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Effects of Lower Limb Resistance Training on Cognitive Function in Older Adults with Mild Cognitive Impairment Risk

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ABSTRACT

Background: Promoting healthy ageing is a major public health challenge, especially with increasing mild cognitive impairment (MCI) prevalence and associated dementia risk in older adults. Exercise training may improve cognitive function, yet studies on its effects in MCI populations remain limited and inconsistent in design and outcomes. This study investigated the impact of a 12-week structured lower limb resistance training (RT) programme on cognitive performance, specifically memory and executive function in older adults at low and high risk of MCI.

Methods: Fifty-three older adults (aged 60–80) completed the study and were categorised into low risk (lrMCI, n = 28) and high risk (hrMCI, n = 25) MCI groups. Participants were assigned to a 12-week RT programme (2 sessions/week, 4 lower-limb exercises, 3 sets of 6–10 reps at 70–85% 1RM) or a passive control group. Cognitive performance was assessed using the Montreal Cognitive Assessment (MoCA) and ANAM4™ neurocognitive battery before and after the intervention.

Results: At week 12, participants with high risk MCI in the resistance training group showed a significant improvement in MoCA total scores, particularly in executive function and delayed recall domains. An increase in MoCA scores was also observed in the control group, suggesting a potential learning effect. Performance across ANAM4 cognitive tasks did not show statistically significant changes following the intervention.

Conclusion: A twice-weekly RT programme over 12 weeks did not produce robust improvements across all cognitive domains, but trends suggested potential benefits in executive function and inhibitory control among older adults at higher risk of MCI. The cognitive response to RT appears to vary by MCI risk level and baseline cognitive status.

Keywords: older adults, MoCA (Montreal Cognitive Assessment), executive function, memory, ANAM4 neurocognitive battery

1. INTRODUCTION

The global ageing population is one of the most striking demographic shifts of our times. As life expectancy increases, the number of older people is growing rapidly and already outpacing the growth rates of other age groups. Currently, a new case of dementia develops approximately every three seconds worldwide (2024 Alzheimer's Disease Facts and Figures, 2024; Alzheimer's Disease International et al., 2024). This rise in prevalence creates an increasing need to promote quality of life in older age (Wolters et al., 2020).

Maintaining physical and cognitive (mental) functions is becoming one of the most important tasks for healthcare and society (World Health Organization, 2024). Although cognitive decline is

almost an inevitable companion of ageing, age-related neurodegenerative changes are more common in older people (Lee & Kim, 2022). For example, it is estimated that up to 50% of people aged 90 or older have developed dementia (2024 Alzheimer's Disease Facts and Figures, 2024). Mild cognitive impairment (MCI), an intermediate stage between normal ageing and dementia (Petersen et al., 1999; Petersen, 2016; Petersen et al., 2018; Anand & Schoo, 2024), is also being diagnosed more frequently among younger segments of the older adult population (Dunne et al., 2021; Bradfield, 2023).

These phenomena raise the question of how cognitive decline can be prevented or at least delayed. Every year of healthy life significantly reduces the burden not only on the individual, but also on their family members, the healthcare system, and the country's economy (Todd et al., 2013).

MCI is described as subjectively perceived and objectively measurable cognitive impairments of memory, attention, executive functions that are beyond the limits of normal ageing but do not yet cause significant impairment in daily functioning (Winblad et al., 2004; Kirova et al., 2015; Iraniparast et al., 2022; Liang et al., 2022). MCI is considered a transitional stage between normal ageing and dementia, and people with MCI are typically at an increased risk of developing Alzheimer's disease or other forms of dementia (Grundman et al., 2004; Petersen et al., 2014). Since the effectiveness of medication in the early stages of cognitive impairment is questionable and limited, more attention is being paid to non-pharmacological, lifestyle-based approaches (Lautenschlager et al., 2019).

When it comes to modifiable risk factors (Han et al., 2022), much attention is paid to physical activity because of its well-known effects on physical health and growing evidence of its positive impact on brain function (Liu et al., 2022; Hu et al., 2024). Most studies have focused on the benefits of aerobic and endurance exercise (Hoffmann et al., 2021; Aghjayan et al., 2022; Huang et al., 2023). However, resistance training has recently gained attention due to its unique effects on brain health, as evidenced by numerous studies (Liu-Ambrose et al., 2012; Best et al., 2015; Herold et al., 2019; Pinho et al., 2019; Syed-Abdul, 2020; Hattabi et al., 2024). Specifically, research indicates that resistance training can promote synaptic plasticity (Esiri & Chance, 2012; Fontes et al., 2017; Broadhouse et al., 2020; Chow et al., 2021; Hortobágyi et al., 2021), increase the levels of neurotrophic factors such as BDNF (brain-derived neurotrophic factor) (Tsai et al., 2019; Molina-Sotomayor et al., 2020; Roh et al., 2020; Kim et al., 2022), improve cerebral blood flow (Macaulay et al., 2022), and reduce inflammation (Calle & Fernandez, 2010; Azevedo et al., 2023; Gökçe et al., 2023; Cheng & Yang, 2024; Vints et al., 2024a)—all of which contribute to increased cognitive resilience (Herold et al., 2019; Hughes et al., 2021).

Based on previous studies, resistance training has been investigated for its benefits in cognitive domains, particularly those related to executive function (Buckner, 2004; Liu-Ambrose et al., 2010; Diamond & Ling, 2019; Feter et al., 2023), inhibition, and working memory (Eriksson et al., 2015; Quentin & Cohen, 2019). These functions often begin to decline in the early stages of MCI but are extremely important for the daily activities of older adults (Petkus et al., 2019; Sebastiani et al., 2020).

