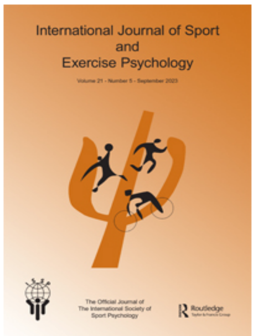

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The effects of a single bout of high-intense strength exercise on cognitive function and postural dual-task control in older adults

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ABSTRACT
In this study we aimed to test if acute strength exercise would induce cognitive improvements. Secondarily, we examined the relationship between exercise-induced changes in cognitive function and postural dual-task control. Thirty-seven cognitively intact, non-faller older adults (≥60 years) were nonrandomly allocated to strength exercise or control. Strength exercise consisted of Smith machine squats (one session, 3 × 3reps at 90%, 95%, and 100% one-repetition maximum). Control participants held seated rest for 45 min. Cognitive functions, recognition (memory search), working memory (mathematical processing), processing speed (2-choice reaction time), and postural dual-task control were tested before and immediately after exercise or control using the Automated Neuropsychological Assessment Metrics-4 (ANAM4) battery and a mathematical counting task while maintaining a tandem Romberg stance with eyes open on a force plate. Outcome measures were response time and performance index (100 × [accuracy/response time]) on the ANAM4 tests and sway activity and entropy during the postural dual-task. We found a non-significant improvement with moderate effect size in performance index on the mathematical processing task of experimental participants compared to control participants ($p = 0.145$, $\eta_p^2 = 0.060$). Improvements in the mathematical processing task over time in the control group were associated with increased sway activity during the postural dual-task. No significant associations were found between changes in cognitive function and changes in postural control in the experimental group. Ultimately, our results

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may direct researchers and healthcare professionals in designing the optimal exercise treatment to improve cognitive function and postural control in older adults.

Abbreviations: ANAM4: Automated Neuropsychological Assessment Metrics-4; BMI: body mass index; BDNF: brain-derived neurotrophic factor; IGF-1: insulin-like growth factor-1; IL-6: interleukin-6; IPAQ: International Physical Activity Questionnaire; MMSE: Mini-Mental State Examination; PI: performance index; RT: response time; 1RM: one-repetition maximum

Introduction

Healthy aging is defined in the World Report on Ageing And Health by the World Health Organization as "the process of developing and maintaining the functional ability that enables wellbeing in older age" (World Health Organization, 2015, p. 28). Maintaining functional ability in older age is a challenge, as cognitive and motor functions including postural control start to decline already from the age of 20 (Degani et al., 2017; Fjell & Walhovd, 2010; McPhee et al., 2016; Seidler et al., 2010). As individuals age beyond a certain point, they experience significant grey matter volume reductions, interruption of white matter microstructural organisation, and age-related decline in functional network segregation and integration leading to cognitive and motor deficits (e.g., Di et al., 2014; King et al., 2018; Seidler et al., 2010). With the cohort of older adults being the fastest-growing subpopulation in current society (Dall et al., 2013), there is an increasing interest in non-pharmacological, low-risk interventions to prevent motor and cognitive declines and improve functional independence and mobility in aging (Netz, 2017), especially as cognitive dysfunction and falls are currently the two most rapidly increasing causes of death in older adults (Mattiuzzi & Lippi, 2020).

Physical exercise is considered a promising candidate to function as a treatment strategy for mitigating age-related cognitive and motor decline (Hunter et al., 2016; Kirk-Sanchez & McGough, 2013). For example, extensive evidence supports the cognitive benefits of moderate to high-intensity cardiovascular or resistance exercise programmes among older adults (Erickson et al., 2011; C. L. Landrigan et al., 2019; Mandolesi et al., 2018; Tsai et al., 2015; C.-L. Northey et al., 2018; Tsai et al., 2019). Improved cognition through chronic cardiovascular exercise has been related to the up-regulation of brain-derived neurotrophic factor (BDNF) (C.-L. Tsai et al., 2019). However, the beneficial effect of chronic cardiovascular exercise on the brain may depend less on the upregulation of neurotrophic factors and to a greater extent to improvements in cardiovascular function or changes in energy metabolism, such as increased delivery of nutrients and oxygen (S. Kim et al., 2019).

The abovementioned benefits of cardiovascular exercise may differ from those related to resistance exercise. However, there is a limited body of work exploring the impact of resistance exercise on cognitive function and exercise-induced neuroplasticity (Huang et al., 2022; Vints et al., 2022). This gap in the current literature could be critical as Huang et al. (2022) reported that chronic resistance exercise has a greater potential than cardiovascular exercise in effectively slowing cognitive decline in older adults with cognitive impairment. According to Huang et al. (2022), chronic resistance training is likely to have more pronounced effects on cognition than cardiovascular exercise through a larger activation of multiple signalling pathways activated by both cytokines and growth factors released from muscle tissue. The enhanced cognitive function resulting from chronic resistance exercise could be mediated through the elevation of brain/circulating levels of insulin-like growth factor-1 (IGF-1) and irisin, which are essential for neurogenesis and synaptogenesis, as well as through the down-regulation of circulating levels of inflammatory cytokines (e.g., interleukin 6 and interleukin 1β) who may inhibit neuroplastic processes (Gruol, 2015; H. J. Kim et al., 2015; Nielsen & Pedersen, 2007; C.-L. Tsai et al., 2019; for reviews see: Gajewski & Falkenstein, 2016 and Vints et al., 2022).

