Resistance Training in Older Adults:
The Importance of Volume and Movement Velocity

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Tese para obtenção do Grau de Doutor em
Ciências do Desporto
(3º ciclo de estudos)

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Declaração de Integridade

Eu, Diogo Luís Sequeira Torgal Marques, que abaixo assino, estudante com o número de inscrição D2175 de Ciências do Desporto da Faculdade de Ciências Sociais e Humanas, declaro ter desenvolvido o presente trabalho e elaborado o presente texto em total consonância com o **Código de Integridades da Universidade da Beira Interior**.

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CHAVE MÓVEL

Dedication

In memory of all the participants who generously collaborated in the experimental studies and are no longer physically among us. I will never forget your smile!

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List of Publications and Communications

The following studies support the present Ph.D. thesis:

Study 1 – Journal article

Marques, D. L., Neiva, H. P., Marinho, D. A., & Marques, M. C. (2023). Manipulating the Resistance Training Volume in Middle-Aged and Older Adults: A Systematic Review with Meta-Analysis of the Effects on Muscle Strength and Size, Muscle Quality, and Functional Capacity. *Sports Medicine*, 53(2), 503–518. https://doi.org/10.1007/s40279-022-01769-x

Study 2 – Journal article

Marques, D. L., Neiva, H. P., Faíl, L. B., Gil, M. H., & Marques, M. C. (2019). Acute Effects of Low and High-Volume Resistance Training on Hemodynamic, Metabolic and Neuromuscular Parameters in Older Adults. *Experimental Gerontology*, 125, 110685. https://doi.org/10.1016/j.exger.2019.110685.

Study 3 – Journal article

Marques, D. L., Neiva, H. P., Marinho, D. A., & Marques, M. C. (2020). Novel Resistance Training Approach to Monitoring the Volume in Older Adults: The Role of Movement Velocity. *International Journal of Environmental Research and Public Health*, 17(20), 7557. https://doi.org/10.3390/ijerph17207557.

Study 4 – Journal Article

Marques, D. L., Neiva, H. P., Marinho, D. A., & Marques, M. C. (2022). Velocity-Monitored Resistance Training in Older Adults: The Effects of Low-Velocity Loss Threshold on Strength and Functional Capacity. The Journal of Strength & Conditioning Research, 36(11), 3200–3208. https://doi.org/10.1519/JSC.0000000000004036

Study 5 – Journal Article

Marques, D. L., Neiva, H. P., Marinho, D. A., Nunes, C., & Marques, M. C. (2021). Load-Velocity Relationship in the Horizontal Leg-Press Exercise in Older Women and Men. *Experimental Gerontology*, 151, 111391. https://doi.org/10.1016/j.exger.2021.111391.

Study 6 – Journal Article

Marques, D. L., Neiva, H. P., Marinho, D. A., Pires, I. M., Nunes, C., & Marques, M. C. (2023). Estimating the Relative Load from Movement Velocity in the Seated Chest-Press Exercise in Older Adults. *Under review in PLOS One.*

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Study 8 – Journal Article

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Additionally, the following communications were performed during the thesis:

Communication 1 – Oral Presentation

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Communication 3 – Virtual Oral Presentation

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Research Stay

The candidate completed a three-month research stay in the following institution:

- Department of Sport Science and Physical Education, Faculty of Health and Sport Sciences, University of Agder, Kristiansand, Norway;
- Supervisor: Professor Sveinung Berntsen Stølevik;
- Date: 4th April to 30th June 2022;
- Certificate in Annex I.

UiA University of Agder Department of Sport Science and Physical Education

Resumo

Na última década, a prescrição do volume do treino de força (TF) através da monitorização da perda de velocidade na mesma série (PV) em desportistas tem assumido grande destaque entre treinadores e investigadores. Contudo, até à data, desconhece-se a sua aplicabilidade e eficácia na otimização dos ganhos musculares e funcionais em idosos. Assim, o objetivo geral da tese consistiu em analisar os efeitos da manipulação do volume do TF através da monitorização da PV na força, potência e capacidade funcional em idosos. Como tal, adotaram-se os seguintes passos: i) revisão sobre os efeitos de séries únicas vs. múltiplas nas adaptações musculares e funcionais em adultos de meia-idade e idosos; ii) comparação dos efeitos agudos do TF com baixo vs. alto volume em parâmetros fisiológicos e neuromusculares em idosos; iii) análise dos efeitos do TF com 20% de PV na força, potência e capacidade funcional em idosos; iv) análise dos efeitos do TF com 10% de PV na força, potência e capacidade funcional em idosos; v) análise da relação carga-velocidade-potência em exercícios de resistência em idosos; vi) comparação dos efeitos do TF com 10% vs. 20% de PV na força, potência e capacidade funcional em idosos. Os principais resultados indicaram: i) múltiplas séries induzem maiores ganhos musculares e funcionais do que séries únicas; ii) alto volume produz maior stress fisiológico e neuromuscular agudo do que baixo volume; iii) 10% e 20% de PV induzem ganhos de força, potência e capacidade funcional em idosos; iv) equações de regressão carga-velocidade permitem estimar com elevada precisão a carga de treino em idosos; v) 10% de PV é mais eficiente a induzir ganhos musculares e funcionais do que 20% de PV, já que necessita de menos volume de treino; contudo, 20% de PV parece ser necessária para otimizar os ganhos. Assim, os resultados da tese sugerem que a manipulação do volume do TF com base na monitorização da PV apresenta-se como uma abordagem efetiva e eficiente na melhoria da força, potência e capacidade funcional em idosos. Futuros estudos devem seguir as linhas de investigação definidas para fortalecer o conhecimento sobre esta temática.

Palavras-chave

Treino de força; volume de treino; perda de velocidade; força muscular; capacidade funcional; envelhecimento.

Resumo Alargado

Este capítulo resume o trabalho de investigação desenvolvido na tese de doutoramento intitulada *"Resistance Training in Older Adults: The Importance of Volume and Movement Velocity"*. O capítulo inicia com uma introdução geral, focando as problemáticas de estudo e os objetivos gerais e específicos da tese. Em seguida, é apresentada uma breve descrição dos estudos, nomeadamente da revisão da literatura e dos estudos experimentais. O capítulo encerra com as conclusões gerais da tese e sugestões para futuras linhas de investigação.

Introdução Geral

Durante a última década, múltiplas revisões e meta-análises têm observado que a prescrição de cargas relativas altas resulta em maiores ganhos de força e massa muscular do que cargas relativas baixas (p. ex., 80% de uma repetição máxima (1RM) vs. 45% 1RM) durante o treino de força (TF) tradicional (i.e., velocidades concêntricas de ~2 segundos) em idosos (Csapo & Alegre, 2016; Peterson et al., 2010; Steib et al., 2010). Por outro lado, outras revisões e meta-análises, verificaram que cargas relativas entre 40-65% 1RM deslocadas a velocidades máximas produzem maiores ganhos na capacidade funcional do que o TF tradicional em idosos (Balachandran et al., 2022; el Hadouchi et al., 2022; Fragala et al., 2019; Marques et al., 2013). No entanto, apesar destas evidências, atualmente ainda não existe consenso científico sobre o volume ótimo do TF (p. ex., número de séries realizadas por exercício) requerido para melhorar a força muscular e a capacidade funcional em idosos (Borde et al., 2015; Peterson et al., 2010; Polito et al., 2021b; Santana et al., 2021; Steib et al., 2010).

De facto, a maioria dos estudos que compararam os efeitos de séries únicas (1) vs. múltiplas (3) não observaram diferenças entre séries na melhoria da força muscular (Abrahin et al., 2014; Antunes et al., 2021; Correa et al., 2014, 2015; Cunha et al., 2020; Galvão & Taaffe, 2005; Polito et al., 2021a; Radaelli et al., 2013, 2014, 2018), tamanho muscular (Antunes et al., 2021; Correa et al., 2014; Cunha et al., 2017, 2020; Galvão & Taaffe, 2005; Radaelli et al., 2013, 2014, 2018; Ribeiro et al., 2015) e capacidade funcional (Abrahin et al., 2014; Galvão & Taaffe, 2005; Radaelli et al., 2018) em idosos. Não obstante, face à ausência de meta-análises a comparar os efeitos de séries únicas vs. múltiplas nos ganhos musculares e funcionais em idosos, parece relevante combinar os resultados dos estudos para uma melhor compreensão sobre este tema (Estudo 1).

Outra observação que deriva da análise dos estudos citados no parágrafo anterior, é que a maioria prescreveu repetições máximas (i.e., até à falha muscular). Sobre este tema, estudos longitudinais observaram que repetições máximas não produzem maiores ganhos de força, potência e capacidade funcional do que repetições submáximas em idosos (Cadore et al., 2018; Silva et al., 2018; Teodoro et al., 2019). Além disso, estudos transversais indicaram que protocolos até a falha produzem maior stress cardiovascular agudo do que volumes menores em idosos (Tajra et al., 2015; Vale et al., 2018). Todavia, desconhece-se se a realização de repetições máximas causa maior stress metabólico e neuromuscular agudo do que repetições submáximas em idosos, sendo, portanto, necessário explorar este tema (Estudo 2).

Importa ainda destacar que repetições máximas aumentam a variabilidade interindividual no número de repetições realizadas em idosos (Farinatti et al., 2013; Grosicki et al., 2014; Jesus et al., 2018). Por exemplo, vários autores observaram que o número de repetições máximas realizadas a 80% 1RM na prensa de pernas variou entre 2-38 repetições em idosos (Grosicki et al., 2014). Além disso, realizar repetições máximas na primeira série causa uma diminuição no número de repetições nas séries seguintes (Farinatti et al., 2013; Jambassi-Filho et al., 2019; Jesus et al., 2018). Assim, como forma de superar as limitações inerentes das repetições máximas, vários investigadores propuseram monitorizar a perda de velocidade na mesma série para controlar objetivamente o número de repetições realizadas durante o TF (González-Badillo et al., 2017). Este processo pode ser feito definindo previamente um limiar de perda de velocidade na mesma série. Deste modo, assim que o indivíduo atinge o limiar programado (p. ex., 20%), a série deve ser terminada (González-Badillo et al., 2011, 2017).

Esta metodologia tem sido aplicada ao longo da última década para comparar os efeitos de diferentes perdas de velocidade na mesma série na força, potência e desempenho físico em jovens adultos treinados. Um resultado comum entre estudos é que realizar cerca de metade do número de repetições máximas possíveis (p. ex., 10-20% de perda de velocidade) é suficiente para induzir ganhos de força e potência muscular semelhantes a repetições realizadas até ou próximo da falha (p. ex., 40% de perda de velocidade) (Pareja-Blanco et al., 2017a, 2017b, 2020a, 2020b; Rodríguez-Rosell et al., 2020). Não obstante, ainda não é claro na literatura se estes resultados se aplicam a diferentes populações, nomeadamente em idosos. Assim, torna-se fundamental analisar os efeitos de diferentes perdas de velocidade na mesma série na força, potência e capacidade funcional em idosos para determinar a eficácia e exequibilidade desta abordagem do TF para monitorizar o volume de treino nesta população (Estudos 3 e 4).

A medição da velocidade também permite monitorizar a carga relativa e perceber em tempo real se o indivíduo está a treinar de acordo com a carga programada (González-Badillo & Sánchez-Medina, 2010). Este conhecimento provém da relação carga-velocidade, onde se assume que cada carga relativa tem o seu valor de velocidade associado (González-Badillo & Sánchez-Medina, 2010). Embora a relação carga-velocidade em exercícios de resistência tenha sido extensivamente analisada em jovens adultos treinados (González-Badillo & Sánchez-Medina, 2010; Morán-Navarro et al., 2020; Sánchez-Medina et al., 2017), a sua análise em idosos é quase nula. Atualmente, o único estudo que se conhece analisou a relação carga-velocidade na prensa de pernas inclinada e no supino com pesos livres em mulheres idosas treinadas (Marcos-Pardo et al., 2019). Contudo, as equações propostas para estimar as cargas relativas são apenas aplicáveis a mulheres idosas treinadas e para os exercícios descritos. Assim, devem ser realizados novos estudos com idosos de ambos os sexos e sem experiência de TF para analisar a relação carga-velocidade em diferentes exercícios, nomeadamente a prensa de pernas horizontal (Estudo 5) e prensa de peito sentada (Estudo 6), já que são dois dos exercícios mais usados em investigação. Além disso, como a potência muscular é um importante preditor da capacidade funcional em idosos (Byrne et al., 2016; Reid & Fielding, 2012), a análise da relação carga-potência permitirá identificar as cargas relativas que maximizam a produção de potência em ambos os exercícios (Estudo 7) e ajudar a desenhar programas de TF orientados para otimizar a potência muscular nesta população. Finalmente, como resultado da realização das análises anteriormente descritas, será possível desenhar estudos experimentais que comparem os efeitos de diferentes perdas de velocidade na mesma série com cargas relativas prescritas usando velocidades específicas na força, potência e capacidade funcional em idosos (Estudo 8).

Face às considerações anteriores, o objetivo geral da tese de doutoramento consistiu em analisar os efeitos da manipulação do volume do TF através da monitorização da perda de velocidade na mesma série na força, potência e capacidade funcional em idosos. Para alcançar o objetivo geral, definiu-se uma sequência de estudos com os seguintes objetivos específicos:

– Estudo 1: comparar, através de uma revisão sistemática com meta-análise, os efeitos de séries únicas vs. múltiplas na força e tamanho muscular, qualidade muscular e capacidade funcional em adultos de meia-idade e idosos.

- Estudo 2: comparar os efeitos agudos de baixo vs. alto volume de TF em parâmetros hemodinâmicos, metabólicos e neuromusculares em idosos.
- Estudo 3: analisar os efeitos de 20% de perda de velocidade na mesma série com cargas relativas entre 40-65% 1RM na força, potência e capacidade funcional em idosos.
- Estudo 4: analisar os efeitos de 10% de perda de velocidade na mesma série com cargas relativas entre 40-65% 1RM na força, potência e capacidade funcional em idosos.
- Estudo 5: examinar a relação carga-velocidade na prensa de pernas horizontal em idosos do sexo masculino e feminino.
- Estudo 6: identificar a relação carga-velocidade na prensa de peito sentada em idosos do sexo masculino e feminino.
- Estudo 7: analisar a relação carga-potência na prensa de pernas e prensa de peito em idosos do sexo masculino e feminino.
- Estudo 8: comparar os efeitos de 10% vs. 20% de perda de velocidade na mesma série com cargas relativas entre 40-65% 1RM na força, potência e capacidade funcional em idosos.

Descrição dos Estudos

Estudo 1

Identificaram-se estudos randomizados controlados (RCT) e não-RCT a comparar os efeitos de séries únicas vs. múltiplas na força muscular, tamanho muscular, qualidade muscular ou capacidade funcional em adultos de meia-idade e idosos (≥ 50 anos) nas bases de dados da PubMed/MEDLINE, Web of Science e Scopus. Foi utilizada uma meta-análise de efeitos aleatórios. Após pesquisa, foram incluídos quinze estudos (430 participantes; 93% mulheres; 57.9–70.1 anos). Séries múltiplas produziram um maior efeito do que séries únicas na força dos membros inferiores (diferença média padronizada (DMP) = 0.29; intervalo de confiança de 95% (IC) = 0.07-0.51; diferença média (DM) = 1.91 kg; IC 95% = 0.50–3.33) e qualidade muscular (DMP = 0.40; IC 95% = 0.05–0.75). Não se verificaram diferenças entre séries únicas e múltiplas na força dos membros superiores (DMP = 0.13; IC 95% = -0.14–0.40; DM = 0.11 kg; IC 95% = -0.52–0.75), tamanho muscular (DMP = 0.15; IC 95% = -0.07–0.37) e capacidade funcional (DMP = 0.01; IC 95% = -0.47–0.50). Além disso, não houve diferenças entre séries únicas e múltiplas na força e tamanho muscular para durações de treino ≤ 12 semanas ou > 12 semanas. Os resultados sugerem que séries múltiplas produzem maiores ganhos de força e qualidade muscular nos membros inferiores do que séries únicas em adultos de meia-idade e idosos, embora a magnitude da diferença seja pequena. Por outro lado, séries únicas são suficientes para melhorar a força dos membros superiores, tamanho muscular e capacidade funcional nestas populações.

Estudo 2

Trinta e um indivíduos (78.9 ± 7.2 anos) realizaram dois protocolos de TF (baixo vs. alto volume), separados por uma semana. Antes e imediatamente após os protocolos de TF, avaliaram-se os seguintes parâmetros: pressão arterial sistólica (PAS), pressão arterial diastólica (PAD), frequência cardíaca (FC) e concentração de lactato sanguíneo ($[La^-]$). O lançamento da bola medicinal (LBM) foi avaliado antes e 5 minutos após os protocolos; a altura do salto vertical com contramovimento (SCM) foi avaliada antes e 6 minutos após os protocolos; e a força de preensão manual absoluta (FPM) foi avaliada antes e 7 minutos após os protocolos. Na linha de base, não se verificaram diferenças significativas entre protocolos nas diferentes variáveis. Após as sessões, ambos os protocolos aumentaram significativamente a PAS (baixo vs. alto volume: 5.3% vs. 10.7%), PAD (5.9% vs. 6.8%), FC (6.8% vs. 17.9%) e $[La^-]$ (86.1 % vs. 200.0%). Além disso, o protocolo de alto volume reduziu significativamente o LBM (-2.5%) e SCM (-8.3%), enquanto o protocolo de baixo volume aumentou significativamente a FPM (3.4%). Assim, os resultados indicaram que ambos os protocolos induziram respostas agudas em parâmetros hemodinâmicos, metabólicos e neuromusculares em idosos. Contudo, verificou-se maior resposta aguda após o protocolo de alto volume, refletindo, assim, maior stress hemodinâmico, metabólico e neuromuscular do que o TF de baixo volume. Além disso, o TF de baixo volume produziu um aumento agudo na força geral.

Estudo 3

Trinta e nove participantes (78.8 ± 6.7 anos) foram divididos por um grupo de controlo (GC; n = 20) e grupo de TF (n = 19). Ao longo de 10 semanas, o grupo de TF realizou duas sessões semanais e a velocidade média de cada repetição foi monitorizada na prensa de pernas e de peito com cargas entre 40-65% 1RM. A série terminou quando os participantes atingiram uma perda de velocidade de 20%. O GC manteve sua rotina diária. No pré e pós-teste, ambos os grupos foram avaliados nas seguintes variáveis: 1RM na prensa de pernas e de peito, FPM, LBM, velocidade de caminhada de 10-m (T10) e levantar e sentar cinco vezes (LS5). No pré-teste, não houve diferenças significativas entre grupos. Após 10 semanas, observaram-se diferenças significativas ($p < 0.001$–0.01) entre grupos no valor de 1RM na prensa de pernas e de peito, LBM com 1 kg e LS5. O grupo de TF realizou um número total de repetições de 437.6 ± 66.1 na prensa de pernas e 296.4 ± 78.9 na prensa de peito. Os resultados demonstraram que a monitorização da perda de velocidade durante o TF é eficaz na prescrição do volume de treino em idosos e que um limiar de 20% melhora a força, potência e capacidade funcional nesta população.

Estudo 4

Quarenta e dois participantes (79.7 ± 7.1 anos) foram divididos por um GC ($n = 21$) e grupo de TF ($n = 21$). Ao longo de 10 semanas, o grupo de TF realizou duas sessões semanais, enquanto o GC manteve a sua rotina diária. Durante as sessões, a velocidade média de cada repetição foi monitorizada na prensa de pernas e de peito com cargas entre 40-65% 1RM. A série terminou quando se atingiu uma perda de velocidade de 10%. No pré e pós-teste, ambos os grupos foram avaliados nas seguintes variáveis: 1RM na prensa de pernas e de peito, FPM, LBM, T10 e LS5. Após 10 semanas, o grupo de TF aumentou significativamente o valor de 1RM na prensa de pernas ($p < 0.001$; *Hedge's g* (g) = 0.55), e de peito ($p < 0.001$; $g = 0.72$), LBM com 1kg ($p < 0.01$; $g = 0.26$), T10 ($p < 0.05$; $g = -0.29$) e LS5 ($p < 0.05$; $g = -0.29$), enquanto o GC aumentou o T10 ($p < 0.05$; $g = 0.15$). No pós-teste, houve diferenças significativas entre grupos no valor de 1RM na prensa de pernas ($p < 0.001$; DM = 14.4 kg) e de peito ($p < 0.001$; DM = 7.52 kg), LBM com 1kg ($p < 0.05$; DM = 0.40 m), T10 ($p < 0.001$; DM = -0.60 s) e LS5 ($p < 0.001$; DM = -1.85 s). Os resultados demostraram que uma perda de velocidade de 10% resulta em poucas repetições por série (prensa de pernas: 5.1 ± 1.2; prensa de peito: 3.6 ± 0.9), mas ainda assim produz melhorias na força, potência e capacidade funcional em idosos.

Estudo 5

Vinte e quatro mulheres e quatorze homens idosos (78.9 ± 7.4 anos) realizaram o teste de cargas progressivas até atingirem 1RM na prensa de pernas horizontal. A velocidade máxima ($V_{máx}$) e a velocidade média ($V_{média}$) alcançadas perante cada peso (kg) foram registadas para análise. Equações de regressão linear foram modeladas para mulheres e homens. Observaram-se relações lineares muito fortes entre ambas as variáveis de velocidade e a carga relativa (% 1RM) na prensa de pernas, tanto nas mulheres ($V_{máx}$: $r^2 = 0.93$ e erro padrão da estimativa (EPE) = 5.96% 1RM; $V_{média}$: $r^2 = 0.94$ e EPE = 5.59% 1RM), como nos homens ($V_{máx}$: $r^2 = 0.93$ e EPE = 5.96% 1RM; $V_{média}$: $r^2 = 0.94$ e EPE =

5.97% 1RM). Os homens apresentaram valores de $V_{máx}$ e $V_{média}$ superiores perante todas as cargas relativas em relação às mulheres (média $V_{máx}$ = 0.81 vs. 0.69 $m \cdot s^{-1}$; média $V_{média}$ = 0.44 vs. 0.38 $m \cdot s^{-1}$), embora as diferenças tenham diminuído à medida que as cargas relativas aumentaram. Os resultados sugerem que a velocidade de movimento é uma variável determinante para estimar com elevada precisão a carga relativa na prensa de pernas horizontal em idosos do sexo masculino e feminino.

Estudo 6

Trinta e dois idosos (17 mulheres; 79.6 ± 7.7 anos) realizaram o teste de cargas progressivas na prensa de peito horizontal até atingirem 1RM. Equações de regressão quadrática foram desenvolvidas para mulheres e homens. Verificou-se uma relação quadrática muito forte entre carga e velocidade na prensa de peito horizontal, tanto nas mulheres ($V_{máx}$: r^2 = 0.97, EPE = 4.5% 1RM; $V_{média}$: r^2 = 0.96, EPE = 5.3% 1RM), como nos homens ($V_{máx}$: r^2 = 0.98, EPE = 3.8% 1RM; $V_{média}$: r^2 = 0.98, EPE = 3.8% 1RM). Os homens apresentaram valores de $V_{máx}$ e $V_{média}$ superiores do que as mulheres perante quase todas as cargas relativas, exceto com 95 e 100% 1RM ($p > 0.05$). Os resultados sugerem que a velocidade de movimento permite estimar com elevada precisão a carga relativa na prensa de peito horizontal em mulheres e homens idosos. Além disso, face às diferenças de velocidade entre mulheres e homens perante um grande espectro de cargas relativas, recomenda-se o uso de equações específicas de acordo com o sexo.

Estudo 7

Trinta e dois idosos (79.3 ± 7.3 anos) realizaram os seguintes testes: LBM, LS5, T10 e teste de cargas progressivas na prensa de pernas e de peito. Regressões quadráticas analisaram i) as relações carga-potência média e máxima na prensa de pernas e de peito e identificaram as cargas que maximizam a produção de potência média ($P_{carga\text{-}média}$) e máxima ($P_{carga\text{-}máx}$), assim como os seus valores absolutos associados de potência média ($P_{média}$) e máxima ($P_{máx}$); ii) as associações entre $P_{média}$ e $P_{máx}$ na prensa de peito com o LBM; iii) as associações entre $P_{média}$ e $P_{máx}$ na prensa de pernas com o LS5 e T10. Na prensa de pernas, a $P_{carga\text{-}média}$ correspondeu a ~66% 1RM, e a $P_{carga\text{-}máx}$ a ~62% 1RM, tanto para mulheres como para homens. Na prensa de peito, a $P_{carga\text{-}média}$ correspondeu a ~62% 1RM e a $P_{carga\text{-}máx}$ a ~56% 1RM, tanto para mulheres como para homens. Verificaram-se diferenças entre a $P_{carga\text{-}média}$ e $P_{carga\text{-}máx}$ dentro e entre os exercícios ($p < 0,01$). A $P_{média}$ e $P_{máx}$ na prensa de peito explicaram ~48% e ~52% da variação no LBM com 1kg e 3kg, respetivamente. Na prensa de pernas, a $P_{média}$ e $P_{máx}$ explicaram ~59% da variação da potência no LS5; contudo, ambas as variáveis não conseguiram explicar a variação no T10 (r^2 ~ 0.02). Este estudo demostra que a carga que maximiza a potência muscular na prensa de pernas e de peito é semelhante entre idosos de ambos sexos, é específica de cada exercício e varia dentro dos exercícios de acordo com a variável de potência analisada. Além disso, este estudo reforça a influência do LBM como um marcador de potência dos membros superiores em idosos.