According to this information, the aim of this study was to evaluate the effects of a 12-week progressive resistance training programme on the cognitive functions of older adults, considering their risk level of MCI. Cognitive functions were assessed using two complementary tools: the Montreal Cognitive Assessment (MoCA) (Nasreddine et al., 2005), which is widely used for the early detection of cognitive impairment, and the Automated Neuropsychological Assessment Metrics (ANAM4™) (Center for the Study of Human Operator Performance (C-SHOP), 2007) neurocognitive battery, which allows for a comprehensive assessment of aspects of attention, memory, executive functions, and reaction time. Study participants were divided into high and low MCI risk groups based on their initial MoCA scores to determine whether those in the high MCI risk group with lower cognitive health status would benefit more from the intervention (Yoon et al., 2018; Zhang et al., 2020). In addition, in the study we analysed potential factors that might influence cognitive outcomes in both the experimental and control groups. Specifically, we considered participants' level of education, physical fitness/physical activity, and BMI, as these variables are known to affect cognitive performance and may partially explain group differences.

2. METHODS

Participants

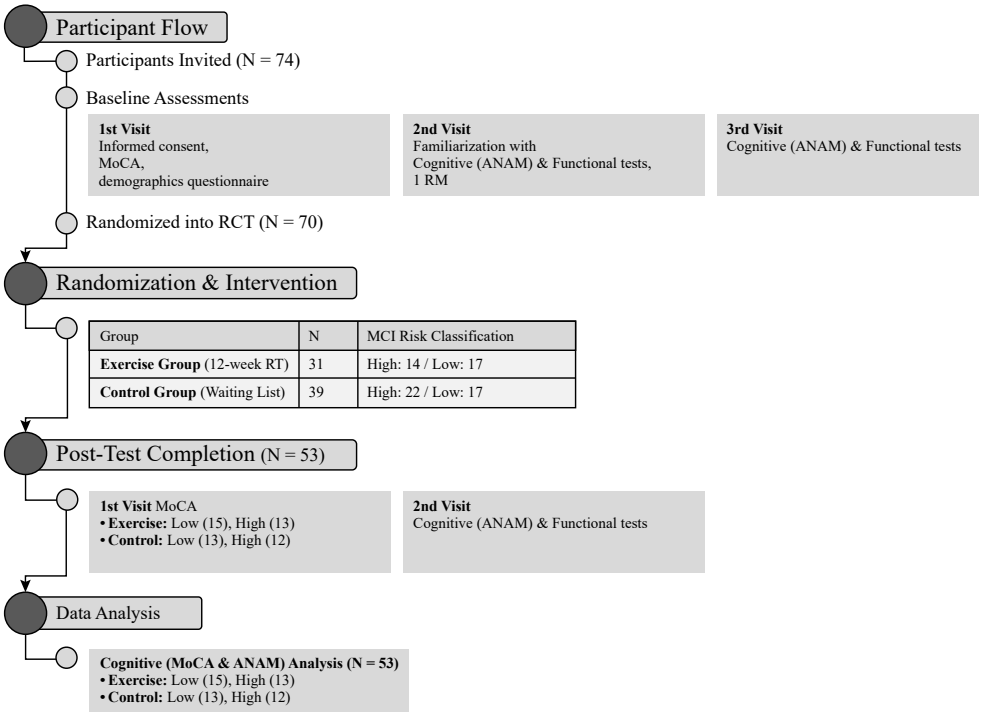
Seventy Lithuanian-speaking older adults (male/female, 32/38) were recruited to a randomised controlled trial from the local community in Kaunas,

Lithuania. The participants were from the same pool as those mentioned in the study (Kušleikienė et al., 2025). All individuals were recruited from the local community via print advertisement with a focus on healthy ageing. Participants had a mean age of 69.26 years (SD = 6.3 years) and ranged in age from 60 to 85 years. Participants were well educated (68 ≥12 years and 2 <12 years of education). All participants provided written informed consent before enrolment and were able to voluntarily withdraw from the study at any time. Each participant was interviewed and participants with serious central nervous system (CNS) injuries, psychiatric brain disorders, alcohol abuse, diabetes, musculoskeletal disorders, neurodegenerative diseases, and oncology were excluded from the study. Participants were instructed not to exercise before all baseline appointments and cognitive tests. The study methods were approved by the Kaunas Regional Biomedical Research Ethics Committee (No. BE-10-7).

Study design

This study was a parallel group randomised controlled trial with a 12-week resistance exercise intervention. Randomisation was done using a stratified permuted block procedure. The stratification factor was the score on the Montreal Cognitive Assessment (MoCA) test, subdividing participants into high and low risk of MCI. A trained mental health specialist (co-author SK) administered all MoCA evaluations. In every block of four participants with low or high risk of MCI, two were randomly allocated to the experimental and two to the control condition. The resistance training protocol was supervised by qualified fitness coaches, who were not involved in pre- and post-intervention data collection. The investigators with this role were blinded to the group allocation. See detailed description of the study procedure and participant flow diagram in Figure 1.

Figure 1. **Randomised controlled trial study design: Exercise and MCI risk**



Assessments

MoCA. The Lithuanian version of MoCA was used to measure the cognitive level of the subjects. MoCA is a 10 min, 30-point clinical assessment of multiple cognitive functions, including orientation (6 points), attention (6 points), short-term memory recall (5 points), abstract thinking (2 points), visuospatial executive function as assessed by the clock drawing task, the trail task, and the geometric figure reproduction (5 points), naming task (3 points), and language function as assessed by the verbal fluency test (3 points). An additional point was added for subjects with less than 12 years of education (n = 2). Although the MoCA test is not a diagnostic tool, a

score of 18–25 is considered a reliable and sensitive marker of MCI, while a score of 26–30 is considered to indicate normal cognitive abilities and a low risk of MCI (Nasreddine et al., 2005; Julayanont et al., 2012). The MoCA test participants' scores ranged from 19 to 30. The sample was stratified according to the total MoCA score. Individuals with a score of 25 or less (n = 36) were considered to meet the guidelines for high risk MCI (Nasreddine et al., 2005), whereas individuals with a score ≥26 (n = 34) were cognitively healthy or at low risk of MCI. The final distribution of the subjects in the groups depended on which group they were in (intervention or control), which MCI risk group they belonged to (low risk MCI (lrMCI) or high risk MCI (hrMCI), and the demographic information of the samples. A total of 53 individuals completed the study.