To further elucidate the exercise-effect mechanism, researchers have investigated the effect of acute (i.e., a single bout of) exercise on cognitive function. It was discovered that even a single bout of physical exercise may transiently enhance cognitive and motor functioning (Y.K. Chang et al., 2012a; Hsieh et al., 2016a; Ludyga et al., 2016; McSween et al., 2019; Netz et al., 2016; Netz et al., 2023; Park et al., 2021; Thomas et al., 2016; Wanner et al., 2020). Again, there are fewer studies examining the acute effects of resistance exercise compared with studies examining the acute effects of cardiovascular exercise (Vints et al., 2022). Therefore, we could not make a firm prediction on differences between cardiovascular and resistance exercise effects nor on mechanisms which may underlie the exercise-induced improvement in cognition following a single bout of resistance exercise. In addition, the optimal design of a resistance exercise protocol for maximising cognitive benefits in older adults remains unclear (Huang et al., 2022; Vints et al., 2022).

Strength training, a specific type of resistance training typically consisting of lifting relatively heavy weights for a low number of repetitions (Schoenfeld et al., 2021), could act as a promising treatment strategy against cognitive and motor decline at older age. Both acute and chronic strength training can improve muscle strength, balance, and mobility (Cassilhas et al., 2007; Hess & Woollacott, 2005; van het Reve & De Bruin, 2014), cognitive functioning (e.g., Y.-K. Chang et al., 2012b; Hsieh et al., 2016a; T. Liu-Ambrose et al., 2012; Mavros et al., 2017), and postural control (after a single bout; Drozdova-Statkevičienė et al., 2021). Furthermore, acute strength training can transiently improve cognition across multiple domains including attention, working memory, executive control and balance control (Y.-K. Chang et al., 2014; Drozdova-Statkevičienė et al., 2021; Dunsky et al., 2017; Hsieh et al., 2016a; Hsieh et al., 2016b). This is of particular interest, as cognitive decline was reported to be associated with fall risk in older adults (T. Y. Liu-Ambrose et al., 2008; Muir et al., 2012). Moreover, falls and dementias were respectively the first (+212.1%) and second (+149.6%) fastest increasing cause of death between 2000 and 2016 in older adults, and displayed respectively the third (+59.9%) and first (+108.8%) largest increment as a cause of disability at older age (Mattiuzzi & Lippi, 2020). Notably, falls and dementias were the only two causes of death to show an increment of more than 100% in 16 years' time (Mattiuzzi & Lippi, 2020).

The similarity of the trends in falling and cognitive decline may be explained by the finding that older adults require a higher level of attention to conserve gait/stance stability, as vestibular and proprioceptive sensitivity decreases with age. Consequently, postural control necessitates increased attentional input (Rogers et al., 2013; Woollacott & Shumway-Cook, 2002). Indeed, an increased risk of falling can already be noticed in older adults with only subtle cognitive impairment (T. Y. Liu-Ambrose et al., 2008; Muir et al., 2012). Particularly in more demanding circumstances, such as activities that require both motor and cognitive activity (i.e., dual-tasks), the performance of older adults on either of the postural or cognitive task or on both may be lower compared to younger adults (Rogers et al., 2013; Woollacott & Shumway-Cook, 2002). Therefore, dual-tasks are considered a sensitive tool for identifying cognitive and balance impairments in older adults (Bayot et al., 2018; Muir-Hunter & Wittwer, 2016). Given the possible facilitatory effects of strength exercise on attentional control and balance (Dunsky et al., 2017; Drozdova-Statkeviciene et al., 2021) and given the importance of these abilities in older age, the present study had two purposes: (1) to study the effect of a single bout of strength exercise with high relative loads and long rest periods on cognitive function in older adults, and (2) to examine whether changes in postural control performance from before to after a single bout of strength exercise with high relative loads and long rest periods would be associated with cognitive function.

In line with the abovementioned goals, our primary objective is to determine the specific cognitive areas impacted by the intervention and whether enhanced performance in these areas leads to overall improvements in maintaining balance. Based on existing research indicating that acute exercise can result in improvements in processing speed, attention, working memory, and basic cognitive abilities (e.g., Y.-K. Chang et al., 2014; Dunsky et al., 2017; Hsieh et al., 2016a; Hsieh et al., 2016b), and considering that immediate strength training positively influences attentional focus on the task of maintaining balance (Drozdova-Statkevičienė et al., 2021), we hypothesise the following: (1) our strength exercise protocol would induce improvements in cognitive function, as was previously reported with different resistance exercise protocols (Y.-K. Chang et al., 2014; Dunsky et al., 2017). Here, we expected that improvement in cognition following acute strength training would not be limited to a specific single cognitive domain, but this improvement would be seen across multiple aspects of cognition as well as in attentional control of balance; and (2) improvements in these cognitive domains will be related to improvement in balance control during dual-task.

Material and methods

Participants and setting

Thirty-seven (19 experimental and 18 control) healthy males above the age of 60 years were recruited in Kaunas, Lithuania. Based on a power analysis using G*Power 3.1.9.7 to calculate the sample size needed to find an interaction in a repeated measures ANOVA implemented on outcome measures obtained from cognitive (section 2.4.2) and postural dual-task (section 2.4.3) assessment tests in this study with a moderate effect size (Cohen's $f = 0.25$), an alpha of 0.05, and a power of 0.80, we needed at least 34 participants in total. Recruitment was done via presentations in local community organisations and via personal contacts with the experimenters (co-authors D-S.M., V.J.C. and N.M.). The same cohort was included in the study of Drozdova-Statkevičienė et al. (2021). Participants were interviewed prior to their inclusion by a public health specialist (co-author V.J.C.) and were introduced to the intervention by a certified trainer and exercise physiology expert (co-author N.M.). All participants and the experimenters who communicated with participants during the test/training sessions (co-authors D-S.M., V.J.C. and N.M.) were Lithuanian native speakers. All participants were free of chronic pain, diabetes mellitus and physical or neurological disorders. Participants were screened for cognitive impairment with the validated Lithuanian version of the Mini-Mental State Examination (MMSE) test by co-author V.J.C., excluding participants scoring below 24/30 (Pangman et al., 2000). We excluded participants with alcohol or drug abuse, psychopharmacological drug use, and those participating in a resistance training programme in the last six months.

