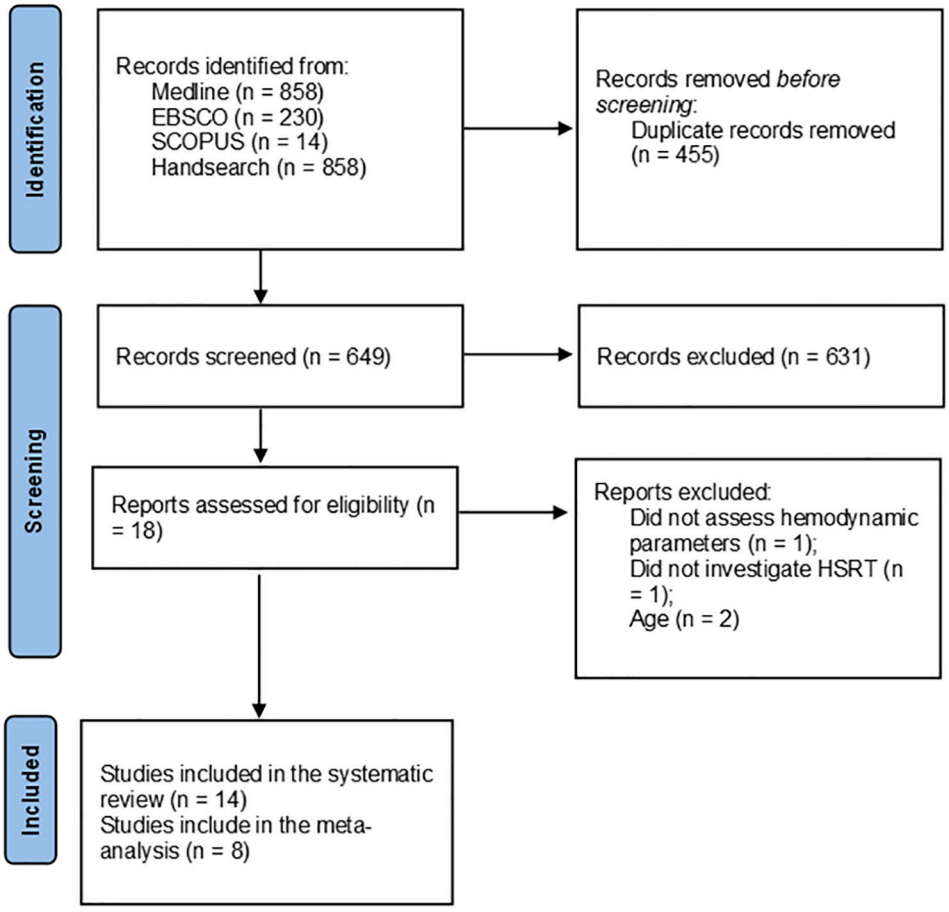

Fig. 3. Flowchart of the systematic review and meta-analysis study.

(Delaney et al., 2010; Kaufmann et al., 1984; Leal et al., 2008). Notably, hypertensive patients seem to have exaggerated metaboreflex response in comparison to normotensive adults (Delaney et al., 2010).

During TRT, as fatigue approaches, muscle contractions become slower (González-Badillo et al., 2017; Sánchez-Moreno et al., 2017; Varela-Olalla et al., 2019) and additional type II muscle fibers are recruited in an attempt to maintain adequate muscular performance (Henneman et al., 1965; Moritani et al., 1992). As such, vascular compression and metabolite accumulation reach progressively higher levels with each subsequent repetition, triggering the metaboreflex and increasing BP (De et al., 2010; de Vos et al., 2008; MacDougall et al., 1985).

On the other hand, HSRT is commonly performed using submaximal repetitions at low-to-moderate intensities avoiding fatigue (Haff and Nimphius, 2012; Kraemer and Looney, 2012; Kraemer and Ratamess, 2004). Furthermore, fast velocity muscle contractions involve short periods of time under tension (Haff and Nimphius, 2012; Kraemer and Looney, 2012; Kraemer and Ratamess, 2004) and vascular occlusion, likely allowing an efficient removal of the products of muscle metabolism.

