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THE EFFECTS OF BLOOD FLOW RESTRICTION AND HIGH-INTENSITY RESISTANCE TRAINING ON MUSCLE CONTRACTILE PROPERTIES IN OLDER ADULTS

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Abstract. The aim of this study was to compare the effects of muscle damage–based resistance training (MDRT) and blood flow restriction training (BFRT) on muscle contractile properties in older men using tensiomyography (TMG). Age-related declines in neuromuscular function are associated with reduced muscle performance and increased risk of functional impairment, highlighting the need for effective and safe training strategies in older populations. Men aged 60 years and older were randomly assigned to MDRT, BFRT, or control groups. The intervention lasted 12 weeks. Muscle contractile properties were assessed using TMG, analyzing contraction time (Tc), delay time (Td), and maximal radial displacement (Dm). Data were analyzed using repeated measures analysis of variance (ANOVA), evaluating the effects of time, group, and their interaction. No statistically significant time × group interactions were found for the majority of TMG parameters ($p > 0.05$), indicating no overall differences between interventions. Significant interaction effects were observed only in isolated muscles. Although no statistically significant differences were detected, MDRT showed more favorable changes in Tc and Dm, whereas BFRT demonstrated greater improvements in Td. In conclusion, neither MDRT nor BFRT induced statistically significant changes in muscle contractile properties compared to the control group. Furthermore, no significant differences were found between the two training interventions. However, observed trends suggest that MDRT may be more beneficial for certain contractile characteristics, while BFRT may have a greater effect on response time.

Keywords: tensiomyography, blood flow restriction training, eccentric training, aging.

Introduction

Aging is associated with a decline in the ability of muscles to perform movements efficiently, including reduced strength, slower reaction time, and prolonged force development. These changes impair movement quality and increase the risk of coordination deficits. Studies indicate that 30–40% of individuals over the age of 65 experience at least one fall per year, and the number of falls increased by 182% between 1990 and 2021 (Chen et al., 2025). It is projected that by 2050, the global population aged 60 years and older will reach 2.1 billion. With aging, muscle mass decreases by approximately 3–8% per decade (Yuan et al., 2023), while muscle strength declines by 12–14% (Li et al., 2023). In addition, neuromuscular control deteriorates, which is essential for maintaining stability and rapid responses. These changes can be mitigated through appropriate physical activity interventions. One of the most effective strategies is resistance training. High-intensity training (70–80% of one-repetition maximum, 1RM) has been shown to increase muscle strength and mass (Baxter et al., 2024); however, its application in older adults may be limited due to increased mechanical stress on joints and the cardiovascular system (Yuan et al., 2023). As an alternative, blood flow restriction training (BFRT) has been proposed. This method allows improvements in strength and hypertrophy using low loads (20–40% 1RM), achieving results comparable to high-intensity training (Cornejo-Daza et al., 2024; Zeng et al., 2025). BFRT induces a hypoxic environment that promotes metabolic stress, fast-twitch fiber recruitment, and anabolic processes. However, proper individualization of cuff pressure is essential, as inappropriate application may compromise both safety and effectiveness (Hurr, 2025). Another approach is muscle damage–based resistance training (MDRT), characterized by eccentric loading of approximately 120% 1RM. During the eccentric phase, muscles can generate 40–50% greater force (Zhong et al., 2026). This loading induces microdamage, which stimulates structural adaptations such as increased muscle fiber thickness, improved force transmission, and greater tendon stiffness (Du et al., 2024). Evidence suggests that eccentric training may be particularly effective in improving muscle strength and mechanical resilience (Chaabene et al., 2026).

Muscle contractile properties can be assessed using tensiomyography (TMG), a non-invasive method that allows the evaluation of contraction time (Tc), delay time (Td), and maximal radial displacement (Dm) (Čular et al., 2023; Labata-Lezaun et al., 2023). These parameters deteriorate with aging and are associated with reduced functional capacity and slower neuromuscular responses (Kalc et al., 2023; Pus et al., 2023). Therefore, TMG can be used as a sensitive tool for assessing training-induced adaptations. Although blood

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flow restriction training and eccentric training with increased load have been widely studied separately, there is still a lack of studies directly comparing their effects on muscle contractile properties in older adults. Furthermore, limited evidence exists regarding the effectiveness of these interventions when assessed using TMG. Consequently, it remains unclear which method is more effective in improving neuromuscular function with aging.

The aim of this study was to compare the effects of blood flow restriction training (BFRT) and muscle damage–based resistance training (MDRT) on muscle contractile properties in older men using tensiomyography (TMG). To achieve this aim, the effects of BFRT and MDRT were analyzed by examining changes in TMG parameters (Tc, Td, and Dm) compared with a control group, as well as by comparing the effects between interventions. It was hypothesized that MDRT would produce greater improvements in Tc and Dm, while both training methods would reduce Td, reflecting enhanced neuromuscular function.