Estudo 8

Dezoito idosos foram distribuídos aleatoriamente por um grupo de perda de velocidade de 10% (PV10; n = 10; 77.9 ± 11.7 anos) ou 20% (PV20; n = 8; 72.5 ± 10.4 anos) para realizarem um TF de 10 semanas constituído por 2-3 séries e cargas relativas de ~40-65% 1RM. As medições primárias foram: 1RM na prensa de pernas e de peito e perfis carga-velocidade-potência em ambos os exercícios, medidos antes (pré-teste), durante (controlo) e após a intervenção (pós-teste). As medições secundárias foram: FPM, LBM, T10 e LS5, avaliadas no pré e pós-teste. Não se verificaram diferenças entre grupos ($p > 0.05$) em nenhuma variável de estudo em qualquer momento de avaliação. Ambos os grupos aumentaram os valores de 1RM e potência na prensa de pernas e os valores de velocidade na prensa de peito do pré para o teste de controlo e pós-teste, enquanto apenas o PV20 melhorou o valor de potência na prensa de peito do pré para o teste de controlo ($p < 0.05$). Além disso, ambos os grupos melhoraram o LS5, enquanto apenas o PV20 aumentou a FPM e a velocidade no T10 no pós-teste ($p < 0.05$). Estes resultados indicam que o PV10 e o PV20 melhoraram eficazmente a força e potência aplicada na prensa de pernas, a velocidade aplicada na prensa de peito e o desempenho no LS5 em idosos, embora o PV10 seja mais eficiente, dado que exige um menor volume de treino do que o PV20. No entanto, apenas o PV20 melhorou a potência produzida durante a prensa de peito, a FPM e a velocidade no T10.

Conclusão Geral e Futuras Linhas de Investigação

O resultado geral da presente tese de doutoramento indica que a manipulação do volume do TF através da monitorização da perda de velocidade na mesma série apresenta-se como uma abordagem eficaz e eficiente para promover ganhos de força, potência e capacidade funcional em idosos. Assim, esta nova abordagem para prescrever o volume do TF deve ser encarada como um passo em frente na otimização do desenho de intervenções e melhoria da capacidade muscular e funcional em idosos. Em termos práticos, realizar 2-3 séries com uma perda de velocidade de 10% e cargas relativas entre 40-65% 1RM parece ser eficiente para melhorar a força, potência e capacidade funcional em idosos. No entanto, 2-3 séries com uma perda de velocidade de 20% e cargas relativas entre 40-65% 1RM parece ser um estímulo necessário para otimizar os ganhos musculares e funcionais nesta população. Futuros projetos de investigação devem definir a velocidade de movimento como a variável aguda determinante para prescrever e monitorizar o volume do TF em idosos e analisar as alterações nos perfis carga-velocidade-potência e adaptações funcionais ao longo das intervenções. Assim, sugerem-se algumas linhas de investigação a serem exploradas em estudos futuros:

i) Comparar as respostas hemodinâmicas, metabólicas, hormonais e mecânicas agudas e o tempo de recuperação entre diferentes perdas de velocidade na mesma série (p. ex., 10% vs. 20% vs. 30%) e semelhantes cargas relativas (p. ex., 60% 1RM) em adultos de meia-idade e idosos;

ii) Analisar os efeitos a longo prazo de diferentes perdas de velocidade na mesma série (p. ex., 10% vs. 20% vs. 30%) e semelhantes cargas relativas (p. ex., 40-65% 1RM) na força e tamanho muscular, potência e capacidade funcional em adultos de meia-idade e idosos;

iii) Examinar os efeitos agudos e crónicos de semelhantes perdas de velocidade na mesma série (p. ex., 20%) e diferentes cargas relativas (p. ex., 40-60% 1RM vs. 70-90% 1RM) na força e tamanho muscular, potência e capacidade funcional em adultos de meia-idade e idosos;

iv) Identificar, a um nível individual, qual a combinação entre perda de velocidade e carga relativa que promove as necessárias adaptações musculares e funcionais para otimizar o desempenho físico em adultos de meia-idade e idosos.

Abstract

In the last decade, the prescription of resistance training (RT) volume based on monitoring the intra-set velocity loss (VL) in sportsmen has assumed great prominence among coaches and researchers. Nevertheless, to date, its applicability and efficacy in optimizing muscle and functional gains in older adults are unknown. Therefore, the general aim of the thesis was to analyze the effects of manipulating the RT volume through monitoring VL on strength, power, and functional capacity in older adults. As such, the following steps were adopted: i) review of the effects of single vs. multiple sets on muscular and functional adaptations in middle-aged and older adults; ii) comparison of the acute effects of low vs. high RT volume on physiological and neuromuscular parameters in older adults; iii) analysis of the effects of RT with 20% VL on strength, power, and functional capacity in older adults; iv) analysis of the effects of RT with 10% VL on strength, power, and functional capacity in older adults; v) analysis of the load-velocity-power relationship in resistance exercises in older adults; vi) comparison of the effects of 10 weeks of RT with 10% vs. 20% VL on strength, power, and functional capacity in older adults. The main results indicated: i) multiple sets induce greater muscular and functional gains than single sets; ii) high volume produces greater acute physiological and neuromuscular stress than low volume; iii) 10% and 20% VL induce strength, power, and functional capacity gains in older adults; iv) load-velocity regression equations allow estimating with high accuracy the training load in older adults; v) 10% VL is more efficient to induce muscular and functional gains than 20% VL since it needs less training volume; however, 20% VL appears to be necessary to optimize gains. Therefore, the results of the thesis suggest that manipulating the RT volume based on monitoring VL presents itself as an effective and efficient approach to improving strength, power, and functional capacity in older adults. Future studies should follow the defined research lines to strengthen the knowledge on this topic.

Keywords

Resistance training, training volume, velocity loss, muscle strength, functional capacity, aging.

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List of Acronyms

% 1RM	Relative load | Carga relativa
[La$^-$]	Blood lactate concentration | Concentração de lactato sanguíneo
10W	Ten meters walking velocity
1RM	One-repetition maximum | Uma repetição máxima
BM	Body mass
BMI	Body mass index
CG	Control group
CI	Confidence Interval
CMJ	Countermovement jump
CP	Chest press
CV	Coefficient of variation
DBP	Diastolic blood pressure
DM	Diferença média
DMP	Diferença média padronizada
DXA	X-ray absorptiometry
EPE	Erro padrão da estimativa
FC	Frequência cardíaca
FPM	Força de preensão manual absoluta
GC	Grupo de controlo
HGS	Absolute handgrip strength
HR	Heart rate
IC	Intervalo de confiança
ICC	Intra-class correlation coefficient
LBM	Lançamento da bola medicinal
LP	Leg press
LS5	Levantar e sentar cinco vezes
MBT	Medicine ball throw
MD	Mean difference
MDC	Minimal detectable change
MMSE	Mini-mental state examination
MP	Mean power
MP_{max}	Maximal mean power
$MP_{max\text{-}load}$	Relative load that maximizes mean power output

MRI	Magnetic resonance imaging
MV	Mean velocity
PAD	Pressão arterial diastólica
PAS	Pressão arterial sistólica
$P_{carga\text{-}máx}$	Carga relativa que maximiza a potência máxima
$P_{carga\text{-}média}$	Carga relativa que maximiza a potência média
$P_{máx}$	Valor absoluto da carga relativa que maximiza a potência máxima
$P_{max\text{-}load}$	Relative load that maximizes power output
$P_{média}$	Valor absoluto da carga relativa que maximiza a potência média
PP_{max}	Maximal peak power
$PP_{max\text{-}load}$	Relative load that maximizes peak power output
PV	Perda de velocidade na mesma série
PV	Peak velocity
PV10	Perda de velocidade de 10%
PV20	Perda de velocidade de 20%
RCT	Randomized controlled trials | Estudos randomizados controlados
RT	Resistance training
SBP	Systolic blood pressure
SCM	Salto vertical com contramovimento
SEE	Standard error of the estimate
SEM	Standard error of measurement
SMBT	Seated medicine ball throw
SMD	Standardized mean difference
STS	Five-repetition sit-to-stand
T10	Ten meters walking velocity | Velocidade de caminhada de 10 metros
TF	Treino de força
TUG	Timed-up and go
VL	Velocity loss
VL10	Velocity loss of 10%
VL20	Velocity loss of 20%
$V_{máx}$	Velocidade máxima
$V_{média}$	Velocidade média
xRM	Maximal repetitions

Chapter 1. General Introduction

The EUROPOP2019 projections for the 27 European Union member states estimate an increase of 11% of European older adults (≥ 65 years) from 2019 to 2080 (EUROSTAT, 2020). These numbers align with Portugal's population projections, which estimate an increase of 15% from 2018 to 2080 in the older population (INE, 2020). As a result of this expected exponential increase in the number of older adults, Portugal's aging index will almost double, passing from 159 to 300 older adults for every 100 young people (INE, 2020). These projections should raise concern in the countries' health systems due to the strong links between aging and functional and cognitive decline, multimorbidity, falls, and the appearance of geriatric syndromes, such as frailty (Izquierdo et al., 2021; Murman, 2015; Pereira et al., 2020; Ryan et al., 2015; Xue, 2011).

Based on this evidence, it is of utmost importance to implement effective and efficient public health strategies to prevent and mitigate the loss of skeletal muscle mass, functional capacity, and cognitive function, including the prescription of physical exercise (Izquierdo et al., 2021; Paterson & Warburton, 2010; Pereira et al., 2016; Rosado et al., 2021; Stathi et al., 2022). In this matter, the scientific literature states that exercising muscle groups against external resistances (i.e., a muscle-building activity also known as strength training or resistance training [RT]) is an effective and practical approach for improving muscle strength, muscle power (i.e., the product of force and velocity), functional capacity, cognitive function, and even the perception of quality of life in older adults (Baker et al., 2021; Kekäläinen et al., 2018; Nagai et al., 2018; Otsuka et al., 2022; Persch et al., 2009; Vikberg et al., 2019; Westcott, 2012).

During RT programs, a core process that coaches, sport-related professionals, and researchers need to be aware of is the manipulation of the acute RT variables (e.g., duration, weekly frequency, volume, load or intensity, exercise selection and order, and movement velocity) to improve sports performance and health (Bird et al., 2005; Fox et al., 2021; Fragala et al., 2019; Kraemer & Ratamess, 2004; Spiering et al., 2008). For example, in older adults, several meta-analyses suggested that during traditional RT (i.e., repetitions performed at controlled velocity [~2 seconds for the concentric and eccentric phases]), high relative loads produce greater muscle mass and strength gains than low relative loads (e.g., 80% of one-repetition maximum [1RM] vs. 45% 1RM) (Csapo & Alegre, 2016; Latham et al., 2004; Peterson et al., 2010; Steib et al., 2010). On the other hand, performing repetitions at maximal intended velocities at 40-65% 1RM seems to promote greater muscle power and functional capacity gains than traditional RT in older people (Balachandran et al., 2022; el Hadouchi et al., 2022; Fragala et al., 2019; Marques et al., 2013). Therefore, prescribing low-to-moderate relative loads seem to be a practical approach to improving physical function in older adults, especially those without a training background (Fragala et al., 2019). However, to date, there is no scientific consensus regarding the optimal volume of RT (e.g., the number of sets performed per exercise) to improve muscle strength and size, and functional capacity in this population (Borde et al., 2015; Peterson et al., 2010; Polito et al., 2021b; Raymond et al., 2013; Santana et al., 2021; Steib et al., 2010).

Indeed, most experimental studies that compared the effects of single vs. multiple sets (i.e., one vs. three sets per exercise) did not find differences between sets in improving muscle strength (Abrahin et al., 2014; Antunes et al., 2021; Correa et al., 2014, 2015; Cunha et al., 2020; Galvão & Taaffe, 2005; Polito et al., 2021a; Radaelli et al., 2013, 2014b, 2018), muscle size (Antunes et al., 2021; Correa et al., 2014; Cunha et al., 2017, 2020; Galvão & Taaffe, 2005; Radaelli et al., 2013, 2014b, 2018; Ribeiro et al., 2015), and functional capacity (Abrahin et al., 2014; Galvão & Taaffe, 2005; Radaelli et al., 2018) in older adults. Some authors suggested that the lack of differences might be related to the untrained status at the beginning of the intervention, in which a minimal stimulus during its course might be enough to increase strength and functional capacity in older adults (Fragala et al., 2019; Radaelli et al., 2014a). However, it is speculated that the higher the RT duration (i.e., > 12 weeks), the higher the strength gains of multiple sets compared to single sets (Antunes et al., 2021; Galvão & Taaffe, 2005; Radaelli et al., 2014a). Nevertheless, given the lack of meta-analyses directly comparing the effects of single vs. multiple sets performed per exercise on muscular and functional gains in older adults, it seems relevant to combine the results of these studies to derive a pooled estimate of the effect size for a better understanding of the differences between sets and the influence of RT duration on these outcomes (Study 1).

Another critical observation derived from the analyses of the experimental research comparing single vs. multiple sets on health outcomes in older adults is that most prescribed repetitions to muscle failure, also known as maximal repetitions (e.g., 10RM) (Abrahin et al., 2014; Antunes et al., 2021; Correa et al., 2014, 2015; Cunha et al., 2017, 2018, 2020; Galvão & Taaffe, 2005; Radaelli et al., 2013, 2014a, 2014b; Ribeiro et al., 2015). About this highly debated issue within the scientific community, plenty of longitudinal-experimental research observed that maximal repetitions do not produce higher muscle strength and power/functional gains than submaximal repetitions in young (Izquierdo-Gabarren et al., 2010; Izquierdo et al., 2006; Martorelli et al., 2017; Sampson & Groeller, 2016) and older adults (Cadore et al., 2018a; Silva et al., 2018; Teodoro et al., 2019). Moreover, evidence from acute studies found that RT protocols to failure, especially those with more sets and repetitions, produce greater acute cardiovascular stress than lower RT volumes in older adults (Tajra et al., 2015; Vale et al., 2018). For this reason, some researchers do not recommend repetitions to failure in hypertensive individuals and those with other cardiovascular diseases (Cadore et al., 2018b; Domingues et al., 2021).

Additionally, literature conducted with strength-trained young adults observed that protocols to failure with a high number of repetitions resulted in higher increases in blood lactate and ammonia and higher decreases in movement velocity and jump height than submaximal protocols immediately after and 48 hours post-training (González-Badillo et al., 2016; Morán-Navarro et al., 2017; Pareja-Blanco et al., 2017a, 2018; Sánchez-Medina & González-Badillo, 2011). These data indicate that avoiding muscle failure might decrease neuromuscular fatigue and recovery time within and between training sessions. Nevertheless, it remains unclear whether performing repetitions to (or close to) muscle failure causes a higher acute metabolic and neuromuscular stress than submaximal repetitions after an RT session in older adults. Therefore, future research is needed to gain deeper insights into the acute physiological and physical demands following low- and high-volume RT sessions in older adults (Study 2).

Another issue that deserves attention is that performing maximal repetitions per set during RT also increases the interindividual variability in the number of repetitions performed in young (González-Badillo et al., 2017; Rodríguez-Rosell et al., 2018, 2019; Shimano et al., 2006) and older adults (Farinatti et al., 2013; Grosicki et al., 2014; Jesus et al., 2018; Silva et al., 2009). For example, research conducted with older women and men observed that the maximal number of repetitions completed at 80% 1RM in the leg press ranged between 2-38 (target number: 8; average number of repetitions performed: 11) (Grosicki et al., 2014). Moreover, performing maximal repetitions in the first set is associated with a decrease in the number of repetitions completed in the following sets (Farinatti et al., 2013; Jambassi-Filho et al., 2019; Jesus et al., 2018; Silva et al., 2009). Therefore, when prescribing a fixed number of maximal repetitions per set, it is expectable to observe i) a considerable variability between individuals in the number of repetitions performed (González-Badillo et al., 2017;

Grosicki et al., 2014) and ii) a gradual decrease in the number of repetitions completed in the following sets due to a significant accumulation of muscle fatigue (Jambassi-Filho et al., 2019). Therefore, to overcome the inherent limitations of the traditional volume prescription (pre-determined number of repetitions), the research group led by Professor González-Badillo proposed monitoring the intra-set decrease in repetition velocity to objectively control the number of repetitions performed and quantify the degree of neuromuscular fatigue (González-Badillo et al., 2017; Rodríguez-Rosell et al., 2019). This monitoring process can be done by defining beforehand a velocity loss threshold to be reached during the set (e.g., 10% or 20%). In this sense, once the individual reaches the programmed relative velocity loss, no more repetitions should be performed, and the set ends (González-Badillo et al., 2011, 2017; Rodríguez-Rosell et al., 2018, 2019).

Over the last decade, cross-sectional research conducted with strength-trained young adults has shown that monitoring intra-set velocity loss is an objective and practical means of quantifying acute metabolic and hormonal stress and mechanical fatigue during RT (González-Badillo et al., 2016, 2017; Pareja-Blanco et al., 2017a; Sánchez-Medina & González-Badillo, 2011). Moreover, longitudinal-experimental research was also conducted to compare the effects of different intra-set velocity loss thresholds on muscle strength, power, and physical performance in strength-trained young adults. Interestingly, a common finding in the longitudinal studies was that performing half or even less than half the maximum number of possible repetitions during the set (e.g., 10% velocity loss) was enough to achieve similar or even greater strength and power gains than a high number of repetitions performed to (or close to) failure (e.g., 40% velocity loss) (Galiano et al., 2020; Pareja-Blanco et al., 2017b, 2017c, 2020a, 2020b; Rodiles-Guerrero et al., 2020; Rodríguez-Rosell et al., 2020). These data suggest that lower relative velocity losses are more efficient than higher ones since the muscle strength and power gains are achieved by performing fewer repetitions per set. Therefore, due to these valuable findings, velocity-based or velocity-monitored RT has assumed great practical relevance among coaches and researchers in the past few years in prescribing RT programs and assessing and monitoring performance. Nevertheless, whether these scientific findings apply to different populations, namely untrained older adults, remains unclear in the literature. In this sense, the effects of different intra-set velocity loss thresholds on strength, power, and functional capacity should be analyzed to understand the practicability and efficacy of this novel RT approach to monitoring the volume in older adults (Studies 3 and 4).

Measuring movement velocity during RT has also been recognized as a valid parameter for monitoring the relative load (% 1RM) in strength-trained young adults (González-Badillo & Sánchez-Medina, 2010; Sánchez-Medina et al., 2017). By measuring the fastest repetition in the set (usually the first or second repetition), coaches and researchers can objectively understand if the individual is training according to the programmed relative load. This knowledge is derived from the load-velocity relationship, which assumes that every relative load (% 1RM) has its associated velocity value (González-Badillo & Sánchez-Medina, 2010; Sánchez-Medina et al., 2017). Therefore, knowing these relationships allow coaches and researchers to prescribe target velocities to be reached in the set and examine if the individual is training according to the programmed relative load. Although the load-velocity relationship in resistance exercises has been extensively examined in strength-trained young adults (González-Badillo & Sánchez-Medina, 2010; Morán-Navarro et al., 2020; Sánchez-Medina et al., 2017), its analysis in older adults is almost nil, thus reinforcing the importance for further analyses on this topic.

To date, the only known study was developed with strength-trained older women aged ~68 years and analyzed the load-velocity relationship in the 45° inclined leg press and free-weight bench press exercises (Marcos-Pardo et al., 2019). Although that study presented novel and insightful findings, the proposed regression equations to estimate the relative loads might only apply to strength-trained older women using the inclined leg press and free-weight bench press exercises. Consequently, future research with untrained older women and men is needed to analyze the load-velocity relationship in different resistance exercises, including the horizontal leg press (Study 5) and seated chest press (Study 6), as they are the most common exercises used in geriatric research (Alcazar et al., 2018). Furthermore, as muscle power is a significant predictor of functional capacity in the older population (Byrne et al., 2016; Reid & Fielding, 2012), the analysis of the load-power relationship will allow identifying the relative loads that maximize power output in both exercises (Study 7) and help design future interventions oriented to optimize muscle power production in this population. Finally, because of performing the previously mentioned analyses, it will be possible to design longitudinal-experimental research comparing the effects of different intra-set velocity losses with relative loads prescribed using target velocities on muscle strength, power, and functional capacity in older adults (Study 8).

Given the considerations mentioned above, the general purpose of the present Ph.D. thesis was to analyze the effects of manipulating the RT volume through monitoring the intra-set velocity loss on muscle strength, power, and functional capacity in older adults. In order to achieve the general purpose, a sequence of studies was defined, which makes up the following thesis structure:

Chapter 2 presents a systematic review with meta-analysis to compare the effects of single vs. multiple sets performed per exercise on muscle strength and size, muscle quality, and functional capacity in middle-aged and older adults (Study 1). After that, Chapter 3 compiles the experimental research conducted to achieve the primary purpose of the thesis, including the following studies:

- Study 2 compares the acute effects of low- and high-RT volumes with the same relative load on hemodynamic, metabolic, and neuromuscular performance in older adults.
- Study 3 analyzes the effects of a 10-week velocity-monitored RT program with a 20% velocity loss and relative loads at 40-65% 1RM on muscle strength, power, and functional capacity in older adults.
- Study 4 examines the effects of a 10-week velocity-monitored RT program with a 10% velocity loss and relative loads at 40-65% 1RM on muscle strength, power, and functional capacity in older adults.
- Study 5 investigates the load-velocity relationship in the horizontal leg press in older women and men.
- Study 6 analyzes the load-velocity relationship in the seated chest press in older women and men.
- Study 7 examines the load-power relationship in the leg press and chest press in older women and men.
- Study 8 compares the effects of 10% vs. 20% velocity loss with relative loads at 40-65% 1RM on older adults' strength, power, and functional capacity.

Then, a general discussion of the results obtained in the different studies is presented in Chapter 4, followed by the main conclusions of the thesis in Chapter 5. Finally, Chapter 6 presents suggestions for future research.

Chapter 2. Literature Review

Study 1. Manipulating the Resistance Training Volume in Middle-Aged and Older Adults: A Systematic Review with Meta-Analysis on the Effects on Muscle Strength and Size, Muscle Quality, and Functional Capacity

Abstract

Objectives: The effects of single vs. multiple sets per exercise on muscle strength and size, muscle quality, and functional capacity in middle-aged and older adults were compared. Moreover, the effects of single vs. multiple sets per exercise on muscular and functional gains were also examined, considering the influence of training duration. **Methods:** Randomized controlled trials (RCTs) and non-RCTs comparing single vs. multiple sets per exercise on muscle strength, muscle size, muscle quality, or functional capacity in middle-aged and older adults (≥ 50 years) in the PubMed/MEDLINE, Web of Science, and Scopus databases (01/09/2021, updated on 15/05/2022) were identified. A random-effects meta-analysis was used. **Results:** Fifteen studies were included (430 participants; 93% women; 57.9–70.1 years). Multiple sets per exercise produced a greater effect than single sets on lower-limb strength (standardized mean difference (SMD) = 0.29; 95% confidence interval (CI) = 0.07-0.51; mean difference (MD) = 1.91 kg; 95% CI = 0.50–3.33) and muscle quality (SMD = 0.40; 95% CI = 0.05–0.75) gains. There were no differences between single vs. multiple sets per exercise for upper-limb strength (SMD = 0.13; 95% CI = -0.14–0.40; MD = 0.11 kg; 95% CI = -0.52–0.75), muscle size (SMD = 0.15; 95% CI = -0.07–0.37), and functional capacity (SMD = 0.01; 95% CI = -0.47–0.50) gains. In addition, there were no differences between single vs. multiple sets on muscle strength and size gains for training durations ≤ 12 weeks or > 12 weeks. **Conclusions:** Multiple sets per exercise produced greater lower-limb strength and muscle quality gains than single sets in middle-aged and older adults, although the magnitude of the difference was small. On the other hand, single sets per exercise were sufficient to improve upper-limb strength, muscle size, and functional capacity in these populations. Despite these findings, researchers should conduct future high-quality pre-registered and blinded RCTs to strengthen the scientific evidence on this topic.

Introduction

The aging process leads to a progressive loss of muscle mass and a reduction in the ability to generate strength during basic tasks of daily life (e.g., walking or standing up from a chair), which compromises functional independence and increases the risk of falls and death in the older population (Brahms et al., 2021; Chen et al., 2021; Doherty, 2003; Mitchell et al., 2012; Rodrigues et al., 2022; Shur et al., 2021). In this sense, the scientific literature advocates the implementation of resistance training (RT) as an effective preventive strategy to counteract the age-related decline of muscle mass, strength, and functional capacity, as well as to prevent falls and increase the quality of life in middle-aged and older adults (Baker et al., 2021; Kekäläinen et al., 2018; Nagai et al., 2018; Otsuka et al., 2022; Persch et al., 2009; Vikberg et al., 2019).

Designing RT programs involves the manipulation of several acute RT variables, namely duration (i.e., weeks), weekly frequency, volume, intensity, exercise selection and order, as well as movement velocity (Bird et al., 2005; Kraemer & Ratamess, 2004; Spiering et al., 2008). Effective manipulation of these variables is fundamental to optimizing the gains of muscle mass, strength, and functional capacity in both healthy and frail older adults (Fragala et al., 2019; Marques et al., 2013; Talar et al., 2021). For example, previous meta-analyses demonstrated that higher intensities might induce greater muscle mass and strength gains than lower intensities (e.g., 80% 1RM vs. 45% 1RM) in middle-aged and older adults (Csapo & Alegre, 2016; Latham et al., 2004; Peterson et al., 2010; Steib et al., 2010). However, the optimal volume of RT (e.g., number of sets performed per exercise) to increase muscle mass and strength gains in middle-aged and older adults remains inconclusive (Borde et al., 2015; Peterson et al., 2010; Polito et al., 2021b; Raymond et al., 2013; Santana et al., 2021; Steib et al., 2010). For example, a meta-analysis suggested increases in muscle strength after 2-3 sets (standardized mean difference [SMD] of 2.99) (Borde et al., 2015), while others did not observe a dose-response relationship between the number of sets performed per exercise and muscle strength gains (Peterson et al., 2010; Raymond et al., 2013; Steib et al., 2010).