4.2. Acute effects of HSRT on hemodynamic parameters

Two major findings about the acute effects of HSRT on hemodynamic parameters of older adults emerged. First, in study one, we noted that an acute session of TRT and HSRT caused significant systolic PEH in frail older adults. However, SBP was significantly reduced over the whole period after TRT and only for approximately 20 min after HSRT. Furthermore, exclusive MAP reductions were observed after TRT. In contrast, in study two, we noted that two of the three investigations that examined the acute effects of HSRT on 24-hour BP did not observe significant reductions. These findings were supported by the pooled analysis, given that no significant acute effects of HSRT on hemodynamic parameters were reported.

Results of the first study are in line with prior investigations that reported PEH after an acute session of TRT (Moraes et al., 2012b; Mota et al., 2013) and HSRT (Coelho-Júnior et al., 2017b; Oliveira-Dantas et al., 2021) in older adults with different conditions. In the last years, a growing number of studies has investigated the acute effects of HSRT on BP in older adults. A pioneering study conducted by our group (Coelho-Júnior et al., 2017b) found significant PEH after an acute session of HSRT in community-dwelling older adults, while no significant changes were observed after TRT (Coelho-Júnior et al., 2017b). Oliveira-Dantas et al. (2021) supported these findings by reporting lower systolic ambulatory BP in the first 4 h after the end of an acute session of HSRT. On the other hand, Orsano et al. (2018), Richardson et al. (2018), Schimitt et al. (2020), and de Oliveira Carpes et al. (2021) did not observe significant acute effects of HSRT on BP in community-dwelling older adults. Subsequently, Machado et al. (2019) reported lower SBP and DBP values after HSRT in older adults with type II diabetes mellitus.

These controversial findings may be at least partially attributed to differences in exercise design (e.g., number of exercises), BP measurement protocol (e.g., for 1 h, 12 h, or 24 h after the exercise session), baseline BP levels, pharmacological therapy, and sample characteristics (e.g., hypertensive, normotensive, frail, and older adults with type II diabetes mellitus).

Notably, a prior study (Coelho-Júnior et al., 2017b) reported greater and longer PEH after moderate-intensity HSRT (~50% 1RM) in comparison to moderate-to-high intensity TRT (~70% 1RM). These findings raise the possibility that HSRT protocols performed at low-to-moderate

Table 3
Characteristics of the included studies.

Year	Study	Sample	Sample size	Age (years)	Intervention period (months)	HSRT protocols	Control group	Hemodynamic parameters	Hemodynamic assessment
Crossover randomized trials									
2022	Coelho-Junior et al.	Frail hypertensive older adults	16	81.0	–	8 sets of 3–5 reps at 70–75% 1RM in 4 exercises; CON = AFAP, ECC = 2.5 s	4 sets of 8–10 reps at 70–75% 1RM in 4 exercises; CON = 2.5 s, ECC = 2.5 s; CG = flexibility sessions for 20 min once a week	Office SBP, DBP, MAP, HR	Oscilometric BP monitor
2021	Carpes et al.[a]	Hypertensive older adults	24	67.0	–	3 sets of 10 reps at 50%1RM in 5 exercises; CON = AFAP, ECC = 1–2 s; 2-min rest interval between sets	Participants remained at seated rest on exercise equipments without exercising	Office and 24-h SBP and DBP, ABPM	Oscilometric BP monitor and ABPM
2021	Machado et al.	Hypertensive older adults	15	66.1	–	4 sets of 8 reps at 60%1RM in the bilateral knee extension exercise; CON = AFAP, ECC = 2 s	4 sets of 8 reps at 60%1RM in the bilateral knee extension exercise; CON = 2 s, ECC = 2 s	Office SBP and DBP	Oscilometric BP monitor
2020	Machado-Filho et al.	Hypertensive older adults	10	64.1	–	3 sets of 8 reps at 50%1RM in 6 exercises; CON = AFAP, ECC = 1–2 s	Participants remained in the sitting position without exercising	Office SBP and DBP	Oscilometric BP monitor
2020	Oliveira-Dantas et al.	Hypertensive older women	14	67.9	–	3 sets of 6 reps at moderate intensity in eight exercises; CON = AFAP, ECC = 3 s	Participants remained in the same exercise position without exercising	Office and 24-h SBP and DBP, ABPM	Oscilometric BP monitor and ABPM
2020	Schimitt et al.[a]	Hypertensive older adults	23	66.7	–	3 sets of 8–10 reps at 50% 1RM in 5 exercises; CON = AFAP, ECC = 1–2 s	Participants remained at seated rest on exercise equipments without exercising	Office and 24-h SBP and DBP, ABPM	Oscilometric BP monitor and ABPM
2018	Orsano et al.	Community-dwelling older women	15	77.1	–	3 sets of 10 reps at 70% 1RM in 10 exercises; CON = AFAP, ECC = 2–3 s	3 sets of 10 reps at 70% 1RM in 10 exercises; CON = 2–3 s, ECC = 2–3 s	Office SBP, DBP, RPP, HR	Oscilometric BP monitor and HR monitor
2018	Richardson et al.	Recreationally active older adults	10	67.0	–	3 sets of 14 reps at 40%1RM in eight exercises; CON = AFAP, ECC = 3 s; 2-min rest interval between sets	3 sets of 7 reps at 80%1RM in eight exercises; CON = 2 s, ECC = 3 s; 2-min rest interval between sets	Office SBP, DBP, MAP, RPP, HR	Oscilometric BP monitor and HR monitor
2017	Coelho-Junior et al.	Normotensive and hypertensive older women	21	67.1	–	3 sets of 8–10 reps at moderate intensity in 9 exercises; CON = AFAP, ECC = 2–3 s	3 sets of 8–10 reps at moderate intensity in 9 exercises; CON = 2–3, ECC = 2–3 s; CG = participants remained at seated rest on exercise equipment without exercising	Office SBP, DBP, MAP, RPP, HR	Oscilometric BP monitor
2007	da Silva et al.	Apparently healthy older women	12	62.6	–	3 sets of 10 RM in the horizontal bench press exercise; CON = AFAP, ECC = 2–3 s	3 sets of 10 RM with 5 and 15 s rest between the fifth and sixth repetitions in the horizontal bench press exercise; CON = AFAP, ECC = 2–3 s	Office SBP and HR	Mercury column syphgmomanometer and HR monitor
Randomized controlled trials									
2021	Coelho-Junior & Uchida	Pre-frail and frail older adults	60	70.5	16	8 sets of 3–5 reps at 70–75% 1RM in 4 exercises; CON = AFAP, ECC = 2.5 s	TRT = 4 sets of 8–10 reps at 70–75% 1RM in 4 exercises; CON = 2.5 s, ECC = 2.5 s; CG = flexibility	Office SBP and DBP	Oscilometric BP monitor