Participants

A total of 63 men aged 60 years and older participated in the study and were randomly assigned to three groups: MDRT (n = 21), BFRT (n = 21), and control (n = 21). Exclusion criteria included excessive alcohol or psychotropic substance use, cognitive, cardiovascular, psychiatric, or oncological disorders, as well as a history of lower limb injuries, osteoarthritis, diabetes, obesity (body mass index > 30 kg/m²), deep vein thrombosis, or the use of psychopharmacological medications within the past five years. Additionally, individuals who had not participated in any structured physical activity program during the previous six months were not included. During the intervention period, some participants dropped out. In the BFRT group, one participant withdrew due to discomfort associated with blood flow restriction. In the MDRT group, six participants withdrew (n = 2 due to knee joint pain, n = 3 due to personal reasons, n = 1 due to the detection of a cerebral vascular dilation during MRI examination). In the control group, ten participants withdrew (n = 2 due to elevated blood pressure, n = 2 due to headaches, and n = 6 due to personal reasons). The final analysis included 46 participants: MDRT (n = 15), BFRT (n = 20), and control (n = 11). Baseline anthropometric characteristics did not differ significantly between groups ($p > 0.05$). In the MDRT group, body mass index was 26.41 ± 3.25 kg/m², age 65.93 ± 3.99 years, height 178.27 ± 5.82 cm, and body mass 83.93 ± 10.89 kg. In the control group, the corresponding values were : BMI 25.64 ± 2.40 kg/m², age 65.73 ± 5.15 years, height 179.73 ± 7.69 cm, and body mass 82.91 ± 10.58 kg. In the BFRT group, BMI was 25.63 ± 2.55 kg/m², age 66.65 ± 4.82 years, height 178.00 ± 6.76 cm, and body mass 81.30 ± 9.97 kg.

Study Design

The study was conducted at the Lithuanian Sports University (LSU). Training sessions took place in the LSU gym, while tensiomyography (TMG) measurements were performed in the LSU laboratory. Ethical approval was obtained from the Kaunas Regional Biomedical Research Ethics Committee (No. 2022-BE-10-0012). The study was preregistered on the AsPredicted (https://aspredicted.org/pm9gp4.pdf) platform to ensure transparency and methodological consistency. All participants were informed about the study procedures in advance and provided written informed consent. Sample size was determined using a priori power analysis to estimate the required number of participants for the primary outcome, contraction time (Tc). The analysis was designed to detect changes across three groups (BFRT, MDRT, control) over two time points (pre- and post-intervention), with particular focus on the group × time interaction. Calculations were performed using G*Power, assuming a medium effect size (Cohen's $f = 0.25$), significance level $\alpha = 0.05$, and statistical power of 80%. The required sample size was at least 14 participants per group (total n = 42). To account for potential dropouts and the limited evidence on BFRT and MDRT effects on TMG parameters in older adults, a total of 63 participants were recruited. Participants were allocated into three groups: BFRT, MDRT, and control. The BFRT group performed resistance training with blood flow restriction, the MDRT group performed high-intensity eccentric resistance training designed to induce muscle damage, and the control group did not participate in any intervention. To minimize baseline differences between groups, participants were assigned using a predefined minimization procedure based on handgrip strength, implemented in Microsoft Excel. The procedure was developed by author W.V. The highest value from four handgrip trials (two per hand) was used for allocation. The first six participants were randomly assigned to groups. Subsequent participants were allocated according to two rules: (1) assignment minimized differences in mean handgrip strength between groups; (2) the difference in group sizes could not exceed three participants. If the first rule resulted in allocation to the largest group, violating the second rule, the second-best allocation option was selected. This approach prevented imbalanced group sizes and large baseline differences in strength. Handgrip strength (kg) was measured using a JAMAR dynamometer, with participants in a standing position. Handle width was adjusted to achieve approximately a 90° angle at the second joint of the index finger. One

submaximal familiarization trial was performed, followed by two maximal trials per hand with a 1-minute rest interval. The highest recorded value was used for analysis. Participants and trainers were aware of group allocation, while outcome assessors and data analysts were blinded. Before the intervention, height and body mass were measured, and body mass index (BMI, kg/m²) was calculated. TMG assessments were performed before the intervention and 7 days after the final training session following the 12-week intervention period, using the TMG S2 device (TMG Measurement System, TMG-BMC Ltd., Ljubljana, Slovenia). A schematic overview of the study design is presented in Figure 1.