Similarly, a meta-analysis with individuals aged 50 years and older found that a high number of sets per exercise session was associated with 1-3 kg lean body mass changes (Peterson et al., 2011), while another meta-analysis indicated that the number of sets could not predict changes in muscle morphology (SMD of 0.78; less than three studies included) in older adults (Borde et al., 2015). From a physiological perspective, multiple sets increase the acute anabolic signaling (i.e., elevation in phosphorylation of key signaling molecules such as p70 ribosomal protein S6 kinase [p70S6K], which seems to enhance muscle protein synthesis rate) to a greater extent than single sets, which might eventually favor muscle hypertrophy in the long-term, namely in young adults (Arantes et al., 2020; Burd et al., 2010; Gonzalez et al., 2015; Terzis et al., 2010). However, as aging is associated with anabolic resistance of muscle protein synthesis rates (Burd et al., 2013; Drummond et al., 2012; Endo et al., 2020; Paulussen et al., 2021), this factor might attenuate muscle mass gains and mask the benefits of performing multiple sets rather than single sets in middle-aged and older adults. Therefore, the discrepancy between previous meta-analyses regarding the training volume suggests that further reviews that include only studies comparing the effects of low vs. high volume (e.g., single vs. multiple sets per exercise) are needed to examine their eventual differences in gains in muscle strength and size in middle-aged and older adults.

Most experimental studies that analyzed the effects of RT volume on muscle and functional adaptations in middle-aged or older adults focused on comparing single vs. multiple sets per exercise, maintaining most training variables equal between groups (e.g., duration, frequency, repetitions, intensity, and exercise selection and order) and generally observed contradictory findings. For example, a few studies reported significantly higher lower-limb strength gains after multiple sets than single sets (e.g., 26-52% vs. 17-37%, respectively) (Radaelli et al., 2014a; Ribeiro et al., 2015), while most failed to observe differences between the number of sets (e.g., 4-54% vs. 0.2-65%, respectively) (Abrahin et al., 2014; Antunes et al., 2021; Correa et al., 2014, 2015; Cunha et al., 2020; Galvão & Taaffe, 2005; Polito et al., 2021a; Radaelli et al., 2013, 2014b, 2018). In addition, most studies did not observe differences between single vs. multiple sets for muscle size (e.g., 1-28% vs. 2-29%, respectively) or muscle quality (e.g., 11-19% vs. 15-22%, respectively) (Antunes et al., 2021; Correa et al., 2014; Cunha et al., 2017, 2018, 2020; Galvão & Taaffe, 2005; Radaelli et al., 2013, 2014b, 2018, 2019), as well as for functional capacity (e.g., 2-11% vs. 3-16%, respectively) (Abrahin et al., 2014; Galvão & Taaffe, 2005; Radaelli et al., 2018). The similarity of muscular and functional gains between single vs. multiple sets might be linked to the untrained status, in which a minimal stimulus seems sufficient to improve physical performance in older adults, at least in the early phase of RT (Fragala et al., 2019; Radaelli et al., 2014a). Nevertheless, some authors indicate that multiple sets per exercise might be more advantageous than single sets during training periods longer than twelve weeks (Antunes et al., 2021; Galvão & Taaffe, 2005; Radaelli et al., 2014a). However, despite these suggestions, it is still unclear whether pooling data from studies comparing single vs. multiple sets per exercise with different RT durations favors one or three sets in the long term.

Given the above considerations, the aim of this study was to conduct a systematic review with meta-analysis to synthesize the evidence and compare the effects of single vs. multiple sets performed per exercise on muscle strength and size, muscle quality, and functional capacity in middle-aged and older adults. In addition, the purpose was to analyze the effects of single vs. multiple sets on muscle and functional gains, considering the influence of the RT duration. Based on the main findings of the experimental research cited above, it was hypothesized that there would not be significant differences between single vs. multiple sets per exercise in improving muscle strength and size, muscle quality, and functional capacity in middle-aged and older adults. In addition, it was hypothesized that multiple sets per exercise would produce significantly higher muscular and functional gains than single sets for training durations longer than twelve weeks in middle-aged and older adults.

Methods

Protocol and Registration

This study was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Page et al., 2021) and the protocol was prospectively registered in PROSPERO (CRD42021277506).

Search Strategy

A comprehensive search was performed on the PubMed/MEDLINE, Web of Science, and Scopus web databases from inception through September 1, 2021, updated on May 15, 2022. In parallel, it was performed a grey literature search in Google Scholar. Studies written in English, Portuguese, or Spanish were considered comparing the effects of single vs. multiple sets per exercise on muscle strength, muscle size, muscle quality, or functional capacity in middle-aged and older adults. The following Boolean search strategy was used: ("resistance training" OR "resistance exercise" OR "resistive training" OR "resistive exercise" OR "strength training" OR "strength exercise" OR "strengthening" OR "weight training" OR "weight lifting" OR "weightlifting") AND (“ageing” OR “aging” OR "older adults" OR “older men” OR “older women” OR "elderly" OR “elderly men” OR “elderly women” OR "seniors" OR “middle age*”) AND ("training volume" OR “volume*” OR "low volume" OR "high volume" OR “set*” OR “repetition*” OR “number of sets” OR "single set" OR "multiple sets" OR "multiset" OR “failure”). Two independent reviewers (DLM and HPN) conducted the initial screening.

Study Selection

PICOS (population, intervention, comparison, outcomes, and study design) approach was used to define the eligibility criteria (Methley et al., 2014). Table 1 presents the inclusion and exclusion criteria. Two reviewers (DLM and HPN) independently screened titles and abstracts, reviewed the full texts, and hand-searched the references from the retrieved articles to find additional articles that met the inclusion criteria. Disagreements were resolved by consensus.

Table 1. Eligibility criteria following the PICOS approach.

Category	Inclusion criteria	Exclusion criteria
Population	Individuals (women or men, or both) aged ≥ 50 years[a] with or without comorbidities.	Children, adolescents, and adults (under 50 years old).
Intervention	Resistance training interventions (≥ 6 weeks) using resistance machines or combining resistance machines with free weights and bodyweight exercises. Experimental interventions labeled "Power Training" were also included.	Blood flow restriction resistance training interventions. Resistance training combined with endurance training (i.e., concurrent training).
Comparison	Single vs. multiple sets per exercise with the other acute resistance training variables equivalent between groups (i.e., duration, frequency, repetitions per set, relative load, movement velocity, and exercise selection and order).	Lack of intervention group for comparison. Comparison between multiple sets (e.g., three vs. six sets). Interventions that did not hold constant the number of sets in both groups during the intervention (e.g., three sets prescribed on the first week and four on the eighth week).
Outcomes	Changes from pre-test to post-test in muscle strength (i.e., 1RM or xRM tests), or muscle size (i.e., muscle regions measured using magnetic resonance imaging, or B-mode ultrasonography, or X-ray absorptiometry, or anthropometric techniques, or predictive equations), or muscle quality (i.e., the ratio between muscle strength and muscle size assessments), or functional capacity (i.e., walking tests, or sit-to-stand tests, or a combination between both tests)	No pre-test or post-test data.
Study design	Randomized and non-randomized controlled trials.	Observational studies, systematic reviews, and meta-analysis.

[a] This age limit was set because some evidence indicates that the fifth decade of life coincides with the beginning of the decline of skeletal muscle mass, strength, muscle quality, and functional capacity (Abe et al., 2016; Deschenes, 2004; Faulkner et al., 2007; Janssen et al., 2000; Kennis et al., 2014; Suetta et al., 2019).

Data Extraction

Two independent reviewers (DLM and HPN) exported the results from the web databases to Microsoft Office Excel®. The extracted data consisted of the following: i) study (authors, year, country, study design); ii) population (sample size, sex, age, body mass, body height, body mass index [BMI], and health, functional, and training status); iii) RT program characteristics (duration, frequency, sets, repetitions, intensity, concentric and eccentric velocity, inter-set rest, session duration, resistance exercises);

iv) data of the outcome measures (mean ± standard deviation (SD) of the outcomes of interest associated with muscle strength, muscle size, muscle quality, or functional capacity). Data on adverse events or injuries directly related to the intervention, the attendance rate (% of sessions completed), and the retention rate (% of participants who completed the intervention) were also extracted. The final sample size was divided by the initial and multiplied by 100 to calculate the retention rate (%). In cases in which the studies presented three or more experimental groups (e.g., one vs. two vs. three sets), only the minimum and maximum sets data were extracted to represent the single and multiple sets groups, respectively. If a study reported multiple time points in which the outcomes of interest were assessed, only the first and last assessment data were extracted. When the studies did not report the SD, the RevMan calculator (RevMan v5.4, Cochrane Collaboration, Oxford, UK) was used to calculate it. Finally, the WebPlotDigitizer v4.5 was used to extract the mean ± SD presented in the figures.

Risk of Bias Assessment

For randomized controlled trials (RCTs), Cochrane Risk of Bias Tool 2.0 (RoB 2) (Sterne et al., 2019) was used. The RoB 2 incorporates five domains: i) randomization process; ii) deviations from intended interventions; iii) missing outcome data; iv) measurement of the outcome; v) selection of the reported results. Each domain is rated as either low risk, some concerns, or high risk (Sterne et al., 2019). For non-RCTs, the Risk Of Bias In Non-Randomized Studies of Interventions (ROBINS-I) was used. The ROBINS-I considers bias from seven domains classified by the time of occurrence: pre-intervention (confounding, selection of the study participants), intervention (classification of intervention), and post-intervention (deviations from intended interventions, missing outcome data, measurement of the outcome, and selection of the reported results). The risk of bias judgment for each domain is interpreted as low risk, moderate risk, serious risk, critical risk, or no information (Sterne et al., 2016). Two reviewers (DLM and HPN) independently assessed the risk of bias, and any disagreements were resolved by consensus.

Statistical Analysis

Separate meta-analyses were conducted for lower- and upper-limb muscle strength, muscle size, muscle quality, and functional capacity using the Review Manager software (RevMan v5.4, Cochrane Collaboration, Oxford, UK). A single measure was included for each outcome to avoid inflating the weighting of the individual studies (Schumann et al., 2021). For muscle strength, multi-joint dynamic tests were included to assess the anterior muscle regions (e.g., 1RM leg press/chest press). For muscle size, measures of the whole region of the quadriceps were included. If a study only presented isolated measures, the largest muscles were chosen (e.g., vastus lateralis rather than rectus femoris). Regarding muscle quality, the ratio between muscle strength (e.g., 1RM) and size (e.g., lower-limb muscle thickness) was selected. Finally, for functional capacity, short-distance walking tests, sit-to-stand tests, or a combination of both were selected (e.g., the "TUG" test).

Firstly, the effects of single and multiple sets on each outcome using the pre-test and post-test mean, SD, and sample size (*n*) of every group were analyzed. Secondly, the effects of single vs. multiple sets on each outcome using the mean change (ΔMean = post-test mean – pre-test mean) and the SD change (ΔSD = √ (pre-test SD^2 + post-test SD^2 – (2 x r x pre-test SD x post-test SD))) were compared and calculated for each outcome in each group on an Excel® spreadsheet. Since most studies did not report the ΔSD, an r of 0.70 (Csapo & Alegre, 2016; Orssatto et al., 2019) was used. Finally, the effects of single vs. multiple sets according to training duration (i.e., ≤ 12 weeks or > 12 weeks) were compared on each outcome via a subgroup analysis. Random-effects meta-analyses were used to estimate the pooled SMD (Hedge's *g*) and 95% confidence intervals (CI) with significance set at $\alpha < 0.05$. The magnitude of the SMD was interpreted as small (0.20–0.49), moderate (0.50–0.79), or large (≥0.80) (Cohen, 1988). Along with the SMD, the pooled mean difference (MD) was presented when the studies had the same unit of measurement. The heterogeneity between studies was assessed using the inconsistency test (I^2), in which values above 25%, 50%, and 75% represented low, moderate, and high heterogeneity, respectively (Higgins, 2003). In addition, substantial heterogeneity was suggested if the chi-squared test ($\chi2$) presented a $p < 0.1$. Finally, a funnel plot was used to assess the publication bias when the meta-analysis included more than ten studies (Higgins et al., 2019).

Results

Study Search Results

The initial search resulted in 6590 records (Figure 1). After removing the duplicates, the titles and abstracts of 5559 records were examined, of which 52 were eligible for full-text revision. After revision, 37 articles were excluded for the following reasons: acute effects; age < 50 years; comparison between multiple sets; data pooled with young adults; fluctuations in the number of sets during the intervention; no available data; no comparison between RT volumes; no intervention group for comparison; no outcome measures of interest reported; repeated data. Therefore, 15 studies met the inclusion criteria for the qualitative and quantitative analysis.

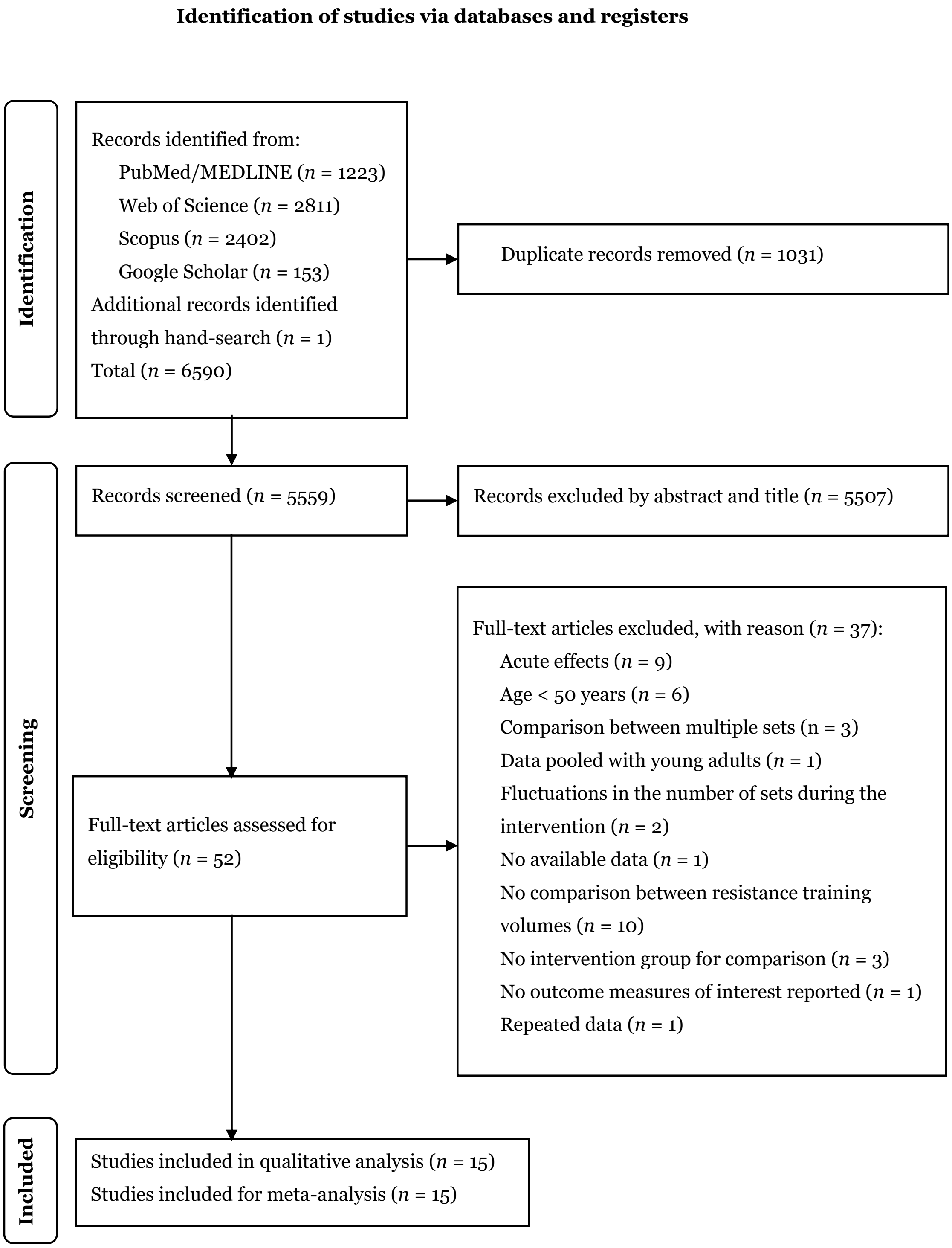

Figure 1. PRISMA flowchart for study inclusion.

Characteristics of the Included Studies

The included studies were six RCTs and nine non-RCTs conducted with functionally independent middle-aged and older adults (*n* = 430; 93% women; 65.6 ± 3.6 years; 66.0 ± 3.5 kg; 159.3 ± 4.5 cm; 25.9 ± 1.2 BMI) (Table 2). Fourteen studies included apparently healthy individuals, and one was conducted with hypertensive individuals (Polito et al., 2021a). All participants were untrained, except those that underwent a 20-week pre-conditioning phase before engaging in the main intervention (Antunes et al., 2021). The RT programs lasted 12.4 ± 3.6 weeks (range: 6-20 weeks) with 2.7 ± 0.8 sessions p/week (range: 2-5 sessions p/week). The single and multiple sets groups performed respectively 1 and 3 sets per exercise, and both performed 12.5 ± 3.8 repetitions per set (range: 6-20 repetitions per set) at relative loads varying between 30-70% 1RM, 6-20RM, or 5-7 according to the OMNI scale, with concentric and eccentric velocities between 1.3 ± 0.6 seconds and 2.0 ± 0.0 seconds, respectively. There was no inter-set rest in the single set groups, while in the multiple set groups, it was 103.2 ± 45.0 seconds (range: 40-180 seconds). In both groups, the number of resistance exercises per session prescribed was 7.7 ± 1.6 (range: 4-10 resistance exercises) and included 3.7 ± 1.0 lower body exercises (e.g., leg press, knee extension, knee flexion) and 4.0 ± 0.9 upper body exercises (e.g., chest press, lat pull down, biceps curl). The sessions lasted 22.1 ± 6.4 minutes (range: 15-30 minutes) in the single set groups and 47.1 ± 3.9 minutes (range: 40-50 minutes) in the multiple set groups. No study reported any adverse events or injuries directly related to the intervention. Finally, the attendance rate was between 80-100% in both groups, while the retention rate was 92 ± 9% (range: 73-100%) in the single set groups and 90 ± 9% (range: 53-100%) in the multiple set groups.

Table 2. Main characteristics of the included studies.

Study; Country; Study design	Group (*n; age*; BMI)	Duration (weeks)	Session`s p/ week	Sets	Reps	Relative intensity	Velocity (con-ecc, s)	Inter-set rest (s)	Session duration (min)	Attendance & retention rates	Resistance exercises
Abrahin et al. (2014); Brazil; Non-RCT	SS (11; 67.1; 27.9)	12	2	1	8-12	8-12RM	2-2	-	20	NR; 73%	BP, DL, UR, SCR, and ABS.
	MS (8; 69.4; 27.7)			3	8-12	8-12RM	2-2	120	50	NR; 53%	
Antunes et al. (2021); Brazil; Non-RCT	SS (20; 70.1; 25.6)	8	3	1	8-12	8-12RM	1-2	-	NR	>85%; 91%	CP, LP, SR, LE, PC, LC, TE, SCR.
	MS (18; 67.4; 28.3)			3	8-12	8-12RM	1-2	60-120	NR	>85%; 82%	
Correa et al. (2014); Brazil; RCT	SS (12; 59.5; 26.1)	12	5	1	15	15RM	NR	-	20	NR; 100%	BP, BC, TH, SABR, LP, KE, KF, and AC.
	MS (11; 59.5; 25.4)			3	15	15RM	NR	40	40	NR; 100%	
Correa et al. (2015); Brazil; RCT	SS (13; 58.9[a]; 26.1)	11	3	1	15	15RM	NR	-	15	NR; 100%	BP, BC, TH, SABR, LP, KE, KF, and AC.
	MS (12; 58.9[a]; 25.4)			3	15	15RM	NR	40	45	NR; 100%	

Table 2. Continued.

Study; Country; Study design	Group (*n; age*; BMI)	Duration (weeks)	Session`s p/ week	Sets	Reps	Relative intensity	Velocity (con-ecc, s)	Inter-set rest (s)	Session duration (min)	Attendance & retention rates	Resistance exercises
Cunha et al. (2020); Brazil; RCT	SS (21; 70.1; 27.8)	12	3	1	10-15	10-15RM	1-2	-	15	≥85%; 91%	CP, LP, SR, KE, PC, LC, TP, and SCR.
	MS (20; 68.6; 26.7)			3	10-15	10-15RM	1-2	60-120	45	≥85%; 87%	
Cunha et al. (2017); Brazil; RCT	SS (21; 66.6; 27.1)	12	3	1	10-15	10-15RM	1-2	-	30	≥85%; 91%	CP, LP, SR, KE, PC, LC, TP, and SCR.
	MS (20; 68.3; 26.7)			3	10-15	10-15RM	1-2	60-120	50	≥85%; 87%	
Cunha et al. (2018); Brazil; RCT	SS (20; 69.7; 28.2)	12	3	1	10-15	10-15RM	1-2	-	NR	>85%; 87%	CP, LP, SR, KE, PC, LC, TP, and SCR.
	MS (20; 68.2; 26.7)			3	10-15	10-15RM	1-2	60-120	NR	>85%; 87%	
Galvão & Taaffe (2005); Australia; Non-RCT	SS (12; 68.9; 25.7)	20	2	1	8	8RM	NR	-	NR	NR%; 75%	CP, SR, TE, BC, LP, LC, and LE.
	MS (16; 69.7; 26.4)			3	8	8RM	NR	NR	NR	NR%; 100%	

Table 2. Continued.

Study; Country; Study design	Group (*n; a*ge; BMI)	Duration (weeks)	Session`s p/ week	Sets	Reps	Relative intensity	Velocity (con-ecc, s)	Inter-set rest (s)	Session duration (min)	Attendance & retention rates	Resistance exercises
Polito et al (2021a); Brazil; RCT	SS (14; 58.1; 24.8[b])	12	3	1	12-15	5-7 OMNI	NR	-	NR	≥80%; 100%	BP, KE, LPD, LP.
	MS (12; 57.9; 25.4[b])			3	12-15	5-7 OMIN	NR	60-90	NR	≥80%; 100%	
Radaelli et al. (2014a); Brazil; Non-RCT	SS (11; 63.7; 24.8)	20	2	1	6-20	6-20RM	2-2	-	NR	≥95%; 92%	KE, LPD, LP, DEF, LC, BP, TE, HAB, HAD, and AC.
	MS (9; 62.9; 23.8)			3	6-20	6-20RM	2-2	120	NR	≥95%; 75%	
Radaelli et al. (2013); Brazil; Non-RCT	SS (11; 64.6; 25.0[b])	13	2	1	10-20	10-20RM	2-2	-	20-25	NR; 100%	KE, LPD, LP, EF, LC, BP, TE, HAB, HAD, and AC.
	MS (9; 63.9; 24.1[b])			3	10-20	10-20RM	2-2	120	50-60	NR; 100%	
Radaelli et al. (2014b); Brazil; Non-RCT	SS (14; 64.7; 24.1)	6	2	1	15-20	15-20RM	2-2	-	NR	100%; 100%	LP, UEF, KE, LPD, LC, TE, BP, HAB, HAD, and AC.
	MS (13; 64.1; 24.9)			3	15-20	15-20RM	2-2	120	NR	100%; 100%	

Table 2. Continued.

Study; Country; Study design	Group (*n; age*; BMI)	Duration (weeks)	Session`s p/ week	Sets	Reps	Relative intensity	Velocity (con-ecc, s)	Inter-set rest (s)	Session duration (min)	Attendance & retention rates	Resistance exercises
Radaelli et al. (2018); Brazil; Non-RCT	SS (13; 64.8; 25.5[b])	12	2	1	8-12	30-60% 1RM	<1-2/3	-	NR	≥95%; 87%	KE, LPD, LC, DEF, HAB, HAD, and EE.
	MS (13; 66.2; 25.2[b])			3	8-12	30-60% 1RM	<1-2/3	180	NR	≥95%; 87%	
Radaelli et al. (2019); Brazil; Non-RCT	SS (13; 64.8; 25.5[b])	12	2	1	8-12	30-60% 1RM	<1-2/3	-	30	86%; 87%	KE, LPD, LC, DEF, HAB, HAD, and EE.
	MS (13; 66.2; 25.2[b])			3	8-12	30-60% 1RM	<1-2/3	180	50	86%; 87%	
Ribeiro et al. (2015); Brazil; Non-RCT	SS (15; 65.6; 25.8)	12	3	1	10-15	10-15RM	1-2	-	NR	>85%; 100%	CP, LP, SR, KE, PC, LC, TP, and SCR.
	MS (15; 67.1; 26.2)			3	10-15	10-15RM	1-2	60-120	NR	>85%; 100%	

ABS abdominal exercises, *AC* abdominal crunch, *BC* biceps curl, *BMI* body mass index, *BP* bench press, *Con-Ecc, s* concentric and eccentric actions duration, in seconds, *CP* chest press, *DEF* dumbbell elbow flexion, *DL* deadlift, *EE* elbow extension, *EF* elbow flexion, *HAB* hip abduction, *HAD* hip adduction, *KE* knee extension, *KF* knee flexion, *LC* leg curl, *LE* leg extension, *LP* leg press, *LPD* lat pull down, *MS* multiple set, *NR* not reported, *OMNI* perceived exertion scale for resistance exercise, *PC* preacher curl, *RCT* randomized controlled trial, *RM* repetition maximum, *SABR* single-arm back row, *SCR* standing calf raises, *SR* seated row, *SS* single set, *TE* triceps extension, *TH* triceps halter, *TP* triceps pushdown, *UEF* unilateral elbow flexion, *UR* unilateral row.

[a] The authors presented the average age for the entire sample.

[b] Data are an estimation based on the average body mass and height values reported by the authors.