(*continued on next page*)

Table 3 (*continued*)

Year	Study	Sample	Sample size	Age (years)	Intervention period (months)	HSRT protocols	Control group	Hemodynamic parameters	Hemodynamic assessment
							sessions for 20 min once a week		
2018	Roberson et al.	Older adults with increased cardiovascular risk	30	69.0	12	1–3 rotations with 12 reps at 50–70%1RM in eleven exercises; CON = AFAP, ECC = 2 s	35 min of treadmill exercise at 55% of HRR	Office SBP and DBP	Impedance cardiography
2011	Kanegusuku et al.	Normotensive older adults	39	63.0	16	3–4 sets of 6–10 reps at 30–50% 1RM in 7 exercises; CON = AFAP, ECC = 2 s	TRT = 2–4 sets of 6–10 reps at 70–90% 1RM in 7 exercises; CON = 2 s, ECC = 2 s; CG = Non-exercise group	Office SBP, RPP and HR	Mercury column sphygmomanometer and ECG
Quasi-experimental design									
2019	Machado et al.	Older adults with type II diabetes mellitus	12	68.7	12	3 sets of 4–10 reps at submaximal intensity in 8 exercises; CON = AFAP, ECC = 1–2 s	–	Office SBP and DBP	Oscilometric BP monitor

ABPM = ambulatory blood pressure monitoring; AFAP = as fast as possible; BP = blood pressure; COM = concentric; DBP = diastolic blood pressure; ECC = eccentric; ECG = electrocardiography; HR = heart rate; HSRT = high-speed resistance training; MAP = mean arterial pressure; RM = repetition maximum; RPP = rate pressure product; SBP = systolic blood pressure.

[a] Same cohort.

loads may elicit greater acute cardiovascular benefits relative to HSRT at moderate-to-high loads. This hypothesis is supported by, who observed longer PEH after a session of resistance exercise performed at 70% 1RM when compared with 80% 1RM.

These inferences might also serve to explain the results of the meta-analysis, given that the low time under tension during some acute sessions of HSRT might be insufficient to stimulate the physiological pathways underlying PEH. Furthermore, the heterogeneous characteristics of HSRT protocols may also have influenced the pooled analysis. For instance, the number of exercises varied from four to 10, while exercise intensity ranged from low to moderate-to-high.