Secondary assessment tests included the Automated Neuropsychological Assessment Metrics (ANAM4) neurocognitive battery (Center for the Study of Human Operator Performance (C-SHOP), 2007). The ANAM4 neurocognitive battery, widely recognised for its ability to assess multiple cognitive domains such as working memory, reasoning, planning, attention, and executive functions, was used to evaluate the effects of a 12-week resistance training (RT) intervention on cognitive functions. ANAM4 offers several advantages over traditional pen-and-paper tests, particularly due to its accuracy in measuring reaction time, processing speed, error frequency, and their relationships (Woodhouse et al., 2013). It is suitable for both short-term and long-term interventional studies (Meyers & Vincent, 2020). Cognitive domains tested with ANAM4 included the subtests for attention and reaction time, processing speed, learning, visuospatial working memory, working memory, and delayed memory, respectively. Using a laptop, participants completed four tests from the ANAM4 library: Two-Choice Reaction Time (2CRT), Mathematical Processing (MP), Memory Search (MS), Go/No-go (G/N-G) cognitive tests. A detailed description of the four tests is given below.

Two-Choice Reaction Time (2CRT). The outcomes of this test are used as a measure of processing speed and alternating attention with a motor speed component (Reeves et al., 2007). Participants were instructed to react as quickly as possible by pressing either the left touchpad button of a laptop with their left hand when an asterisk (*) appeared in the centre of the screen or the right touchpad button of a laptop with their right hand when "o" appeared on the display.

Mathematical Processing (MP). Results of this test are used as an index of basic computational skills, concentration, and working memory (Meyers & Vincent, 2020). During this task, an arithmetic problem involving three single-digit numbers and two operators was displayed (e.g. "5 – 2 + 3 ="). The user had to press either the left touchpad button of a laptop with their left hand if the answer to the problem was less than five or the right touchpad button of a laptop with their right hand if the answer to the problem was greater than five.

Memory Search (MS). The test assesses verbal working memory, immediate recognition, and attention. A set of six letters (the positive memory set) was displayed for memorisation (the time was unlimited). Individual characters (letters) were then displayed, and the user had to press either the left touchpad button of a laptop with their left hand if the character was a member of the memorised set or the right touchpad button of a laptop with their right hand if the character was not a member of the memorised set.

Go/No-go (G/N-G). This test assesses response inhibition (Vincent et al., 2018). Participants were presented with two characters, "x" and "o". In the go condition, subjects were instructed to respond as quickly as possible to the character "x" by pressing the left touchpad button of a laptop using their forefinger of the right hand each time the stimulus appeared in the centre of the screen and to remain still (inhibit their response) to the letter "o". The entire task lasted for 2 min.

Practice trials of each task were provided, which ensured that the test takers understood what was required before the actual test was taken. Raw test scores were converted to standardised scores using published normative data. Outcome measures were reaction time and percent of correct responses.

These tests were selected based on literature data indicating their suitability for assessing cognitive abilities in ageing, as well as in various neurological conditions independent of age (Woodhouse et al., 2013; Tayer-Shifman et al., 2020). The tests cover several important cognitive processes—visual working memory, attention span, and executive control—which, according to research, can be positively influenced by physical activity (Engeroff et al., 2018; Herold et al., 2019).

The testing was conducted at the Lithuanian Sports University using a computer with testing software installed in a quiet environment. Before data recording, all participants performed one practice trial for each task and familiarised themselves

with the procedure 48–72 hours before the test day. Participants were informed that speed and accuracy were equally important evaluation criteria. The software automatically provided the averaged results of each test. The main outcome measure was reaction time (in milliseconds, ms). Quality control measures were applied: tests in which the participant made more than 50% errors were excluded, and reaction times exceeding the fastest normative data limits were rejected to avoid random results. All tests met these quality criteria, so none were excluded from the analysis. The same testing conditions were ensured for each participant, conducted at the same time of day (between 8 AM and 11 AM) both before and after the 12 weeks. Participants were instructed to refrain from unusual physical activity, alcohol, and caffeine the day prior, and to sleep at least seven hours. They were also asked to have breakfast 1–2 hours before testing.

Resistance training intervention

Participants assigned to the exercise group completed a 12-week progressive lower-limb resistance training programme, whereas those in the control group received no intervention and were instructed to maintain their usual physical activity levels until post-intervention assessments. The resistance exercise protocol followed the most recent guidelines from the National Strength and Conditioning Association (NSCA) (USA) for resistance training for older adults (Fragala et al., 2019). Older adults in the exercise group trained two times per week under the direct supervision of professional fitness instructors. The training sessions took place in the gym at the Lithuanian Sports University using resistance training equipment from Technogym (Italy). Before training all participants had to undergo a warm-up of 5-min cycling on a cycle ergometer, at an intensity (in Watts) approximately equal to the participant's body weight in kilograms, followed by a few dynamic stretching and activation exercises. The resistance exercise programme consisted of three sets of four lower limb exercises: (1) leg press, (2) leg curl, (3) leg extension, and (4) calf raises with no fixed order (Figure 2). During the first week, participants were familiarised with proper technique and completed 1-repetition maximum (1-RM) testing for each exercise following standardised NSCA procedures (Haff & Triplett, 2016).

Figure 2. **Resistance training intervention**

Statistical analysis

All statistical analyses were performed using IBM SPSS Statistics Version 27 (IBM Corp., Armonk, NY). Prior to conducting the main analyses, data were screened for normality, outliers, and homogeneity of variance. Descriptive statistics were calculated for all groups. Baseline differences between groups were assessed using independent samples t tests for continuous variables and Chi-Square or Fisher's exact tests for categorical variables, depending on the expected cell counts.