Risk of Bias Assessment

Table 3 shows the risk of bias assessment for RCTs. For muscle strength, three studies presented an overall rating of some concerns (Correa et al., 2015; Cunha et al., 2020; Polito et al., 2021a), and one had a high risk of bias (Correa et al., 2014). For muscle size, three studies presented an overall rating of some concern (Correa et al., 2015; Cunha et al., 2017, 2020), and one had a high risk of bias (Correa et al., 2014). Finally, for muscle quality, all studies (two) had an overall rating of some concern (Cunha et al., 2018, 2020). None RCT assessed functional capacity. In general, the rating for some concern came about for the following reasons: i) randomization process (i.e., lack of information regarding the allocation sequence or if there were significant differences between groups on the outcome measure at baseline); ii) measurement of the outcome (i.e., the measurement could have been influenced by the participant's and assessor's knowledge regarding the intervention); and iii) selection of the reported result (i.e., lack of trial registrations or a pre-specified analysis plan in the protocol). On the other hand, the high risk of bias rating arose due to the lack of outcome data (i.e., the authors did not present measures of dispersion in the outcomes of interest).

Table 3. Risk of bias assessment (RoB 2) of each outcome in the randomized controlled trials.

Outcome	Study	Randomization process	Deviations from intended interventions	Missing data	Measurement of the outcome	Selection of the reported result	Overall risk of bias
Muscle strength	Correa et al. (2014)	Some concerns	Low risk	High risk	Some concerns	Some concerns	High risk
	Correa et al. (2015)	Some concerns	Low risk	Low risk	Some concerns	Some concerns	Some concerns
	Cunha et al. (2020)	Some concerns	Low risk	Low risk	Some concerns	Some concerns	Some concerns
	Polito et al. (2021a)	Some concerns	Low risk	Low risk	Some concerns	Some concerns	Some concerns
Muscle size	Correa et al. (2014)	Some concerns	Low risk	High risk	Some concerns	Some concerns	High risk
	Correa et al. (2015)	Some concerns	Low risk	Low risk	Some concerns	Some concerns	Some concerns
	Cunha et al. (2020)	Some concerns	Low risk	Low risk	Some concerns	Some concerns	Some concerns
	Cunha et al. (2017)	Some concerns	Low risk	Low risk	Low risk	Some concerns	Some concerns
Muscle quality	Cunha et al. (2020)	Some concerns	Low risk	Low risk	Some concerns	Some concerns	Some concerns
	Cunha et al. (2018)	Some concerns	Low risk	Low risk	Some concerns	Some concerns	Some concerns

Table 4 shows the risk of bias assessment for non-RCTs. For muscle strength, all studies (eight) presented an overall rating of serious risk of bias (Abrahin et al., 2014; Antunes et al., 2021; Galvão & Taaffe, 2005; Radaelli et al., 2013, 2014a, 2014b, 2018; Ribeiro et al., 2015). For muscle size, two studies had an overall rating of moderate risk of bias (Antunes et al., 2021; Ribeiro et al., 2015), and five had a serious risk of bias (Galvão & Taaffe, 2005; Radaelli et al., 2013, 2014a, 2014b, 2018). For muscle quality, all studies (two) presented an overall rating of serious risk of bias (Radaelli et al., 2013, 2014b). Finally, for functional capacity, all studies (four) had an overall rating of serious risk of bias (Abrahin et al., 2014; Galvão & Taaffe, 2005; Radaelli et al., 2018, 2019). In general, the rating for serious risk of bias arose due to the measurement of the outcome (i.e., the measurement could have been influenced by the participant's and assessor's knowledge regarding the intervention). On the other hand, the rating for moderate risk of bias arose due to the selection of the reported result (i.e., lack of trial registrations or a pre-specified analysis plan in the protocol).

Table 4. Risk of bias assessment (ROBINS-I) of each outcome in the non-randomized controlled trials.

Outcome	Study	Confounding	Selection of participants	Classification of intervention	Deviations from intended interventions	Missing data	Measurement of the outcome	Selection of the reported result	Overall risk of bias
Muscle strength	Abrahin et al. (2014)	Low risk	Low risk	Low risk	Low risk	Low risk	Serious risk	Moderate risk	Serious risk
	Antunes et al. (2021)	Low risk	Low risk	Low risk	Low risk	Low risk	Serious risk	Moderate risk	Serious risk
	Galvão & Taaffe (2005)	Low risk	Low risk	Low risk	Low risk	Low risk	Serious risk	Moderate risk	Serious risk
	Radaelli et al. (2014a)	Low risk	Low risk	Low risk	Low risk	Low risk	Serious risk	Moderate risk	Serious risk
	Radaelli et al. (2013)	Low risk	Low risk	Low risk	Low risk	Low risk	Serious risk	Moderate risk	Serious risk
	Radaelli et al. (2014b)	Low risk	Low risk	Low risk	Low risk	Low risk	Serious risk	Moderate risk	Serious risk
	Radaelli et al. (2018)	Low risk	Low risk	Low risk	Low risk	Low risk	Serious risk	Moderate risk	Serious risk
	Ribeiro et al. (2015)	Low risk	Low risk	Low risk	Low risk	Low risk	Serious risk	Moderate risk	Serious risk

Table 4. Continued

Outcome	Study	Confounding	Selection of participants	Classification of intervention	Deviations from intended interventions	Missing data	Measurement of the outcome	Selection of the reported result	Overall risk of bias
Muscle size	Antunes et al. (2021)	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk	Moderate risk	Moderate risk
	Galvão & Taaffe (2005)	Low risk	Low risk	Low risk	Low risk	Low risk	Serious risk	Moderate risk	Serious risk
	Radaelli et al. (2014a)	Low risk	Low risk	Low risk	Low risk	Low risk	Serious risk	Moderate risk	Serious risk
	Radaelli et al. (2013)	Low risk	Low risk	Low risk	Low risk	Low risk	Serious risk	Moderate risk	Serious risk
	Radaelli et al. (2014b)	Low risk	Low risk	Low risk	Low risk	Low risk	Serious risk	Moderate risk	Serious risk
	Radaelli et al. (2018)	Low risk	Low risk	Low risk	Low risk	Low risk	Serious risk	Moderate risk	Serious risk
	Ribeiro et al. (2015)	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk	Moderate risk	Moderate risk

Table 4. Continued

Outcome	Study	Confounding	Selection of participants	Classification of intervention	Deviations from intended interventions	Missing data	Measureme nt of the outcome	Selection of the reported result	Overall risk of bias
Muscle quality	Radaelli et al. (2013)	Low risk	Low risk	Low risk	Low risk	Low risk	Serious risk	Moderate risk	Serious risk
	Radaelli et al. (2014b)	Low risk	Low risk	Low risk	Low risk	Low risk	Serious risk	Moderate risk	Serious risk
Functional capacity	Abrahin et al. (2014)	Low risk	Low risk	Low risk	Low risk	Low risk	Serious risk	Moderate risk	Serious risk
	Galvão & Taaffe (2005)	Low risk	Low risk	Low risk	Low risk	Low risk	Serious risk	Moderate risk	Serious risk
	Radaelli et al. (2018)	Low risk	Low risk	Low risk	Low risk	Low risk	Serious risk	Moderate risk	Serious risk
	Radaelli et al. (2019)	Low risk	Low risk	Low risk	Low risk	Low risk	Serious risk	Moderate risk	Serious risk

Effects of Single vs. Multiple Sets on Muscle Strength and Size, Muscle Quality, and Functional Capacity

Table 5 summarizes each combined effect of outcome measures between single vs. multiple sets.

Table 5. Summary of the pooled effect between single vs. multiple sets for each outcome measure.

Outcome measure	Studies	Participants	Pooled effect (95% CI)	Interpretation	*p*-value	I^2	χ^2 (*p*-value)
Lower-limb muscle strength (SMD, Hedge's *g*)	12	323	0.29 (0.07, 0.51)	Small	0.009	0%	1.89 (1.00)
Lower-limb muscle strength (MD, kg)	12	323	1.91 (0.50, 3.33)	NA	0.008	0%	2.41 (1.00)
Upper-limb muscle strength (SMD, Hedge's *g*)	8	221	0.13 (-0.14, 0.40)	Small	0.34	0%	6.72 (0.46)
Upper-limb muscle strength (MD, kg)	8	221	0.11 (-0.52, 0.74)	NA	0.73	13%	8.06 (0.33)
Muscle size (SMD, Hedge's *g*)	11	319	0.15 (-0.07, 0.37)	Small	0.19	0%	1.41 (1.00)
Muscle quality (SMD, Hedge's *g*)	4	128	0.40 (0.05, 0.75)	Small	0.03	0%	1.01 (0.80)
Functional capacity (SMD, Hedge's *g*)	4	99	0.01 (-0.47, 0.50)	Small	0.96	31%	4.38 (0.22)

CI confidence intervals, I^2 inconsistency test, *MD* mean difference, *NA* not applicable, *SMD* standardized mean difference, χ^2 chi-squared test.

Lower-Limb Muscle Strength

Pooling the pre-test and post-test data of each group revealed increases ($p < 0.001$) on lower-limb strength in both single (SMD = 0.77; 95% CI = 0.46, 1.09; MD = 7.65 kg; 95% CI = 5.84, 9.45) and multiple sets (SMD = 1.08; 95% CI = 0.65, 1.50; MD = 9.53 kg; 95% CI = 7.19, 11.87). Of the twelve studies that compared the effects of single vs. multiple sets on lower-limb strength, two found significant differences between groups at post-test with a greater effect of multiple than single sets (Radaelli et al., 2014a; Ribeiro et al., 2015) (Table A1 in Appendix I). Combined SMD and MD showed a greater effect of multiple than single sets on lower-limb strength gains, without evidence of heterogeneity (Table 5, Figure A1 in Appendix I). The symmetrical funnel plots did not suggest the presence of publication bias (Figure A2 in Appendix I).

Upper-Limb Muscle Strength

Pooling the pre-test and post-test data of each group showed increases ($p < 0.001$) in upper-limb strength in both single (SMD = 1.29; 95% CI = 0.74, 1.83; MD = 5.49 kg; 95% CI = 3.15, 7.82) and multiple sets (SMD = 1.61; 95% CI = 1.04, 2.19; MD = 5.43 kg; 95% CI = 3.58, 7.28). Of the eight studies that compared the effects of single vs. multiple sets on upper-limb strength, two found significant differences between groups at post-test with a greater effect of multiple sets than single sets (Antunes et al., 2021; Ribeiro et al., 2015) (Table A1 in Appendix I). Pooled SMD and MD showed no differences between single vs. multiple sets on upper-limb strength gains, without evidence of heterogeneity (Table 5, Figure A3 in Appendix I).

Muscle Size

Pooling the pre-test and post-test data of each group showed increases ($p < 0.001$) in muscle size in both single (SMD = 0.35; 95% CI = 0.13, 0.57) and multiple sets (SMD = 0.51; 95% CI = 0.25, 0.77). Of the eleven studies that compared the effects of single vs. multiple sets on muscle size, two found significant differences between groups at post-test with a greater effect of multiple sets than single sets (Correa et al., 2015; Radaelli et al., 2014a) (Table A2 in Appendix I). There were no differences between single vs. multiple sets on muscle size gains and no evidence of heterogeneity (Table 5, Figure A4 in Appendix I). The symmetrical funnel plot did not suggest the presence of publication bias (Fig. A5 in Appendix I).

Muscle Quality

Pooling the pre-test and post-test data of each group revealed increases ($p < 0.001$) in muscle quality in both single (SMD = 0.63; 95% CI = 0.28, 0.98) and multiple sets (SMD = 0.89; 95% CI = 0.52, 1.26). Of the four studies that compared the effects of single vs. multiple sets on muscle quality, no study found significant differences between groups at post-test to improve this outcome (Table A3 in Appendix I). Pooled SMD showed a greater effect of multiple than single sets on muscle quality gains, without evidence of heterogeneity (Table 5, Figure A6 in Appendix I).

Functional Capacity

Pooling the pre-test and post-test data of each group revealed increases ($p < 0.001$) in functional capacity in both single (SMD = 0.66; 95% CI = 0.19, 1.12) and multiple sets (SMD = 0.56; 95% CI = 0.16, 0.96). Of the four studies that compared the effects of single vs. multiple sets on functional capacity, one found significant differences between groups at post-test with a greater effect of multiple than single sets (Radaelli et al., 2019) (Table A4 in Appendix I). Combined SMD showed no differences between single vs. multiple sets on functional capacity gains and no evidence of heterogeneity (Table 5, Figure A7 in Appendix I).

Effects of Single vs. Multiple Sets on Muscle Strength and Size According to Training Duration

There were no differences ($p > 0.05$) between single vs. multiple sets in improving lower- and upper-limb strength and muscle size when the duration was ≤ 12 weeks and > 12 weeks (Table A5 in Appendix I). The effects of single vs. multiple sets on muscle quality and functional capacity according to training duration were not compared due to the lack of study groups for comparison.

Discussion

Main Findings

The current review compared the effects of single vs. multiple sets performed per exercise on muscle strength and size, muscle quality, and functional capacity in middle-aged and older adults. In addition, this review examined the effects of single vs. multiple sets per exercise on muscle strength and size according to RT duration. The data suggest that multiple sets per exercise seem effective in optimizing lower-limb strength and muscle quality gains, while single sets are sufficient for increasing upper-limb strength, muscle size, and functional capacity in middle-aged and older adults. Moreover, performing multiple sets per exercise does not appear to be more effective than single sets for increasing muscle strength and size for training durations higher than twelve weeks (i.e., 13-20 weeks). Despite the low heterogeneity among studies observed in the pooled analysis, these data should be interpreted with caution as most of the included studies presented an overall rating of some concern or serious risk of bias. These results also highlight the need for high-quality pre-registered and blinded RCTs to determine a more precise estimate of the effect of single vs. multiple sets per exercise on muscle strength and size, muscle quality, and functional capacity in middle-aged and older adults.

Effects of Single vs. Multiple Sets on Muscle Strength

The pooled analysis demonstrated that multiple sets performed per exercise produced higher lower-limb strength gains than single sets, although the magnitude of the difference was considered small. Therefore, although prescribing three sets per exercise might be indicated to optimize lower-limb strength gains, future studies should examine whether an MD of ~1.9 kg is clinically relevant in functionally independent middle-aged and older adults. In addition, it is essential to note that these results did not find an advantage of multiple sets over single sets for durations longer than twelve weeks (i.e., 13-20 weeks). These results contradict previous studies that have suggested that performing multiple sets per exercise during long RT periods produces greater gains in lower-limb strength than single sets (Antunes et al., 2021; Galvão & Taaffe, 2005; Radaelli et al., 2014a). Nevertheless, it is important to mention that although the data did not show differences between single vs. multiple sets on lower-limb strength gains for durations between 13-20 weeks, the SMD and MD revealed a tendency to favor longer durations. As the current review only included three studies with a duration longer than 12 weeks (Galvão & Taaffe, 2005; Radaelli et al., 2013, 2014a) and nine with shorter durations (Abrahin et al., 2014; Antunes et al., 2021; Correa et al., 2014, 2015; Cunha et al., 2020; Polito et al., 2021a; Radaelli et al., 2014b, 2018; Ribeiro et al., 2015), the sample size differences might have prevented longer durations from reaching statistical significance. Therefore, performing more longitudinal-experimental studies is mandatory to better understand the differences between single vs. multiple sets per exercise on lower-limb strength gains in middle-aged and older adults.

The combined analysis did not reveal differences between single vs. multiple sets per exercise in improving upper-limb strength in middle-aged and older adults. According to the literature, in functionally independent older adults, lower-limb strength might be better preserved than upper-limb strength due to the higher request of the former to perform daily life activities (e.g., walking, climbing stairs, rising from a chair) (Antunes et al., 2021; Radaelli et al., 2014a; Sousa et al., 2011). In this sense, the upper body might be more sensitive to changes than the lower body when exposed to single or multiple sets in older adults (Antunes et al., 2021; Radaelli et al., 2014a; Sousa et al., 2011). Therefore, given the apparent high trainability of the upper-limb strength, performing single sets per exercise seems sufficient to develop this body region in older adults. In addition, RT durations longer than twelve weeks do not seem to increase the magnitude of upper-limb strength gains when performing single or multiple sets per exercise. Interestingly, these results agree with previous findings from experimental studies showing that upper-limb strength gains might be achieved with single or multiple sets, regardless of training duration (Antunes et al., 2021; Radaelli et al., 2013, 2014a). Nevertheless, as the current review only included three studies with a duration longer than twelve weeks (Galvão & Taaffe, 2005; Radaelli et al., 2013, 2014a), more longitudinal-experimental studies are necessary to corroborate or refute these observations.

Effects of Single vs. Multiple Sets on Muscle Size

Although all the included studies reported higher gains after multiple sets than single sets, the combined analysis did not show differences between RT sets in improving muscle size in middle-aged and older adults. These results suggest that performing single or multiple sets per exercise similarly increases muscle size in this population. Previous meta-analyses observed contradictory findings regarding the number of sets per exercise required to increase muscle size in middle-aged and older adults. For example, Peterson et al. (2011) observed that around twenty sets per exercise session produced higher lean body mass increases than less than twenty sets. On the other hand, Borde et al. (2015) indicated that the number of sets performed per exercise could not predict muscle size changes in older adults, although these authors observed greater effects sizes performing 2-3 sets per exercise. Nevertheless, both meta-analyses lacked studies directly comparing the effects of single vs. multiple sets on muscle size, limiting the generalizability of their results. Therefore, these data provide new insights into this topic by suggesting that single sets performed per exercise promote similar muscle size gains as multiple sets in middle-aged and older adults. Interestingly, these results agree with a recent meta-analysis suggesting 1-3 sets to increase muscle size in individuals aged 55 years and older (Polito et al., 2021b). In addition, performing more than three sets per exercise does not seem to promote higher muscle mass gains than 1-3 sets in this population (Polito et al., 2021b). Taken together, manipulating the RT volume from one to three sets seems an appropriate stimulus to increase muscle mass in middle-aged and older adults.

Effects of Single vs. Multiple Sets on Muscle Quality

None of the four included studies observed differences between single vs. multiple sets per exercise in improving muscle quality in middle-aged and older adults. However, after combining the results of each study, the meta-analysis showed an advantage of multiple sets over single sets to improve muscle quality. Muscle quality (or specific tension) refers to the strength or force generated per unit of muscle mass (Lynch et al., 1999; Tracy et al., 1999). According to several authors, it is a more robust indicator of muscle function than muscle strength alone, as it allows estimating the influence of muscle size and neuromuscular parameters on strength changes (Lynch et al., 1999; Tracy et al., 1999). Therefore, muscle quality might be a valuable clinical tool for monitoring sarcopenia and dynapenia, the functional capacity of muscle tissue, and the RT program effectiveness (Fragala et al., 2014, 2015; Pinto et al., 2014; Russ et al., 2012). Regarding this topic, a recent meta-analysis observed that RT improves muscle quality (ratio of muscle strength and size) in healthy older adults (Radaelli et al., 2021). However, as stated by the authors, the high heterogeneity between studies did not allow them to determine the RT volume required to improve muscle quality in this population (Radaelli et al., 2021). Therefore, these meta-analytical data provide new insights into the RT volume required to increase muscle quality in middle-aged and older adults. However, these results should be considered preliminary due to the few studies included in the analysis. In this sense, researchers should conduct new studies to strengthen the evidence about the number of sets required to improve muscle quality in middle-aged and older adults. In addition, future meta-analyses are necessary to summarize the effects of manipulating training volume on muscle quality assessed by image techniques, such as ultrasound echo intensity, as this outcome is strongly associated with functional capacity in older adults (Cadore et al., 2012).

Effects of Single vs. Multiple Sets on Functional Capacity

The meta-analytical data revealed no differences between single vs. multiple sets per exercise to improve functional capacity in middle-aged and older adults. Few meta-analyses addressed the effects of RT volume on functional capacity in these populations. For example, Lopez et al. (2018) observed that RT had a positive impact on measures of functional capacity (e.g., walking speed and "TUG" test) in frail older adults aged over 65 years. However, due to the high heterogeneity between studies and the lack of information about the volume prescribed, the authors could not determine the RT volume required to improve functional capacity in this population (Lopez et al., 2018). Furthermore, another meta-analysis (Orssatto et al., 2019) that quantified the effects of low-to-moderate vs. high-velocity RT on functional capacity in individuals aged 60 years and over did not determine the RT volume required to improve functional capacity in this population. Therefore, given the scarcity of data, the present study presents new insights regarding the effectiveness of RT volume in improving this parameter in middle-aged and older adults, showing that single or multiple sets per exercise seem enough to improve functional capacity. Nevertheless, given the preliminary evidence due to the few studies included in the analysis, more high-quality research is needed to corroborate or refute the current findings.

Strengths and Limitations

A strength of this review is that it limited the analysis only to studies directly comparing the effects of single vs. multiple sets performed per exercise in middle-aged and older adults, avoiding combining interventions with different methodological designs (e.g., experimental vs. control groups, low- vs. high-intensity groups, three vs. six sets groups). In addition, only studies that kept the number of sets constant in both groups during the RT program were included to avoid the influence of different stimuli during the intervention. Therefore, these selection criteria might have reduced the heterogeneity between studies and strengthened the validity and generalizability of the results. In addition, another strength of this review is that, along with SMD, it also reported the combined MD for muscle strength outcomes, increasing the clinical interpretability of the results (Takeshima et al., 2014) and allowing researchers to design future experimental studies on this topic.

On the other hand, the current review presents some limitations that should be addressed. Firstly, as 93% of the participants were women, these data should not be generalized to middle-aged and older men. Therefore, researchers should develop future studies with middle-aged and older men to see whether these results are similar to those observed in women. Secondly, the methods used to assess muscle size differed between the experimental studies (e.g., dual-energy X-ray absorptiometry or B-mode ultrasonography), which may have influenced the results. Thirdly, the small number of included studies comparing the effects of single vs. multiple sets per exercise on muscle quality and functional capacity outcomes does not allow for a generalization of the results. Therefore, the current results should be considered preliminary until further research is conducted to compare the effects of single vs. multiple sets performed per exercise on these outcomes. Fourthly, the publication bias in some outcomes was not assessed because when there are fewer than ten studies, the power is too low to distinguish a chance from a real asymmetry (Higgins et al., 2019). Finally, the included studies presented an overall rating of some concern or serious risk of bias, mainly due to limitations in the outcome measurement and selection of the reported result domains. Therefore, future high-quality pre-registered and blinded RCTs are needed to overcome the risk of bias highlighted in this review and strengthen the evidence regarding the optimal RT volume required to increase muscle strength and size, muscle quality, and functional capacity in middle-aged and older adults.

Practical Applications

In general, the data of this review suggest that clinicians, sport-related professionals, and researchers can prescribe multiple sets per exercise to optimize lower-limb strength and muscle quality gains in middle-aged and older adults. On the other hand, single sets per exercise are sufficient to improve upper-limb strength, muscle size, and functional capacity. Interestingly, as previously suggested, a minimal dose of RT volume comprising single sets might be indicated for untrained older adults and those who report time constraints to engage in RT (Fröhlich et al., 2010; Fyfe et al., 2022; Iversen et al., 2021; La Scala Teixeira et al., 2018). In addition, when performing the same number of repetitions per exercise at the same relative load, single sets will always produce less mechanical work (i.e., if it is considered as the product of sets, repetitions, and load (Marston et al., 2017)) than multiple sets, which eventually might be beneficial for untrained older adults or those with less resistance to fatigue (e.g., frail individuals). It is also essential to note that 80% of the included studies prescribed repetitions until muscle failure. Regarding this matter, several studies have already observed that repetitions performed close to or until failure cause high acute cardiovascular, metabolic, and neuromuscular stress in older adults, which might be detrimental in this population (Marques et al., 2019; Tajra et al., 2015; Vale et al., 2018). Therefore, since more than three sets and repetitions to failure might decrease the magnitude of the RT effect on muscle strength and size in middle-aged and older adults (Fragala et al., 2019; Polito et al., 2021b), prescribing 1-3 sets without repetitions to failure seems a rational option. In addition, the resistance exercise selection should include multi-joint and single-joint exercises targeting the lower and upper limbs, namely the leg press, leg curl, leg extension, chest press, seated row, lat pull-down, biceps curl, and triceps extension. Finally, although some studies recommend single sets per exercise to prevent hypothetical dropouts and enhance RT participation (Galvão & Taaffe, 2005; Radaelli et al., 2013), the current results revealed similar attendance and retention rates between single and multiple sets during the interventions. In addition, both one and three sets seem safe given the absence of adverse events or injury reports directly related to the RT programs.

Conclusions

This systematic review with meta-analysis indicates that multiple sets performed per exercise are more effective than single sets in optimizing lower-limb strength and muscle quality in functionally independent middle-aged and older adults, although with a small magnitude of effect. On the other hand, single sets per exercise might be sufficient to increase upper-limb strength, muscle size, and functional capacity in these populations (Figure 2). In addition, the data do not suggest a more effective effect of multiple sets over single sets to increase muscle strength and size for training durations between 13-20 weeks. Therefore, although more high-quality RCTs are needed to corroborate or refute these findings, this review increases the current scientific evidence about the effects of single vs. multiple sets performed per exercise during RT on muscle strength and size, muscle quality, and functional capacity in middle-aged and older adults.