A randomisation process was implemented at first to allocate subjects to one of the two groups (i.e., exercise and passive controls). Specifically, we intended to allocate participants eligible for inclusion to experimental or control group in a random order based on day of birth (odd days – control group; even days – experimental group) and participant entry to the research (the latter was used to compensate for unequal sample size). However, when we explained the nature of the strength exercise protocol to the participants allocated to the experimental group, some of the recruited participants were less keen to undergo the high-intense strength exercise intervention. Given the difficulty to find older adults willing to participate in our experimental group, about the last half of the recruited participants were allowed to be reallocated to the opposite group when they refused to start in the experimental group. Note that reallocation of participants to the opposite group was applied only on participants that did not agree to join the experimental (training group) whereas individuals that were allocated to the experimental group were selected randomly from the overall pool of subjects. Participants in both groups could voluntarily withdraw from the study at any time. The study was approved by the Kaunas Regional Biomedical Research Ethical Committee (No. BE-2-46) and a written informed consent was obtained from all participants prior to their inclusion in the study.

Procedure

An overview of the study design has already been presented in (Drozdova-Statkevičienė et al., 2021) and is illustrated in Figure 1. Participants were invited to visit the Lithuanian Sports University, Institute of Sport Science and Innovation in Kaunas on two separate days, with 2–3 days between visits. Testing took place between 9 and 11 am. On the first day, after recording demographic and clinical characteristics, participants in the

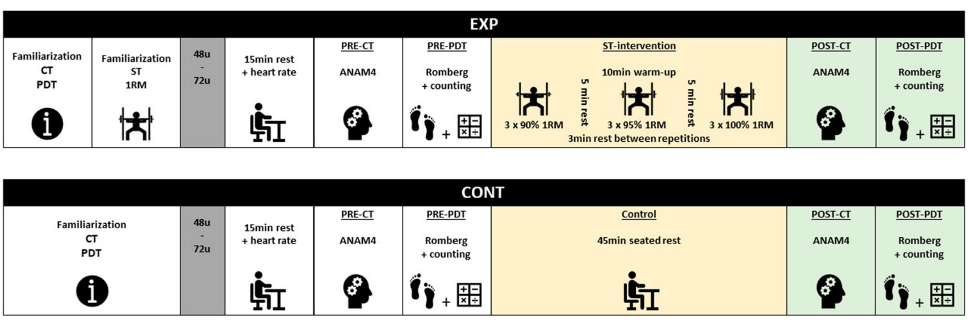

Figure 1. Study design overview. Abbreviations: 1RM, one-repetition maximum test; ANAM4, Automated Neuropsychological Assessment Metrics 4; CONT, control group; CT, cognitive task; EXP, experimental group; PDT, postural dual task; ST, strength training.

experimental group underwent one-repetition maximum (1RM) testing. On the second visit, testing took place in the following order: 15 min rest with heart rate monitoring using a pulse metre (Sigma Sport PC 15.11) in a sitting position, cognitive testing, postural dual-task testing, strength exercise (see section 2.3.1), 5 min rest, cognitive testing and (about 15–20 min after exercise) postural dual-task testing. Cognitive testing consisted of three tasks that were selected from the Automated Neuropsychological Assessment Metrics-4 (ANAM4) battery (see section 2.4.2). Postural dual-task testing consisted each time of three trials where participants were requested to maintain a tandem Romberg stance while performing a mathematical counting task (see section 2.4.3) and was described in more detail in Drozdova-Statkevičienė et al. (2021)

Control participants underwent the same familiarisation procedure on the first visit but were not required to undergo 1RM testing. On the second visit, testing was performed in the same order as in the experimental group, but strength exercise was replaced by 45 min seated rest (see section 2.3.2). During both visits, the whole procedure was led by the same researcher (co-author D-S.M.), who was not blinded for the group allocation.

Interventions

Experimental condition: acute strength exercise intervention

Participants in the experimental group underwent a single session of strength exercise consisting of barbell squats on a Smith machine (Drozdova-Statkevičienė et al., 2021). The strength exercise session was preceded by a 10 min warm-up on a cycle ergometer (Monark 834E) at a power output of 60–80 W and a cadence of 50–60 rpm. Next, participants performed three sets of three repetitions of barbell squats with increasing intensity, i.e., 90%, 95%, and 100% of 1RM. Specifically, participants completed nine repetitions in total: three repetitions with 90% 1RM loading, three repetitions with 95% 1RM loading, and three repetitions with 100% 1RM loading. A 3-minute rest was given between repetitions at each loading condition, and 5-minute rest was given at the end of every 3rd repetition loading while weight was increased by the trainer. Participants were instructed to reach a squat depth with a knee angle of approximately 90°. During the squats, verbal encouragement was provided by the trainer. All participants were able to complete the whole protocol. The total duration of the intervention was 30 min. During the whole duration of the intervention, heart rate was monitored for safety reasons. 1RM testing was done 2–3 days before the intervention. A standard 1RM testing protocol was used as outlined by the National Strength and Conditioning Association (Baechle & Earle, 2000; Macht et al., 2016). Starting weight was decided individually so that the 1RM could be achieved in as few attempts as possible. In each trial, weight was gradually increased by 10–20% until the participant was no longer able to lift it three times while maintaining a squat dept so that the knees of the participant were at about a 90° angle at the lowest point. This was visually checked by the trainer. Participants were verbally encouraged during each repetition. Rest periods between sets during the 1RM testing protocol were approximately 3 min. The predicted 1RM was calculated using an online 1RM calculator https://exrx.net/Calculators/OneRepMax (*ExRx.Net : Predicting One-Rep Max*, n.d.).

