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Effects of resistance training intensity and a dietary protein intervention on psychosocial outcomes, executive function, and quality of life in frail community-dwelling older adults

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Abstract

Background

Psychosocial functioning, executive function, and quality of life are important contributors to resilience and daily functioning in frail older adults. Resistance training may improve these outcomes, but it remains unclear whether training intensity, with or without a dietary protein intervention, modifies these effects. We examined changes in these outcomes after 12 weeks of supervised resistance training to volitional muscular failure in frail community-dwelling older adults.

Methods

This secondary analysis of the TEAMS randomized controlled trial included 295 community-dwelling adults (mean age 74.0 ± 6.0; 69% female) who completed twice-weekly resistance training. Participants were randomized to training only or training plus a dietary protein intervention. Training intensity was randomized from 20% to 80% of one-repetition maximum (1-RM) in 5% increments. Psychosocial outcomes included depressive symptoms (Geriatric Depression Scale–15), anxiety (6-item State–Trait Anxiety Inventory), pain, fatigue, and fear of falling (Numeric Rating Scales), and sleep quality (Pittsburgh Sleep Quality Index). Executive function was assessed using the Trail Making Test (A and B), Stroop Color–Word Test, and Letter Fluency. Quality of life was measured with the 12-item Short Form Health Survey. Linear mixed models were applied, with significance at $P < 0.05$.

Results

After twelve weeks, participants showed reduction in depressive symptoms (β = −0.167, 95% CI − 0.27 to − 0.06), executive function (TMT-A β = −4.71 s; TMT-B β = −12.11 s; SCWT log β = −0.091; LF β = +2.46 words), and improvement in quality of life (β = +1.26, 95% CI 0.62–1.91), regardless of training intensity. The dietary protein intervention led to a greater reduction in fear of falling compared with resistance training only (log β = −0.257, 95% CI − 0.491 to − 0.023), but showed no consistent additional effects on other outcomes.

Conclusion

In frail, community-dwelling older adults, twelve weeks of resistance training led to improvements in depressive symptoms, executive function, and quality of life. Training intensity did not consistently influence these improvements, and the protein intervention showed no additional benefits. These results demonstrate that resistance training to failure is effective at different intensities, allowing programs to be tailored to individual needs.

Trial registration

: NL-OMON54919 (at ICTRP Search Portal), date of registration: 09-02-2021

Background

Resistance-training research in frail older adults has largely focused on muscle-centered outcomes, leaving the effects on psychosocial functioning, executive function, and quality of life less well understood, despite their importance as contributors to resilience and daily functioning. Evidence from studies in healthy older adults shows that resistance training can enhance psychosocial functioning, improve health-related quality of life, and reduce depressive symptoms and anxiety [1–4]. In addition, resistance training has been shown to improve executive function in healthy and (pre-)frail older adults, potentially through neurophysiological adaptations and the cognitively demanding nature of resistance exercise [5–8]. Together, these findings suggest that resistance training may offer benefits beyond muscle-centered outcomes, but the extent to which these effects occur in frail, community-dwelling older adults remains insufficiently studies.

Training characteristics, such as intensity, commonly expressed as a percentage of one-repetition maximum (1-RM), may influence how resistance training affects psychosocial outcomes, executive function, and quality of life. Higher intensities provide a stronger mechanical stimulus and may better support strength gains, whereas lower intensities tend to be more tolerable and may promote adherence and enjoyment [9,10]. Beyond these physiological differences, individual preferences, expectations, and the perceived fit of a given intensity may also shape how older adults respond, which may be particularly relevant for psychosocial outcomes. In frail older adults, lower-intensity resistance exercise may further enhance feasibility, given common challenges such as fatigue, fear of injury, and limited physical capacity. Although resistance-exercise guidelines often emphasize high-intensity training, meta-analyses in healthy adults, including older adults, indicate that when sets are performed to volitional muscular failure, heavier intensities may still produce greater maximal strength gains, whereas lower intensities can also elicit meaningful improvements in strength and physical performance [11,12]. When sets are performed to failure, lower intensities can still elicit high motor-unit recruitment and greater time under tension, which may help explain the clinically relevant improvements observed [13,14]. Therefore, low- to medium-intensity training performed to failure may represent a feasible and clinically relevant option for frail older adults. However, whether training intensity modifies psychosocial outcomes, executive function, and quality of life during training to failure in frail, community-dwelling older adults remains unknown.

In addition to training characteristics, nutritional factors may further modify the effects of resistance training [15]. Adequate dietary protein intake during resistance training, typically 1.2–1.5 g/kg/day for older adults, is recommended to support muscle health and has been associated with a lower risk of frailty [16]. While protein may support training adaptations, it remains uncertain whether increasing protein intake also modifies the effects of resistance training on psychosocial functioning, executive

function, and quality of life in frail older adults. Such effects, if present, are likely indirect, either through improvements in physical reserve or through broader nutrition-related pathways. Clarifying whether training intensity and a dietary protein intervention independently or jointly shape these outcomes may help inform clinical strategies aimed at addressing the impact of frailty on daily functioning and well-being.

In this secondary analysis of the TEAMS randomized controlled trial, we examined the effects of different training intensities and a dietary protein intervention on psychosocial outcomes, executive function, and quality of life in frail, community-dwelling older adults following a twelve-week resistance-training program performed to volitional muscular failure.