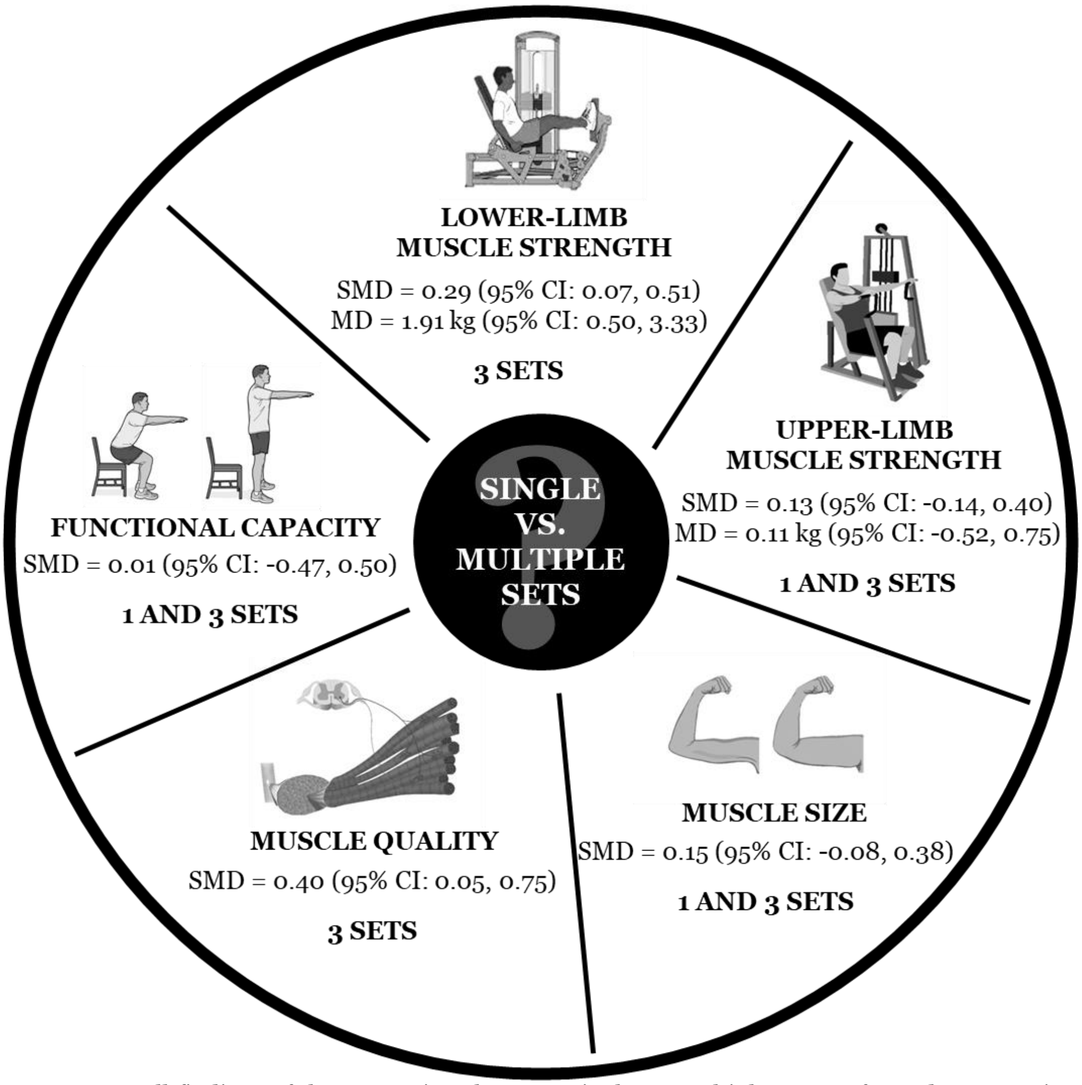

Figure 2. Overall findings of the comparison between single vs. multiple sets performed per exercise on muscle strength and size, muscle quality, and functional capacity in middle-aged and older adults. CI confidence interval, MD mean difference, SMD standardized mean difference.

Chapter 3. Experimental Studies

Study 2. Acute Effects of Low and High-Volume Resistance Training on Hemodynamic, Metabolic and Neuromuscular Parameters in Older Adults

Abstract

Objective: To analyze the acute effects of low or high-volume resistance training (RT) on hemodynamic, metabolic and neuromuscular parameters in institutionalized older adults. **Methods:** Thirty-one subjects (78.9 ± 7.2 years old) performed two RT protocols (low versus high-volume), separated by one-week rest. Systolic blood pressure (SBP), diastolic blood pressure (DBP), heart rate (HR) and blood lactate concentration ($[La^-]$) were evaluated before and immediately after both RT protocols. The seated medicine ball throw (SMBT) was evaluated before and 5 minutes after both sessions, the countermovement jump (CMJ) height was evaluated before and 6 minutes after both RT protocols and the absolute handgrip strength (HGS) was evaluated before and 7 minutes after both RT protocols. **Results:** At baseline, no significant differences between RT protocols were found in all variables. After training session, both RT protocols induced significant increases in SBP (low versus high-volume: 5.3% vs 10.7%), DBP (5.9% vs 6.8%), HR (6.8% vs 17.9%) and $[La^-]$ (86.1% vs 200.0%). Moreover, the high-volume protocol induced significant decreases in SMBT (-2.5%) and CMJ (-8.3%), whilst the low-volume protocol significantly increased the HGS (3.4%). **Conclusions:** Both RT protocols induced significant acute responses on cardiovascular and metabolic parameters, as well as on neuromuscular function in institutionalized older adults. However, a greater acute response after the high-volume RT protocol was found, thus reflecting greater hemodynamic, metabolic and neuromuscular stress than low-volume RT. Moreover, low-volume RT showed an acute increase in general strength.

Keywords: elderly, training volume, strength, blood pressure, lactate

Introduction

Resistance training (RT) is an effective strategy to promote increases in skeletal muscle mass and strength in older adults (Guizelini et al., 2018; Lopez et al., 2018; Papa et al., 2017; Pereira et al., 2012a, 2012b). The manipulation of RT variables, mainly intensity (load) and training volume (sets x repetitions), is a continuous and essential process in order to induce specific stimulus and promote optimal strength adaptations (Kraemer & Ratamess, 2004). In older adults, it was previously revealed that high training loads (≥ 70% of one-repetition maximum [1RM]) tended to be superior for strength improvement when compared to lower loads (Hunter et al., 2004; Peterson et al., 2010; Peterson & Gordon, 2011). However, recent literature showed that low-to-moderate loads can also induce significant strength gains in this population (Pereira et al., 2012a, 2012b; Ramírez-Campillo et al., 2014, 2017, 2018), specifically when training volume is increased (Csapo & Alegre, 2016; Van Roie et al., 2013, 2017).

Training volume seems to play an important role when designing RT programs in older adults (Borde et al., 2015). Nevertheless, some controversy exists regarding the optimal RT volume (Borde et al., 2015; Steib et al., 2010; Straight et al., 2016). Some authors suggested that higher RT volume, which causes greater metabolic stress, appear to be more effective than low volume to induce lower body strength gains in older adults (Radaelli et al., 2014a) (Radaelli et al., 2014a). Conversely, others claimed that low RT volume is also effective to improve strength (Cannon & Marino, 2010). In fact, the influence of training volume in older adults' strength seems to be dependent on training program duration, suggesting that both volumes are equally effective to improve strength in short-term RT programs, whilst higher volumes are needed to promote additional strength adaptations in long-term RT programs (Borde et al., 2015).

Nonetheless, research is scarce regarding the comparison of the acute effects of low and high-volume RT on cardiovascular and metabolic parameters, as well as on the neuromuscular performance of older adults. To our best knowledge, only three studies analyzed the acute effects of low and high-volume RT on hemodynamic parameters in older adults, with contradictory results (Brito et al., 2014; Mediano et al., 2005; Tajra et al., 2015). Some investigations showed increased blood pressure immediately (Mediano et al., 2005) and during the 24h following low and high-volume RT (Tajra et al., 2015), but others reported significant decreases in blood pressure over the 90 min of recovery that followed the high-volume RT (Brito et al., 2014). Thus, to better understand the physical and physiological demands of low and high-volume RT in older adults, metabolic parameters and strength-related variables need to be further investigated. Thus, the purpose of the present research was to compare, in the same session, the acute effects of low and high-volume RT on physiological and neuromuscular responses in institutionalized older adults. We hypothesized that the high-volume RT protocol would elicit greater cardiovascular and metabolic stress, as well as higher losses on the neuromuscular performance after the training session when compared to the low-volume RT protocol.

Methods

Subjects

Thirty-one subjects volunteered to participate in the study (Table 1). Inclusion criteria were considered as follows: aged ≥ 65 years, institutionalized, being able to stand-up from a chair with the arms crossed over the chest and being able to execute a vertical jump. Exclusion criteria were: simultaneous participation in a physical exercise program, severe cognitive impairment (mini-mental state examination [MMSE] score < 20) (Folstein et al., 1975), cardiovascular/respiratory disorders, hypertension (systolic blood pressure [SBP] ≥ 140 mmHg and/or diastolic blood pressure [DBP] ≥ 90 mmHg) (Williams et al., 2018), musculoskeletal injuries in the previous 6 months and terminal illness. All subjects received detailed information regarding the study procedures and signed a written informed consent. This study was approved by the Ethical Committee of the University of Beira Interior (code: CE-UBI-Pj-2019-019) and followed the recommendations of the Declaration of Helsinki.

Table 1. Subjects characteristics at baseline (mean ± SD).

Subjects	***n***	**Age (years)**	**Weight (kg)**	**Height (m)**	**BMI (kg/m²)**	**MMSE**
Men	14	77.1 ± 6.9	78.3 ± 14.8	1.66 ± 0.1	28.5 ± 4.4	24.7 ± 3.4
Women	17	80.4 ± 7.2	65.6 ± 12.2	1.50 ± 0.1	29.3 ± 5.6	23.9 ± 1.7
Total	31	78.9 ± 7.2	71.3 ± 14.7	1.57 ± 0.1	28.9 ± 5.0	24.3 ± 2.6

BMI: body mass index; MMSE: mini-mental state examination.

Procedures

A crossover design was used to compare the acute effects of two different RT protocols on physiological and neuromuscular parameters of institutionalized older adults. After initial screening, subjects underwent an adaptation period of 2 weeks, to familiarize them with the gym and the exercises. During this period, anthropometric and cardiovascular variables were also assessed. Furthermore, 4 testing sessions on two separate weeks to determine the 1RM on the leg-press and chest-press, as well as the reliability between measurements, were performed. After that, subjects were submitted to two RT protocols, with a rest interval of seven days between them (Orsano et al., 2018). First, they performed the low-volume protocol and then the high-volume protocol. In both sessions, all subjects were assessed before and after the intervention in the same order in the following parameters: SBP, DBP, heart rate (HR), blood lactate concentration ([La^-]), seated medicine ball throw (SMBT) distance, countermovement jump (CMJ) height and handgrip strength (HGS) (Figure 1). All tests and protocols were performed on the same place, at the same time of the day (1:30 p.m. – 4:30 p.m.), and at room temperature between 22 and 24°C.

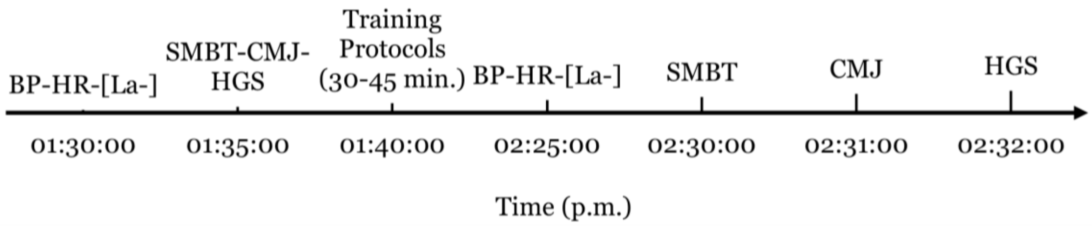

Figure 1. Timeline of the experimental procedures. Blood pressure, heart rate and lactate were measured before and immediately after (0-1 minutes) both RT protocols; seated medicine ball throw was measured before and 5 minutes after training; countermovement jump height was measured before and 6 minutes after training; handgrip strength was measured before and 7 minutes after training.

One-Repetition Maximum Leg-Press and Chest-Press

Subjects were assessed on the leg-press and after 48h on the chest-press. For the leg-press, subjects had to sit on the bench (back in contact with the machine), bending the knees at 90° and place the feet shoulder-width apart on the platform. On command, subjects had to fully extend their legs as fast as possible, and slowly return to the initial position. In the chest-press, subjects had to sit on the bench, abduct the shoulders at 90°, flex the elbows at 90°, grab the handles with a full grip and maintain the wrists in a neutral position. They were then instructed to perform a purely concentric action as fast as possible and slowly return to the initial position. The warm-up consisted of 5-min on a stationary bicycle, followed by a specific warm-up of two sets (the first set of 5-10 repetitions at 40-60% of the maximum load perceived, followed by 1 min rest, and then 3-5 repetitions at 60-80% of the maximum load perceived). Thereafter, 3-5 single attempts to reach the 1RM were conceded, with a 3-5 min rest between each maximal attempt. 1RM was assessed following the procedures described by Sheppard & Triplett

(2016). Test-retest absolute reliability for the leg-press and chest-press, as measured by the coefficient of variation (CV) was 3.01% and 4.90%, respectively, whilst the relative reliability, as measured by the intra-class correlation coefficient (ICC), was 0.99 on both exercises.

Anthropometric, Hemodynamic and Blood Lactate Measurements

In the first experimental session, body mass (kg) and height (cm) (Seca Instruments, Ltd., Hamburg, Germany) were measured. Body mass index (BMI) was calculated by dividing body mass, in kg, by height squared, in meters (kg/m2). The SBP, DBP, and HR were measured with an automatic blood pressure monitor (Omron HEM-7113 model, Kyoto, Japan). The measurements were performed after 5 min of seated rest and immediately after both training protocols. The cuff size was adapted to the arm circumference of each subject. Regarding lactate measurements, after cleansing the site with 70% alcohol, the fingertip was punctured using a disposable lancet (Accu-Chek Aviva Test Strips). The first drop of blood was discarded to avoid contamination with sweat and then a very small blood sample (0.3 µl) was collected for analysis (Lactate Pro 2 LT-1730, Arkay, Inc., Japan). Blood sampling was performed before exercise (15 min rest) and immediately after both training protocols.

Neuromuscular Performance

In the SMBT, subjects had to sit on the chair with the back straight and hold the ball in front of the chest with both hands. After instruction, they had to throw a 2 kg medicine ball as far and fast as possible (Pereira et al., 2012a). Before and 5-min after each training protocol, three attempts were performed with a minimum rest interval between each attempt. The throwing distance was determined using a flexible steel tape and the best result was used for analysis. The CV was 4.52% and the ICC was 0.98.

In the CMJ, subjects began in an upright position with arms akimbo. After instruction, they performed a rapidly downward movement (about 90° of knee flexion) and immediately a maximal vertical jump into the air (Ramírez-Campillo et al., 2017). For safety, an experienced assistant stood alongside each subject while performing the test. Before and 6-min after each training protocol, three attempts were made with a minimum rest interval between attempts. The vertical jump height was estimated using an infrared timing system (Optojump, Microgate, Bolzano, Italy) and the best jump was used for data analysis. The CV was 8.63% and the ICC was 0.98.

The participants were seated on a chair in an erect position, with a 90° hip, knee, and elbow flexion position (Pereira et al., 2012a), for the HGS assessment. They were then instructed to exert a maximal grip in both hands, using an adjustable portable hand dynamometer (Lafayette Instruments, model 78010, Japan). Before and 7-min after each training protocol, three attempts were performed in both hands, with a minimum rest interval between each attempt. The three measures on the right and left hand were averaged to calculate the absolute HGS. In the HGS of the left hand, the CV was 6.44% and the ICC was 1.00, while in the right hand the CV was 6.70% and the ICC was 0.99.

Resistance Training Protocols

After a general warm-up of 10 min on a treadmill, the participants performed the following exercises: CMJ, SMBT, leg-press, chest-press, and chair-squat. A rest interval of 2-3 min between sets and exercises was provided. The order and loads of the exercises were the same in both protocols, only differing in RT volume. The characteristics of both RT protocols are presented in Table 2.

Table 2. Resistance training protocols.

Exercises	Low-Volume RT	High-Volume RT
CMJ (S x R)	2 x 5	4 x 5
SMBT (S x R x kg)	3 x 6 x 2	3 x 12 x 2
Leg-Press (S x R x %1RM)	3 x 8 x 65	3 x 15 x 65
Chest-Press (S x R x %1RM)	3 x 8 x 65	3 x 15 x 65
Chair-Squat (S x R x kg)	3 x 6 x 5	3 x 12 x 5

RT: resistance training; CMJ: countermovement jump; SMBT: seated medicine ball throw; S: sets; R: repetitions; 1RM: one-repetition maximum.

Statistical Analysis

Data are presented as mean ± SD and 90% confidence intervals (CI). Normality and homoscedasticity were examined and confirmed using the Kolmogorov-Smirnov and Levene tests, respectively. To detect significant differences within-protocols and between the percentage of change [(Post-test – Pre-test)/Pre-test) x 100] from pre to post-test in both protocols, paired samples t-test were used. In addition, an ANCOVA was performed to identify significant differences between-protocols (fixed factor) in any variable at post-test (dependent variables) using the pre-test as a covariate. Cohen's d effect size was calculated using a modified classification system (trivial, 0.0-0.2; small, 0.2-0.6; moderate, 0.6-1.2; large, 1.2-2.0; very large, > 2.0; extremely large, > 4.0) (Hopkins et al., 2009). A magnitude-based inferences approach was used to detect the likely practical outcome of the intervention (Batterham & Hopkins, 2006). The chances that the differences in performance were better/greater (i.e., greater than the smallest worthwhile change [0.2 multiplied by the between-subject SD]), similar or worse/smaller were calculated. Quantitative chances of better or worse effects were assessed qualitatively as follows: < 1%, almost certainly not; 1–5%, very unlikely; 5–25%, unlikely; 25–75%, possibly; 75–95%, likely; 95–99%, very likely; and > 99%, most likely. If the chances of obtaining beneficial/better or detrimental/worse were both >5%, the true difference was assessed as unclear (Hopkins et al., 2009). The level of significance was set at $p < 0.05$. Statistical data were analyzed using SPSS v23 (SPSS Inc., Chicago, IL, USA), except for the magnitude-based inferences, which were calculated through specific online spreadsheets (Batterham & Hopkins, 2006).

Results

All subjects were classified with high normal blood pressure (SBP = 133.0 ± 13.6 mmHg; DBP = 69.3 ± 7.7 mmHg) (Williams et al., 2018) and normal cognitive function (24.3 ± 2.6) (Creavin et al., 2016). At baseline, no significant differences ($p > 0.05$) between variables in both RT protocols were observed. After both training protocols, significant increases in SBP, DBP, HR and [La^-] were observed, which resulted in significant differences between-protocols in SBP, HR and [La^-] (Table 3). In the high-volume protocol, significant decreases in the SMBT and CMJ were observed (Table 3). Regarding the low-volume protocol, a significant increase in the absolute HGS after training was observed, resulting in a significant difference between protocols (Table 3).

Table 3. Mean ± SD values of the variables assessed in pre and post evaluation momentum. *p*-values are presented for differences within subjects and between low and high-volume training protocol.

Variable	Protocol	Pre	Post	*p*-value (within)	*p*-value (between)
SBP (mmHg)	Low-Volume	131.10 ± 16.03	137.81 ± 19.21	0.003	0.045
	High-Volume	133.03 ± 13.59	147.03 ± 20.81	0.000	
DBP (mmHg)	Low-Volume	68.58 ± 8.60	72.29 ± 10.24	0.014	0.652
	High-Volume	69.32 ± 7.70	73.81 ± 10.32	0.006	
HR (bpm)	Low-Volume	71.23 ± 11.33	75.87 ± 11.79	0.000	0.000
	High-Volume	70.10 ± 10.43	81.87 ± 10.77	0.000	
$[La^-]$ (mmol/L)	Low-Volume	1.72 ± 0.42	3.13 ± 1.07	0.000	0.000
	High-Volume	1.75 ± 0.50	4.92 ± 1.79	0.000	
SMBT (m)	Low-Volume	2.31 ± 0.49	2.32 ± 0.49	0.713	0.116
	High-Volume	2.38 ± 0.50	2.31 ± 0.47	0.045	
CMJ (cm)	Low-Volume	4.62 ± 2.67	4.40 ± 2.56	0.166	0.448
	High-Volume	4.35 ± 2.28	3.99 ± 2.21	0.021	
HGS (kg)	Low-Volume	17.48 ± 7.96	17.94 ± 7.95	0.013	0.027
	High-Volume	17.56 ± 8.01	17.35 ± 8.26	0.383	

SBP: systolic blood pressure; DBP: diastolic blood pressure; HR: heart rate; $[La^-]$: blood lactate concentration; SMBT: seated medicine ball throw; CMJ: countermovement jump; HGS: absolute handgrip strength.

After training, the percentage of change in HR and $[La^-]$ was significantly higher in the high-volume protocol than the low-volume protocol, with a most likely harmful effect (Figure 2).

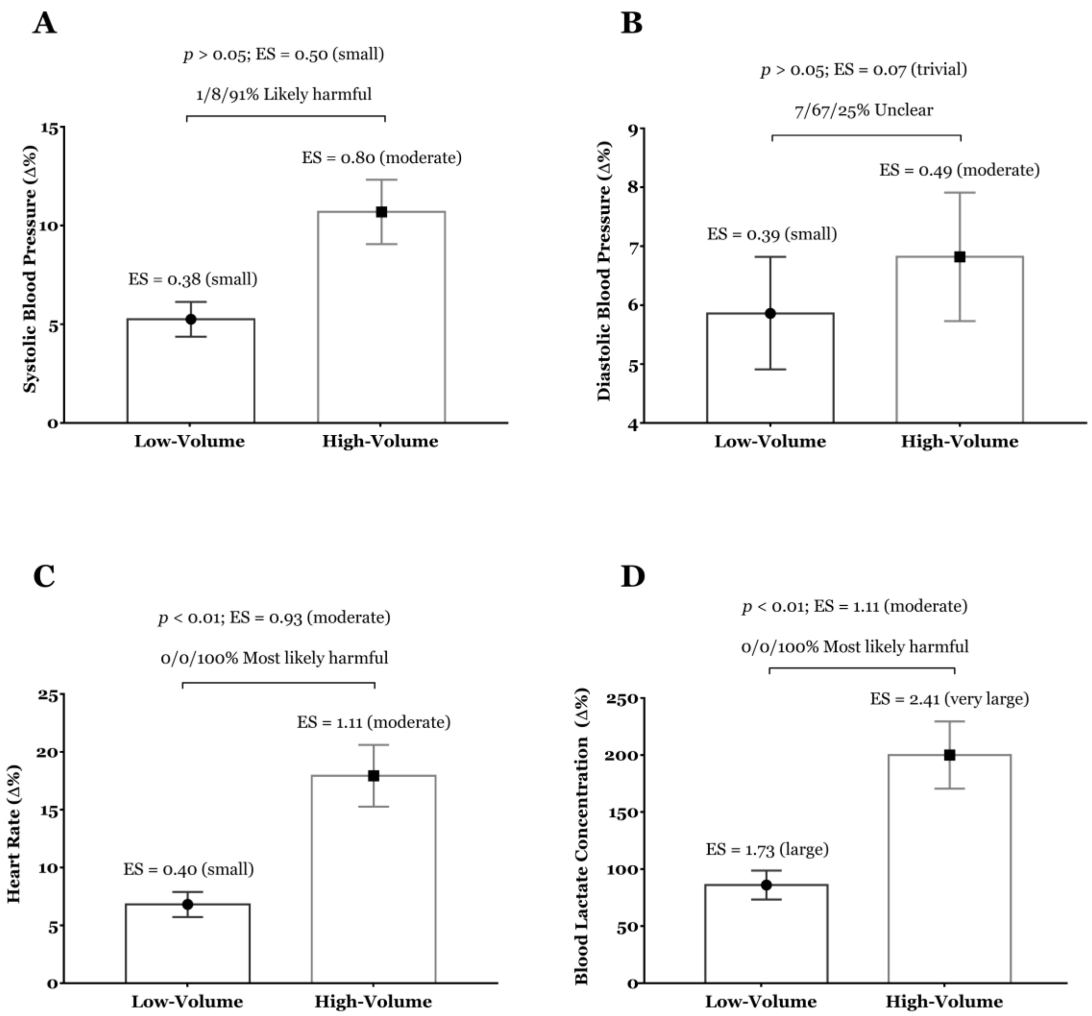

Figure 2. Comparisons between the percentage of change (90% CI) and the magnitude of the effects from pre to post in both resistance training protocols in hemodynamic and metabolic variables. ES: Cohen's d effect size; A: changes in systolic blood pressure; B: changes in diastolic blood pressure; C: changes in heart rate; D: changes in blood lactate concentration.

Furthermore, the percentage of change in the SMBT and HGS was also significantly higher in the high-volume protocol than the low-volume protocol, with a most likely harmful effect (Figure 3).