The aforementioned scenario is important because prior evidence indicates that hypotension post-high speed resistance exercise might be accompanied by significant increases in nitric oxide (NO) bioavailability (Coelho-Júnior et al., 2017b). NO is a powerful vasodilator with an important role in BP regulation and is synthetized by endothelial cells is response to numerous stimuli, including exercise-induced shear stress (Aguiar et al., 2020; Asano et al., 2014; Farah et al., 2018; Ignarro, 1990; Ignarro et al., 1987). Santana et al. (2011, 2013) noted that PEH mediated by NO release occurred in a dose-dependent fashion in older adults, which might suggest that some HSRT programs were insufficient to stimulate NO production and, then, PEH.

A contrasting possibility is that acute sessions of HSRT performed at higher intensities might have caused exaggerated sympathetic response and consequently blunted PEH since sympathetic tonus might increase proportionally to the amount of type II muscle fibers and large motor units recruited during resistance exercise (Figueiredo et al., 2015b).

Finally, the possibility that a large variability in inter-individual responses among participants might have impacted the measures of dispersion cannot be ruled out (Prestes et al., 2015). In fact, we observed that specific frailty parameters might influence hemodynamic responses to RT. Specifically, no differences in PEH after TRT and HRST were observed in people with slowness and weakness, whereas TRT caused greater effects in people with unintentional weight loss.

Prior investigations have tested the association between physical performance tests and hemodynamic parameters. Acar et al. (2015) did not observed differences in balance between normotensive and hypertensive Japanese older adults. In contrast, Hausdorff et al. (2003) reported a higher prevalence of balance problems and slowness in hypertensive older patients. These findings were further expanded by Coelho-Júnior et al. (2017a), who noted a signficant association between hypertension and aerobic capacity, but not balance, muscle stregnth and power, and mobility. More recently, Feng et al. (2021) noticed that Chinese older adults with lower upper limb muscle strength were at a higher risk of hypertension.

Taken together, these findings might indicate that the presence of specific frailty criteria (e.g., weakness, unintentional weight loss) can influence BP responses to exercise training. However, these assumptions could not be tested using our study design and future investigations based on a meta-analysis of primary patient data are required.

4.3. Chronic effects of HSRT on hemodynamic parameters

A major finding of the present study is that HSRT significantly reduced office SBP, but not DBP, in older adults. These results were found when HSRT was compared to CG and baseline levels. Such findings added to the current literature by indicating that HSRT might be used to manage BP in older adults. The lack of trials investigating the chronic effects of HSRT on BP limits our ability to discuss the current findings and argue about the possible mechanisms underlying such effects.

Only one of the three included studies examined the hemodynamic changes produced by HSRT. Roberson et al. (2018) observed that reductions in BP after a 12-week HSRT program were accompanied by increases in end diastolic volume and stroke volume, whereas systemic vascular resistance was reduced. According to these findings, BP lowering after HSRT might be mainly mediated by changes in the afterload, given that preload and cardiac output seem to be augmented. However, these results must be interpreted with caution since Roberson et al. (2018) used a circuit exercise program, which involves a greater aerobic demand than traditional protocols (Ramos-Campo et al., 2021).

NO regulates BP by interacting with the cardiovascular and the nervous system (Aguiar et al., 2020; Asano et al., 2014; Farah et al., 2018; Ignarro, 1990; Ignarro et al., 1987; Togashi et al., 1992).