Methods

Study design

This study is a secondary analysis of the TEAMS randomized controlled trial, which evaluated a twelve-week, supervised, progressive resistance training program with or without a dietary protein intervention in frail, community-dwelling older adults. The TEAMS study was conducted in accordance with CONSORT (Supplementary file 1), Good Clinical Practice (GCP), and the Declaration of Helsinki. The Medical Ethics Committee of Amsterdam UMC, location VUmc, approved the protocol (NL74601.029.20; Protocol ID NL8785). The trial was registered in the ICTRP Search Portal (Study ID NL-OMON54919; registered 09 February 2021). Methodological details, including study objectives, recruitment and screening procedures, sample size calculation, blinding, protocol adherence, and handling of dropouts, are described in the TEAMS study protocol [17].

Participants and randomization

Participants were frail, community-dwelling older adults aged ≥ 65 years who received in-home care or had a Tilburg Frailty Indicator (TFI) score ≥ 5 and were required to have sufficient cognitive functioning to provide informed consent and follow study procedures, as determined during screening. Exclusion criteria included an inability to understand the Dutch language, use of parenteral nutrition, or medical conditions such as unstable coronary heart disease, advanced heart failure (NYHA > 3), uncontrolled hypertension, arrhythmias, degenerative neurocognitive disorders, or severe COPD (GOLD > 3). A study physician reviewed each participant's screening data including medical history, physical assessments, and frailty scores to confirm eligibility. All participants provided written informed consent. Further details on the screening procedures and eligibility criteria are described in the TEAMS study protocol [17].

Randomization was performed in two steps. First, participants were randomly assigned to training intensity levels ranging from 20% to 80% of their one-repetition maximum (1-RM) in 5% increments. The 20% level was excluded from the present analyses because participants were unable to achieve volitional muscular failure within the predefined time limit per exercise, which constituted a protocol violation. For exploratory subgroup analyses, the remaining intensity levels were grouped into four

clusters: low (25–35% 1-RM), medium-low (40–50% 1-RM), medium-high (55–65% 1-RM), and high (70–80% 1-RM). This clustering was pre-specified in the statistical analysis plan and reflects guideline-based intensity ranges commonly applied in older adults [18–20]. Second, participants were randomized to progressive resistance training only (PRT-only) or progressive resistance training plus the dietary protein intervention (PRT-Pro).

Progressive resistance training

All participants engaged in a structured full-body progressive resistance training program, twice weekly for twelve weeks. Training sessions were delivered in small groups (four to eight participants), with one-on-one guidance from a qualified trainer to ensure safety, proper execution, and performance of each set to volitional muscular failure. Details of the standardized resistance-training protocol, including exercise selection, progression, tempo strategies, and safety procedures, are described in the TEAMS study protocol [17].

Dietary protein intervention

Participants randomized to the protein intervention group received a dietary protein intervention targeting a daily intake of 1.2–1.5 g/kg body weight/day. The intervention included two group sessions and five individual tele-coaching sessions led by a dietitian, plus two daily 10-g protein supplements (whey protein isolate and protein-enriched orange juice), which were made available for consumption to support achievement of the daily intake target.

Outcomes

Psychosocial outcomes, executive function, and quality of life were measured at baseline and at twelve weeks [17]. Psychosocial outcomes included depressive symptoms, anxiety, fear of falling, pain, fatigue, and sleep quality. Depressive symptoms were measured with the Geriatric Depression Scale-15 (GDS-15), anxiety with the 6-item State-Trait Anxiety Inventory (STAI-6), and fear of falling, pain, and fatigue with Numeric Rating Scales (NRS). Sleep quality was measured with the Pittsburgh Sleep Quality Index (PSQI), using the self-rated sleep quality item with four ordered response categories (very good, fairly good, fairly bad, very bad). Executive function was measured using the Trail Making Test parts A and B (TMT A/B), the Stroop Color-Word Test (SCWT), and Letter Fluency (LF), capturing visual attention, processing speed, cognitive flexibility, inhibition, and executive control. Quality of life was measured with the 12-item Short Form Health Survey (SF-12). Participant characteristics, such as age, sex, BMI, ethnicity, lifestyle behaviours, and medical history were measured at baseline to characterize the study population.

Statistical analysis

Baseline characteristics were summarised as mean ± SD for normally distributed continuous variables, medians with interquartile ranges (25th–75th percentiles) for skewed continuous variables, and

frequencies with proportions for categorical variables. For longitudinal analyses, linear mixed models with random intercepts for participants were used to account for repeated measurements. Model assumptions were checked by inspecting the normality of residuals. Outcomes with non-normally distributed residuals were log-transformed prior to analysis and presented as relative changes where appropriate. Sleep quality, an ordered four-level outcome, was analysed using multinomial logistic mixed models and presented as odds ratios. To visualise the overall change, plots were created showing the mean change from baseline to twelve weeks for all participants and stratified by intensity cluster and protein intervention (yes/no) and are provided in Supplementary file 1 (Figures S1–S10).

Analyses followed four steps: (1) Overall effect of resistance training: we examined the change in each outcome over time for the full sample using time as a fixed factor. (2) Differences between intensity clusters: we tested whether changes differed between the four intensity clusters by including an interaction term between time and cluster (high-intensity cluster as reference). (3) Overall effect of the protein intervention: we evaluated whether the dietary protein intervention influenced the changes in outcomes by including time and the time × protein interaction as fixed factors. (4) Protein effects across intensity clusters: finally, we explored whether the effect of the dietary protein intervention differed across the four intensity clusters by examining the time × protein interaction within each cluster. Analyses comparing training intensity clusters, with or without the protein intervention, are exploratory and involve multiple comparisons; therefore, results should be interpreted cautiously due to an increased risk of type I error, and no formal correction for multiple comparisons was applied.