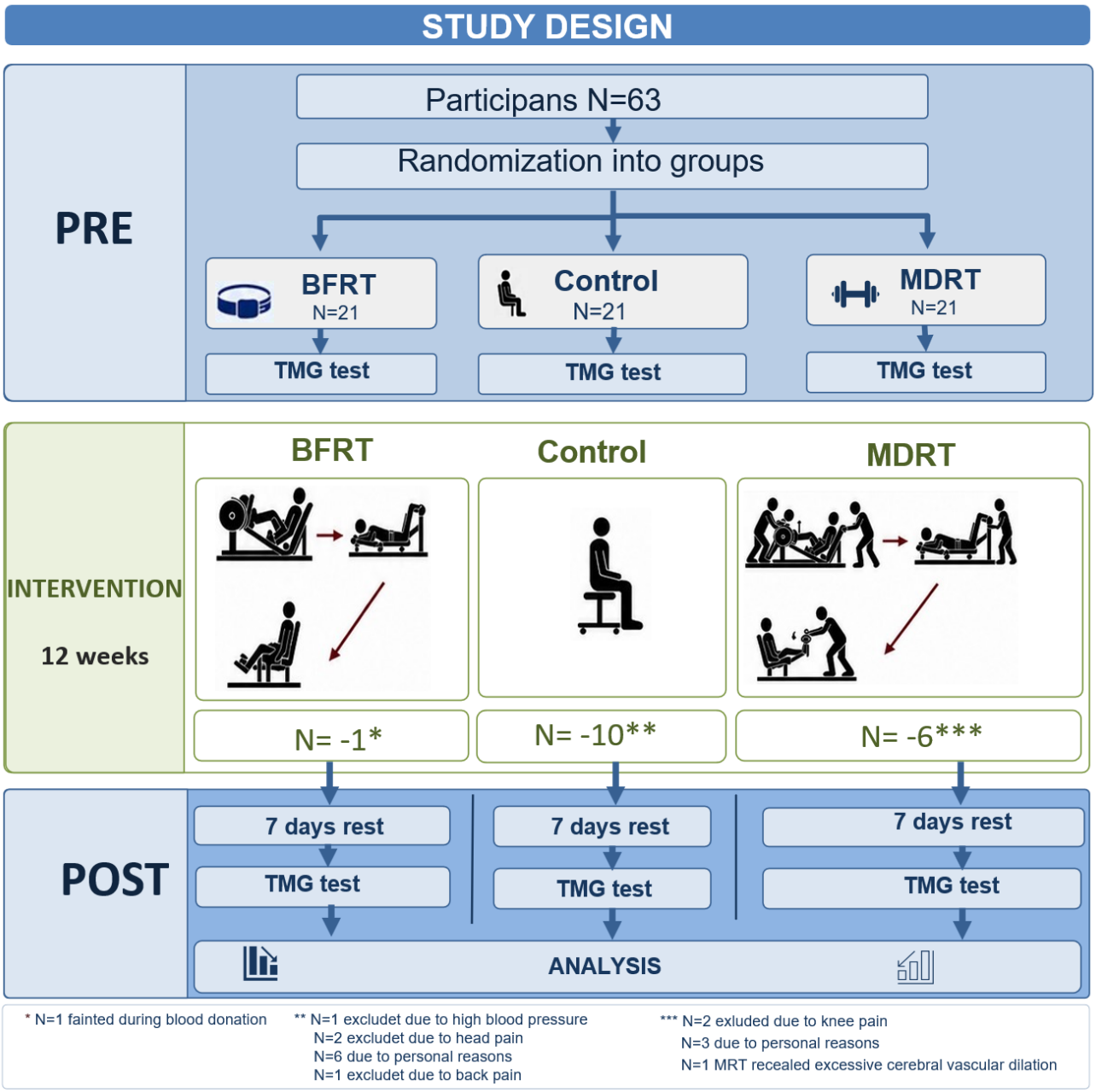

Fig. 1. Study design

Training Protocol

The training intervention lasted 12 weeks. During this period, both BFRT and MDRT groups performed two resistance training sessions per week, with three exercises per session. Each session began with a 10-minute warm-up performed on a cycle ergometer. The workload (W) was set based on a 1:1 ratio with body mass (kg), maintaining a cadence of 60–80 rpm, followed by several dynamic stretching exercises. After the warm-up, participants performed three lower-body exercises: leg press, leg curl, and leg extension. Training load for both intervention groups was adjusted based on the participants' rating of perceived exertion (RPE) using the 10-point Borg scale. Load was increased when participants reported a value lower than 7 (Zourdos

et al., 2016). In the BFRT group, participants rested 3 minutes between exercises and 30 seconds between sets. Training intensity was set at 40% of one-repetition maximum (1RM). During the first week, cuff pressure was set at 50% of arterial occlusion pressure and progressively increased by 10% each week until reaching 80% in week four. Each exercise was performed for 4 sets of 12 repetitions. Cuffs were released during rest periods between exercises. The MDRT group performed the same exercises; however, to avoid the repeated bout effect, training was divided into two sessions on separate days. One session emphasized the concentric phase (CRT) at 80% 1RM, while the other emphasized the eccentric phase (ERT) at 120% 1RM. The ratio of concentric to eccentric sessions was 3:1. During CRT sessions, participants performed 4 sets of 6 repetitions, with a concentric phase lasting 1–2 seconds. During ERT sessions, the concentric phase was fully assisted by two trainers, while the eccentric phase was performed independently and lasted 5–6 seconds. Participants completed 4 sets of 4 repetitions. In both CRT and ERT sessions, rest intervals were standardized at 3 minutes between exercises and 2 minutes between sets. Training volume was equated between groups (V = 57,6%) using the formula: volume (%) = repetitions × sets × exercises × %1RM. One-repetition maximum (1RM) was estimated for each participant prior to the intervention. Due to the advanced age of participants, 1RM was calculated from a 5-repetition maximum (5RM) test (Gail et al., 2015; Gail & Künzell, 2014) using a standard prediction calculator. A detailed training protocol is presented in Figure 2.