Descriptive statistics were computed for baseline and post-intervention performance. To examine the effects of the 12-week resistance training intervention on cognitive function, a series of mixed-design analyses of variance (ANOVAs) were conducted. A three-way repeated measures ANOVA was employed with time (baseline vs. post-intervention) as the within-subjects factor, and group (experimental vs. control) and MCI risk (low vs. high) as between-subjects factors.

The primary outcome was the total MoCA score, while secondary outcomes included MoCA subdomain scores (executive function, visuospatial skills, and delayed memory).

Statistical significance was set at $p < 0.05$. Partial Eta Squared (ηp^2) values are reported to indicate effect sizes. All reported p values are uncorrected unless otherwise specified.

3. RESULTS

Participants

The randomised controlled trial included 74 older adults, 33 males (44.6%) and 41 females (55.4%), aged between 60 and 85 years (mean age: 69 ± 6.2 years). Four participants were excluded from the baseline analysis. Two participants had completed baseline assessments but were involved in the pilot version of the intervention, after which the final resistance exercise protocol was established. Two other participants withdrew following initial assessments, one due to a claustrophobic episode during magnetic resonance imaging (MRI) and the other due to a pathological finding on brain MRI. MRI data collected in the study are not presented in this article. For MRI results, see Gökçe et al. (2023), Vints et al. (2024a), Kušleikienė et al. (2025).

A total of 53 participants (74.3%) completed the intervention, including 23 (43.4%) males and 30 (56.6%) females. Seventeen participants (25.7%) discontinued the intervention, mentioning reasons such as COVID-19 infection or fear of catching SARS-COV-2 infection, lengthy MRI sessions, lack of motivation, intervention-related trauma or fear of injury, and medical issues unrelated to the exercise programme. Most of these dropouts occurred within both control groups (nine in the lrMCI group, and five in the hrMCI group; one in the experimental hrMCI group and two in lrMCI group, respectively).

At baseline, significant differences were observed between the experimental and control groups regarding age. However, when the groups were further divided into four subgroups (experimental lrMCI, experimental hrMCI, control lrMCI, and control hrMCI), age differences among them were not statistically significant ($p = 0.419$). Differences across all groups regarding sex, weight, height, BMI, muscle strength (right-hand handgrip), caloric intake, and physical activity level were also not statistically significant. The duration of participants' education ranged from 4 to 18 years, with 44 individuals (83.0%) having 12 or more years of education. There were no significant differences in education between genders. The descriptive statistics for baseline characteristics of all four groups are presented in Table 1.

Table 1. **Baseline participant characteristics and group differences of participants' complete intervention**

	hrMCI		lrMCI	
	Experimental	**Control**	**Experimental**	**Control**
	(n = 13)	**(n = 13)**	**(n = 15)**	**(n = 12)**
Age	71.7 (1.7)	68.4 (1.6)	68.7 (1.4)	68.8 (1.7)
Sex:				
- Male	7 (53.8%)	6 (46.2%)	4 (26.7%)	6 (50.0%)
- Female	6 (46.2%)	7 (53.8%)	11 (73.3%)	6 (50.0%)
Education:				
- ≥12 years	9 (69.2%)	11 (84.6%)	13 (86.7%)	11 (91.7%)
- <12 years	4 (30.8%)	2 (15.4%)	2 (13.3%)	1 (8.3%)
IPAQ-SF kcal/ week	3,260.7 (863.4)	5,327.8 (1,147.8)	3,460.3 (631.4)	5,017.0 (1,058.1)
IPAQ-SF PA level:	1.1 (0.2)	1.6 (0.2)	1.4 (0.2)	1.7 (0.1)
- sedentary	3 (23.1%)	1 (7.7%)	1 (6.7%)	–
- moderately active	6 (46.2%)	3 (23.1%)	7 (46.7%)	4 (33.3%)
- highly active	4 (30.8%)	9 (69.2%)	7 (46.7%)	8 (66.7%)
BMI (kg/m²)	28.0 (1.3)	27.3 (1.0)	35.3 (1.5)	27.1 (1.0)
Body fat (%)	29.3 (3.0)	31.7 (2.6)	35.3 (1.5)	29.9 (2.3)
Right handgrip strength (kg)	31.7 (2.3)	34.2 (3.8)	31.7 (2.4)	33.8 (2.6)
MoCA score	23.29 (1.773)	22.55 (1.870)	27.53 (1.328)	27.71 (1.448)

Note: Continuous parameters are expressed as mean values (SD), categorical parameters are expressed as n (% of total). BMI – body mass index; IPAQ-SF – International Physical Activity Questionnaire-Short Form; MCI – mild cognitive impairment; MoCA – Montreal Cognitive Assessment; PA – physical activity.

After the 12-week period, body composition remained largely unchanged, while right handgrip strength improved in the hrMCI subgroups, particularly in the experimental group. Physical activity levels assessed by the IPAQ-SF (International Physical Activity Questionnaire-Short Form) declined in control participants, most notably in the lrMCI group (see Supplementary Table 1 in the Appendix).

Cognitive outcomes

MoCA

Statistical analysis revealed significant cognitive improvements in the experimental and control hrMCI groups, with increase across several MoCA domains, including executive function ($p = 0.018$), delayed memory ($p = 0.006$), and total MoCA scores ($p < 0.01$). By contrast, participants at low risk of MCI showed minimal changes, and none of their score increases reached statistical significance after correction. Descriptive values of baseline/12 weeks MoCA percentage change are summarised in Supplementary Table 2 in the Appendix.

Both experimental and control participants at high risk of MCI showed significant improvements in MoCA total scores over the 12-week period ($p = 0.005$ and $p = 0.004$, respectively), with mean increases of more than two points. In contrast, participants at low risk of MCI demonstrated only minimal, non-significant changes in MoCA scores, consistent with ceiling effects. Detailed descriptive values are provided in Table 2.