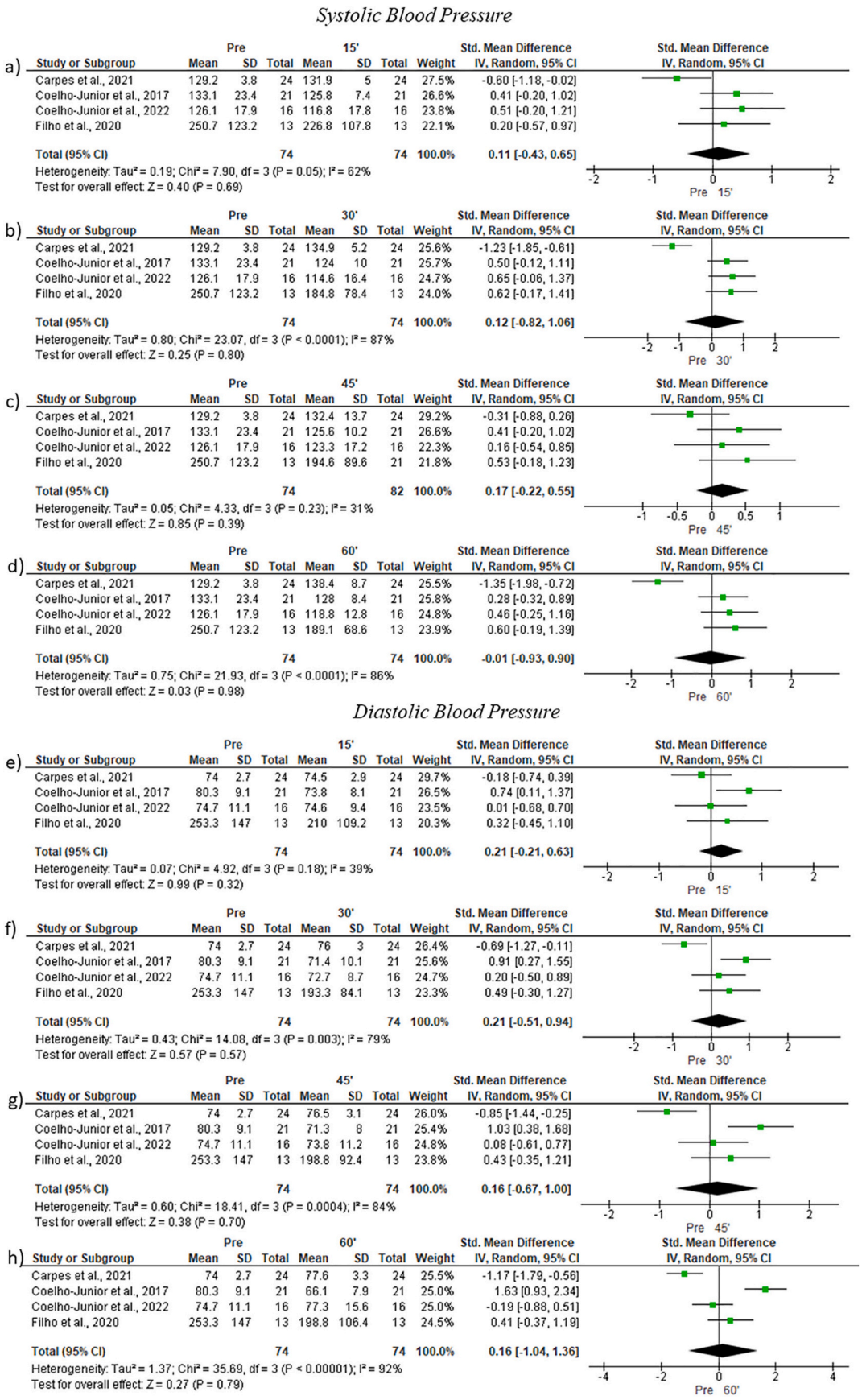

Fig. 4. SBP and DBP behavior 15 (a, e), 30 (b, f), 45 (c, g) and 60 (d, h) minutes after the end of an acute session of HSRT in comparison to baseline values.