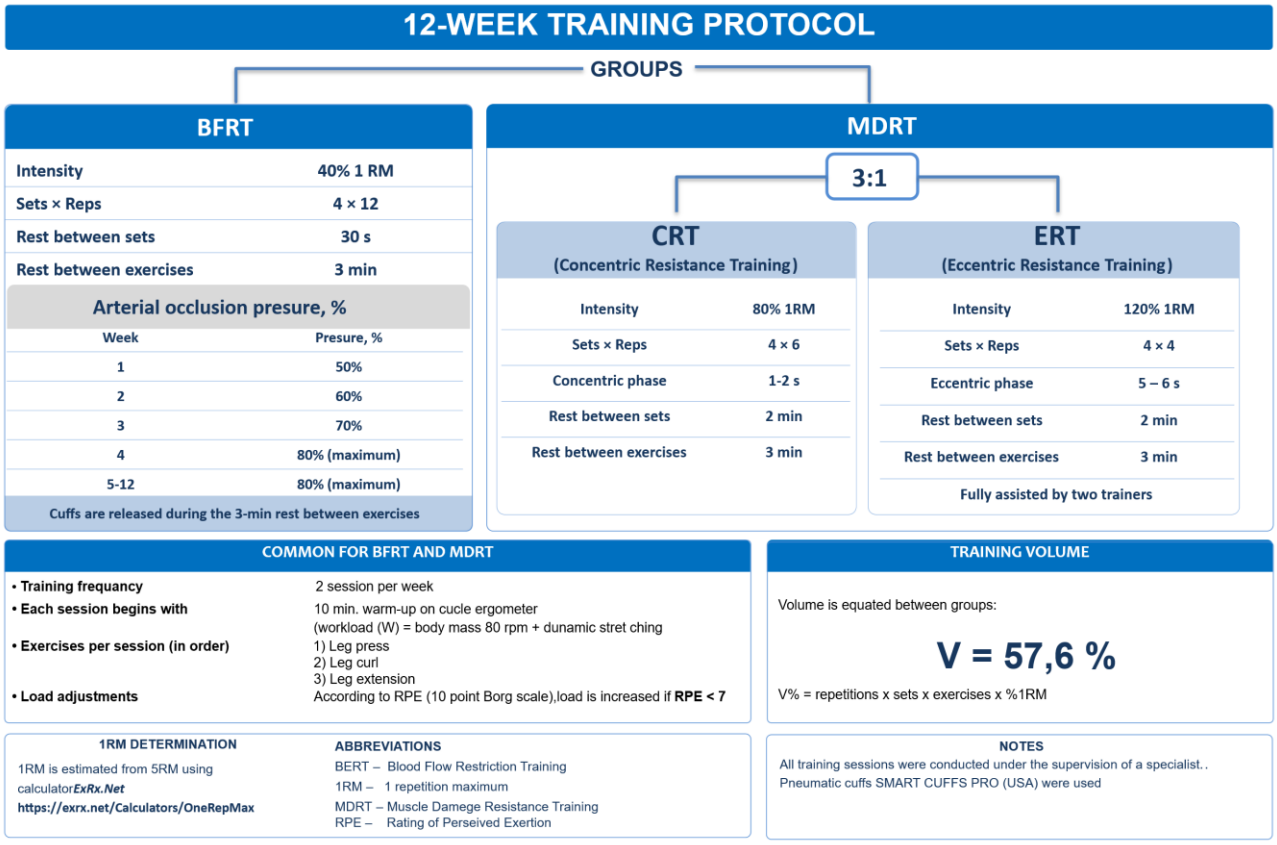

Fig. 2. Training protocol

Statistical Analysis

Statistical data analysis was performed using JASP (Version 0.95.4) and Microsoft Excel. Group differences and changes over time were evaluated using repeated measures analysis of variance (Repeated Measures ANOVA). Differences were considered statistically significant at $p < 0.05$.

Results

No statistically significant differences were found between the groups in anthropometric characteristics, including age and body mass index ($p > 0.05$), indicating that the groups were comparable at baseline (Table 1).

Table 1. Comparison of anthropometric characteristics

Anthropometric parameter	Group	N	Mean (± SD)	Shapiro–Wilk test p-value	*p*
BMI (kg/m²)	BFRT	20	25,63 ± 2,55	0,425	**0,674**
	MDRT	15	26,41 ± 3,25	0,956	
	Control	11	25,64 ± 2,40	0,725	
Age (years)	BFRT	20	66,65 ± 4,82	0,481	**0,840**
	MDRT	15	65,93 ± 3,99	0,968	
	Control	11	65,73 ± 5,15	0,115	
Height (cm)	BFRT	20	178,00 ± 6,76	0,906	**0,755**
	MDRT	15	178,27 ± 5,82	0,671	
	Control	11	179,73 ± 7,69	0,694	
Body mass (kg)	BFRT	20	81,30 ± 9,97	0,050	**0,781**
	MDRT	15	83,93 ± 10,89	0,218	
	Control	11	82,91 ± 10,58	0,502	

Repeated measures analysis of variance (Repeated Measures ANOVA) was used for the primary analysis, evaluating the effects of time (pre- and post-intervention), group, and their interaction (time × group). Outliers were defined as values exceeding 3×IQR from the mean and were excluded from further analysis. Three pairwise comparisons were performed between all groups: BFRT vs. control, MDRT vs. control and BFRT vs. MDRT. In total, 144 tests were conducted (48 per comparison), of which 9 showed statistically significant time × group interaction effects. Statistical significance was set at $p < 0.05$. Three significant results were found between BFRT and control, four between MDRT and control, and two between BFRT and MDRT groups. These summarized results are presented in Table 2.