For all models, β-coefficients with 95% confidence intervals (CI) are reported. A p-value < 0.05 was considered statistically significant. Analyses were performed in IBM SPSS Statistics (version 28), and figures were created in RStudio (version 2024.04.2 + 764). The dataset, statistical analysis plan, and study protocol are available in a Figshare repository (https://doi.org/10.21943/auas.31915353), with access restrictions; details are provided in the Data Availability statement.

Results

Participant characteristics

A total of 313 individuals were screened for eligibility, of whom 18 were excluded, resulting in 295 frail participants. These participants were first randomised to a training intensity between 20% and 80% of 1-RM (in 5% increments) and were subsequently randomised to either resistance training only (PRT-Only, n = 146) or resistance training combined with a protein intervention (PRT-Pro, n = 149). During the intervention, 24 participants assigned to the 20% 1-RM intensity level were unable to reach volitional muscular failure within the required protocol time frame, constituting a protocol violation. The remaining 271 participants constituted the sample used to describe baseline characteristics (Table 1). Of these 271 participants, 37 did not complete the post-intervention assessments or had missing outcome data and were therefore considered lost to follow-up. For the primary analyses (Tables 2 and 3), data were

available for 234 participants (PRT-Only, n = 111; PRT-Pro, n = 123), who were therefore included in the main analyses (Fig. 1).

At baseline, participants were on average 74.0 ± 6.0 years; 69% were female and 76% had a Western background. Mean BMI was 27.6 ± 5.2 kg/m² (range 19.2–44.3 kg/m²), with 35% having normal weight, 34% overweight, and 29% obesity. Diabetes was present in 13% of participants, and ≥ 1 cardiovascular condition in 43%. Additional baseline characteristics are shown in Table 1.

Overall and intensity-specific effects of resistance training on psychosocial outcomes, executive function, and quality of life

Across all participants, twelve weeks of supervised resistance training performed to volitional muscular failure was associated with a decrease in depressive symptoms, improvement in executive function, and quality of life (Table 2; Supplementary file 1, Figures S1 and S6–S10). Depressive symptoms decreased by 15.4% (GDS-15 β = −0.17, 95% CI − 0.27 to − 0.06, p = 0.002). Executive function improved across multiple tests. Visual attention and processing speed improved on the Trail Making Test (part A: β = −4.71 s, 95% CI − 6.51 to − 2.90, p < 0.001; part B: β = −12.11 s, 95% CI − 21.03 to − 3.18, p = 0.008). The score on the Stroop Color-Word Test improved by 8.7% (β = −0.091, 95% CI − 0.148 to − 0.035, p = 0.002), and letter fluency increased by 2.46 words (95% CI 1.42–3.51, p < 0.001). Quality of life increased by 1.26 points (95% CI 0.62–1.91, p < 0.001). Anxiety (STAI-6), fear of falling, pain, fatigue (NRS- scale), and sleep quality (PSQI) showed no statistically significant change (all p ≥ 0.05; Table 2; Supplementary file 1, Figures S2–S5).

Pre–post changes were generally comparable across the four intensity clusters (Table 2; Supplementary file 1, Figures S1–S10). Given the number of outcomes and comparisons, these cluster-specific findings should be interpreted cautiously and considered hypothesis-generating. Two outcomes showed statistically significant differences between intensity clusters, using the high-intensity cluster as reference. Letter fluency improved more in the low-intensity (β = 3.18 words, 95% CI 0.98–5.38, p = 0.005) and medium-low clusters (β = 4.18 words, 95% CI 2.01–6.35, p < 0.001) (Supplementary file 1, Figure S9), while anxiety decreased in the medium-low cluster (β = −0.47, 95% CI − 0.91 to − 0.04, p = 0.032) and increased in the high-intensity cluster (β = 0.55, 95% CI 0.03–1.07, p = 0.040) (Supplementary file 1, Figure S2). For all other outcomes, including quality of life, depressive symptoms, and executive function (TMT-A/B and SCWT), effect sizes were generally similar in direction across intensity clusters (Table 2; Supplementary file 1, Figures S1 and S6–S10), whereas pain, fatigue, fear of falling, and sleep quality showed small and inconsistent effects (Table 2; Supplementary file 1, Figures S3–S5).

Overall and intensity-specific effects of dietary protein intervention

In the total cohort, assignment to the resistance training combined with the protein intervention was associated with a 22.7% reduction in fear of falling (β = −0.26, 95% CI − 0.49 to − 0.02, p = 0.031) compared with resistance training only (Table 3; Supplementary file 1, Figure S5), while no additional effects were observed for other psychosocial outcomes, executive function, or quality of life (Table 3;

Figures S1–S4 and S6–S10). Across the four training-intensity clusters, no consistent differences emerged between resistance training only and resistance training plus a dietary protein intervention for any of the assessed outcomes (Table 3). These exploratory findings should be interpreted cautiously, as they likely reflect imprecision in the estimates and limited power to detect differences. A few within-cluster effects were observed: in the low-intensity cluster, pain decreased more in the protein group (β = −0.55, 95% CI − 0.98 to − 0.13, p = 0.012) (Supplementary file 1, Figure S3) and in the high-intensity cluster, letter fluency improved more with protein supplementation (β = 4.75, 95% CI 0.65 to 8.85, p = 0.024) (Supplementary file 1, Figure S9), compared with resistance training only.