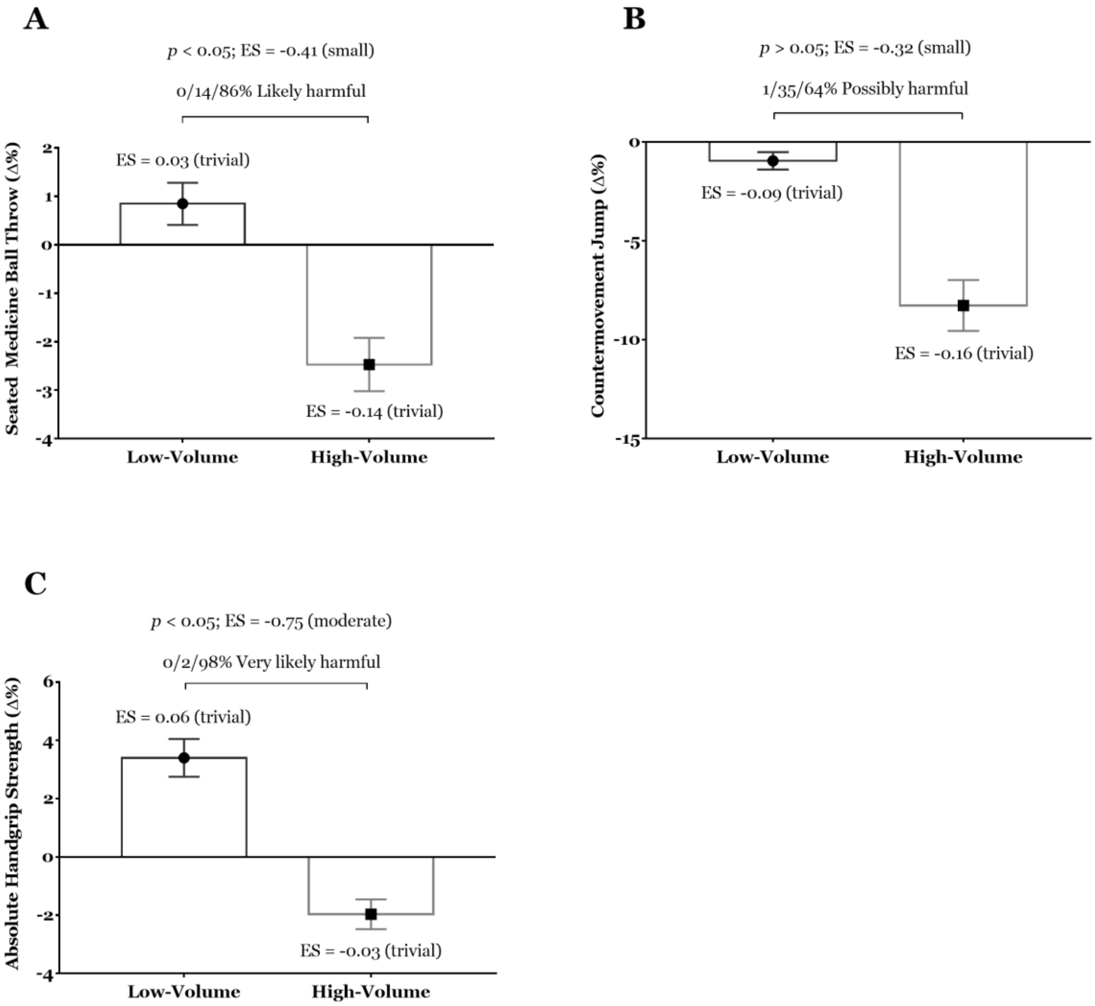

Figure 3. Comparisons between the percentage of change (90% CI) and the magnitude of the effects from pre to post in both resistance training protocols in strength-related variables. ES: Cohen's d effect size; A: changes in seated medicine ball throw; B: changes in countermovement jump; C: changes in absolute handgrip strength.

Discussion

The present study aimed to compare the acute effects of low and high-volume RT on blood pressure, HR, [La^-], and strength-related variables in institutionalized older adults. The main finding was that the high-volume RT protocol induced a greater acute response on hemodynamic and metabolic parameters, as well as on neuromuscular performance after training. These data support our main hypothesis that the high-volume RT would cause greater cardiovascular and metabolic stress, as well as greater losses on neuromuscular function when compared to the low-volume RT protocol. These results might have some clinical relevance, warning of the possible danger of using high-volume RT in institutionalized older adults, particularly due to the great increases in hemodynamic parameters, during and immediately after the session.

Significant increases in SBP, DBP, and HR after training were observed in both RT protocols, with the high-volume protocol presenting a greater increase in comparison to the low-volume protocol. These differences can be attributed to the fact that more repetitions were performed in the high-volume session, thus requiring a higher level of effort, which in turn is related to greater mechanical stress and neuromuscular fatigue (Martorelli et al., 2017). Studies that aimed to compare exclusively the acute effects of low and high-volume RT on blood pressure in the elderly have shown different acute responses. Mediano et al. (2005) observed significant and similar increases in SBP and DBP at the end of either one or three sets of ten repetitions in 20 hypertensive subjects (61 ± 12 years), whilst Tajra et al. (2015) found a greater cardiovascular response after three sets leading to failure in comparison to three sets not to failure, in normotensive elderly women. On the contrary, Brito et al. (2014) found that higher RT volumes caused higher post-exercise hypotension (i.e., a decrease in blood pressure in the minutes following the acute exercise) than lower volumes (10 exercises performed with 1 or 3 sets of 10 repetitions with 50% of 1RM), in hypertensive elderly subjects. The latter results suggest that a higher training volume has the potential to reduce SBP and DBP in hypertensive older adults. However, it is questionable if in the long-term higher RT volumes can effectively decrease blood pressure, due to the heterogeneous response of SBP to RT, both in normotensive and hypertensive older adults (Nascimento et al., 2018). In the current study, the subjects were classified with high-normal blood pressure, and thus we did not aim to measure blood pressure overtime after both RT protocols. Future studies aiming to compare the acute effects of low versus high-volume RT on post-exercise hypotension in institutionalized older adults with high normal blood pressure are necessary.

As expected, the high-volume RT protocol presented a significantly higher percentage of change on HR and [La^-], in comparison to the low-volume RT protocol. These relative changes in HR and [La^-] reinforce the high level of demand of the high-volume RT protocol during the session. It is assumed that [La^-] is a measure of metabolic stress resultant from different intensities (loads), movement velocities, exercise order, as well as volumes, in which higher RT volumes contribute to a greater extent to an increase in [La^-] (Date et al., 2013; Wirtz et al., 2014). To our knowledge, only two studies compared the acute effects of RT on metabolic responses in the elderly (Orsano et al., 2018; Paunksnis et al., 2018). Paunksnis et al. (2018) found a non-significant increase on [La^-] 2h after performed two RT methods (multiple-set constant intensity versus multiple-set of variable intensity, also known as ascending pyramid), returning to similar baseline values after 24h. These results cannot be compared with ours, since the measurement time and the methodologic procedures were different. On the other hand, Orsano et al. (2018) observed a significant increase on [La$^-$] 3 minutes after both traditional RT and high-velocity RT in elderly hypertensive women, with a greater increase after traditional RT. Although both intensity and volume were somewhat identical to the low-volume RT protocol of our study (3 x 10 repetitions at 70% of 1RM), comparisons cannot be done, since training sessions were composed of 10 exercises. However, according to literature and our results, it seems that the [La$^-$] response to RT is directly proportional to the intensity (% 1RM) and the number of repetitions performed (Date et al., 2013; Wirtz et al., 2014).

Regarding the neuromuscular performance, significant decreases in the SMBT and CMJ in the high-volume protocol were observed. These differences could be caused by the increased [La$^-$] in the working muscles in the high-volume RT, which might reduce the force-generating capacity and consequently impairing both ball throw and vertical jump performance (Ahtiainen et al., 2003; Weakley et al., 2017). In our study, these two variables were only measured once after training, thus we are not able to speculate if in the short-term (e.g., 24-48h) the performance on the SMBT and CMJ would be impaired, recovered (i.e., returned to baseline values) or improved. Thus, future studies should try to analyze the acute and short-term effects of low and high-volume RT on the SMBT and CMJ of elderly people, and if possible, to examine most sensitive variables to detect fatigue-induced changes on neuromuscular function, such as the ratio of flight time to contraction time in the case of the CMJ (Gathercole et al., 2015) and the velocity with which the ball is thrown.

After the low-volume RT, a significant increase in the absolute HGS was observed, which might indicate a temporary improvement of overall muscle strength of the subjects. Since grip strength is a valid predictor of physical disability and mobility limitation (Sallinen et al., 2010), an improvement on this specific task after a low-volume RT session, even momentary, must be considered as a significant effect.

Studies that aimed to analyze the time course effects of low and high-volume RT on neuromuscular performance, found that during the early phase of RT (1-2 months), both volumes have similar capacity to induce neuromuscular adaptations in older adults (Cannon & Marino, 2010; Radaelli et al., 2014a, 2014b). Thus, considering that the stimulus thresholds required to cause neuromuscular adaptations in older adults are low, one can speculate that a low-volume RT seems sufficient to induce significant gains, even more, when the subjects have no RT experience (Cannon & Marino, 2010).

However, more studies comparing the acute and chronic effects of low and high-volume RT on neuromuscular performance are necessary to a better understanding on the most adequate training volume to maximize adaptive responses to RT, namely in older adults, since the available literature is still scarce and inconclusive (Cunha et al., 2018).

In the present study, the lack of measurements at different time points (e.g., 0-72h post-exercise) on hemodynamic, metabolic and strength-related variables, should be considered as the main limitation of this investigation. Future studies should measure blood pressure, HR, [La^-], and neuromuscular function more than once after training, in order to gain a deeper understanding of changes on those variables during recovery. Moreover, several hormones, both involved in anabolic (e.g., testosterone and insulin-like growth factor) and catabolic processes (e.g., cortisol), should also be measured to understand their responses to low and high-volume RT in older adults.

In summary, after both RT protocols, an acute response on hemodynamic, metabolic, and neuromuscular parameters in institutionalized older adults was observed. However, a greater acute response after the high-volume RT protocol was evidenced. On the other hand, a major finding of this study was that a low-volume RT protocol can result in lower magnitude of the acute response on hemodynamic and metabolic variables, and at the same time allows the improvement of general strength, which is determinant for elderly people.

Conclusions

In conclusion, the results of the current study showed higher cardiovascular, metabolic and neuromuscular acute responses after the high-volume protocol than the ones observed for the low-volume protocol. Furthermore, the latter RT method seems to be beneficial to the enhancement of general strength in elderly people. In this way, professionals and clinicians should be aware of the importance of the training volume in the adaptive processes during RT, as well as the relevance of manipulating this training variable over the training program. RT with low-volume (e.g., 2-3 sets of 5-8 repetitions at 65% of 1RM), using a combination of free-weights and machine-based exercises, seemed to be sufficient to enhance strength in this population, without achieving high hemodynamic, metabolic and neuromuscular stress. Nonetheless, future research should try to investigate the long-term effects of low and high-volume RT on hemodynamic, metabolic, and neuromuscular parameters in institutionalized elderly people.

Study 3. Novel Resistance Training Approach to Monitoring the Volume in Older Adults: The Role of Movement Velocity

Abstract

Objective: We analyzed the effects of velocity-monitored resistance training (RT) with a velocity loss of 20% on strength and functional capacity in institutionalized older adults. **Methods:** Thirty-nine participants (78.8 ± 6.7 years) were divided into a control group (CG; n = 20) or an RT group (n = 19). Over 10 weeks, the RT group performed two sessions per week, and the mean velocity of each repetition was monitored in the leg-press and chest-press exercises at 40–65% of one-repetition maximum (1RM). The set ended when the participants reached a velocity loss of 20%. The CG maintained their daily routine. At pre- and post-test, both groups were assessed in the 1RM leg-press, 1RM chest-press, handgrip strength, medicine ball throw (MBT), walking speed, and sit-to-stand (STS). **Results:** At baseline, we did not find significant differences between groups. After 10 weeks, we observed significant differences (p < 0.001–0.01) between groups in the 1RM leg-press, 1RM chest-press, MBT-1 kg, and STS. The RT group performed a total number of repetitions of 437.6 ± 66.1 in the leg-press and 296.4 ± 78.9 in the chest-press. **Conclusions:** Our results demonstrate that velocity loss effectively prescribes the volume in older adults and that a threshold of 20% improves strength-related variables in this population.

Keywords: aging; functional capacity; low loads; low volume; strength; velocity loss

Introduction

A significant challenge for public and private health services is to preserve functional capacity as people get older (Pahor et al., 2014; Valenzuela et al., 2019). The progressive loss of skeletal muscle mass and strength, described as sarcopenia, contributes to a decrease in the capacity to generate force rapidly, leading to an increase in the incidence of falls and consequent bone fractures (Yeung et al., 2019). These common and devastating events in older populations are intrinsically related to institutionalization, morbidity, and mortality (Yeung et al., 2019). Therefore, reversing the deleterious effects of aging through effective evidence-based intervention programs must be considered a priority of the healthcare systems worldwide (Pahor et al., 2014; Valenzuela et al., 2019).

Resistance training (RT) is considered an effective method to improve strength and counteract age-related declines in older adults (Aagaard et al., 2010; Fragala et al., 2019). From a geriatric perspective, the manipulation of intensity (load) and volume (sets × repetitions) is essential to maximize strength gains, prevent injuries, and dropouts (Fragala et al., 2019; Marques et al., 2013). Evidence suggests that both low-to-moderate loads (<70% of one-repetition maximum [1RM]) and high loads (≥70% 1RM) are significant to improving muscle strength and functional capacity in older adults (Fragala et al., 2019; Marques et al., 2013; Pereira et al., 2012; Ramírez-Campillo et al., 2014, 2017). On the one hand, when using low-to-moderate loads, high movement velocities seem to be more effective than low velocities in increasing 1RM strength and functional capacity in older adults (Bottaro et al., 2007; Nogueira et al., 2009). On the other hand, although high loads are also useful for improving strength and psychosocial well-being in older adults, they might be problematic for those with musculoskeletal impairments and for naïve RT practitioners (Fragala et al., 2019). Therefore, a low-load RT approach with high movement velocities might be a suitable strategy for older adults in order to improve 1RM strength and functional capacity, at least during the early phase of RT (Bottaro et al., 2007; Fragala et al., 2019; Marques et al., 2013; Nogueira et al., 2009).

The literature is inconsistent and inconclusive regarding the optimal RT volume in older adults (Cannon & Marino, 2010; Radaelli et al., 2014). Both low and high volumes (i.e., one vs. three sets) seem to be equally useful for inducing strength adaptations in the short-term (Cannon & Marino, 2010; Galvão & Taaffe, 2005; Radaelli et al., 2014), yet more sets and repetitions appear to be required to increase 1RM strength in the long term (Cannon & Marino, 2010; Galvão & Taaffe, 2005; Radaelli et al., 2014). Nevertheless, several studies already observed that higher volumes do not provide additional strength gains than lower volumes in older adults (Barbalho et al., 2017; Cannon & Marino, 2010; Fragala et al., 2019; Galvão & Taaffe, 2005; Silva et al., 2018). It is also important to note that when older adults perform a high number of repetitions per set closely to concentric failure, there is a higher acute cardiovascular, metabolic, and neuromuscular stress than for a low volume, which might be harmful in this population (Marques et al., 2019; Tajra et al., 2015; Vale et al., 2018). Therefore, considering that no consensus exists regarding the optimal training volume in older adults, alternative approaches must be evaluated.

Velocity-monitored RT is an effective strategy for improving physical performance and controlling the training load in trained young adults (González-Badillo et al., 2017; Pareja-Blanco et al., 2017; Rodríguez-Rosell et al., 2020; Sánchez-Medina & González-Badillo, 2011). Using this method, coaches and practitioners can monitor the degree of fatigue and individualize the training volume by controlling the velocity loss during the sets (González-Badillo et al., 2017; Pareja-Blanco et al., 2017; Rodríguez-Rosell et al., 2018, 2020; Sánchez-Medina & González-Badillo, 2011). Instead of a fixed, predetermined number of repetitions per set, the participants perform the repetitions until reaching a velocity loss threshold (e.g., 20%) (González-Badillo et al., 2017; Pareja-Blanco et al., 2017; Rodríguez-Rosell et al., 2020; Sánchez-Medina & González-Badillo, 2011). Studies with trained young adults showed that a velocity loss lower or equal to 20% resulted in lower repetitions per set, and lower acute metabolic, hormonal, and mechanical fatigue than a velocity loss higher than 20% did (González-Badillo et al., 2017; Rodríguez-Rosell et al., 2018). Besides, in the long term, a velocity loss lower or equal to 20% promotes similar or even higher strength gains than a velocity loss higher than 20% does (Pareja-Blanco et al., 2017; Rodríguez-Rosell et al., 2020). Thus, a velocity loss of around 20% seems to be enough to induce strength adaptations in trained young adults (Pareja-Blanco et al., 2017; Rodríguez-Rosell et al., 2020). However, to date, no research has analyzed the effects of monitoring velocity loss during RT interventions in older adults. Considering that older individuals might benefit from one of three things: high loads, high effort, or high velocity (Gentil et al., 2017), a combination of low loads and high movement velocities while monitoring velocity loss might probably be a more practical and safe approach in this population. This novel procedure would allow senior coaches and researchers to individualize the level of effort, avoid the adverse effects of fatigue, and eventually optimize the training stimulus (González-Badillo et al., 2017; Rodríguez-Rosell et al., 2018; Sánchez-Medina & González-Badillo, 2011).

Therefore, the purpose of the current research was to analyze the effects of velocity-monitored RT with a velocity loss of 20% in each set on strength and functional capacity in institutionalized older adults. Considering that older individuals exhibit a degree of adaptation to RT comparable to that of younger adults due to their neuromuscular plasticity (Aagaard et al., 2010; Hakkinen et al., 2001; Kamen & Knight, 2004), we hypothesized that a velocity loss of 20% would be a sufficient stimulus for enhancing muscle strength and functional capacity in this population. Moreover, we also hypothesized that performing a lower total number of repetitions than previously reported in high-velocity RT interventions with older people would be enough to increase 1RM strength.

Methods

Study Design

This study was a nonblinded, nonrandomized controlled trial. Forty-five older adults living in community-dwelling centers were divided into an RT group or a control group (CG), based upon their perceived availability to attend the training sessions regularly. The participants reported their availability to the institutions' geriatricians, who then communicated their decision to our research team. After that, we divided the participants between groups. Before the pretest, all participants underwent a familiarization period of two weeks (two sessions p/week) to ensure a proper adaptation to the fitness health club facilities, coaches, and exercises. During this period, we measured the body mass, in kg, (TANITA BC-601, Japan) and height, in m (Portable stadiometer SECA, Germany). We also performed a first assessment of the 1RM in the horizontal leg-press and seated chest-press exercises. After the adaptation period, we conducted two testing sessions separated by 48 h rest. In session 1, we measured the seated medicine ball throw distance with 1- (MBT-1kg) and 3-kg (MBT-3kg) medicine balls, the 10 m walking speed time (T_{10}), and the time in the five-repetition sit-to-stand (STS). In session 2, we measured the handgrip strength (HGS) and the 1RM in the horizontal leg-press and seated chest-press. Following the pretests, the RT group performed a 10-week velocity-monitored RT program with two sessions per week separated by 48 h rest. The CG maintained their regular daily routine, without any form of physical exercise. In week 5 (session 10), we performed a new assessment of the 1RM in both exercises to adjust the absolute loads in the RT group (Van Roie et al., 2013). At post-test, we first assessed the handgrip strength and the 1RM in the leg-press and chest-press in both groups because we aimed to analyze the performance on these tests immediately after the RT program (week 10, session 20). To avoid an excessive accumulation of fatigue that could impair the performance during the strength tests in the RT group, we decreased the number of sets in all exercises in session 19 (tapering strategy). After five days of rest (week 11), we assessed the MBT-1kg, MBT-3kg, T10, and STS in both groups. With five days of rest, we aimed to provide full recovery and increase the performance in tests that required high movement velocities. Figure 1 presents the schematic representation of the study design.

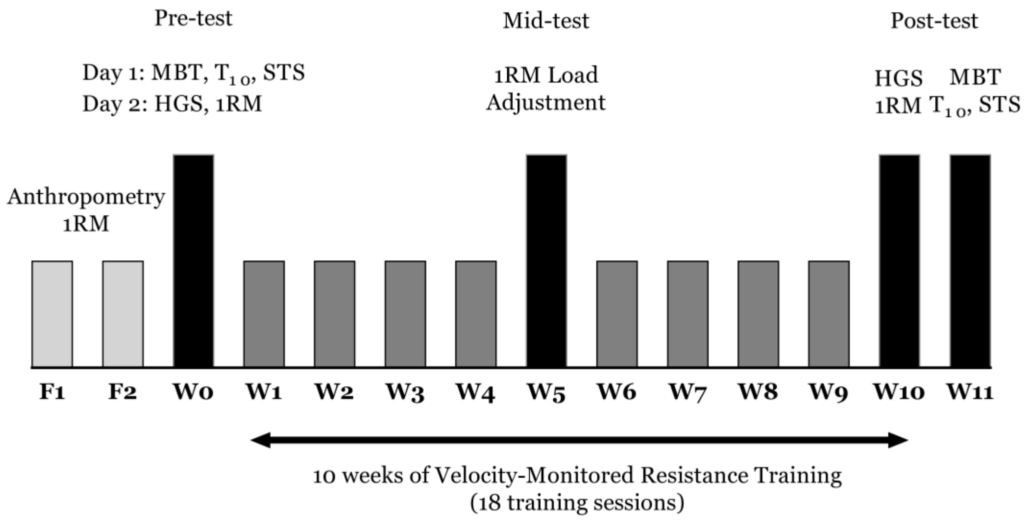

Figure 1. Study design; Abbreviations: 1RM: one-repetition maximum; F1: week 1 of familiarization; F2: week 2 of familiarization; HGS: handgrip strength; MBT: medicine ball throw; STS: five-repetition sit-to-stand; T_{10}: 10 m walking speed; W: week.

Participants

In collaboration with the geriatricians of several community-dwelling centers, we recruited institutionalized older adults to participate in this study. Inclusion criteria were age ≥ 65 years old, male and female, able to walk 10 m, independently stand up from a chair, with a willingness to participate in the study and collaborate with the researchers. Exclusion criteria were a simultaneous participation in another training program, severe cognitive impairment, cardiovascular/respiratory disorders, musculoskeletal injuries in the previous three months, and terminal illness. After screening, 30 women and 15 men without previous RT experience were divided into an RT group (n = 22) or a control group (CG; n = 23). From these, we excluded six participants due to the absence of training sessions and evaluations. Thus, 39 participants remained for the final analysis (Figure 2).

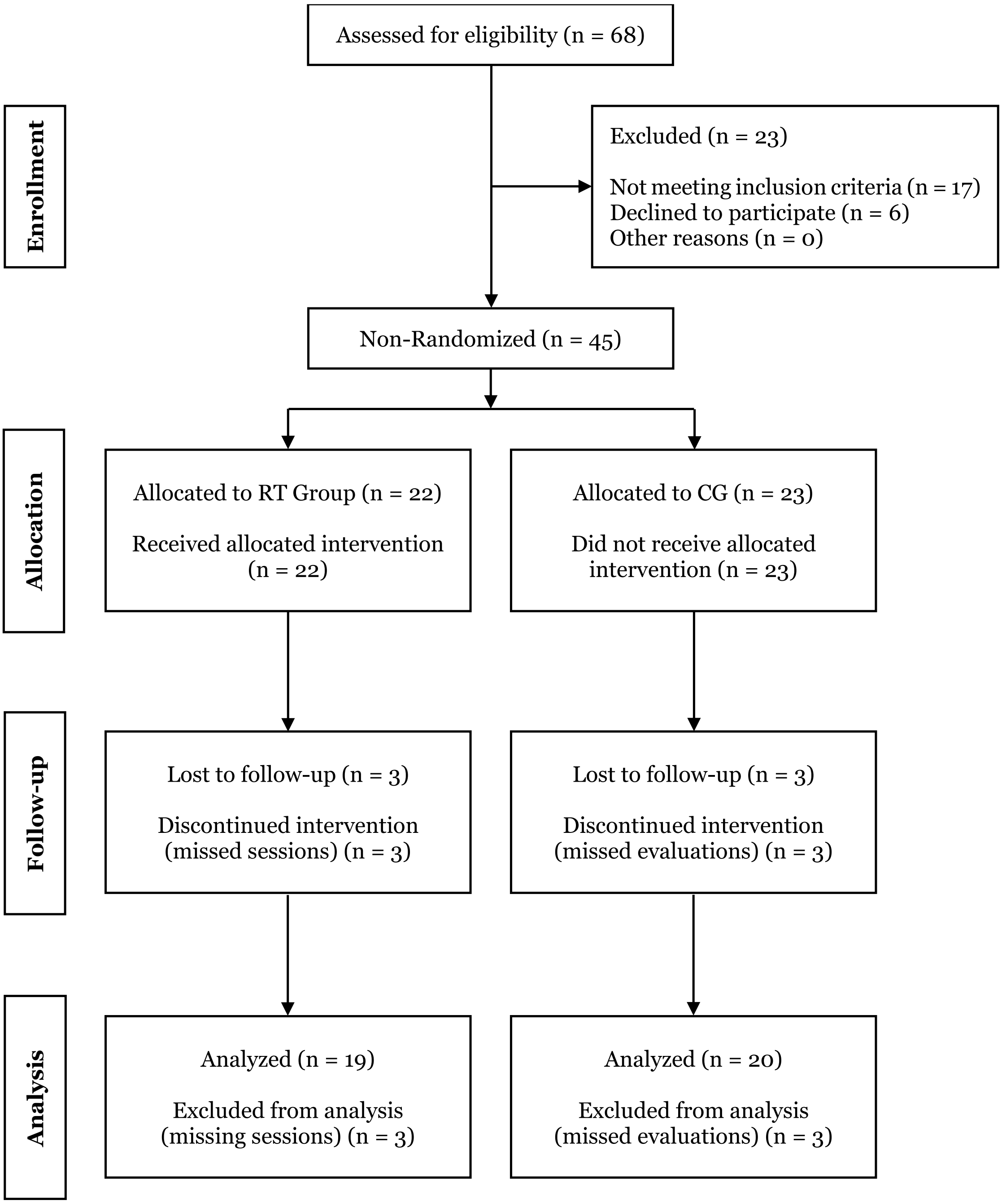

Figure 2. Study flow diagram; Abbreviations: CG: control group; RT: resistance training.

Table 1 presents the characteristics of the participants at baseline. All participants received detailed information regarding the procedures and signed a written informed consent. The Ethical Committee of the University of Beira Interior (code: CE-UBI-Pj-2019-019) approved this study. The experimental procedures followed the recommendations of the Declaration of Helsinki.

Table 1. Participants characteristics at baseline.

Variable	RT Group (12 women; 7 men)	CG (14 women; 6 men)	*p*-value
Age (years)	78.6 ± 7.6 (range: 69 to 92)	79.0 ± 6.0 (range: 70 to 89)	0.85
Body mass (kg)	70.4 ± 14.3	70.3 ± 12.6	0.98
Height (m)	1.55 ± 0.11	1.57 ± 0.09	0.68
BMI (kg/m²)	29.3 ± 5.4	28.6 ± 4.0	0.66
MMSE	24.3 ± 2.3	24.5 ± 1.8	0.78

Notes: Data are presented as mean ± SD. Abbreviations: BMI: body mass index; CG: control group; MMSE: mini-mental state examination; RT: resistance training group.