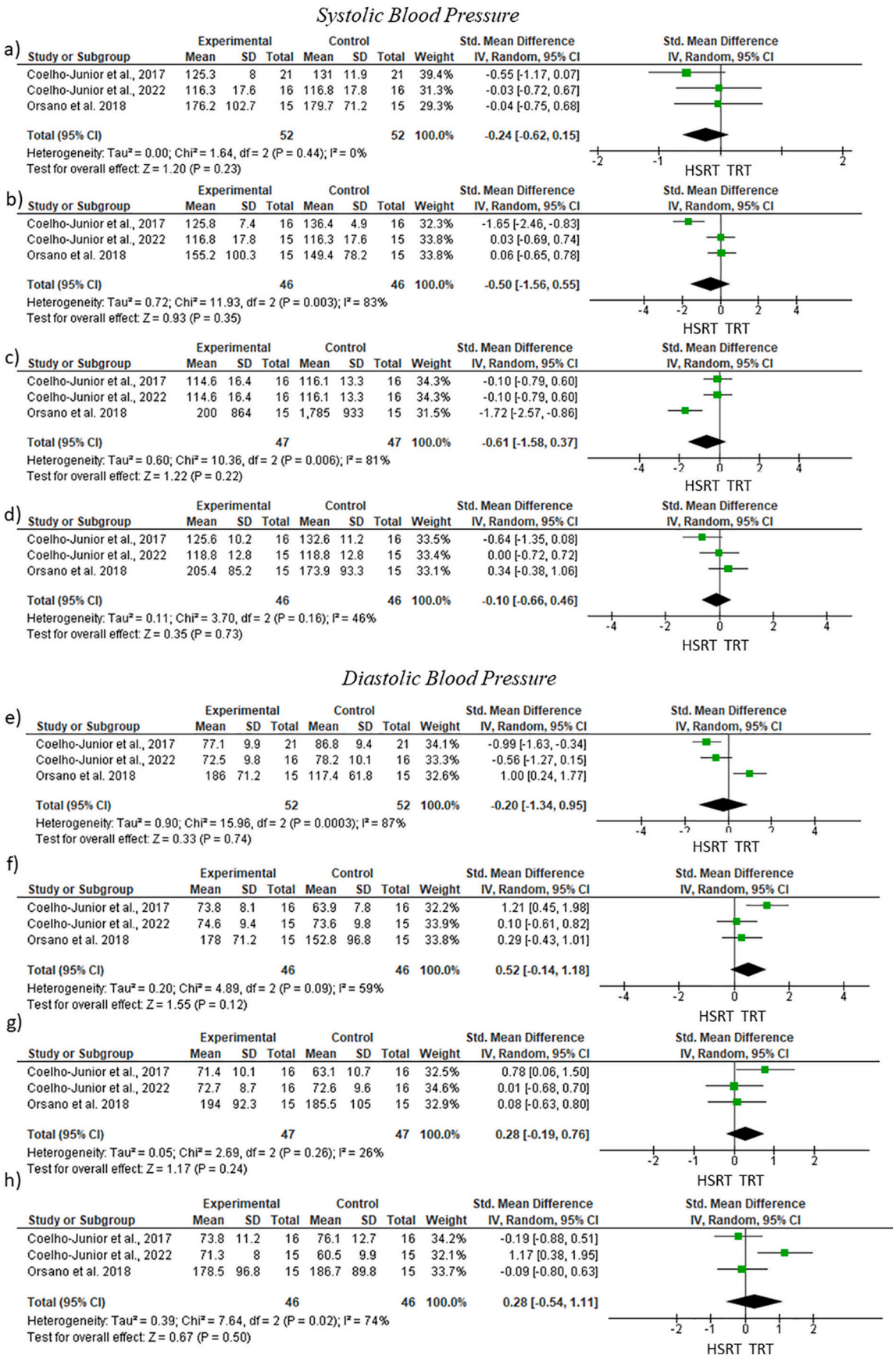

Fig. 5. SBP and DBP behavior 5–10 (a, e), 20 (b, f), 30 (c, g) and 45 (d, h) minutes after the end of HSRT and TRT.

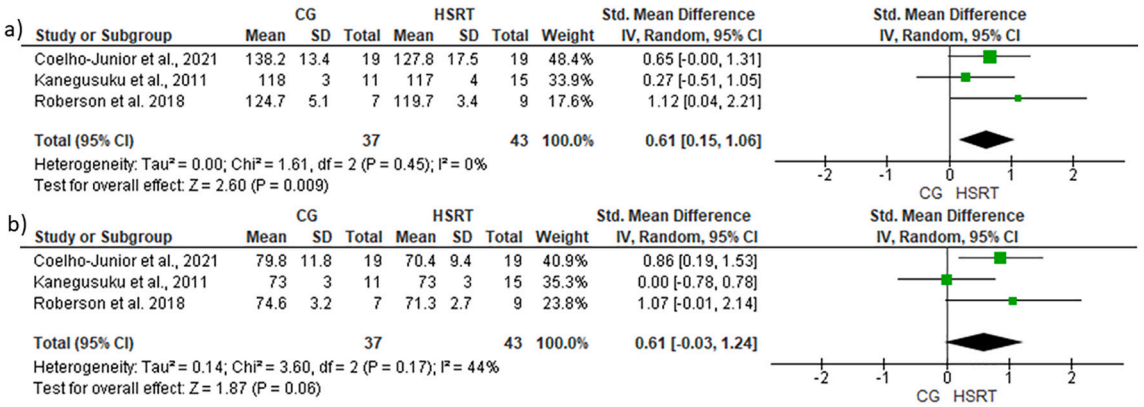

Fig. 6. Effects of HSRT on SBP (6a) and DBP (6b) in comparison to CG.