Control condition: 45 min seated rest

Participants in the control condition were instructed to remain seated in the waiting room for 45 min and were allowed to read magazines or to interact with the researchers.

Assessments

Demographic and exercise-related characteristics

All participants were asked to report their age, smoking status, and medical history. Participants also completed the International Physical Activity Questionnaire (IPAQ) Short Form, which was used to assess participants' physical activity levels (Sjostrom et al., 2005). We also calculated the participants' body mass index (BMI).

Cognitive tasks

To assess cognitive performance, we used a reliable computerised test, namely the ANAM4 battery (Vista Life Sciences, USA) (Vincent et al., 2017). The ANAM4 is a library containing 28 cognitive tests and behavioural questionnaires, which can be configured for various clinical or experimental applications. A selection of tests from this library was used, including (a) the 2-choice reaction time test, (b) the memory search task, and (c) the mathematical processing task, in this order (Center for the Study of Human Operator Performance, 2007). The three tasks included in our study were selected based on previous evidence showing they are valid for assessing executive functions and global cognition in aging but also for age-unrelated neurological conditions (e.g., Tayer-Shifman et al., 2020; Vincent et al., 2012). Specifically, these tasks incorporate several cognitive processes, including visual working memory, attention, and executive control, which are key cognitive domains that can be alleviated by exercise (Engeroff et al., 2018; Herold et al., 2019). All participants were familiarised with the three cognitive tasks during their first visit to the lab, 48–72 h before the testing day. On the testing day, participants performed the tasks before and about 5 min after the strength exercise intervention (experimental group) or after 45 min of rest (control group); see Figure 1. It took the participants approximately 10–12 min to complete these three tests. They were instructed that speed and accuracy were equally important. For all three cognitive tasks, we assessed accuracy (% correct answers), response time (RT in ms), and performance index (PI, in arbitrary units). The PI (computed as $PI = 100 \times$ [accuracy/response time]) is an outcome parameter used to compensate for the fact that some participants may be faster despite lower accuracy, while others may be more accurate despite slower speeds, e.g., (Netz et al., 2016). Accuracy measures were used to exclude trials with more than 50% incorrect responses, as this may indicate that the participant did not understand the task. For all trials, response accuracy was never below 50%.

(a) The *memory search task* is used as an index of verbal working memory, immediate recognition, and attention. For this task, six characters (the positive memory set) are displayed for memorisation. Next, individual characteristics are presented, and the participant needs to press designated buttons to indicate whether or not the character is a member of the memorised set.
(b) The *mathematical processing task* examines basic computing skills, concentration, and working memory. During this task, an arithmetic problem involving three

single-digit numbers and two operators is displayed on a computer screen (e.g., "5 − 2 + 3 = "). The participant needs to press the left or right mouse button, left button if the answer to the problem is less than five, and right button if the answer is higher than five.

(c) The *2-choice reaction time test* examines processing speed and alternating attention with a motor speed component. It is a psychomotor reaction time task where the participant is presented with a "*" or "o" on the computer display. The participant needs to press the left or right mouse button depending on which stimulus appears.

Postural dual-task

The protocol for postural dual-task testing consisted of maintaining a tandem Romberg stance position on a single piezoelectric force plate (KISTLER, Slimline System 9286) with their eyes open, while performing a mathematical counting task, as has been presented before (Drozdova-Statkevičienė et al., 2021). On the testing day, all participants performed the postural dual-task after the ANAM4 tests before and about 15–20 min after the intervention or a 45 min rest period. In contrast to the results presented in this previous study, we reported the total component of sway activity and entropy instead of presenting the anteroposterior and mediolateral components separately. The total vectors were calculated from the anteroposterior and mediolateral ground reaction forces, using a custom-written MATLAB script (MathWorks, Natick, MA) (Drozdova-Statkevičienė et al., 2018). High sway activity reflects poor postural control. Sway entropy is a measure of statical sway regularity. Higher sway entropy indicates more irregular sway activity, which is linked with automatic postural control and decreased deployment of attention to the postural task. In contrast, lower sway entropy indicates more regular sway activity which is hypothesised to be associated with the deployment of more attention to the postural task (Donker et al., 2007).

Statistical analysis

Statistical analysis was performed using SPSS Statistics version 27 (IBM, USA). None of the data contained extreme outliers, defined as a value lying further than three times the interquartile range away from the median. All data were normally distributed, as was decided based on visual interpretation of histograms and measurements of skewness and kurtosis (normality assumed when values were between −2 and +2) (George & Mallery, 2010).

To test our primary research question, we used a two-way repeated measures ANOVA (Group*Time) with repeated measures on the Time factor. Additionally, as part of an exploratory analysis, we used two-way ANCOVA with pre-test results and age as covariates and with post-test cognitive and postural task results as the dependent variables because it has been suggested to provide higher statistical power and accuracy when assessing groups changed from pre-test to post-test (Rausch et al., 2003). In case the ANOVA or the ANCOVA results were of moderate to high effect size (partial eta squared, $\eta_p^2 > 0.06$), they were further explored using paired samples t-tests to report the change over time in experimental or control groups separately (Cohen, 1988; Netz et al., 2023). To test our secondary research question, we used multiple linear regression analysis adjusted for age to search for an association between the pre-to-post difference on RT or PI on each one of the ANAM4 cognitive tests and pre-to-post difference in sway activity or entropy during the postural dual-task.