Table 2. **Descriptive statistics for pre- and post-intervention MoCA scores**

Group		N	MoCA points (SD) BASE-LINE	MoCA points (SD) 12 WEEKS	Δ (%)	Post- to pre- p value
Experi-mental						
	hrMCI	13	23.5 (1.7)	26.1 (2.8)	+11.1%	**0.005***
	lrMCI	15	27.5 (1.3)	28.3 (1.6)	+2.9%	0.148
Control						
	hrMCI	13	21.9 (2.1)	24.7 (3.0)	+12.8%	**0.004***
	lrMCI	12	27.7 (1.4)	27.9 (2.5)	+0.7%	0.610

*Notes: All uncorrected p values, Δ values were calculated by subtracting the post-intervention value from the pre-intervention value in percent. MCI – mild cognitive impairment; MoCA – Montreal Cognitive Assessment; hrMCI – high risk of mild cognitive impairment; lrMCI – low risk of mild cognitive impairment; p value * – p < 0.05.*

A three-way repeated-measures ANOVA revealed a significant main effect of time, indicating overall cognitive improvement across all participants over the 12-week period ($F(1, 49) = 30.690$, $p < 0.001$, $\eta p^2 = 0.385$) (Table 2). However, the interaction between Time and Group (experimental vs. control) was not significant ($F(1, 49) = 0.122$, $p = 0.728$, $\eta p^2 = 0.002$), suggesting that the intervention did not lead to significantly greater improvements compared to usual conditions. In contrast, a significant Time × MCI risk interaction was found ($F(1, 49) = 14.818$, $p < 0.001$, $\eta p^2 = 0.232$), indicating that baseline cognitive status influenced the degree of change in MoCA scores – hrMCI participants improved more than lrMCI participants, likely due to ceiling effects in the latter group. No significant three-way interaction was observed between Time, Group, and MCI risk ($F(1, 49) = 0.232$, $p = 0.632$, $\eta p^2 = 0.005$), suggesting that these combined factors did not produce differential outcomes.

Between-subjects analysis did not reveal a significant main effect of group on MoCA scores ($F(1, 49) = 2.456$, $p = 0.124$, $\eta p^2 = 0.048$), indicating that the intervention did not produce significantly greater improvements than the control condition. However, there was a strong main effect of MCI risk ($F(1, 49) = 54.493$, $p < 0.001$, $\eta p^2 = 0.527$), showing that hrMCI and lrMCI participants differed significantly in their cognitive trajectories, with greater improvements observed among the former. The Group × MCI risk interaction was not significant ($F(1, 49) = 0.673$, $p = 0.416$, $\eta p^2 = 0.015$), and pairwise comparisons of post-intervention MoCA scores showed no significant differences between groups ($p > 0.05$), with confidence intervals overlapping zero, suggesting a possible practice effect across all groups (see Supplementary Table 3 in the Appendix).

ANAM4

The effects of the 12-week resistance training (RT) programme on ANAM4-based cognitive performance have been previously reported (Vints et al., 2024a; Kušleikienė et al., 2025). In the present analysis, no significant changes were observed in task accuracy (percentage of correct responses) across any of the four participant groups ($p > 0.05$) after correction, suggesting that the intervention did not influence response accuracy (Table 3).

Table 3. **Descriptive values of baseline/12 weeks percentage of correct answers (%) and mean response time (milliseconds) on the ANAM4 cognitive tests**

		Accuracy (percentage of correct answers)				Mean response time (milliseconds)			
		Baseline (Mean (SD)	12 weeks (Mean (SD)	Δ (%)	p value (uncorrected)	Baseline (Mean (SD)	12 weeks (Mean (SD)	Δ (%)	p value (uncorrected)
Two-Choice Reaction Time test									
Experimental	hrMCI	97.1 (3.5)	98.2 (3.2)	+1.07	0.395	663 (124)	645 (133)	–2.71	0.674
	lrMCI	97.5 (4.8)	97.7 (3.0)	+0.20	0.829	617 (128)	634 (142)	+2.76	0.577
Control	hrMCI	97.7 (3.1)	92.4 (14.0)	–5.44	0.134	589 (122)	623 (111)	+5.77	0.450
	lrMCI	99.0 (1.7)	98.1 (3.6)	–0.84	0.305	621 (110)	568 (74.7)	–8.53	0.229
Go/No-go task									
Experimental	hrMCI	94.0 (8.2)	94.8 (9.5)	+0.83	0.548	480 (56.1)	460 (56.7)	–4.35	0.084
	lrMCI	94.8 (5.2)	97.0 (1.8)	+2.30	0.159	465 (62.6)	460 (72.3)	–1.07	0.767
Control	hrMCI	96.4 (3.2)	94.0 (5.7)	–2.45	0.237	476 (53.0)	488 (76.0)	+2.52	0.359
	lrMCI	95.6 (4.5)	95.1 (5.9)	–0.53	0.827	**468 (60.5)**	**436 (58.0)**	**–6.83**	**0.007**
Memory Search test									
Experimental	hrMCI	96.0 (4.3)	94.8 (6.0)	–1.22	0.525	1,326 (213)	1,289 (267)	–2.79	0.636
	lrMCI	93.7 (6.8)	89.8 (13.8)	–4.14	0.342	1,305 (272)	1,378 (367)	+5.59	0.384
Control	hrMCI	94.2 (13.5)	87.7 (19.0)	–6.85	0.253	1,146 (208)	1,259 (408)	+9.86	0.324
	lrMCI	**97.5 (2.8)**	**92.9 (5.6)**	**–4.70**	**0.026**	1,179 (337)	1,146 (309)	–2.80	0.580
Mathematical Processing test									
Experimental	hrMCI	94.0 (5.4)	93.0 (10.0)	–1.06	0.710	3,286 (920)	3,226 (609)	–1.83	0.768
	lrMCI	91.9 (10.3)	89.2 (9.8)	–2.93	0.110	3,089 (475)	3,186 (826)	+3.14	0.557
Control	hrMCI	93.3 (4.5)	82.4 (16.7)	–11.64	0.054	3,521 (1,356)	3,320 (1,377)	–5.71	0.125
	lrMCI	92.1 (8.1)	92.1 (9.6)	0.00	1.000	2,990 (726)	2,793 (686)	–6.59	0.343