Table 2. Statistically significant time × group interactions in TMG parameters (p<0,05)

Compared groups	TMG parameter	Muscle	Side	Time × group p	Time × group η^2
BFRT-Control	Td	GM	Left	0,038	0,028
		RF	Left	0,004	0,041
		VL	Left	0,007	0,055
MDRT-Control	Tc	TA	Right	0,014	0,070
	Td	TA	Right	0,024	0,065
		TA	Left	0,017	0,063
	Dm	VL	Right	0,003	0,051
BFRT-MDRT	Dm	VL	Right	0,011	0,021
	Tc	BF	Right	0,034	0,027

Repeated measures analysis of variance (Repeated Measures ANOVA) showed no statistically significant time × group interaction for the majority of analyzed TMG parameters ($p > 0.05$), indicating that the different interventions (MDRT, BFRT, and control) did not produce differential effects on most of the assessed muscle parameters. To further explore changes between groups after the intervention, percentage changes in Tc, Td, and Dm were compared across all groups. Percentage change was calculated using a modified formula (Pre × 100 / Post) − 100, which was selected to ensure a consistent interpretation of results, where positive values represent functionally favorable changes. Considering that a decrease in certain TMG parameters (e.g., Tc and Td) is interpreted as a positive functional adaptation, this calculation method allows a unified interpretation across all parameters. The results are presented graphically in Figures 3–5 and are based on the data provided in Table A3 (Appendix).

Following this analysis, percentage changes in TMG parameters after the intervention varied depending on the parameter, body side, and intervention, with generally high data variability. For Tc, the BFRT group showed more negative mean values, whereas MDRT and control groups remained closer to zero. For Td, the MDRT group demonstrated more negative mean values, while BFRT and control groups generally showed positive values. For Dm, all groups demonstrated positive mean values, with the highest values observed in the MDRT and control groups. Although some tendencies toward greater changes were observed in the MDRT group, the results were inconsistent across parameters and body sides. Overall, the high variability and overlapping intervals do not indicate a clear superiority of either intervention.