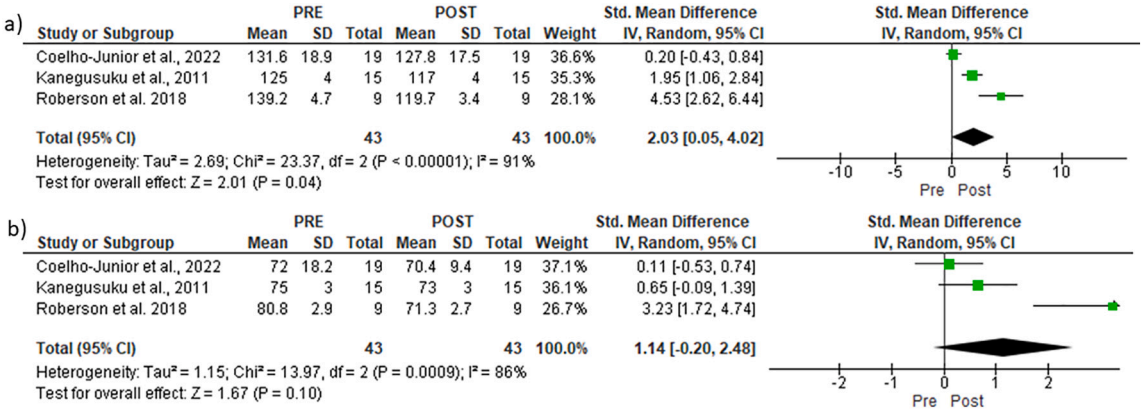

Fig. 7. Effects of HSRT on SBP (6a) and DBP (6b) in comparison to baseline values.

Numerous studies have reported concomitant chronic reductions in BP levels and increases in NO bioavailability in older adults who took part in exercise training programs (Aguiar et al., 2020; Togashi et al., 1992). Two studies also reported augmented NO concentrations after an acute session of HSRT (Coelho-Júnior et al., 2017b; Orsano et al., 2018), suggesting that NO might play a role in the reduced BP observed after HSRT. However, de Oliveira Carpes et al. (2021) did not observe significant effects of an acute session of HSRT on endothelium-dependent vasodilation, a physiological index of the vasodilator effects of NO on endothelial cells. Furthermore, it is important to note that not all trials observed increased NO levels after RT-exercise type (Coelho-Júnior et al., 2018; Moraes et al., 2012a), in addition to the fact that acute events observed in response to exercise may not convert into chronic changes (Witvrouwen et al., 2021).

Improvements in the cardiac autonomic control are another possible mechanism for explaining HSRT-reduced BP. The autonomic nervous system plays an important role in short-term BP regulation by mediating changes in HR and vascular resistance (Fisher and Paton, 2011; Irigoyen et al., 2016; Mancia and Grassi, 2014). Although there is not consensus, some studies have observed improved autonomic function after RT protocols (Gambassi et al., 2019), and it is possible that this scenario might be extended to HSRT.

However, in young normotensive people, exercise regimes that involve fast body movements commonly produce increase in the sympathetic vagal balance (Wong et al., 2020, 2021). Evidence in older adults is scarce and only one study investigated the effects of HSRT on autonomic control. In this trial, de Oliveira Carpes et al. (2021) did not observe significant changes in the BP variability, a measurement of cardiovagal baroreflex sensitivity.

Numerous other mechanisms might have influenced our results. Oxidative stress is a key element of vascular dysfunction and has a major role on the genesis and progression of hypertension (Griendling et al., 2021; Paneni et al., 2017). Orsano et al. (2018) observed that HSRT might acutely increase markers of oxidative damage (thiobarbituric acid reactive substances [TBARS] and 6-hydroxy-2,5,7,8-tetramethylchroman-2-carboxylic acid equivalent antioxidant capacity [TEAC]) in hypertensive older women. Moreover, although not unanimously, some studies have noted that HSRT might increase the release of hormones of the hypothalamic-pituitary axis (Häkkinen et al., 2002), which may have a role in BP regulation (Conti et al., 2004; Schutte et al., 2014; Vitale et al., 2005). Finally, given the biomechanical and biological similarities between HSRT and TRT protocols, it is reasonable to speculate that the mechanisms underlying RT-mediated reduction in BP can also be responsible for the changes observed after HSRT (reviewed in Fecchio et al., 2021 and Queiroz et al., 2010).