*Notes: Only the values of the participants with pre-and post-intervention measurements were used for analysis. All uncorrected p values, Δ values were calculated by subtracting the post-intervention value from the pre-intervention value in percent. ANAM – Automated Neuropsychological Assessment Metrics; CON – control; EXP – experimental; hrMCI – high risk of mild cognitive impairment; lrMCI – low risk of mild cognitive impairment; p value * – $p < 0.05$.*

In contrast, response time data showed more nuanced insights. Exercise-induced changes in response time were negatively correlated with baseline performance for both the Memory Search task ($r = – 0.391$, $p = 0.048$) and the Mathematical Processing task ($r = –0.399$, $p = 0.044$), indicating greater improvements among participants with initially slower reaction times. In addition, a significant reduction in reaction time was observed in the Go/No-go task control lrMCI group (–6.83%, $p = 0.01$), indicating improved performance despite the absence of intervention. However, these correlations did not remain statistically significant after applying the False Discovery Rate (FDR) correction (threshold $p = 0.0125$), warranting cautious interpretation.

Further analysis of the Go/No-go task revealed a significant three-way interaction between Time (pre vs. post), Group (experimental vs. control), and MCI risk level (high vs. low), demonstrating that both group assignment and baseline cognitive status jointly influenced post-intervention response times ($F(1, 45) = 6.01$, $p = 0.018$, $\eta p^2 = 0.118$) (see Supplementary Table 4 in the Appendix).

4. DISCUSSION

This study contributes to the growing body of evidence that resistance training can be useful for preserving cognitive function in older adults (Cassilhas et al., 2007; Fiatarone Singh et al., 2014; Herold et al., 2019; Morishita et al., 2019; Cavalcante et al., 2020; Coelho-Júnior et al., 2020; Landrigan et al., 2020; Zhang et al., 2020; Vints et al., 2024a). Furthermore, this study emphasises the importance of methodological accuracy and the need to consider initial individual cognitive differences when planning, analysing, and interpreting the results of cognitive interventions.

The study is part of a larger project in which we were combining cognitive testing with advanced brain imaging (MRI and 1H-MRS) and blood-based biomarkers of inflammation (Vints et al., 2022; Gökçe et al., 2023; Sheoran et al., 2023; Vints et al., 2024a; Vints et al., 2024b; Kušleikienė et al., 2025). Within this broader framework, the present paper focuses specifically on the cognitive and methodological aspects of the intervention. In contrast to most previous studies that examined resistance training (RT) effects in older adults as a single group (Cassilhas et al., 2007; Fiatarone Singh et al., 2014; Coelho-Júnior et al., 2020; Santos et al., 2020), our trial stratified participants into high- and low risk MCI subgroups using MoCA scores. Our aim was to highlight how factors such as baseline risk stratification and physical activity influence the interpretation of training outcomes. By paying attention to these methodological details, we lay the groundwork for integrating behavioural results with the imaging and biomarker data collected in the larger study. This step is essential for building a more complete picture of how resistance training may influence brain and cognitive health in older adults.

Study results demonstrate that resistance training may differentially influence cognitive outcomes depending on baseline cognitive risk status. Improvements in MoCA scores were observed in hrMCI participants across both experimental and control groups. However, the magnitude of change did not differ significantly between groups, suggesting that the observed gains likely reflected a learning effect rather than a specific RT benefit. In contrast, participants in the lrMCI groups—who began the study with higher baseline MoCA scores—showed minimal non-significant improvements, consistent with a ceiling effect, approaching the maximum result of the test, making it difficult to objectively record further improvement (Liu & Wang, 2021).

One major factor associated with the so-called "ceiling" or "floor" effects in cognitive testing is educational attainment (Koshimoto et al., 2023). Recent studies show that the level of education and cognitive reserve, regardless of place of residence, gender, age, or duration of illness, are the main factors associated with the manifestation of these effects in most cognitive domains (Kim et al., 2023). People with higher education are more likely to experience the "ceiling effect", where the test becomes insufficiently sensitive to change due to a high initial level of functioning. Conversely, participants with lower levels of education may experience a "floor effect", where the test is too difficult and does not reveal their true abilities (Wang et al., 2008). In our cohort, higher educational attainment was more common among lrMCI participants, which likely contributed to their elevated baseline MoCA scores and limited room for improvement. Conversely, hrMCI participants, who had lower baseline scores, demonstrated larger numerical gains, but without clear evidence that these changes reflected intervention-specific effects. This emphasises the need to account for education and cognitive reserve when interpreting intervention outcomes.

These results are consistent with previous studies showing that the effectiveness of interventions is often greater among participants with lower initial

cognitive levels (Collie et al., 2003). It is also necessary to assess the learning effect, a phenomenon whereby repeated testing leads to improved results not because of a real improvement in cognitive abilities, but because of familiarity with the test structure. Studies show that MoCA or Mini-Mental State Examination (MMSE) tests performed several times can cause this effect (Falleti et al., 2006; Cooley et al., 2015). In our study, this is evident in the hrMCI control group, where MoCA scores increased by as much as 12.8% without any intervention. Similar conclusions were reported by Cooley and co-authors, who observed a significant improvement in MoCA scores between the first and second tests (after one year), but no significant differences in subsequent tests (12–48 months) (Cooley et al., 2015).

Finally, given the widely used MoCA cut-off score (≥26) for MCI screening (Dautzenberg et al., 2020), it is important to note that recent meta-analyses recommend using lower thresholds—23 or 24 points—to improve sensitivity and reduce the probability of false positives (Thomann et al., 2020; Islam et al., 2023). This is particularly important in the context of our study, as the baseline scores of the lrMCI group were close to the maximum score (30), which limited their potential to demonstrate the effectiveness of the intervention.