Results

Participants' characteristics

Participants' age ranged between 60 and 77 years old, BMI ranged between 21.0 and 29.0, and the MMSE scores ranged between 27 and 30. Mean values and differences between groups are presented in Supplementary table A1. Three of the included participants were smokers (8.1%), and physical activity level of all participants was moderate based on the IPAQ short form questionnaire. In the experimental group, the mean increase in heart rate during exercise compared to before exercise was +59.2%. No significant group differences in age, BMI and MMSE scores were found (all $p \geq 0.455$; see Supplementary Table A1), suggesting that the two groups were demographically balanced.

The effect of acute strength exercise on ANAM4 cognitive performance and postural MPcontrol

Mean values of our outcome measures at baseline and pre-to-post change (in % changes from baseline) within control ($n = 18$) and experimental ($n = 19$) subjects are illustrated in Figure 2. There were no significant Time*Group interaction effects for any of the cognitive tests or postural control tasks (see Table 1). This indicates that strength training did not significantly influence the change in performance. However, the Time*Group interaction

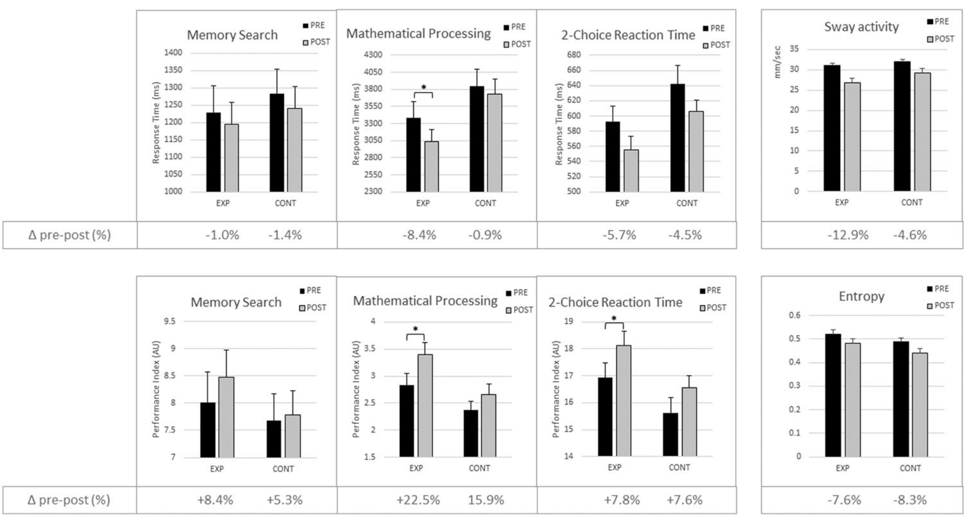

Figure 2. ANAM4 and postural dual task test results. Mean and standard error values of pre- and post-test cognitive test and postural dual task results in experimental and control group. The first row illustrates response time values, the second row illustrates performance index values. The right column illustrates the postural results. * $p < 0.05$ Abbreviations: AU, arbitrary units; CONT, control; EXP, experimental.

Table 1. Repeated measures ANOVA test results.

		p-value	Partial Eta Squared
RT Memory Search	Time	0.292	0.032
	Group	0.586	0.009
	Time*Group	0.910	0.000
RT Mathematical Processing	Time	0.056	0.101
	Group	0.061	0.097
	Time*Group	0.313	0.029
RT 2 choice RT test	Time	0.003*	0.228
	Group	0.055	0.101
	Time*Group	0.987	0.000
PI Memory Search	Time	0.285	0.033
	Group	0.441	0.017
	Time*Group	0.488	0.014
PI Mathematical Processing	Time	0.00006*	0.374
	Group	0.031*	0.126
	Time*Group	0.145	0.060
PI 2 choice RT test	Time	0.003*	0.230
	Group	0.040*	0.115
	Time*Group	0.704	0.004
Postural sway DT	Time	0.005*	0.201
	Group	0.583	0.009
	Time*Group	0.576	0.009
Entropy DT	Time	0.0003*	0.312
	Group	0.065	0.094
	Time*Group	0.778	0.002

* $p < 0.05$ Abbreviations: DT, dual task; PI, performance index; RT, response time.

effect for PI on the mathematical processing test had a moderate effect size ($p = 0.145$, $\eta_p^2 = 0.060$). Further exploration with paired t-tests showed that the experimental group and not the control group improved significantly over time ($p < 0.001$), see Figure 2 and Supplementary Table A2.

Exploratory analysis

Exploratory analysis on the effect of acute strength exercise on ANAM4 cognitive performance and postural control using ANCOVA

ANCOVA results showed that RT on the mathematical processing post-test was significantly faster in the experimental group compared to the control group after adjusting for the pre-test results and for age ($p = 0.042$, $\eta_p^2 = 0.119$). None of the other ANCOVA results for RTs or PIs of the ANAM4 cognitive tests were significantly different between groups. After adjusting for pre-test and age, both post-test postural sway activity and entropy during the postural dual-task did not differ between the experimental and control group, see Table 2.

Exploratory analysis of results with moderate to strong effect sizes

Non-significant results with at least moderate effect sizes ($\eta_p^2 > 0.06$) were found for PI on the mathematical processing task ($p = 0.091$, $\eta_p^2 = 0.084$), and PI on the 2-choice reaction time test ($p = 0.143$, $\eta_p^2 = 0.064$). In each case, it was the experimental group that improved significantly over time, $p < 0.001$ and $p = 0.010$ for mathematical processing PI and 2-choice reaction time PI, respectively, see Figure 2 and Supplementary Table A2.