Sample Size

To detect a final difference between groups of 20 kg in the 1RM leg-press (Ramírez-Campillo et al., 2014) with a baseline SD of 21.91 kg and using an alpha of 5%, a sample size of 24 participants was needed to obtain a power of 80%. A dropout rate of 20% was also considered. The calculations were performed using a Microsoft Office Excel® spreadsheet (Arifin, 2017).

Outcome Measures

One-Repetition Maximum Leg-Press and Chest-Press

All participants were assessed in two variable resistance machine exercises: horizontal leg-press (Leg-Press G3, Matrix, USA) and seated chest-press (Chest-Press G3, Matrix, USA). For the leg-press, the participants had to sit on the bench (lower back in contact with the machine), bend the knees at 90°, and place the feet shoulder-width apart on the platform. On command, they had to fully extend their legs, as fast and forcefully as possible, and slowly return to the initial position. In the chest-press, the participants had to sit on the bench, abduct the shoulders, flex the elbows at 90°, grab the handles with a full grip, and maintain the wrists in a neutral position. Then, we instructed them to perform a purely concentric action, as fast and forcefully as possible, and slowly return to the initial position. In the leg-press, we controlled the eccentric phase by standing alongside the participants and placing the hands on the platform handle. In the chest-press, we were behind the participants and placed the hands on the machine's arms to control the descending phase. The general warm-up consisted of 10 min walking on a treadmill (2–4 km/h) or pedaling on a stationary bicycle (50–70 rpm with resistance levels varying between 1–5). The specific warm-up consisted of two sets (the first set of 5–10 repetitions at 40–60% of the perceived maximum load, followed by a 1 min rest, and the second set of 3–5 repetitions at 60–80% of the perceived maximum load). After that, 3–5 single attempts to reach the 1RM were conceded, with a 3–5 min rest between each maximal attempt. The procedures were already described elsewhere (Marques et al., 2019). For the leg-press, the coefficient of variation (CV) was 2.83%, and the intraclass correlation coefficient (ICC) was 0.99 (95% confidence interval, CI: 0.98–0.99). For the chest-press, the CV was 3.55%, and the ICC was 0.99 (CI: 0.98–0.99).

Handgrip Strength

The participants were seated on an armless chair (0.49 m) in an erect position, with a 90° hip, knee, and elbow flexion position (Marques et al., 2019). They exerted a maximal grip in both hands after instruction, using an adjustable portable digital hand dynamometer (Saehan, Model DHD-1) connected by USB to a personal computer. Three measures (~3 s) to the nearest 0.1 kg were performed with both hands, with a 1 min rest between each attempt. The three measures with both hands were averaged to calculate the absolute HGS. The CV was 3.54% in the left hand, and the ICC was 0.98 (CI: 0.98–0.99), while in the right hand the CV was 3.00%, and the ICC was 0.98 (CI: 0.98–0.99).

Seated Medicine Ball Throw

Seated on an armless chair (0.49 m) with the back straight and the medicine ball held in front of the chest, the participants had to throw the ball as far and fast as possible after instruction (Marques et al., 2019). They performed three attempts with 1- and 3-kg medicine balls, with a 1 min rest between each attempt. The throwing distance was measured to the nearest 0.1 cm from the chest to where the ball landed, using a flexible tape. The best result was analyzed. For the 1-kg ball, the CV was 3.17%, and the ICC was 0.97 (CI: 0.96–0.98). For the 3-kg ball, the CV was 2.46%, and the ICC was 0.98 (CI: 0.96–0.98).

10 m Walking Speed

The walking speed time was recorded in an indoor wooden track. We instructed the participants to start one meter behind the starting line and finish one meter after the 10 m, to attenuate the acceleration and deceleration phases. After instruction, the participants walked over 10 m linearly as fast as possible, without running (Pereira et al., 2012). For safety, a coach walked alongside each participant while performing the test. The time was measured to the nearest 0.01 s using pairs of photoelectric cells (Race Time Kit 2, Microgate, Bolzano, Italy) attached to tripods, raised to a height of 0.5 m, and placed in pairs (0 and 10 m). Three trials separated by a 3 min rest were recorded, and the best time was analyzed. The mean velocity (MV) in T_{10} (T_{10}-MV) was calculated by dividing the distance by the time ($m \cdot s^{-1}$). The CV was 2.98%, and the ICC was 0.95 (CI: 0.92–0.96).

Five-Repetition Sit-to-Stand

The participants had to sit on an armless chair (0.49 m) with the back straight and the arms crossed over the chest. After instruction, the participants stood up and sat down as fast as possible five times (Alcazar et al., 2018). During the test, a coach stood alongside the participants to verbally encourage them and guarantee safety during the ascending and descending phases. The time was measured to the nearest 0.01 s using a digital stopwatch (Casio HS-3V-1R, Tokyo, Japan). Two trials, separated by 2 min, were conceded, and the best one was analyzed. The STS-MV ($m \cdot s^{-1}$) and the STS mean power (STS-MP) (Watts, W), were calculated using the equations proposed by Alcazar et al. (2018). The CV was 2.64%, while the ICC was 0.94 (CI: 0.91–0.96).

Resistance Training Program

All training sessions were supervised by an experienced researcher and three specialist senior coaches to ensure safety and the proper execution of all the exercises. The sessions lasted 45 min and were performed in a fitness health club, at the same time (2:00–3:00 pm), with a room temperature of 22–24 °C. After a general warm-up of 10 min walking on a treadmill (2–4 km/h) or pedaling on a stationary bicycle (50–70 rpm; resistance levels: 1–5), the participants performed the following exercises: horizontal leg-press; seated chest-press; MBT; chair squats with a weight-vest. Between sets and exercises, they rested for 2–3 min. The cool-down consisted of 5 min walking or pedaling at low intensity. For the leg-press and chest-press, the relative loads progressed from 40–65% 1RM (Fragala et al., 2019). The training volume consisted of 2–3 sets with a velocity loss of 20%. The sets ended when the participants reached the 20% threshold (Rodríguez-Rosell et al., 2020). We verbally encouraged the participants to perform the concentric phase as fast and forcefully as possible and slowly return to the initial position. In the leg-press, coaches controlled the eccentric phase by standing alongside the participants and placing their hands on the platform handle. In the chest-press, coaches were behind the participants and controlled the eccentric phase by placing their hands on the machine's arms. Table 2 shows the characteristics of the training program.

Table 2. Resistance training program.

	Week 1		Week 2		Week 3		Week 4		Week 5	
Exercises	**TS1**	**TS2**	**TS3**	**TS4**	**TS5**	**TS6**	**TS7**	**TS8**	**TS9**	**TS10**
LP & CP (S x VL [%])	2 x 20%	2 x 20%	3 x 20%	3 x 20%	2 x 20%	2 x 20%	3 x 20%	3 x 20%	2 x 20%	
1RM (%)	40%	40%	40%	40%	50%	50%	50%	50%	55%	1RM Mid-test
Chair-Squat (S x R x kg)	1 x 10 x 3	1 x 10 x 3	2 x 10 x 3	2 x 10 x 3	2 x 10 x 3	2 x 10 x 3	3 x 10 x 3	3 x 10 x 3	3 x 10 x 3	Load Adjustment
MBT (S x R x kg)	1 x 10 x 1	1 x 10 x 1	2 x 10 x 1	2 x 10 x 1	2 x 10 x 1	2 x 10 x 1	3 x 10 x 1	3 x 10 x 1	3 x 10 x 1	
	Week 6		**Week 7**		**Week 8**		**Week 9**		**Week 10**	
Exercises	**TS11**	**TS12**	**TS13**	**TS14**	**TS15**	**TS16**	**TS17**	**TS18**	**TS19**	**TS20**
LP & CP (S x VL [%])	2 x 20%	2 x 20%	3 x 20%	3 x 20%	2 x 20%	2 x 20%	3 x 20%	3 x 20%	2 x 20%	
1RM (%)	55%	55%	60%	60%	60%	60%	65%	65%	65%	1RM Post-test
Chair-Squat (S x R x kg)	4 x 8 x 3	4 x 8 x 3	4 x 8 x 3	4 x 8 x 3	4 x 8 x 3	4 x 8 x 3	4 x 8 x 3	4 x 8 x 3	2 x 8 x 3	
MBT (S x R x kg)	4 x 8 x 1	4 x 8 x 1	4 x 8 x 1	4 x 8 x 1	4 x 8 x 1	4 x 8 x 1	4 x 8 x 1	4 x 8 x 1	2 x 8 x 1	

Abbreviations: 1RM: one-repetition maximum; CP: chest-press; LP: leg-press; MBT: medicine ball throw; R: repetitions; S: sets; TS: training session; VL: velocity loss.

Data Collection

The MV (i.e., the average velocity from the start of the concentric phase until the weight stack plate reached the maximum height) of each repetition was recorded in real time using a linear velocity transducer (T-Force System, Ergotech, Murcia, Spain) (González-Badillo & Sánchez-Medina, 2010). The T-Force collects data at a sampling frequency of 1000 Hz and is a valid and reliable device to measure kinetic and kinematic variables during RT (Courel-Ibáñez et al., 2019). We connected the T-Force to the resistance machines by attaching a steel snap hook with a nylon cable tie to the T-Force cable extension. Following this, we attached the nylon cable tie to the weight stack pin that fixed the load (Figure 3). The load and the T-Force cable extension were simultaneously displaced in a vertical direction, allowing the measurement of MV. A custom software (T-Force v2.36) displayed the data in real time. In every session, we analyzed the following variables: total repetitions (sum of all completed repetitions), repetitions per set (average of repetitions performed in each set), fastest MV (maximum value of MV attained), average MV (average MV of all repetitions), and velocity loss (average of the percent change from the fastest to the slowest repetition in each set). In the software, we selected the option to identify the fastest MV in the first three repetitions. In the leg-press, the fastest MV was attained, on average, in repetition 2.6 ± 0.5, while in the chest-press it was attained in repetition 2.2 ± 0.3.

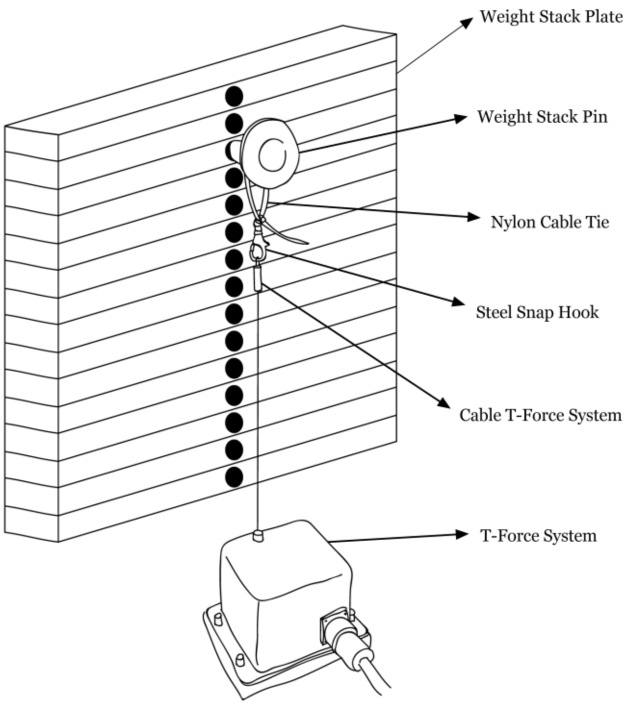

Figure 3. Illustration of the connection between the T-Force System and the resistance machines.

Statistical Analysis

Data are presented as mean ± SD unless otherwise indicated. The normality and homogeneity of variances were calculated and confirmed using the Shapiro–Wilk and Levene tests, respectively. The ICC (95% CI) was calculated using a two-way random effect, absolute agreement, single rater/measurement model ($ICC_{2,1}$) (Koo & Li, 2016), while the CV was calculated as (SD/mean) × 100. An independent-samples t-test analyzed the differences between groups at baseline and between the variables collected during the leg-press and chest-press exercises. A mixed design 2 × 2 factorial analysis of variance (ANOVA) analyzed the differences between groups (RT group, CG) and time (pretest, post-test) for all variables. Paired samples t-tests compared the differences within groups from pre- to post-test. A repeated-measures ANOVA (within subject-factor: time 4 levels) with post hoc Bonferroni adjustments analyzed the differences in the number of repetitions per set and the fastest MV attained against the same relative load (e.g., fastest MV in session 1 at 40% 1RM vs. fastest MV in session 2 at 40% 1RM vs. fastest MV in session 3 at 40% 1RM vs. fastest MV in session 4 at 40% 1RM). The percentage change was calculated with a 90% CI. The effect size (ES) between and within groups was calculated using Hedge's *g* formula (Hedges & Olkin, 1985). The ES was interpreted as follows: trivial, 0.0–0.2; small, 0.2–0.6; moderate, 0.6–1.2; large, 1.2–2.0; very large, 2.0–4.0; extremely large, > 4.0 (Hopkins et al., 2009). The alpha level was set at $p < 0.05$. Statistical analyses were performed in Microsoft Office Excel® (Microsoft Inc., Redmond, WA, USA) and SPSS v26 (SPSS Inc., Chicago, IL, USA). The data were plotted in GraphPad Prism v7 (GraphPad Inc., San Diego, CA, USA).

Results

At baseline, we did not observe significant differences between groups in any of the analyzed variables. Changes from pre- to post-test are presented in Table 3. After 10 weeks, significant differences between groups were observed in the 1RM leg-press, 1RM chest-press, MBT-1kg, STS, STS-MV, and STS-MP. We observed significant gains in 1RM leg-press, 1RM chest-press, MBT-1kg, STS, STS-MV, and STS-MP in the RT group. In CG, we found a significant

Table 3. Changes in strength-related variables from pre- to post-test in the RT group and CG (mean ± SD).

	RT Group				CG				RT vs. CG	
Variable	**Pre-test**	**Post-test**	**Δ (90% CI)**	**ES**	**Pre-test**	**Post-test**	**Δ (90% CI)**	**ES**	***p***	**ES**
1RM LP (kg)	74.79 ± 23.12	85.00 ± 22.79 ***	15.07 (11.77 to 18.37)	0.43	67.65 ± 20.5	67.15 ± 18.42	-0.26 (-1.81 to 1.29)	-0.02	<0.001	0.85
1RM CP (kg)	31.54 ± 13.15	39.26 ± 12.48 ***	31.35 (21.05 to 41.66)	0.58	30.10 ± 9.40	29.75 ± 8.58	-0.24 (-2.84 to 2.37)	-0.04	<0.001	0.87
HGS (kg)	25.20 ± 8.50	25.07 ± 8.01	-0.08 (-2.34 to 2.18)	-0.02	25.55 ± 7.19	25.15 ± 6.90	-1.08 (-3.74 to 1.59)	-0.05	>0.05	-0.01
MBT-1kg (m)	3.01 ± 0.60	3.24 ± 0.62 ***	8.09 (4.80 to 11.38)	0.37	2.91 ± 0.59	2.87 ± 0.64	-1.59 (-3.67 to 0.50)	-0.06	<0.001	0.57
MBT-3kg (m)	2.26 ± 0.43	2.31 ± 0.38	2.99 (0.04 to 5.94)	0.12	2.13 ± 0.37	2.17 ± 0.43	1.74 (-1.23 to 4.70)	0.10	>0.05	0.33
T_{10} (s)	6.17 ± 0.82	6.05 ± 0.94	-1.77 (-5.94 to 2.40)	-0.14	6.57 ± 0.99	6.69 ± 0.91	2.00 (0.46 to 3.55)	0.12	>0.05	-0.68
T_{10}-MV (m·s-1)	1.65 ± 0.22	1.69 ± 0.25	3.04 (-1.40 to 7.47)	0.18	1.55 ± 0.22	1.52 ± 0.20 *	-1.81 (-3.24 to -0.38)	-0.15	>0.05	0.74
STS (s)	9.70 ± 1.22	8.56 ± 1.39 ***	-11.72 (-14.73 to -8.71)	-0.84	10.36 ± 1.10	10.38 ± 1.01	0.38 (-0.99 to 1.75)	0.02	<0.001	-1.48
STS-MV (m·s-1)	0.29 ± 0.07	0.33 ± 0.08 ***	13.93 (9.89 to 17.97)	0.51	0.28 ± 0.05	0.27 ± 0.05	-0.24 (-1.61 to 1.13)	-0.01	<0.001	0.78
STS-MP (W)	183.54 ± 73.66	211.12 ± 87.37 ***	14.86 (10.61 to 19.12)	0.33	173.93 ± 55.72	173.27 ± 56.80	-0.47 (-1.87 to 0.92)	-0.01	<0.001	0.51

Notes: * *p*-value < 0.05; *** *p*-value < 0.001; Abbreviations: Δ: percent change; 1RM: one-repetition maximum; CG: control group; CI: confidence interval; CP: chest-press; ES: effect size Hedge' s *g*; HGS: absolute handgrip strength; LP: leg-press; MBT: medicine ball throw; MP: mean power-output; MV: mean velocity; RT: resistance training; STS: five-repetition sit-to-stand; T_{10}: 10 m walking speed.

Table 4 shows a general description of the acute RT variables in the leg-press and chest-press. The total repetitions and the number of repetitions per set in the leg-press were significantly higher than in the chest-press. The fastest and average MV values in the leg-press were higher than in the chest-press. We observed significant differences between the fastest MV and the average MV in the leg-press ($p < 0.001$; ES = 0.83) and chest-press ($p < 0.001$; ES = 0.73). The velocity loss in the leg-press was lower than in the chest-press.

Table 4. Overall description of the acute training variables in the leg-press and chest-press.

	Leg-Press	**Chest-Press**	***p***	**Effect Size**	
Variable	**Mean (95% CI)**	**Mean (95% CI)**	**between**	***g***	**Magnitude**
Total repetitions	437.63 (407.89 to 467.37)	296.37 (260.89 to 331.84)	<0.001	1.90	Large
Repetitions per set	9.75 (8.44 to 11.06)	6.58 (5.48 to 7.68)	<0.001	1.15	Moderate
Fastest MV ($m \cdot s^{-1}$)	0.44 (0.41 to 0.48)	0.37 (0.33 to 0.40)	<0.001	0.97	Moderate
Average MV ($m \cdot s^{-1}$)	0.38 (0.35 to 0.41) [a]	0.31 (0.28 to 0.35) [b]	<0.001	0.98	Moderate
Velocity loss (%)	22.87 (22.16 to 23.59)	23.77 (22.80 to 24.73)	<0.001	-0.46	Small

Notes: [a] Denotes a significant difference ($p < 0.001$) between the fastest MV and the average MV in the leg-press exercise; [b] Denotes a significant difference ($p < 0.001$) between the fastest MV and the average MV in the chest-press exercise; Abbreviations: CI: confidence interval; ES: effect size Hedge's *g*; MV: mean velocity.

The repetitions per set performed in the leg-press at 55% 1RM significantly decreased from session 9 to sessions 11 and 12 (Figure 4). The fastest MV in the leg-press at 40% 1RM significantly increased from session 1 to 3, while at 55% 1RM it significantly decreased from session 9 to 11 (Figure 4). The fastest MV in the chest-press at 55% 1RM significantly decreased from session 9 to 11 (Figure 5).

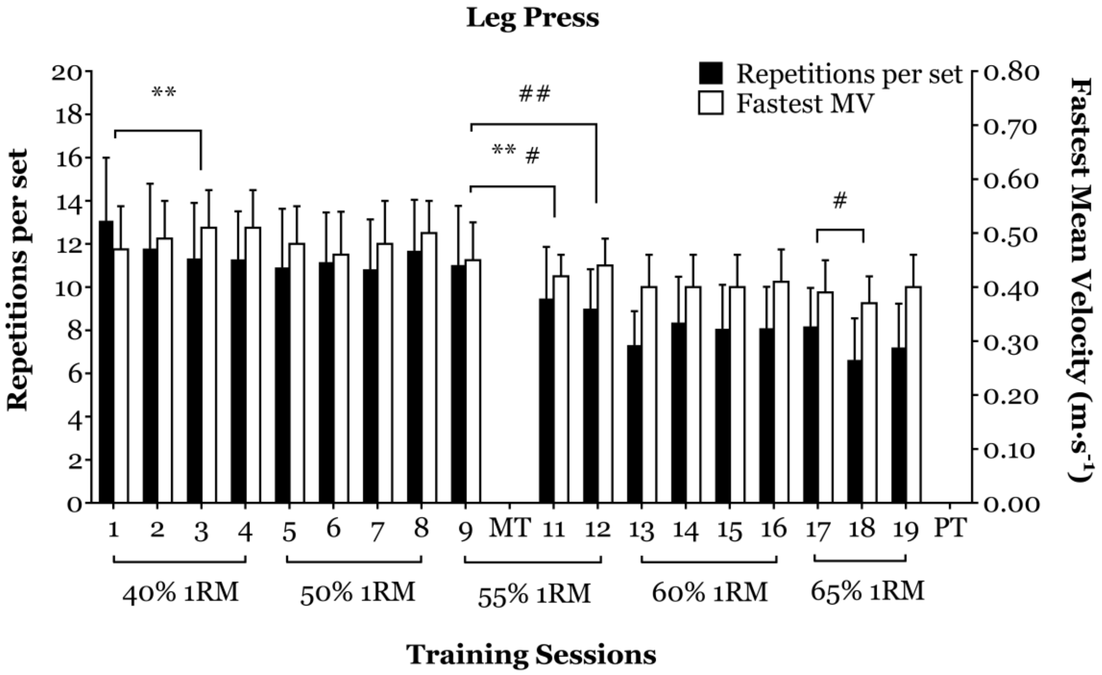

Figure 4. Repetitions per set and fastest MV (mean ± SD) in the leg-press exercise throughout the RT program; 1RM: one-repetition maximum; MT: 1RM mid-test load adjustment; MV: mean velocity; PT: post-test; ** p-value < 0.01 for the fastest MV; # p-value < 0.05 for the number of repetitions per set; ## p-value < 0.01 for the number of repetitions per set.

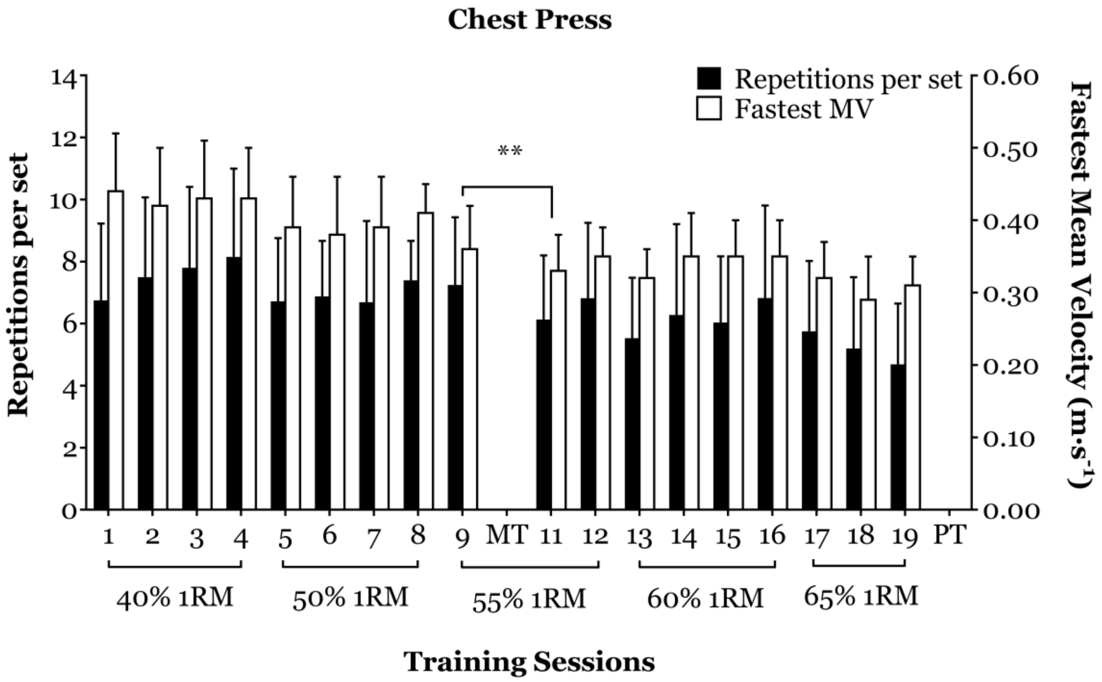

Figure 5. Repetitions per set and fastest MV (mean ± SD) in the chest-press exercise throughout the RT program; 1RM: one-repetition maximum; MT: 1RM mid-test load adjustment; MV: mean velocity; PT: post-test; ** p-value < 0.01 for the fastest MV.

Discussion

We analyzed the effects of velocity-monitored RT with a velocity loss of 20% on strength and functional capacity in institutionalized older women and men. The main finding was that a velocity loss of 20% was sufficient to increase strength and functional capacity in older adults, thus confirming our main hypothesis. Therefore, these data support velocity loss as an effective variable to prescribe the training volume in older adults. Our results also confirm our second hypothesis that performing a lower total number of repetitions than previously reported in high-velocity RT interventions with older people is enough to increase 1RM strength.