The ANAM4 neurocognitive battery provided additional insights into specific cognitive domains. While task accuracy showed no significant pre–post changes, reaction time outcomes revealed group- and risk-dependent differences. Notably, correlations indicated that participants with slower baseline reaction times benefited more from training in Memory and Mathematical Processing tasks. However, these associations did not survive FDR (False Discovery Rate) correction, underscoring the need for caution and suggesting that the findings should be considered exploratory. The absence of changes in accuracy may be partly because the task was relatively easy for the participants who performed well at baseline, leaving limited room for measurable improvement. In contrast, reaction time data provided more insights, particularly for ANAM4 sensitivity in this domain compared to traditional tests.

In the Go/No-go task, a significant interaction between time and MCI risk was detected. Experimental hrMCI participants showed a trend toward improvement, whereas the lrMCI control group demonstrated a significant reduction in reaction time despite not receiving the intervention. The discrepancy between experimental and control outcomes likely reflects non-specific influences, such as cognitive reserve and resilience or measurement variability. Importantly, IPAQ-SF assessments indicated that control participants tended to have higher baseline physical activity and showed shifts in activity patterns during the 12-week period, even though they were instructed not to alter their lifestyle. At the same time, resilience-related factors such as habitual activity, social engagement, or adaptive coping could have contributed to the improvements seen in the control group.

Taken together, these findings suggest that inhibitory control may be a domain sensitive to change in older adults at higher risk of MCI, but the effects observed in our study did not reach statistical significance after correction. Moreover, improvements in the control group highlight the influence of lifestyle factors and non-specific effects, which must be carefully considered when interpreting intervention outcomes. Thus, while our results do not provide conclusive evidence that resistance training improves inhibitory control, they point to this domain as a promising target for future investigations.

This interpretation is in line with previous meta-analytic evidence showing that individuals with MCI may derive greater cognitive benefit from exercise than either cognitively healthy older adults or those with dementia (Tsai et al., 2019; Hoffmann et al., 2021; Chantanachai et al., 2022; Xu et al., 2023). In our study, no consistent improvements were observed in tasks related to processing speed or working memory (Sweeney, 2001; Levin et al., 2017, 2021), which aligns with prior findings that resistance training may preferentially influence executive functions rather than working memory (Tian et al., 2023; Zeng et al., 2023).

Finally, it is important to acknowledge that social interaction inherent in group-based RT interventions may have contributed to the observed cognitive benefits, particularly among hrMCI participants. Prior research has demonstrated that participating in social leisure activities can help older adults maintain cognitive function (Zhu et al., 2022). Similarly, taking part in group activities has been linked to increased cognitive function by promoting an overall sense of well-being. Therefore, future studies should include control groups involved in social interaction to reduce potential confounding factors related to social experiences (Ziv et al., 2024).

In summary, this study suggests that RT may support inhibitory control in older adults at higher risk of MCI, whereas individuals with intact cognitive function at baseline showed minimal or no significant response. Interpretation of these findings

requires careful consideration of education, baseline cognitive status, learning effects, and potential confounders such as physical activity and social interaction. Addressing these factors will be essential in future research aimed at clarifying the role of RT in preserving cognitive function in ageing populations. However, the relatively small sample size and limited follow-up period constrain the generalisability of our findings. Future studies should include larger, more diverse cohorts, extend the duration of intervention, and integrate multimodal measures such as neuroimaging and biomarkers to provide deeper insights into the mechanisms underlying exercise-induced cognitive changes.

5. CONCLUSIONS

In conclusion, our findings suggest that baseline cognitive risk status plays an important role in shaping cognitive trajectories in older adults. While resistance training did not lead to robust, statistically corrected improvements in inhibitory control, trends indicated that participants at higher risk of MCI may have shown greater responsiveness than those at lower risk. At the same time, improvements observed in the control group highlight the potential influence of non-specific factors such as cognitive reserve, resilience, lifestyle changes, or baseline activity levels. These results emphasise the importance of considering cognitive status and methodological factors when evaluating the effects of resistance training on cognition, and they point to inhibitory control as a promising target for future investigations.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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APPENDIX. SUPPLEMENTARY TABLES

Supplementary Table 1. **Descriptive values of baseline and 12-week body composition, physical performance, and physical activity outcomes in experimental and control groups stratified by MCI risk**

		N	Baseline Mean (SD	12 weeks Mean (SD)	Δ (%)	p value (uncorrected)
BMI (kg/m²)						
Experimental	hrMCI	12	28.63 (4.29)	28.93 (3.87)	1.05	0.181
	lrMCI	14	28.79 (4.60)	29.02 (4.57)	0.80	0.137
Control	hrMCI	10	26.91 (3.11)	27.20 (3.09)	1.10	0.208
	lrMCI	12	27.14 (3.49)	27.43 (3.70)	1.08	0.047
Body fat %						
Experimental	hrMCI	11	30.25 (7.22)	30.70 (6.96)	1.51	0.375
	lrMCI	14	35.61 (6.07)	35.38 (6.72)	–0.66	0.598
Control	hrMCI	10	32.95 (9.03)	33.16 (8.19)	0.64	0.756
	lrMCI	12	29.91 (7.84)	30.11 (8.09)	0.67	0.622
Right handgrip strength (kg)						
Experimental	hrMCI	11	32.14 (8.27)	34.82 (9.12)	8.35	**0.008***
	lrMCI	15	31.67 (9.47)	31.85 (9.63)	0.59	0.797
Control	hrMCI	11	31.18 (12.65)	32.55 (12.93)	4.37	**0.049***
	lrMCI	12	33.79 (9.15)	34.06 (9.63)	0.80	0.696
IPAQ-SF kcal/week						
Experimental	hrMCI	13	3,260.65 (3,113)	3,034.69 (2,452)	–6.93	0.838
	lrMCI	15	3,460.33 (2,445)	3,701.80 (4,712)	6.98	0.866
Control	hrMCI	12	5,149.75 (4,270)	3,527.50 (3,475)	–31.50	0.183
	lrMCI	10	5,099.40 (3,991)	2,734.40 (2,684)	–46.38	**0.012***
IPAQ-SF PA level						
	N	Baseline Mean (SD)	12 weeks Mean (SD)	Sedentary N (%)	Moderate N (%)	High N (%)
Experimental						
hrMCI	13	1.08 (0.76)	1.23 (0.73)	3 (23.1%) → 2 (15.4%)	6 (46.2%) → 6 (46.2%)	4 (30.8%) → 5 (38.5%)
lrMCI	15	1.40 (0.63)	1.20 (0.68)	1 (6.7%) → 2 (13.3%)	7 (46.7%) → 8 (53.3%)	7 (46.7%) → 5 (33.3%)
Control						
hrMCI	13	1.62 (0.65)	1.46 (0.66)	1 (7.7%) → 1 (7.7%)	3 (23.1%) → 5 (38.5%)	9 (69.2%) → 7 (53.8%)
lrMCI	12	1.67 (0.49)	1.17 (0.58)	0 (0.0%) → 1 (8.3%)	4 (33.3%) → 8 (66.7%)	8 (66.7%) → 3 (25.0%)