Table 2. ANCOVA test results adjusted for pre-test values and age.

	Group	Mean (SE)	*p*-value	Partial Eta Squared
RT Memory Search	Control	1223.06 (45.64)	0.851	0.001
	Experimental	1210.95 (44.42)		
RT Mathematical Processing	Control	3584.71 (140.30)	0.042*	0.119
	Experimental	3166.76 (136.47)		
RT 2 choice RT test	Control	592.35 (13.20)	0.203	0.049
	Experimental	568.02 (12.83)		
PI Memory Search	Control	7.89 (0.33)	0.306	0.032
	Experimental	8.38 (0.32)		
PI Mathematical Processing	Control	2.88 (0.13)	0.091	0.084
	Experimental	3.20 (0.13)		
PI 2 choice RT test	Control	16.92 (0.41)	0.143	0.064
	Experimental	17.80 (0.40)		
Postural sway DT	Control	28.79 (1.64)	0.493	0.014
	Experimental	27.20 (1.60)		
Entropy DT	Control	0.45 (0.01)	0.238	0.042
	Experimental	0.47 (0.01)		

* $p < 0.05$ Note that the mean (standard error) values presented here are those used for ANCOVA testing. They are evaluated at the mean age (67.9) and mean pre-test results. The mean values before adjusting for age and pre-test results are illustrated in Figure 2. Abbreviations: DT, dual task; PI, performance index; RT, response time; SE, standard error.

The relationship between ANAM4 cognitive test results and postural dual-task control

Multiple linear regression analysis with age and pre-to-post difference in RT on the mathematical processing task for the dependent pre-to-post difference in sway activity showed that a decrease in mathematical processing RT from pre to post was associated with an increase in sway activity on the postural dual-task in the control group ($\beta = -0.556$, $p = 0.020$). This model, including age and pre-to-post differences in RT on the mathematical processing task, had a statistically insignificant ($p = 0.059$) R^2 of 0.314. Multiple linear regression analysis with age and pre-to-post difference in PI on the mathematical processing task for the dependent pre-to-post difference in sway activity showed that an increase in mathematical processing PI from pre-to-post was associated with an increase in sway activity on the postural dual-task in the control group ($\beta = 0.675$, $p = 0.001$). This model, including age and pre-to-post difference in RT on the mathematical processing task, had a statistically significant ($p = 0.004$) R^2 of 0.515. No significant relationships were found for the other ANAM4 cognitive tests nor for changes in the experimental group, see Table 3.

Discussion

We hypothesised that a single bout of high-intensity strength exercise would induce beneficial effects on cognition in older adults and that this cognitive performance improvement would be associated with improved postural control during a dual-task. Cognitive performance was examined for recognition (memory search), working memory (mathematical processing), processing speed (2-choice reaction time), and attention (all three tests). To our knowledge, this is the first study to investigate the effects of high-intensity strength exercise on cognitive function versus attentional control of balance in challenging dual-task conditions in older adults. Our data partially support the first hypothesis. Specifically, we found pre-to-post improvement in performance on the mathematical

Table 3. Multiple linear regression results with independents age and pre-to-post change on one of the ANAM4 cognitive performance outcome measures, with dependents pre-to-post change in sway activity or entropy for control and experimental groups separately.

	PRE-TO-POST DIFFERENCE			
	Sway activity			
	Control		Experimental	
	Model summary including age	Coefficient Δ adjusted for age	Model summary including age	Coefficient Δ adjusted for age
RT Memory Search	$R^2 = 0.069$	$\beta = 0.257$	$R^2 = 0.148$	$\beta = -0.328$
	$p = 0.587$	$p = 0.319$	$p = 0.277$	$p = 0.195$
RT Mathematical Processing	$R^2 = 0.314$	$\beta = -0.556$	$R^2 = 0.115$	$\beta = 0.242$
	$p = 0.059$	$p = 0.020$*	$p = 0.378$	$p = 0.299$
RT 2-Choice Reaction Time	$R^2 = 0.130$	$\beta = 0.352$	$R^2 = 0.086$	$\beta = 0.192$
	$p = 0.353$	$p = 0.160$	$p = 0.489$	$p = 0.447$
PI Memory Search	$R^2 = 0.060$	$\beta = -0.239$	$R^2 = 0.057$	$\beta = 0.084$
	$p = 0.630$	$p = 0.356$	$p = 0.623$	$p = 0.744$
PI Mathematical Processing	$R^2 = 0.515$	$\beta = 0.672$	$R^2 = 0.124$	$\beta = -0.283$
	$p = 0.004$*	$p = 0.001$*	$p = 0.346$	$p = 0.264$
PI 2-Choice Reaction Time	$R^2 = 0.132$	$\beta = -0.351$	$R^2 = 0.066$	$\beta = -0.124$
	$p = 0.345$	$p = 0.155$	$p = 0.581$	$p = 0.623$
	Entropy			
	Control		Experimental	
	Model summary including age	Coefficient Δ adjusted for age	Model summary including age	Coefficient Δ adjusted for age
RT Memory Search	$R^2 = 0.165$	$\beta = 0.345$	$R^2 = 0.122$	$\beta = -0.093$
	$p = 0.259$	$p = 0.189$	$p = 0.354$	$p = 0.730$
RT Mathematical Processing	$R^2 = 0.068$	$\beta = 0.099$	$R^2 = 0.134$	$\beta = 0.140$
	$p = 0.590$	$p = 0.713$	$p = 0.318$	$p = 0.566$
RT 2-Choice Reaction Time	$R^2 = 0.061$	$\beta = -0.048$	$R^2 = 0.188$	$\beta = 0.299$
	$p = 0.622$	$p = 0.857$	$p = 0.189$	$p = 0.247$
PI Memory Search	$R^2 = 0.115$	$\beta = -0.250$	$R^2 = 0.115$	$\beta = 0.020$
	$p = 0.401$	$p = 0.347$	$p = 0.375$	$p = 0.939$
PI Mathematical Processing	$R^2 = 0.065$	$\beta = 0.073$	$R^2 = 0.122$	$\beta = -0.093$
	$p = 0.606$	$p = 0.772$	$p = 0.353$	$p = 0.727$
PI 2-Choice Reaction Time	$R^2 = 0.064$	$\beta = -0.075$	$R^2 = 0.144$	$\beta = -0.186$
	$p = 0.607$	$p = 0.775$	$p = 0.290$	$p = 0.476$