Discussion

In this secondary analysis of the TEAMS randomized controlled trial, frail community-dwelling older adults who completed a twelve-week supervised resistance-training program performed to volitional muscular failure, with or without a dietary protein intervention, showed improvements in depressive symptoms, executive function, and quality of life. In contrast, no statistically significant overall pre–post changes were observed for anxiety, sleep quality, pain, fatigue, or fear of falling. These patterns were generally comparable across training intensities, with no consistent intensity-dependent pattern across outcomes. In addition, the dietary protein intervention was associated with a greater reduction in fear of falling compared with resistance training only, although no consistent effects were observed for the other outcomes. A few exploratory within-cluster effects emerged: in the low-intensity cluster, pain decreased more in participants receiving the dietary protein intervention, and in the high-intensity cluster, letter fluency improved more in those receiving the dietary protein intervention compared with resistance training only.

For the overall cohort, the pre-post improvements in depressive symptoms, executive function, and quality of life align with prior randomized evidence indicating that resistance training can enhance perceived health, well-being, and executive function in older adults [21,22]. These improvements may reflect a combination of improved physical reserve and a greater perceived ability to manage daily activities [22]. The structured and socially engaging context of supervised group sessions may have played an important role, as depressive symptoms and quality of life may be influenced both by physiological adaptations and contextual factors such as routine and social interaction, factors that are particularly relevant in frail older adults [23]. Taken together, these findings reinforce that resistance training, including training programs performed to failure, may confer benefits that extend beyond physical capacity, supporting broader health-related domains in frail community-dwelling older adults [7,21,24].

A unique feature of the TEAMS trial was the randomized training intensities, all performed until volitional muscle failure. Based on established training principles, it was reasonable to expect intensity-dependent effects on multiple outcomes. Higher intensities provide a stronger mechanical and metabolic stimulus, which could lead to larger improvements in outcomes linked to physical reserve, such as fatigue, and pain [18,25,26]. In contrast, lower-intensities exercise may be better tolerated by frail older adults and

support adherence, enjoyment, and perceived competence, potentially influencing psychosocial outcomes, such as depressive symptoms and quality of life [10]. We anticipated that different intensities might shape these outcomes in different directions through both physiological and behavioural pathways. However, changes in most outcomes were comparable across the four intensity clusters, and no cluster consistently outperformed the others. Two exploratory intensity-related differences were observed (letter fluency and anxiety), but these findings were not part of a consistent pattern across outcomes and should therefore be interpreted as hypothesis-generating.

Although these results require confirmation in larger samples of frail older adults, there are some explanations for these findings. First, when sets are performed to failure, the internal effort stimulus and motor-unit recruitment may become more similar across loads, reducing the likelihood of large intensity-dependent differences. This interpretation aligns with the TEAMS primary findings, which showed meaningful improvements in muscle strength and physical performance across a broad range of intensities without an optimal intensity [8]. Second, exercise itself may confer meaningful benefits, as meta-analyses found that all levels, from low to high, of physical activity or exercise (aerobic, resistance, or combined), protected against the occurrence of cognitive decline and improved depressive symptoms and quality of life [27–29]. Third, many of the outcomes in this study (anxiety, sleep, pain, fatigue, and fear of falling) are multifactorial and often require behavioural, psychological, or multicomponent interventions, making it unlikely that differences in training intensity alone would produce distinct effects within a twelve-week period [30].

The dietary protein intervention did not resulted in consistent benefits across the assessed outcomes, and protein effects were not consistently different across intensity clusters, aside from an overall modest reduction in fear of falling. From a mechanistic perspective, higher protein intake during resistance training is primarily expected to support muscle protein synthesis and training adaptations [15]. Whether this translates into psychosocial outcomes, executive function, and quality of life is likely indirect and may require a larger nutritional contrast, longer duration, or stronger changes in physical reserves to become detectable [15,31]. In this cohort, baseline protein intake was already relatively high (approximately 1.0 g/kg body weight), which likely reduced the contrast between groups and limited the potential for the intervention to yield measurable effects [16,32]. Taken together, these findings suggest that dietary protein intervention did not exert a consistent modifying effect on most psychosocial, cognitive, or quality-of-life outcomes, and the isolated reduction in fear of falling should be interpreted cautiously given the absence of corresponding changes in related domains.

This study has several notable strengths. The pragmatic design and large sample of frail community-dwelling older adults support generalizability. Adherence to the training protocol was high and dropouts were low, likely supported by the supervised exercise program [23]. The inclusion of multiple outcomes enables a broad evaluation of intervention impact beyond muscle-centred outcomes. Finally, the randomized assignment to a wide range of intensities, combined with a standardized train-to-failure protocol and a parallel dietary protein intervention, provides a rare opportunity to examine intensity-dependent patterns and to explore whether the protein intervention may modify these

associations, while the clinically meaningful clustering enhances interpretability. The use of clinically interpretable intensity clusters further supports translation to practice, although these cluster-based analyses should be considered exploratory.

Several limitations should be acknowledged. First, although training intensity was randomized, the present secondary analysis of overall pre–post change lacked a non-exercise control group, which means that improvements over time cannot be attributed solely to the resistance training. Second, this secondary analysis was not powered for detailed comparisons between intensity clusters with or without a protein intervention; cluster group-specific findings should therefore be considered exploratory and interpreted cautiously. Third, this study deliberately chose to manipulate training intensity during resistance training, while standardizing other key components including frequency, training until volitional muscle failure or effort, progression and other training characteristics. Consequently, the findings specifically reflect the role of training intensity, and no conclusions can be drawn about the effects of modifying other training variables. Finally, the twelve-week duration may be insufficient for outcomes that typically require longer exposure or additional behavioural components, such as anxiety or sleep, and it remains possible that training intensity could influence these outcomes over a longer timeframe.