4.4. *Future directions and limitations*

The role of numerous exercise variables (e.g., sets, volume) on BP responses to RT have been extensively studied and allowed the release of specific recommendations to manage BP (Pescatello et al., 2015). However, the possible effects of the velocity of muscle contractions, the main determinant of HSRT, on this scenario have been neglected, despite an increasing number of studies in this field. Hence, the present investigation was designed to be a first step to combine and elucidate the current knowledge on the acute and chronic effects of HSRT on BP of older adults.

Our findings support the notion that HSRT is a safe, feasible, and effective strategy for the management of BP in older adults. Mean acute and chronic BP reductions after HSRT were 4.4 mmHg and 5.4 mmHg,

respectively. These changes in BP have practical implications, given that slight decreases in BP significantly reduce cardiovascular and cerebrovascular risk (Antonakoudis et al., 2007). In addition, such reductions were greater than those observed after TRT (~5 mmHg) (MacDonald et al., 2016) and aerobic exercise (AE) (~4.7 mmHg) (Kelley and Kelley, 2018), suggesting that HSRT might be a potential therapy to counteract hypertension-related parameters in older adults.

However, direct comparisons between HSRT and well-established exercise training protocols (e.g., AE) should be made with caution because numerous limitations still exist that impede the prescription of HSRT as a standard therapy. Regarding study 1, exercise sessions were conducted by study authors, which might increase the risk of confirmation bias due to observer-expectancy effect. Participants were recruited by convenience and no sample size calculations were conducted to reduce the risk of type II error. The small sample size prevented us from conducting deeper analyses to characterize responders and non-responders. In addition, our study did not involve measurements of hemodynamic parameters during exercise. Our findings were obtained in institutionalized frail older adults and may not be extended to community-dwelling frail people or robust older adults. The study sample was predominantly composed by women. Finally, the lack of ABPM impeded appreciating further effects of LSRT and HSRT, given that reduced night-time, but not daytime ambulatory blood pressure was reported after acute TRT (Tibana et al., 2013).

Study 2 also has limitations. The meta-analysis was conducted based on 3–4 investigations, impeding dichotomized analysis and meta-regression. Second, BP changes during HSRT sessions were mostly assessed using oscilometric BP monitors. Although these instruments allow valid measurements of resting BP (Cuckson et al., 2002), Finapress is considered the most accurate noninvasive technique for assessing BP (Polito et al., 2007). Differences of approximately 4 mmHg were reported between the methods (Raamat et al., 2001). Third, only tree studies, with two examining people from the same cohort, assessed PEH over a period of 60 min and using ABPM. This characteristic is important because ABPM seems to be superior to office BP in predicting cardiovascular events (Niiranen et al., 2014). Fourth, the included randomized clinical trials were highly heterogeneous regarding sample and HSRT characteristics. Fifth, the mechanisms underlying acute and chronic effects of HSRT have been insufficiently explored and the discussion of the present study was mainly speculative. Sixth, the meta-analysis of acute and chronic effects was performed using different studies which might explain the reason why results are contradictory. Seventh, even if most investigations used the same oscilometric monitor to assess BP, the measurement was insufficiently described in most studies. Thus, the pooled ES was estimated using SMD instead of MD. Finally, only a few investigations included an exercise-CS/CG.

5. Conclusion

In study one, we observed that both TRT and HSRT caused systolic PEH in comparison to baseline in frail older adults. However, specific patterns were observed according to each type of RT. Indeed, a longer PEH in comparison to baseline was observed after TRT, whereas HSRT had greater reductions in comparison to CS. In addition, TRT had exclusive reductions in MAP. These results were not supported by our meta-analysis, given that no significant effects of an acute session of HSRT on office and ambulatorial BP were observed. On the other hand, our findings suggest that HSRT might significantly reduce SBP in older adults.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.exger.2022.111775.

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CRediT authorship contribution statement

Conceptualization: HJCJ, BR, EM, MCU; **Data curation**: HJCJ, SSA, RC, AP, DAC, JCZS; **Formal analysis**: HJCJ, SSA, FB, MC, EM, MCU; **Investigation**: HJCJ, SSA, DAC, JCZS; **Methodology**: HJCJ, SSA, RC, AP, DAC, BR, JCZS, EM, MCU; **Project administration**: HJCJ, EM, MCU; **Supervision**: BR, EM, MCU; **Roles/Writing - original draft**: HJCJ, SSA, RC, AP, BR; **Writing - review & editing**: HJCJ, FB, MC, EM, MCU.

Data availability

All data are available from the authors on request.

Declaration of competing interest

All authors declare they have no conflicts of interest.

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