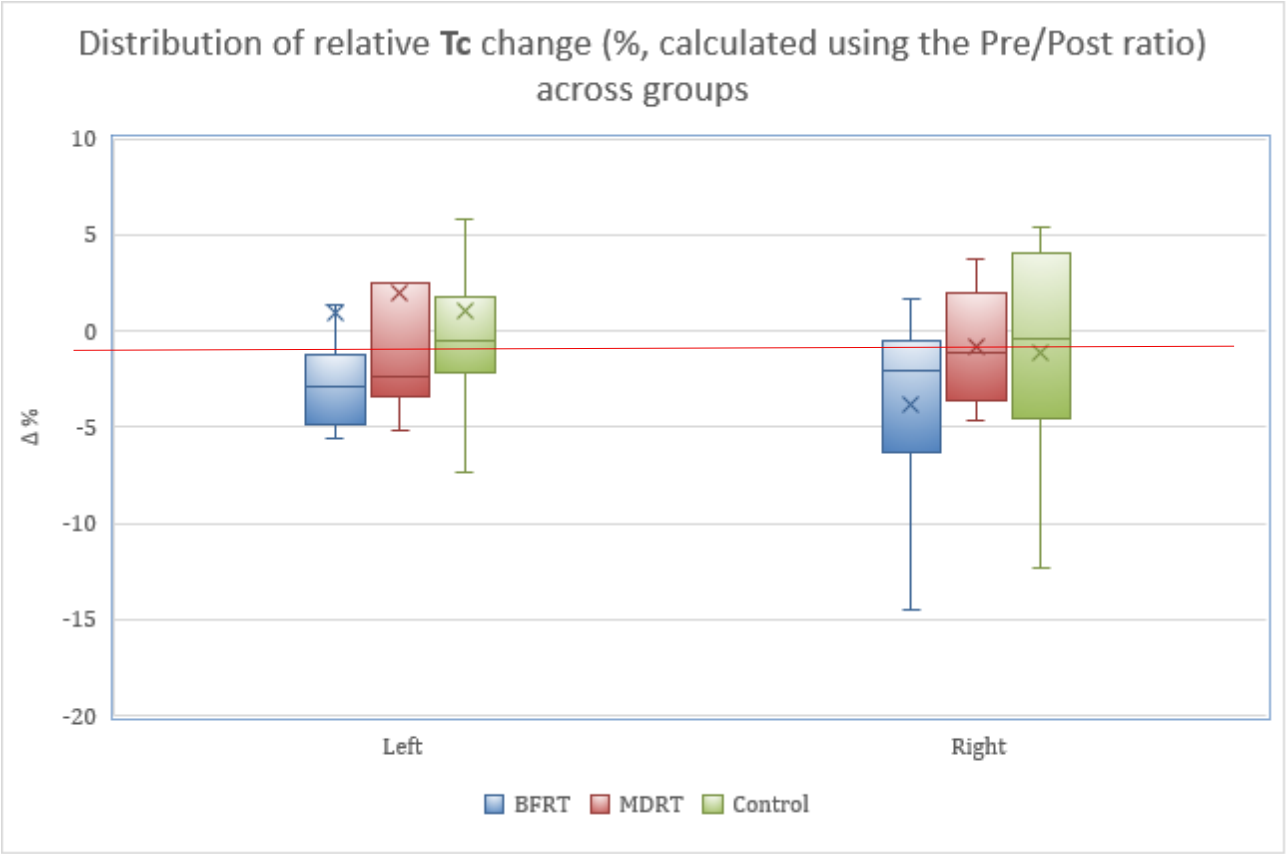

Fig. 3. Distribution of relative changes (%) in TMG Tc parameter between groups after the intervention (positive values indicate a decrease in Tc (ms)).

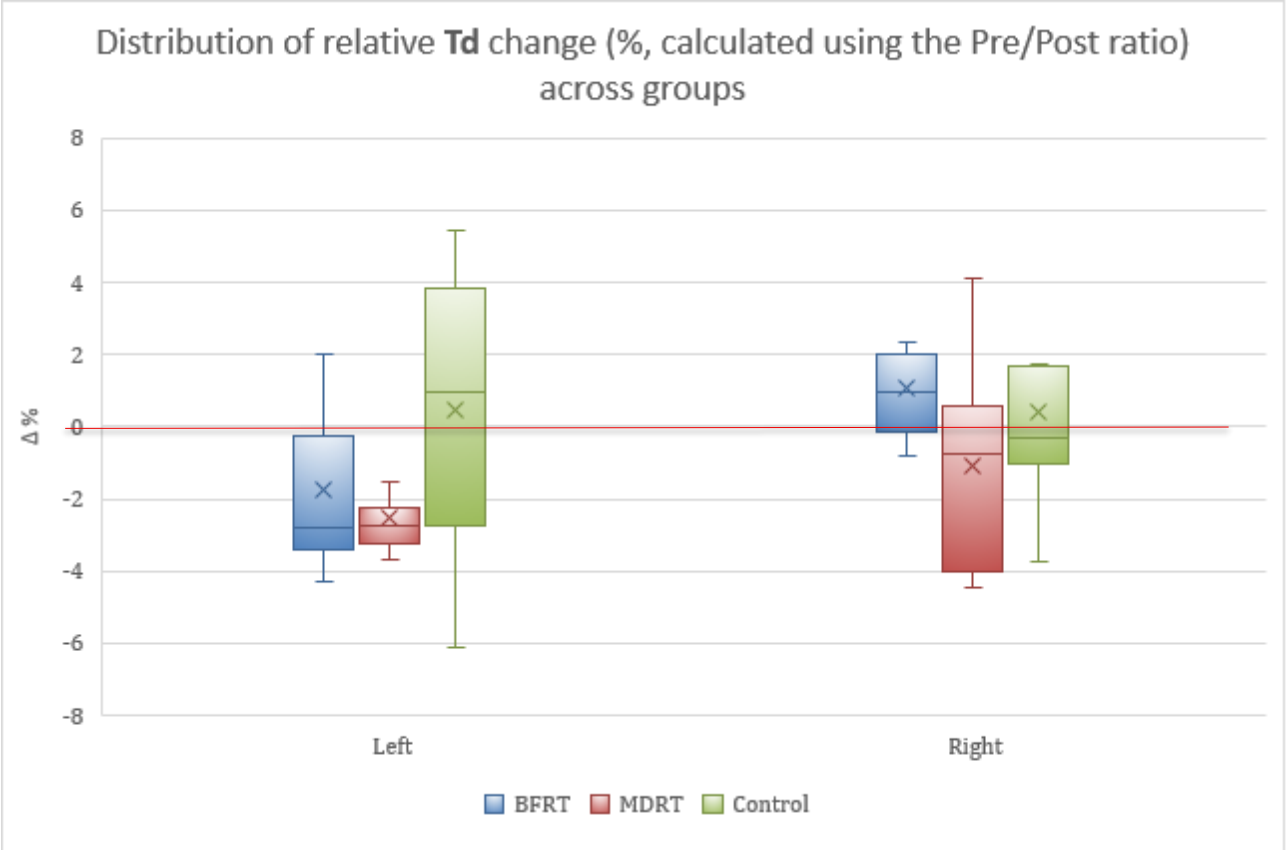

Fig. 4. Distribution of relative changes (%) in TMG Td parameter between groups after the intervention (positive values indicate a decrease in Td (ms)).