For frail community-dwelling older adults, our findings indicate that twice-weekly supervised resistance training performed to failure can be prescribed across a broad intensity range. The absence of a clear advantage for any intensity suggests that training can be selected flexibly, guided by feasibility, safety, symptom tolerance, and individual preference, without compromising improvements in psychosocial outcomes, executive function, or quality of life. At the same time, these clinical implications should be interpreted in light of the secondary and partly exploratory nature of the present analyses. The observed improvements therefore suggest that resistance exercise may contribute to attenuating or potentially reversing aspects of frailty, and improving resilience. However, if the goal is to modify outcomes such as anxiety, sleep, or fear of falling, resistance training alone may be insufficient; these outcomes may require additional behavioural strategies, targeted psychological support, or multicomponent exercise approaches to achieve meaningful change.

Conclusion

In this secondary analysis of the TEAMS randomized controlled trial, twelve weeks of supervised resistance training performed to volitional muscular failure was associated with improvements in psychosocial outcomes, executive function, and quality of life in frail community-dwelling older adults. These results underscore that meaningful adaptations to frailty are not limited to muscle-centred outcomes but also encompass broader aspects that contribute to resilience. The improvements were not modified by training intensity or by the dietary protein intervention, although these findings need to be confirmed in larger samples of frail older adults. Clinically, this suggests that resistance training, when performed to failure, can be prescribed across a broad and tolerable intensity range, allowing intensity to be tailored to individual capacity, safety, preference, and comfort.

Declarations

Ethics approval and consent to participate

The TEAMS study was approved by the Medical Ethics Committee of the Amsterdam University Medical Centers (Protocol ID: VUMC2020.452; submitted protocol version 6.0; OMON trial ID NL8785). All procedures were conducted in accordance with the ethical standards of the 1964 Declaration of Helsinki and its later amendments. All participants provided written informed consent prior to inclusion.

Consent for publication

Not applicable.

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Author Contribution

Mohammed Benali and Esmée J.M. Biersteker performed the secondary analyses for the manuscript. Mohammed Benali drafted the first version of the manuscript. Esmée J.M. Biersteker conducted the statistical analyses. Mohammed Benali and Esmée J.M. Biersteker jointly interpreted the findings and refined the analytical narrative and clinical implications. Jantine van den Helder, Jos Twisk, Josje D. Schoufour, Peter J.M. Weijs and Michael Tieland critically revised the manuscript for important intellectual content. All authors read and approved the final manuscript.

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Data Availability

The dataset, statistical analysis plan, and study protocol are available in a Figshare repository (https://doi.org/10.21943/auas.31915353), with access restrictions; details are provided in the Data

Availability statement.

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Tables

Table 1
Baseline characteristics of participants of the TEAMS study.

Characteristics	Full cohort (n = 271)	Low intensity (25–35%) (n = 59)	Medium-low intensity (40–50%) (n = 70)	Medium-high intensity (55–65%) (n = 72)	High intensity (70–80%) (n = 70)
Age	74.0 (6.0)	73.8 (5.5)	73.2 (5.3)	74.0 (6.0)	74.9 (6.8)
Female, n (%)	187 (69)	37 (63)	54 (77)	49 (68)	47 (67)
BMI (kg/m^2)	27.6 (5.2)	27.6 (4.6)	27.6 (5.6)	27.7 (5.8)	27.5 (4.6)
- Normal weight (18.5–24.9 kg/m²), n (%)	95 (35)	20 (34)	27 (40)	27 (39)	21 (31)
- Overweight (25.0-29.9 kg/m²), n (%)	93 (34)	25 (42)	16 (24)	24 (35)	28 (41)
- Obesity (≥ 30 kg/m²), n (%)	75 (29)	14 (24)	24 (36)	18 (26)	19 (28)
Frailty status, n (%)[1]					
- Frail (TFI 5–9), n (%)	178 (66)	35 (59)	48 (69)	51 (71)	44 (63)
- Severely Frail (TFI ≥ 10), n (%)	23 (9)	5 (9)	4 (6)	6 (8)	8 (11)
- Receiving In-Home Care, n (%)	70 (26)	19 (32)	18 (26)	15 (21)	18 (26)
Ethnicity, n (%)					
- Western	202 (75)	42 (71)	49 (70)	55 (76)	56 (80)
- Non-Western	69 (26)	17 (29)	21 (30)	17 (24)	14 (20)
Living Situation, n (%)[2]					
- Independently	173 (64)	34 (58)	46 (66)	49 (68)	44 (63)
- Together	88 (33)	25 (42)	20 (29)	21 (29)	22 (31)
- Service Flat	10 (4)	-	4 (6)	2 (3)	4 (6)
Smoking, n (%)					
- Non-smoker	131 (48)	31 (53)	38 (54)	31 (43)	31 (44)
- Current smoker	15 (6)	3 (5)	-	7 (10)	5 (7)