*Notes: All uncorrected p values, Δ values were calculated by subtracting the post-intervention value from the pre-intervention value in percent. IPAQ-SF – International Physical Activity Questionnaire-Short Form; MCI – mild cognitive impairment; hrMCI – high risk of mild cognitive impairment; lrMCI – low risk of mild cognitive impairment; p value * – $p < 0.05$; PA – physical activity.*

Supplementary Table 2. **Descriptive values of baseline/12 weeks MoCA percentage change**

		N	Baseline	12 weeks	Δ (%)	p value (uncorrected)
Executive function						
Experimental	hrMCI	13	3.07 (0.917)	4.08 (0.954)	+32.9	0.018*
	lrMCI	15	4.59 (0.795)	4.60 (0.910)	+0.2	
Control	hrMCI	13	3.18 (1.402)	4.08 (1.038)	+28.3	0.014*
	lrMCI	12	4.35 (0.702)	4.50 (0.674)	+3.47	
Delayed memory						
Experimental	hrMCI	13	2.29 (0.994)	3.77 (1.166)	+64.6	0.018*
	lrMCI	15	4.41 (0.712)	4.67 (0.617)	+5.9	
Control	hrMCI	13	2.14 (1.552)	3.23 (1.641)	+50.9	0.006*
	lrMCI	12	4.06 (0.899)	4.42 (0.793)	+8.9	
Total points						
Experimental	hrMCI	13	23.29 (1.773)	26.15 (2.853)	+12.3	0.005*
	lrMCI	15	27.53 (1.328)	28.27 (1.624)	+2.7	
Control	hrMCI	13	22.55 (1.870)	24.69 (3.011)	+9.5	0.004*
	lrMCI	12	27.71 (1.448)	27.92 (2.503)	+0.7	

Notes: Only the values of the participants with measurements at baseline and after 12 weeks (number of participants, N) were used for analysis. CON – control; EXP – experimental; hrMCI – high risk of mild cognitive impairment; lrMCI – low risk of mild cognitive impairment.

Supplementary Table 3. **Results of the three-way Time × Group × MCI risk ANOVAs for MoCA scores**

	df	F	p	ηp^2
MoCA test				
Time	1, 49	30.690	**<0.001***	0.385
Time × Group	1, 49	0.122	0.728	0.002
Time × MCI risk	1, 49	14.818	**<0.001***	0.232
Time × Group × MCI risk	1, 49	0.232	0.632	0.005
Group	1, 49	2.456	0.124	0.048
MCI risk	1, 49	54.493	**<0.001***	0.527
Group × MCI risk	1, 45	0.673	0.416	0.015

Notes: df – degrees of freedom; F – F-statistic from ANOVA; p – p value (statistical significance); ηp^2 – Partial Eta Squared (effect size). MoCA – Montreal Cognitive Assessment; MCI – mild cognitive impairment.

Supplementary Table 4. **Results of the three-way Time × Group × MCI risk ANOVAs for mean response time on the ANAM4 cognitive tests**

	df	F	p	ηp^2
Two-Choice Reaction Time test				
Time	1, 46	0.068	0.796	0.001
Time × Group	1, 46	0.065	0.800	0.001
Time × MCI risk	1, 46	0.428	0.516	0.009
Time × Group × MCI risk	1, 46	2.407	0.128	0.050
Group	1, 46	2.039	0.160	0.042
MCI risk	1, 46	0.486	0.489	0.010
Group × MCI risk	1, 46	0.097	0.757	0.002
Go/No-go test				
Time	1, 45	3.345	0.074	0.069
Time × Group	1, 45	0.042	0.838	<0.001
Time × MCI risk	1, 45	1.295	0.261	0.028
Time × Group × MCI risk	**1, 45**	**6.010**	**0.018***	**0.118**
Group	1, 45	0.002	0.967	<0.001
MCI risk	1, 45	1.224	0.274	0.026
Group × MCI risk	1, 45	0.480	0.492	0.011
Memory Search test				
Time	1, 45	0.509	0.479	0.011
Time × Group	1, 45	0.041	0.841	<0.001
Time × MCI risk	1, 45	0.024	0.878	<0.001
Time × Group × MCI risk	1, 45	2.325	0.134	0.049
Group	1, 45	3.693	0.061	0.076
MCI risk	1, 45	<0.001	0.992	<0.001
Group × MCI risk	1, 45	0.277	0.601	0.006
Mathematical Processing test				
Time	1, 45	1.090	0.302	0.024
Time × Group	1, 45	1.575	0.216	0.034
Time × MCI risk	1, 45	0.216	0.645	0.005
Time × Group × MCI risk	1, 45	0.196	0.660	0.004
Group	1, 45	0.026	0.871	<0.001
MCI risk	1, 45	1.685	0.201	0.036
Group × MCI risk	1, 45	0.673	0.416	0.015

Notes: df – degrees of freedom; F – F-statistic from ANOVA; p – p value (statistical significance); ηp^2 – Partial Eta Squared (effect size). MCI – mild cognitive impairment.