Pre-to-post difference (Δ) was calculated by subtracting the values from second testing from those of the first testing. The model summary with independents age and one of the ANAM4 cognitive test outcome measures and with dependents one of the postural dual task outcomes are presented. In addition, the table includes the relationship (β and p-value) between each one of the ANAM4 cognitive test outcome measures and sway activity or entropy on the postural dual task adjustedg for age.

* $p < 0.05$. Abbreviations: DT, dual task; PI, performance index; RT, response time.

processing task and reduction in sway activity and sway entropy. However, our data did not support the second hypothesis. We observed that pre-to-post improvements in these cognitive domains were not associated with improvements in balance control.

The abovementioned observations suggest that exercise-related pre-to-post gains in attentional (conscious) control of balance (as expressed by decreased entropy) and working memory may be mediated by separate neuronal substrates. However, in the control group, the multiple linear regression analysis revealed significant associations between pre-to-post changes in sway activity (or entropy) and pre-to-post improvements in the performance of the mathematical processing task. Furthermore, the control group also showed a significant pre-to-post decline of sway entropy, indicating an increase in regularity of balance (e.g., Drozdova-Statkeviciene et al, 2021). In line with these findings, one should not exclude the possibility that pre-to-post changes observed in our study were partly influenced by test-retest learning effects. However, a careful examination of the findings showed that: (1) gains on entropy in the control group were not associated with pre-to-post changes in cognition, and (2) improvement in balance stability (i.e., pre-to-post decrease in sway activity) was associated primarily with a decrease in performance of the mathematical processing task. Therefore, it is possible that test–retest learning gains in balance stability were more prominent in individuals with poorer working memory and processing speed.

Results from a two-way repeated measures ANOVA showed that a single bout of high-intensity strength exercise induced a non-significant improvement with moderate effect size in PI on the mathematical processing task compared to the control group. Further exploratory analysis with a two-way ANCOVA with pre-test results and age as covariates showed a significantly larger improvement in RT on the mathematical processing task compared to control. None of the other cognitive tests changed significantly.

However, within this exploratory analysis, we discovered moderate effect sizes for an improvement in PI on the mathematical processing and 2-choice reaction time task in the experimental group compared to the control group. Our findings partly support those of previous literature, albeit tasks used in our study were not similar to those used by others. For example, Netz et al. (2016) reported that a single bout of moderate-intensity cardiovascular exercise in middle-aged adults induced improvements in response inhibition on the Go/No-Go task, where participants need to press a button when a visual stimulus is being presented on a computer screen and inhibit pressing the button when another stimulus is being presented (Netz et al., 2016). Hsieh et al. (2016a) discovered that response time on the Go/No-Go task also improved after a single bout of eight resistance exercises (two sets of ten repetitions at 70% 10RM) in older men. They reported that compared to young adults, older adults improved more on tasks with higher working memory demands (Hsieh et al., 2016b).

Furthermore, Chang and Etnier (2009) showed that a single session of six resistance exercises, each performed for two sets of ten repetitions at 75% 1RM, induced improvements in processing speed and tended to improve executive function (Yu Kai Chang & Etnier, 2009). In contrast, Pontifex et al. (2009) indicated that only acute cardiovascular exercise and not resistance exercise resulted in working memory task improvements (Pontifex et al., 2009). However, Dunsky et al. (2017) refuted their finding by reporting similar changes following acute cardiovascular and resistance exercise on executive functions in middle-aged physically active adults.

Our findings revealed no significant associations between the pre-to-post change in cognitive performance on the ANAM4 cognitive test battery and the pre-to-post change in performance on the postural balance task in the experimental group. Therefore, we could not confirm our hypothesis that improvements in one or more cognitive domains following a single bout of high-intensity strength exercise would coincide with the improvement of balance control. In contrast, our results indicated that improvements in the performance of the mathematical processing task over time were associated with increased sway activity during the postural dual-task in the control group. It should be noted that both the ANAM4 mathematical processing task and the mathematical counting task performed during the postural dual-task are generally working memory tests. Therefore, it was surprising that those performing better on the working memory test following the control session were also those who performed worse on the postural dual-task. Since pre-to-post gains observed in the control group could be attributed in part to a learning effect, it is reasonable to assume that improvements would be also evident in one or more cognitive domains in this group. Nonetheless, no significant pre-to-post performance gains on cognitive outcome measures were visible in the controls (see Supplementary Table A2). An alternative explanation is that test-retest learning effect in the control group was associated with increased prioritisation of this task under dual-task condition which in turn may have a detrimental effect on balance. Another reason why our results are surprising is that previous studies reported that impaired executive function (which includes working memory) is the cognitive deficit most consistently reported to be associated with an increased risk of falls in older adults (Horak, 2006; Yogev-Seligmann et al., 2008). Therefore, one would expect that postural stability in older adults would be more affected in those with more difficulty on the cognitive component of the dual-task. To know if worse performance on postural dual-task studies is linked to the type of cognitive deficit in the older adult or the type of task being used in combination with the balance task, we advise other researchers to follow our example and report findings from both postural dual-task and cognitive tests.