Characteristics	Full cohort (n = 271)	Low intensity (25–35%) (n = 59)	Medium-low intensity (40–50%) (n = 70)	Medium-high intensity (55–65%) (n = 72)	High intensity (70–80%) (n = 70)
- Previous smoker	125 (46)	25 (42)	32 (46)	34 (47)	34 (49)
Alcohol consumption, n (%)					
- Non-Drinker	98 (36)	18 (31)	26 (37)	28 (39)	26 (37)
- Drinker	173 (64)	41 (70)	44 (63)	44 (61)	44 (63)
Protein intake (g/kg bodyweight/day)	1.0 (0.3)	1.1 (0.3)	1.0 (0.3)	1.1 (0.4)	1.0 (0.3)
Morbidities, n (%)[3]					
- Musculoskeletal	102 (38)	24 (41)	23 (33)	24 (33)	31 (44)
- Cardiovascular	116 (43)	28 (48)	28 (40)	26 (36)	34 (49)
- Hypertension	82 (30)	20 (34)	20 (29)	22 (31)	20 (29)
- Respiratory	37 (14)	5 (8)	9 (13)	11 (15)	12 (17)
- Diabetes	35 (13)	10 (17)	8 (11)	9 (13)	8 (11)
- Arthrosis	102 (38)	18 (31)	31 (30)	19 (26)	34 (49)
Body composition, median (IQR)					
- Fat mass	23.9 (18.2–32.6)	23.7 (19.0-29.2)	24.2 (17.8–34.3)	23.2 (17.9–33.8)	26.6 (19.9–32.7)
- Fat free mass	48.4 (42.6–58.7)	51.0 (42.7–60.6)	48.4 (43.3–54.5)	49.1 (42.3–58.9)	47.0 (42.2–58.8)
Bartel index, median (IQR)	20 (19–20)	20 (19–20)	20 (19–20)	20 (19–20)	20 (18–20)
Depressive symptoms, median (IQR)4	1 (0–3)	1 (0–2)	1 (1–3)	1 (0–3)	2 (0–4)
Anxiety, median (IQR)[5]	14 (12–15)	14 (13–15)	14 (13–15)	14 (12–15)	13 (12–14)
NRS scale score, median (IQR)					

Characteristics	Full cohort (n = 271)	Low intensity (25–35%) (n = 59)	Medium-low intensity (40–50%) (n = 70)	Medium-high intensity (55–65%) (n = 72)	High intensity (70–80%) (n = 70)
- Pain	10 (0–30)	15 (0–30)	10 (0–30)	10 (0–40)	2 (0–40)
- Fatigue	40 (20–60)	40 (10–60)	30 (20–50)	40 (20–60)	40 (15–70)
- Fear of Falling	10 (0–50)	10 (0–40)	10 (0–40)	10 (0–50)	20 (0–44)
Sleep quality, n (%)					
- Very good	70 (26)	14 (24)	24 (35)	16 (23)	16 (23)
- Moderate good	134 (50)	31 (53)	37 (54)	37 (52)	29 (42)
- Moderate bad	50 (19)	10 (17)	5 (7)	17 (24)	18 (26)
- Very bad	14 (5)	4 (7)	3 (4)	1 (1)	6 (9)
Executive function, median (IQR)					
- Trail making test part A (s)	36.0 (28.7–47.0)	36.0 (27.0–48.0)	36.0 (29.0–48.0)	36.0 (30.0-48.5)	32.4 (27.0–43.0)
- Trail making test part B (s)	87.0 (62.0-132.0)	85.0 (62.0-121.0)	78.0 (59.3-115.8)	89.0 (62.5-141.9)	94.0 (64.0-175.0)
- Stroop color word test score	53.0 (37.3–72.3)	55.5 (40.0-67.5)	50.0 (37.0-71.8)	51.0 (37.8–69.5)	53.2 (35.6–81.4)
- Letter fluency score, mean (SD)	38.9 (13.6)	41.3 (12.4)	38.7 (13.4)	40.2 (14.1)	35.9 (13.8)
Quality of life, median (IQR)[6]	43 (39–49)	44 (40–50)	44 (39–48)	43 (39–50)	42 (37–49)

BMI, body mass index; NRS scale, Numeric Rating Scale.

[1] Frailty status was determined with the Tilburg Frailty Indicator (TFI) where available; TFI 5–9 = frail, TFI ≥ 10 = severe frailty. Not all participants completed the TFI. For participants without TFI, study eligibility as “frail” was established a priori by receiving in-home care services. Accordingly, frail percentages are calculated among participants with TFI data only, whereas receiving in-home care is reported for participant who did not complete the TFI.

[2] Living situation categorized as follows: Independently = living on their own, Together = living with others, such as a spouse, family members, or roommates and Service Flat = either independently or with others but living in housing that support services like meals, housekeeping, or medical assistance.

[3] Morbidities: The counts are reported per participant. If a participant has one or more issues within a given subcategory, it is recorded as a single occurrence. Musculoskeletal disorders contains musculoskeletal disorders as well as neuromuscular disorders and rheumatism.

[4] Depressive symptoms was measured with the Geriatric Depression Scale 15 items (GDS-15).

[5] Anxiety was measured with the State–Trait Anxiety Inventory 6 items (STAI-6).

[6] Quality of life was measured with the Short Form Health Survey 12 items (SF-12).

Table 2
Effects of resistance training overall and stratified by training intensity cluster