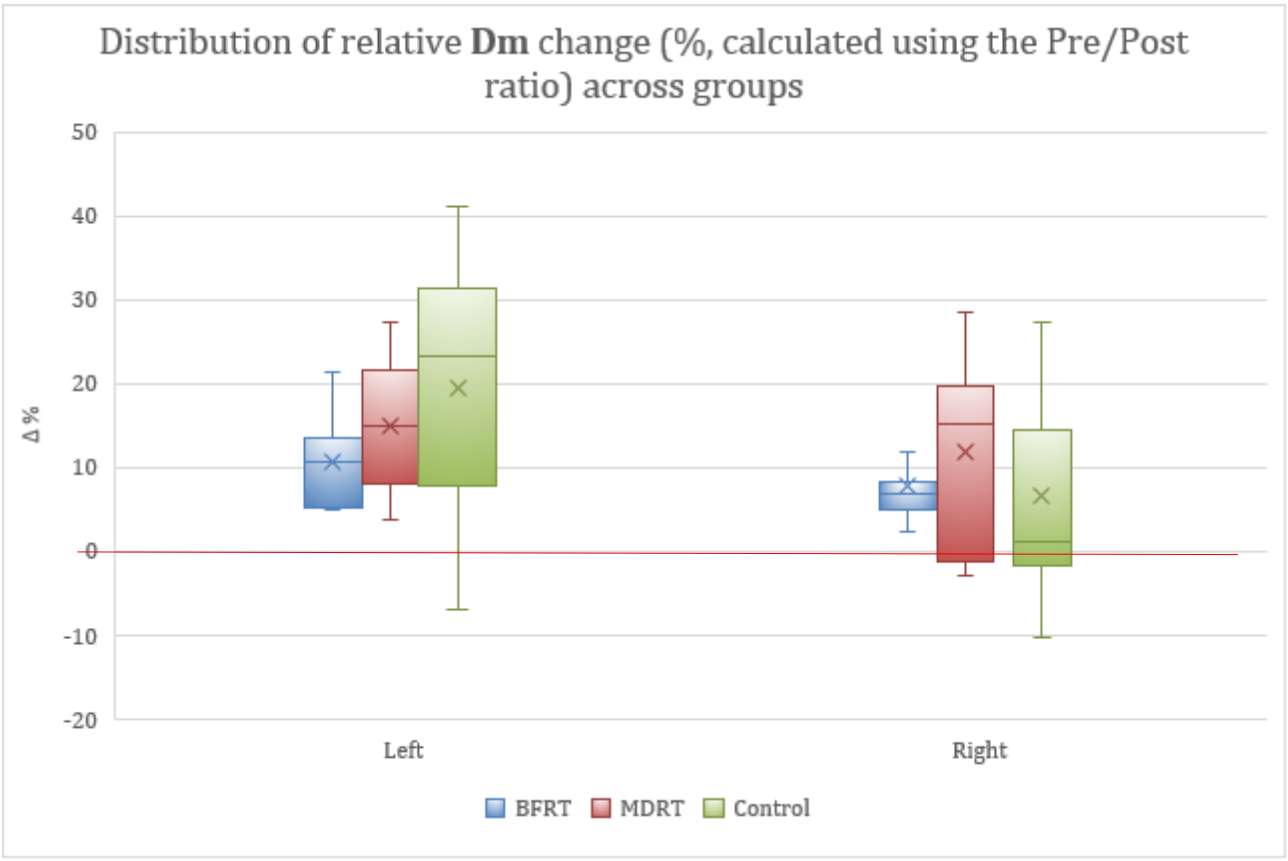

Fig. 5. Distribution of relative changes (%) in TMG Dm parameter between groups after the intervention (positive values indicate a reduction in Dm (mm)).

Discussion

The aim of this study was to evaluate the effects of blood flow restriction training (BFRT) and high-intensity resistance training (MDRT) on muscle contractile properties in older men.

The results showed no statistically significant time × group interaction for the majority of analyzed parameters, indicating that different training methods had similar effects on muscle contractile properties. Significant interaction effects were observed only in isolated muscles and were not consistent, therefore they cannot be considered evidence of a systematic advantage of one intervention. In addition, effect sizes (η^2) were small in most cases, suggesting limited practical relevance. These findings indicate that the observed changes may be related to general physical activity or adaptive processes occurring independently of the specific training modality.

When interpreting TMG parameters, their physiological meaning must be considered. Contraction time (Tc) is defined as the time from 10% to 90% of maximal muscle displacement and reflects contraction speed. Lower Tc is generally associated with faster contractile dynamics and potentially more efficient force production (Chai et al., 2016; Čular et al., 2023). Tc is also related to muscle fiber composition, where longer Tc is associated with a higher proportion of type I fibers, and shorter Tc with a higher proportion of type II fibers and faster contractile properties (Macgregor et al., 2018). However, Tc is not fully independent, as it is partly influenced by Dm, and therefore should be interpreted in combination with other parameters (Lohr et al., 2019). It may also reflect excitation–contraction coupling efficiency (Čular et al., 2023).