From a mechanistic point of view, we used a strength exercise protocol with high relative loads and long rest periods. This protocol is optimal to improving muscle strength (Schoenfeld et al., 2021). However, its effects on cognitive performance and brain structure and function in apparently healthy older individuals have remained unclear. Previous studies with cardiovascular exercise like Thomas et al. (2016) and Opie and Semmler (2019), indicated that high-intensity exercise has a larger beneficial effect on motor skill learning than low-intensity exercise (Opie & Semmler, 2019; Thomas et al., 2016). Importantly, pooled data from the meta-analysis of Wanner et al. (2020) suggested that only high-intensity exercise can significantly improve motor task performance when compared to rest at both short-term and long-term retention testing.

Furthermore, high-intensity exercise was reported to induce higher levels of IGF-1, irisin and BDNF, which are suggested to mediate (part of) the beneficial effect of exercise on the brain through enhancing neuroplasticity (Daskalopoulou et al., 2014; Huh et al., 2014; Müller et al., 2020; Schwarz et al., 1996; Vints et al., 2022). Possibly, the augmented increase in circulating IGF-1, irisin and BDNF with high-intensity cardiovascular exercise is caused in part by pathways activated by lactate, as was suggested by others (El Hayek et al., 2019; Kujach et al., 2020; Müller et al., 2020; Salgueiro et al., 2014; Schiffer et al., 2011). In contrast to these studies, we adopted strength exercise with high relative loads and long rest intervals, which was probably not associated with elevated lactate levels. Thus, although we used a high-intensity protocol, the significant difference in the improvement on the mathematical processing task between experimental and control groups was probably not mediated by lactate-induced pathways. In addition, high-intensity resistance exercise has been shown to induce elevated inflammatory markers, such as interleukin-6 (IL-6), associated with exercise-induced muscle damage (Mendham et al., 2011). High inflammatory markers exert detrimental effects on neurotrophic signalling pathways and may thus counteract the effect of elevated neurotrophic factors (Bourgognon & Cavanagh, 2020; Sun et al., 2017). Although we did not measure blood biomarkers in this study, our exercise protocol most likely induced muscle damage to some extent in our cohort of older adults not participating regularly in any resistance training programme, and thus resulted most likely in elevated inflammatory markers. Taken together, we found an effect of high intensity strength exercise on RT performance on the mathematical processing task even though proposed lactate- and inflammation-mediated pathways were most likely not in our favour. Studies including blood analysis are needed to test if strength exercise can induce high levels of neurotrophic factors in the absence of lactate elevations, which may explain the beneficial effects of strength exercise on cognitive function.

Some notes and limitations should be mentioned concerning our study design. First, we failed to randomly allocate participants to the experiment because of the difficulty finding older adults willing to participate in high-intensity resistance exercise. This may have caused fitter or healthier participants to be allocated to the exercise condition. This may be linked with better cognitive and postural performance at baseline (Erickson et al., 2019; Nemmers & Miller, 2008). However, baseline performance was not significantly different in our study. Second, we included only healthy older adults with preserved physical and cognitive abilities and no history of falls, as was also the case in the study of Degani et al. (2017), who found increased sway activity in old compared to young adults (Degani et al., 2017). Of note, in the study of Fino et al. (2016), older adults with regular fall incidents showed different behaviours in postural control compared to older adults without regular fall incidents (Fino et al., 2016). Therefore, our results indicating no significant changes in postural control on the dual-task following acute strength exercise cannot be extrapolated to older adults with frequent fall incidents. It is arguable that the effects of acute strength exercise on postural control, which were not significant in our study, could have been more prominent in older adults an elevated fall risk.

In conclusion, our findings indicated that a single bout of high-intensity strength exercise induced a marginal improvement in working memory, measured as PI on the mathematical processing task. Further exploratory analysis also discovered a significant improvement in RT speed on the same task, which was not seen in the control group. In contrast to the hypothesis that improvements in one or more cognitive domains will be related to improvement in balance control in dual-task, improvements in RT and PI on the mathematical processing task were associated with increases rather than decrease in sway activity during the postural dual-task. The current findings call for future research into the effects of acute strength training on the interplay between cognitive and motor domains in older adults towards the discovery of tailored exercise programmes for this population that could be beneficial for both cognitive and functional outcomes. Specifically, researchers should investigate the combined effects of exercise on the interplay between cognitive processes and motor functions related to postural control and locomotion. Future studies may also consider investigating the impact of a chronic intervention with high-intensity strength training on cognitive and postural performance.

Author's contributions

Margarita Drozdova-Statkevičienė, Vida J. Česnaitienė, Oron Levin and Nerijus Masiulis contributed to conception and design of the study. Margarita Drozdova-Statkevičienė and Vida J. Česnaitienė were involved in data collection and/or analysis. Wouter Vints performed the statistical analysis. Wouter Vints wrote the first draft of the manuscript. Feryal Ghafelzadeh Ahwaz, Charlotte Westhof-Jacobs and Lisa Pauwels wrote sections of the manuscript. Wouter Vints prepared the figures. Gal Ziv, Lisa Pauwels, Oron Levin, Jeanine Verbunt, and Nerijus Masiulis had a role in supervision. All authors contributed to manuscript revision, read, and approved the submitted version.

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Data availability statement

The authors confirm that the data supporting the findings of this study are available within the article and/or its supplementary materials.

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