Outcome variable	Full cohort (n = 234)	Low intensity (25–35%) (n = 54)	Medium-low intensity (40–50%) (n = 61)	Medium-high intensity (55–65%) (n = 61)	High intensity (70–80%) (n = 58)
	β (95% CI)	β (95% CI)	β (95% CI)	β (95% CI)	β (95% CI)
Depressive symptoms (log)[1]	**-0.17 (-0.27- -0.06)**	-0.22 (-0.51- 0.06)	-0.14 (-0.33- 0.05)	-0.22 (-0.44- 0.01)	-0.11 (-0.30- 0.09)
Anxiety[2]	-0.04 (-0.28- 0.20)	-0.20 (-0.61- 0.21)	**-0.47 (-0.91- -0.04)***	-0.04 (-0.55- 0.48)	**0.55 (0.03– 1.07)**
Pain (log)[3]	0.07 (-0.07- 0.22)	-0.02 (-0.28- 0.25)	0.07 (-0.16- 0.31)	0.11 (-0.24- 0.46)	0.15 (-0.20- 0.50)
Fatigue (log)[3]	-0.07 (-0.17- 0.03)	-0.14 (-0.37- 0.10)	-0.06 (-0.27- 0.15)	-0.01 (-0.19- 0.16)	-0.11 (-0.32- 0.09)
Fear of falling (log)[3]	-0.02 (-0.16- 0.12)	0.08 (-0.30- 0.45)	-0.04 (-0.27- 0.20)	-0.09 (-0.36- 0.18)	-0.01 (-0.32- 0.29)
Sleep quality (log)[4]	-0.24 (0.55– 1.13)	-0.62 (0.25– 1.17)	0.22 (0.59– 2.65)	-0.32 (0.35– 1.51)	-0.25 (0.39– 1.56)
Trail making test part A (s)	**-4.71 (-6.51- -2.90)**	**-4.65 (-7.49- -1.81)**	**-5.69 (-8.82- -2.56)**	**-6.59 (-11.30- -1.89)**	-1.53 (-4.85- 1.79)
Trail making test part B (s)	**-12.11 (-21.03- -3.18)**	**-15.69 (-30.50- -0.89)**	1.97 (-12.86- 16.79)	-9.69 (-29.79- 10.41)	**-25.87 (-46.94- -4.81)**
Stroop color word test score (log) (s)	**-0.09 (-0.15- -0.04)**	**-0.12 (-0.23- -0.02)**	-0.07 (-0.16- 0.01)	-0.08 (-0.21- 0.05)	-0.10 (-0.23- 0.04)
Letter fluency score	**2.46 (1.42– 3.51)**	**3.18 (0.98– 5.38)**	**4.18 (2.01– 6.35)***	0.68 (-1.12- 2.49)	1.81 (-0.43- 4.06)
Quality of life (score)[5]	**1.26 (0.62– 1.91)**	**1.70 (0.32– 3.08)**	**1.43 (0.35– 2.50)**	0.56 (-0.88- 2.00)	**1.39 (0.06– 2.71)**

Data were analysed using linear mixed models to account for repeated measures within participants. Time and the time × intensity-cluster interaction were included as fixed effects, with a random intercept for participants; the high-intensity cluster (70–80% 1-RM) was the reference group. Results are presented as β-coefficients with 95% confidence intervals (95% CI). Outcomes analyzed on the log scale

(depressive symptoms, pain, fatigue, fear of falling, and the Stroop Color–Word Test) are indicated with **(log)** and may be interpreted as relative (%-based) change.

Bold values indicate $p < 0.05$ for within-cluster change over time.

* indicates a statistically significant difference in change compared with the high-intensity reference cluster (i.e., effect modification by training intensity based on the time × cluster interaction).

[1] Depressive symptoms was measured with the Geriatric Depression Scale 15 items (GDS-15).

[2] Anxiety was measured with the State–Trait Anxiety Inventory 6 items (STAI-6).

[3] Pain, fatigue, and fear of falling were measured with the Numeric Rating Scale (NRS).

[4] Sleep quality was measured with the Pittsburgh Sleep Quality Index (PSQI) self-rated sleep quality item (very good, fairly good, fairly bad, very bad) and analysed using multinomial logistic mixed models; results are presented as OR with 95% CI.

[5] Quality of life was measured with the Short Form Health Survey 12 items (SF-12).

Table 3
Additional effects of the dietary protein intervention during resistance training, overall and stratified by intensity cluster.

Outcome variable	**Full cohort (n = 234)**	**Low intensity (25–35%) (n = 54)**	**Medium-low intensity (40–50%) (n = 61)**	**Medium-high intensity (55–65%) (n = 61)**	**High intensity (70–80%) (n = 58)**
	β (95% CI)	**β (95% CI)**	**β (95% CI)**	**β (95% CI)**	**β (95% CI)**
Depressive symptoms (log)[1]	-0.06 (-0.25-0.13)	-0.28 (-0.76-0.20)	0.07 (-0.28-0.41)	0.04 (-0.34-0.41)	-0.14 (-0.50-0.22)
Anxiety[2]	0.11 (-0.28-0.50)	-0.24 (-0.94-0.47)	0.23 (-0.48-0.94)	0.44 (-0.39-1.26)	-0.02 (-0.87-0.83)
Pain (log)[3]	-0.09 (-0.32-0.15)	**-0.55 (-0.98--0.13)**	0.17 (-0.23-0.57)	-0.18 (-0.74-0.38)	0.19 (-0.37-0.76)
Fatigue (log)[3]	0.08 (-0.09-0.24)	-0.03 (-0.41-0.34)	0.08 (-0.24-0.41)	0.14 (-0.16-0.45)	0.06 (-0.27-0.38)
Fear of falling (log)[3]	**-0.26 (-0.49--0.02)**	-0.39 (-0.97-0.20)	-0.25 (-0.66-0.16)	-0.14 (-0.58-0.31)	-0.24 (-0.76-0.27)
Sleep quality (log)[4]	-0.13 (0.47–1.65)	-0.78 (0.12–1.77)	-0.74 (0.13–1.76)	0.41 (0.43–5.28)	0.34 (0.41–4.82)
Trail making test part A (s)	-1.92 (-5.09-1.25)	1.04 (-4.02-6.11)	-2.60 (-8.06-2.86)	-3.28 (-11.40-4.84)	-2.57 (-8.65-3.51)
Trail making test part B (s)	-2.41 (-17.24-12.41)	0.27 (-24.35-24.89)	13.06 (-11.04-37.17)	-22.58 (-56.80-11.64)	-0.94 (-34.21-32.34)
Stroop color word test score (log) (s)	-0.07 (-0.18-0.03)	-0.10 (-0.29-0.10)	0.05 (-0.11-0.21)	-0.08 (-0.32-0.15)	-0.16 (-0.40-0.08)
Letter fluency score	1.36 (-0.64-3.35)	1.19 (-2.95-5.33)	-0.07 (-4.26-4.12)	0.091(-3.45-3.63)	**4.75 (0.65–8.85)**
Quality of life (score)[5]	0.36 (-0.83-1.55)	1.09 (-1.40-3.58)	0.06 (-1.98-2.10)	0.65 (-1.96-3.25)	0.08 (-2.41-2.57)