Delay time (Td) is defined as the time from electrical stimulus onset to 10% of maximal displacement and represents the earliest phase of mechanical response. Although often interpreted as reaction speed, Td reflects a complex process influenced not only by neural factors but also by mechanical properties of the muscle–tendon unit, tissue stiffness, and contractile state (Macgregor et al., 2018). Therefore, a decrease in Td may indicate faster mechanical response onset but should not be interpreted as a direct indicator of improved neuromuscular function without considering other parameters.

Maximal displacement (Dm) reflects the radial movement of the muscle belly and is commonly associated with mechanical muscle properties. Lower Dm is typically interpreted as higher muscle stiffness, whereas

higher Dm indicates lower stiffness (Macgregor et al., 2018). However, Dm is also influenced by muscle architecture and force transmission efficiency. Decreases in Dm following training have been associated with increased strength and structural adaptations (Wilson et al., 2019). In older adults, Dm may also reflect muscle quality, although its relationship with functional performance is not always consistent (Labata-Lezaun et al., 2023).

Based on these interpretations, reductions in Tc and Td observed in this study may indicate faster contraction dynamics and more efficient mechanical response, while decreases in Dm may reflect increased muscle stiffness and potentially improved force transmission. However, these parameters should not be interpreted in isolation, as they are influenced by complex interactions of structural and functional factors.

Regarding intervention effects, neither BFRT nor MDRT demonstrated a consistent advantage compared to the control group. Although some tendencies were observed, they were not consistent across parameters or body sides. Similarly, no systematic differences were found between BFRT and MDRT, suggesting that both training modalities may induce similar neuromuscular adaptations. Despite different underlying mechanisms—mechanical loading in MDRT and metabolic stress in BFRT—the resulting adaptations may converge.

In older individuals, reduced neuromuscular plasticity may limit the magnitude of training adaptations (Gustafsson & Ulfhake, 2024). Aging is associated with a decline in motor unit number, impaired recruitment, and slower neural conduction, which may reduce responsiveness to training (Hunter et al., 2016). Additionally, anabolic resistance may attenuate muscle protein synthesis in response to exercise, resulting in smaller and slower adaptations (Breen & Phillips, 2011).

It is also important to note that nutritional intake, particularly protein consumption, was not controlled in this study. This is relevant, as older adults require higher protein intake to support muscle maintenance and adaptation (Rogeri et al., 2021). Insufficient or low-quality protein intake may have limited training-induced adaptations and contributed to variability in results. Furthermore, training-related discomfort was not assessed. BFRT is known to induce considerable discomfort (Spitz et al., 2022), which may influence perceived exertion and reduce actual effort despite reported maximal engagement.

Methodological aspects of TMG should also be considered. Although TMG is a reliable non-invasive method for assessing muscle mechanical properties, its sensitivity to small changes is limited, particularly in heterogeneous populations and when multiple muscles are analyzed (Macgregor et al., 2018). Another factor that may have influenced the results is the 7-day period between the last training session and post-intervention measurements. Literature suggests that recovery following high-intensity, especially eccentric, exercise may take longer than 168 hours (Paulsen et al., 2012). Therefore, measurements may have been performed before full recovery, particularly in older individuals.

Additionally, a large number of variables were analyzed, including multiple muscles, both body sides, and several TMG parameters, resulting in numerous statistical comparisons. This increases the risk of Type I error (false positives) (AbdulRaheem, 2023). At the same time, the relatively small sample size may reduce statistical power and increase the risk of Type II error, meaning that real differences may not reach statistical significance. Furthermore, although the control group did not participate in structured training, their daily physical activity was not controlled, which may have influenced outcomes.

Finally, it should be emphasized that TMG parameters reflect local muscle mechanical properties and are not always directly related to functional outcomes such as strength or mobility. Therefore, results should be interpreted with caution and, where possible, complemented with functional assessments.

In summary, both training methods appear to be potentially effective for older men; however, neither demonstrated a clear advantage in terms of TMG parameters.

Conclusions

1. The BFRT intervention did not produce consistent statistically significant changes in TMG parameters compared to the control group. Although isolated significant changes were observed, they were not consistent and did not indicate a clear advantage of BFRT.
2. The MDRT intervention resulted in isolated changes in TMG parameters, some of which were statistically significant; however, these changes were not consistent across all parameters and body sides. No clear and systematic effect of MDRT was observed compared to the control group.
3. When comparing BFRT and MDRT groups, some statistically significant differences were identified, but they were not unidirectional. Overall, both training methods had similar effects on TMG parameters, and the results do not support the superiority of one intervention over the other.

Recommendations

Future studies should consider increasing sample size to improve statistical power and more accurately detect differences between groups. It is also recommended to control dietary intake, particularly protein consumption, and to monitor daily physical activity. For a more comprehensive evaluation, tensiomyography should be combined with functional outcomes such as muscle strength or mobility. In addition, primary outcome measures should be more clearly defined, and the number of analyzed variables should be reduced. It is also important to assess intervention tolerability and perceived discomfort. Finally, in older populations, longer-duration or higher-frequency training programs may be more appropriate to better capture training-induced adaptations.

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