Data were analysed using Linear Mixed Models to account for repeated measures within subjects with time and the interaction between time and protein intervention as fixed variables. Subjects were added as a random intercept. The β-coefficient of the intervention between time and protein intervention are given with the 95% confidence interval (95% CI). Outcomes analyzed on the log scale (depressive

symptoms, pain, fatigue, fear of falling, and the Stroop Color–Word Test) are indicated with **(log)** and may be interpreted as relative (%-based) change.

Bold values indicate $p < 0.05$ for within-cluster change over time.

[1] Depressive symptoms was measured with the Geriatric Depression Scale 15 items (GDS-15).

[2] Anxiety was measured with the State–Trait Anxiety Inventory 6 items (STAI-6).

[3] Pain, fatigue, and fear of falling were measured with the Numeric Rating Scale (NRS).

[4] Sleep quality was measured with the Pittsburgh Sleep Quality Index (PSQI) self-rated sleep quality item (very good, fairly good, fairly bad, very bad) and analysed using multinomial logistic mixed models; results are presented as OR with 95% CI.

[5] Quality of life was measured with the Short Form Health Survey 12 items (SF-12).

Figures

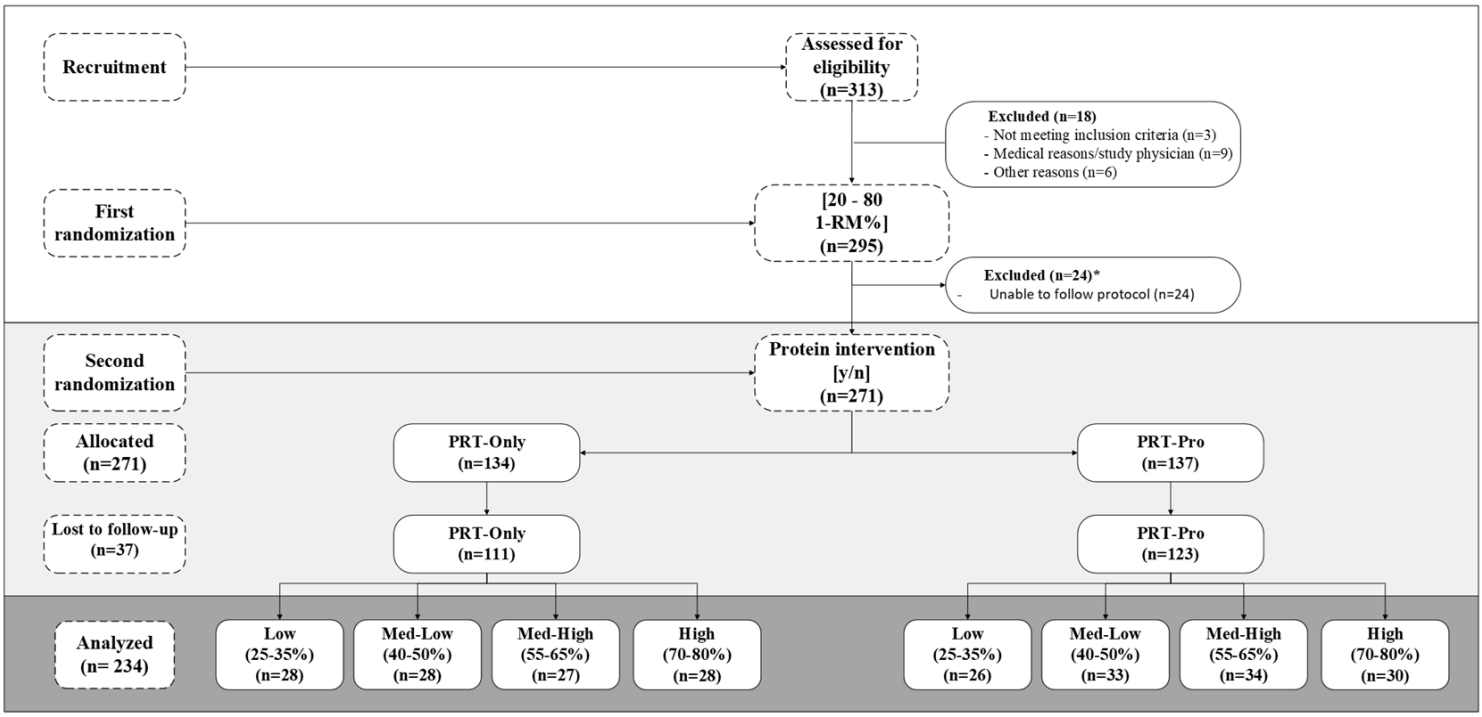


Figure 1

CONSORT flow diagram showing participant recruitment, two-step randomisation (training intensity and protein intervention yes/no), exclusions, including removal of the 20% 1-RM group (n = 24) due to inability to reach volitional muscular failure within the protocol time limit, follow-up, and inclusion in the final analyses. Training intensity was randomized continuously (20–80% 1-RM in 5% increments) and grouped

into four intensity clusters for analysis. PRT-Only refers to resistance training without a protein intervention; PRT-Pro refers to resistance training combined with a dietary protein intervention.

Supplementary Files

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- Supplementaryfile1.docx