Although 1RM gains have been similar and, in some cases, higher than those reported in previous high-velocity RT studies with older adults (Balachandran et al., 2014; Bottaro et al., 2007; Henwood & Taaffe, 2006; Marsh et al., 2009; Miszko et al., 2003; Ramírez-Campillo et al., 2014, 2017, 2018; Richardson et al., 2019b, 2019a), the total number of repetitions performed in the leg-press and chest-press was inferior compared to all studies. Based on the study duration, sessions per week, sets, and repetitions performed in only one exercise, a total number of repetitions between 600 and 1056 in the chest-press (Balachandran et al., 2014; Bottaro et al., 2007; Henwood & Taaffe, 2006; Miszko et al., 2003; Nogueira et al., 2009; Richardson et al., 2019a, 2019b) and leg-press (Balachandran et al., 2014; Bottaro et al., 2007; Henwood & Taaffe, 2006; Marsh et al., 2009; Miszko et al., 2003; Nogueira et al., 2009; Ramírez-Campillo et al., 2014, 2017, 2018; Richardson et al., 2019a, 2019b) was performed in these studies, which means ~50% more than the total repetitions performed in our study. Therefore, these results suggest that a low volume is as effective as a high volume for improving 1RM strength in older adults. A previous study with older adults corroborates this observation (Silva et al., 2018). Participants who performed 50% of the possible maximal repetitions increased their 1RM strength gains to a similar extent as those that performed the repetitions until concentric failure did (Silva et al., 2018). Thus, taken together, this evidence suggests that, with a low number of repetitions per set completed at a high movement velocity, it is possible to achieve similar strength gains in older adults when compared to a high number of repetitions per set. Despite the low number of total repetitions, one possible explanation for the 1RM strength gains might be associated with the use of high movement velocities, which seems to promote an increase in type II fast-twitch fibers in older adults after RT (Hakkinen et al., 2001; Wang et al., 2017). However, to our knowledge, most studies that assessed muscle fiber changes after RT using high movement velocities either applied a combination of low and high loads (Hakkinen et al., 2001) or only high loads (Wang et al., 2017). Thus, future studies should investigate the influence of high movement velocities against low loads on fast-twitch fiber changes in older adults. Another possible cause for the 1RM gains might be related to the use of velocity loss. Using this variable during each RT session, we could control the degree of fatigue and individualize the training volume, which might have contributed to optimizing the training stimulus and consequently enhancing the 1RM strength in the leg-press and chest-press.

Our results demonstrated that, despite the prescribed magnitude of velocity loss had been identical in both exercises, the number of repetitions per set was significantly higher in the leg-press than in the chest-press (~3 repetitions more). These data suggest that the upper muscles fatigue faster than the lower muscles in older adults when matching the same velocity loss. Our study supported this evidence by the significantly higher percentage of velocity loss observed in the chest-press than in the leg-press. These differences can be explained by the smaller muscle groups involved during upper body exercises (e.g., bench press) compared to lower body exercises (e.g., squat). Besides, the higher presence of fast-twitch fibers in the upper musculature causes a higher degree of fatigue (Rodríguez-Rosell et al., 2018; Sánchez-Medina & González-Badillo, 2011). Therefore, as observed in a study with trained young adults, to equalize the number of repetitions per set, the magnitude of the velocity loss must be different (at least by 5%) between the lower and upper body exercises (Rodríguez-Rosell et al., 2018). However, these results were only observed in younger populations, which means that this evidence remains to be explored in older adults.

In the leg-press, from sessions 1 to 3 we observed a significant increase in MV at 40% 1RM. Considering that an increase in MV against the same weight is an indicator of performance improvement (Rodríguez-Rosell et al., 2020), our participants' strength increased, possibly after one week. In a study with older adults that evaluated changes in strength during RT, the authors observed a significant increase of 10% in the maximal force after repeated isometric contractions over only two days (Kamen & Knight, 2004). Similarly, some studies observed significant increases in 1RM after 5–6 weeks of RT in older adults (Pinto et al., 2014; Van Roie et al., 2013). In our study, the significant decreases in MV from session 9 to 11 in both resistance exercises were influenced by an increase in the weight after the 1RM mid-test (load adjustment), which indicated a strength improvement after five weeks. Thus, taken together, these results reflect the early and rapid increases in muscle strength in older adults, which can be mainly attributed to neural adaptations (Hakkinen et al., 2001; Kamen & Knight, 2004).

After 10 weeks, we did not observe any change in the HGS in the RT group. Although the HGS is a strong predictor of mortality and an indicator of general strength, its sensitivity is questionable in relation to detecting physical performance changes in older adults after RT interventions (Tieland et al., 2015). Thus, future studies should analyze the underlying mechanisms for nonsignificant changes in the HGS after RT in this population. Considering that we only included exercises for the chest and the quadriceps, future studies should also include exercises targeting the forearm muscles to analyze their influence on the HGS.

At post-test, we observed significant gains in the MBT-1kg, while in the MBT-3kg we found a nonsignificant increase. These differences can be justified because only the MBT-1kg was included as part of the RT program. Indeed, when the same medicine ball weight is used both in the test and the intervention, significant gains tend to occur (Dias et al., 2020; Pereira et al., 2012; Ramírez-Campillo et al., 2014). Conversely, when the MBT is not included in the RT program, the findings are less conclusive about the transference effects of RT on this parameter. In a study that analyzed the effects of 12 weeks of high-velocity RT on the MBT-3kg distance in older individuals, nonsignificant gains of 3% were observed in the group that performed the RT in pneumatic machines, and a significant gain of 6% was observed in the group that performed the RT in plate-loaded machines (Balachandran et al., 2017). In that study, the participants performed three sets of 8–10 repetitions in six upper body exercises. Considering that our participants only used the chest-press exercise and performed a lower number of repetitions than in that study, more exercises should be included, and more repetitions performed, possibly to enhance the MBT-3kg distance. Future studies should include exercises targeting the shoulder flexors and elbow extensors to analyze their transference effect on the ball throwing distance with heavier weights in older adults.

Despite the nonsignificant improvements in T_{10}, our results found a relevant aspect. In the RT group, the T_{10}-MV increased, while in the CG it significantly decreased. These results suggest the loss of walking speed during aging and reinforce the importance for older adults to engage in RT (Ramírez-Campillo et al., 2014). Studies observed significant gains in T_{10} (−18% to −6%) after high-velocity RT programs with older adults (Pereira et al., 2012; Ramírez-Campillo et al., 2014, 2017, 2018). On average, the total repetitions varied between 576 and 864. More than one lower body exercise was used in three of them: leg-press, leg-extension, and leg-curl (Ramírez-Campillo et al., 2014, 2017, 2018). Thus, increasing the walking speed in older adults may require more volume and exercises targeting both the quadriceps and the hamstring muscles. However, future studies are warranted to confirm this hypothesis.

In our study, we observed significant decreases in the STS time. This result agrees with previous findings, in which significant gains from −15% to −11.8% were observed after high-velocity RT with older adults (Balachandran et al., 2014; Henwood & Taaffe, 2006; Tiggemann et al., 2016). Of these, only one study prescribed a total number of repetitions per exercise lower than ours (~312 repetitions) (Tiggemann et al., 2016). However, given that the leg-press, knee-extension, and leg-curl were included, the participants performed ~936 repetitions on average. In the studies of Henwood and Taaffe (2006), and Balachandran et al. (2014), three and two lower-body exercises were used, resulting in approximately 1800 and 3168 repetitions, respectively. Thus, comparing these numbers to ours, we present an efficient and effective strategy to improve the ability to rise from a chair and enhance older adults' functional capacity.

This study presents some limitations. A larger sample size would allow us to generalize the results and reduce the probability of a type II error. Moreover, an additional experimental group could give us important insights into the effects of different velocity loss thresholds on older adults' strength and functional capacity. Including resistance exercises targeting the forearm muscles could be important to analyze their effects on the HGS. Therefore, future velocity-monitored RT interventions with older adults should include larger sample sizes, more experimental groups, and additional exercises targeting the forearm muscles.

In summary, our data suggest that monitoring the velocity loss during RT is an efficient and effective strategy to prescribe the training volume in older adults and to increase muscle strength and functional capacity in this population.

Conclusions

The current research presents a novel RT approach to prescribe the volume in older adults by monitoring each set's velocity loss. The training method presented here opens a new possibility for coaches and clinicians to adopt an individualized intervention and optimize muscular adaptations during RT with older adults. In practical terms, two RT sessions per week with a velocity loss of 20% (i.e., 2–3 sets of ~10 and 7 repetitions per set in the leg-press and chest-press, respectively) and relative loads progressing from 40–65% 1RM seem to be enough to induce muscle strength adaptations and improve functional capacity in older adults aged between 70 and 90 years.

Study 4. Velocity-Monitored Resistance Training in Older Adults: The Effects of Low-Velocity Loss Threshold on Strength and Functional Capacity

Abstract

Objective: This study analyzed the effects of velocity-monitored resistance training (RT) with a velocity loss of 10% on strength and functional capacity in older adults. **Methods:** Forty-two participants (79.7±7.1 years) were allocated into an RT group (n=21) or a control group (CG; n=21). Over 10-weeks, the RT group performed two sessions per week, while the CG maintained their daily routine. During RT sessions, we monitored each repetition's mean velocity in the leg-press and chest-press exercises at 40-65% of one-repetition maximum (1RM). The set ended when a velocity loss of 10% was reached. At pre and post-test, both groups were assessed in the 1RM leg-press and chest-press, handgrip strength, medicine ball throw (MBT), walking speed (T_{10}), and five-repetition sit-to-stand (STS). **Results:** After 10-weeks, the RT group significantly improved the 1RM leg-press ($p<0.001$; Hedge's g effect size [g]=0.55), 1RM chest-press ($p<0.001$; g=0.72), MBT-1kg ($p<0.01$; g=0.26), T_{10} ($p<0.05$; g=-0.29), and STS ($p<0.05$; g=-0.29), while the CG significantly increased the T_{10} ($p<0.05$; g=0.15). Comparisons between groups at post-test demonstrated significant differences in the 1RM leg-press ($p<0.001$; mean difference [MD]=14.4 kg), 1RM chest-press ($p<0.001$; MD=7.52), MBT-1kg ($p<0.05$; MD=0.40 m), T_{10} ($p<0.001$; MD=-0.60 s) and STS ($p<0.001$; MD=-1.85 s). **Conclusions:** Our data demonstrate that velocity-monitored RT with velocity loss of 10% results in a few repetitions per set (leg-press: 5.1±1.2; chest-press: 3.6±0.9) and significantly improves strength and functional capacity in older adults.

Keywords: aging, physical performance, movement velocity, low-volume, low-loads

Introduction

Resistance training (RT) is an effective approach to prevent age-related loss of muscle mass and improve strength and functional capacity in older adults (Fragala et al., 2019; Marques et al., 2013). During RT programs, coaches and researchers manipulate several acute variables, namely load and volume, to maximize strength and improve older adults' functional capacity (Fragala et al., 2019; Marques et al., 2013). Traditionally, the load is prescribed based on a percentage of one-repetition maximum (1RM), while the volume is based on a fixed number of repetitions per set, which can be maximum or not (Fragala et al., 2019; González-Badillo et al., 2017). A combination example of both variables can be 3 x 10 x 75% 1RM, which means that all participants should perform three sets of ten repetitions at a relative load of 75% 1RM.

Although it seems practical to prescribe a specific number of repetitions per set for all participants, the maximal number of repetitions completed against a relative load (% 1RM or xRM) presents high inter-individual variability in young (González-Badillo et al., 2017; Rodríguez-Rosell et al., 2018) and older adults (Farinatti et al., 2013; Jesus et al., 2018; Silva et al., 2009). For example, when older women were instructed to perform three sets of 10RM, it was found that the maximal number of repetitions completed, in addition to having decreased throughout the sets, also varied among participants (Farinatti et al., 2013; Jesus et al., 2018; Silva et al., 2009). Thus, considering that the same stimulus will elicit different responses in older adults (Ahtiainen et al., 2016), alternative approaches are necessary to prescribe the volume and overcome the repetition-based method's limitation.

A velocity-monitored RT approach was recently proposed to prescribe the training volume in older adults between 70 and 90 years old (Marques et al., 2020). Contrary to the repetition-based method, the authors prescribed the volume based on a velocity loss threshold. The participants performed the repetitions at the maximal intended velocity until reaching a velocity loss of 20% in each set. Throughout the intervention, the authors observed inter-individual variability in the number of repetitions per set with the same relative load. In general, the participants performed a range of repetitions between 8.4-11.1 in the horizontal leg-press and 5.5-7.7 in the seated chest-press. Although both exercises' total repetitions were lower than previous high-velocity RT studies with older adults (Balachandran et al., 2014; Bottaro et al., 2007; Henwood & Taaffe, 2006; Marsh et al., 2009; Miszko et al., 2003; Nogueira et al., 2009; Ramírez-Campillo et al., 2014, 2017, 2018; Richardson et al., 2019a, 2019b), the strength and functional gains were comparable to those studies (Marques et al., 2020). Thus, the authors suggested that monitoring velocity loss in each set during RT is efficient and effective in prescribing the volume and improving strength and functional capacity in older adults (Marques et al., 2020).

To date, no study analyzed whether a velocity loss lower than 20% is enough to improve strength and functional capacity in older adults. Several velocity-monitored RT studies with trained young adults observed that velocity losses of 5% (Galiano et al., 2020), 10% (Pareja-Blanco et al., 2020a; Rodiles-Guerrero et al., 2020; Rodríguez-Rosell et al., 2020), and 15% (Pareja-Blanco et al., 2020b) were as effective as higher velocity loss percentages to improve strength. These velocity losses were also considered by authors more efficient since the gains on physical performance were obtained by performing fewer repetitions compared to higher velocity losses (Galiano et al., 2020; Pareja-Blanco et al., 2020b, 2020a; Rodiles-Guerrero et al., 2020; Rodríguez-Rosell et al., 2020). Nonetheless, it remains unclear if these scientific findings are also applicable to older populations.

Therefore, we aimed to analyze the effects of velocity-monitored RT with a velocity loss of 10% on strength and functional capacity in older adults. We hypothesized that a low-velocity loss in each set would be enough to enhance older adults' strength and functional capacity.

Methods

Experimental Approach to the Problem

This study was a non-blinded, non-randomized controlled trial. Fifty institutionalized older adults (35 women and 15 men) without previous RT experience were divided into an RT group or a control group (CG), based upon their perceived availability to participate regularly in the training sessions. Those who were able to attend the training sessions regularly were allocated to the RT group. In contrast, those that were only available for the testing sessions were allocated to the CG. The participants reported their availability to the community-dwelling centers' geriatricians, who then informed us about their decision. Before the pre-test, all participants underwent a familiarization period of 2-weeks (two sessions p/week) to ensure a proper adaptation to the fitness health club facilities, coaches, and strength exercises. The body mass, in kg (TANITA BC-601, Japan) and height, in m (Portable stadiometer SECA, Germany) were also measured during these sessions. After this period, two testing sessions separated by 48 hours were performed. In the first session, the seated medicine ball throw distance with 1 (MBT-1kg) and 3 kg (MBT-3kg) medicine balls, the 10 m walking speed time (T_{10}), and the time in the five-repetition sit-to-stand (STS) were measured. In the second session, the handgrip strength (HGS) and the 1RM load in the horizontal leg-press and seated chest-press were assessed. Following the initial evaluations, the RT group performed a 10-week velocity-monitored RT program with two sessions per week separated by 48 hours rest. The CG maintained their normal daily activities inside the community-dwelling centers without any form of physical training, as reported by the clinicians. In week 5 (session 10), a new assessment of the 1RM load in both exercises was performed to adjust the absolute loads (kg) in the RT group (Marques et al., 2020; Van Roie et al., 2013). At week 10, session 20, the HGS and the 1RM load in the leg-press and chest-press were assessed in both groups. The aim was to analyze the participant's performance on these tests immediately after the intervention. In session 19, the number of sets in all exercises was reduced to avoid an excessive accumulation of fatigue that could prejudice the performance during the RT group's strength tests. In week 11 (i.e., after five days of rest), the MBT-1kg, MBT-3kg, T_{10}, and STS were assessed in both groups. The purpose of this rest period was to enable the participants to fully recover and increase their performance in tests that demand high movement velocities. All testing and training sessions were supervised by a researcher and three certified senior coaches' specialists to ensure safety and proper execution in all the exercises. Figure 1 illustrates the study design.

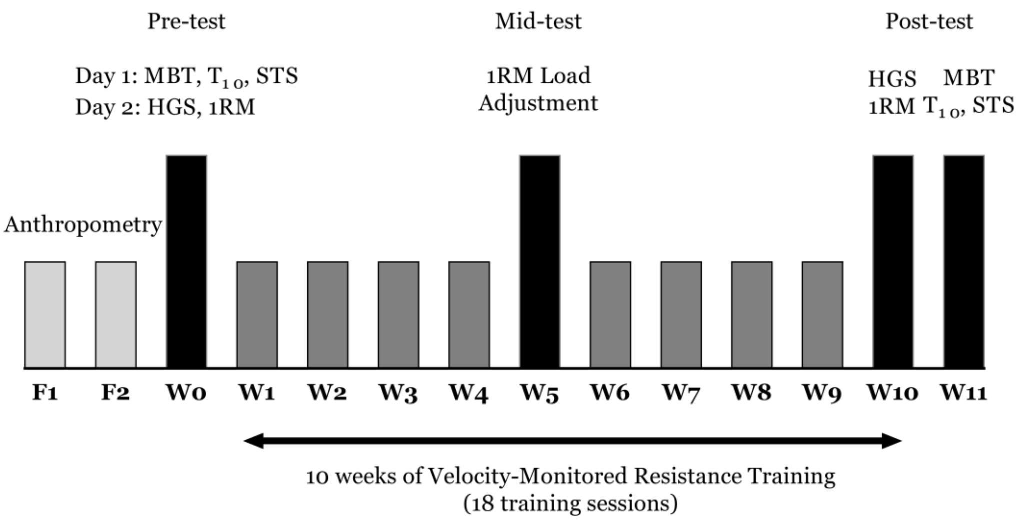

Figure 1. Study design. 1RM = one-repetition maximum; F1 = week 1 of familiarization; F2 = week 2 of familiarization; HGS = handgrip strength; MBT = medicine ball throw; STS = five-repetition sit-to-stand; T_{10} = 10 m walking speed; W = week.

Subjects

Older adults were recruited from community-dwelling centers. Inclusion criteria were age ≥ 65 years old, male and female, able to walk 10 m, independently stand-up from a chair, willing to participate in the study, and collaborate with the research team. Exclusion criteria were participation in another training program, severe cognitive impairment, cardiovascular/respiratory disorders, musculoskeletal injuries in the previous three months, and terminal illness. After screening, 35 women and 15 men were divided into an RT group (n = 25) or a CG (n = 25). From the initial sample, 8 participants were excluded due to the absence of the training sessions and evaluations. Thus, 42 participants (79.7 ± 7.1 years; 68.7 ± 11.2 kg; 1.55 ± 0.08 m) remained for the final analysis (Figure 2).

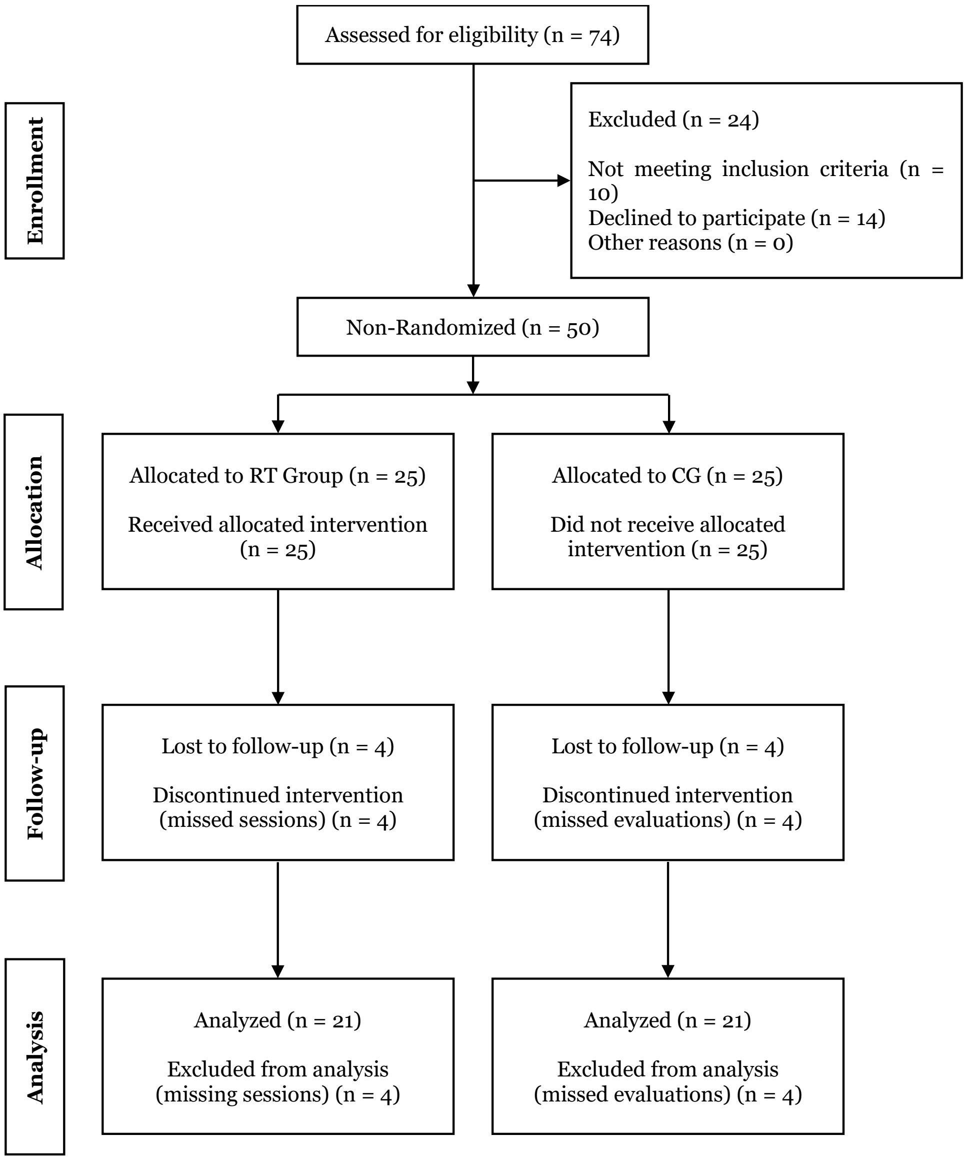

Figure 2. Study flow diagram. CG = control group; RT = resistance training group.

Table 1 presents the characteristics of the participants at baseline. All participants received detailed information regarding the procedures and signed a written informed consent. The Ethical Committee of the University of Beira Interior approved this study (code: CE-UBI-Pj-2019-019). All experimental procedures followed the recommendations of the Declaration of Helsinki.

Table 1. Participants characteristics at baseline.

Variable	RT Group (14 women; 7 men)	CG (13 women; 8 men)	*p*-value
Age (years)	79.2 ± 7.7 (range: 67 to 92)	80.3 ± 6.5 (range: 70 to 95)	0.621
Body mass (kg)	68.3 ± 11.6	69.1 ± 11.2	0.813
Height (m)	1.54 ± 0.09	1.56 ± 0.08	0.418
BMI (kg/m^2)	28.9 ± 5.5	28.2 ± 3.9	0.635
MMSE	24.6 ± 2.7	24.5 ± 1.5	0.886

BMI = body mass index; CG = control group; MMSE = mini-mental state examination; RT = resistance training; Data are mean ± SD; *p*-value indicates significant differences between groups.

Procedures

One-Repetition Maximum Leg-press and Chest-press

The 1RM load was assessed in two variable resistance machine exercises: horizontal leg-press (Leg-Press G3, Matrix, USA) and seated chest-press (Chest-Press G3, Matrix, USA). In the leg-press, the participants seated on the bench (lower back in contact with the machine) bent the knees at 90° and placed the feet shoulder-width apart on the platform. After instruction, they fully extended their legs at the maximal intended velocity and slowly returned to the initial position. In the chest-press, the participants had to sit on the bench, abduct the shoulders, flex the elbows at 90°, grab the handles with a full grip, and maintain the wrists in a neutral position. On command, they performed a purely concentric action at the maximal intended velocity and slowly returned to the initial position. In the leg-press, we controlled the eccentric phase by standing alongside the participants and placing the hands on the platform handle. In the chest-press, we were behind the participants and placed the hands on the machine's arms to control the descending phase. The general warm-up consisted of 10 min walking on a treadmill (2-4 km/h) or pedaling on a stationary bicycle (50-70 rpm with resistance levels varying between 1-5). The specific warm-up in both exercises consisted of 1 set of 5-10 repetitions at 40-60% of the maximum load perceived, followed by 1 min rest, and another set of 3-5 repetitions at 60-80% the maximum load perceived. After that, 3-5 single attempts to reach the 1RM load were conceded, with a 3-5 min rest between attempts. The 1RM load testing procedures were already described elsewhere (Marques et al., 2019, 2020). The intra-class correlation coefficient (ICC) from our laboratory in both exercises is 0.99, while the coefficient of variation (CV) is ~3% and 4% for the leg-press and chest-press, respectively (Marques et al., 2019, 2020).

Handgrip Strength Test

All participants were instructed to sit on an armless chair (0.49 m) in an erect position, with a 90° hip, knee, and elbow flexion position, shoulder adducted, and neutral wrist. Next, they grabbed a digital hand dynamometer (Saehan, Model DHD-1) and exerted a maximal grip lasting ~3 s. Three measures to the nearest 0.1 kg were performed in both hands, with 1-min rest between attempts (Marques et al., 2019, 2020). The three measures on the right and left hands were averaged to calculate the absolute HGS (Marques et al., 2019, 2020). The CV was 3.56% in the left hand, and the ICC was 0.98 (95% confidence interval, CI: 0.97-0.98), while in the right hand, the CV was 3.13%, and the ICC was 0.98 (CI: 0.97-0.99).

Seated Medicine Ball Throw Test

Seated on an armless chair (0.49 m) with the back straight and the medicine ball held in front of the chest, the participants had to throw the ball as far and fast as possible after instruction (Marques et al., 2019, 2020). Three attempts were performed with 1 and 3 kg medicine balls, with 1 min rest between each attempt. The throwing distance was measured to the nearest 0.1 cm from the chest to where the ball landed, using a flexible tape. The best result was analyzed. For the 1 kg ball, the CV was 2.91%, and the ICC was 0.97 (CI: 0.96-0.98). For the 3 kg ball, the CV was 2.44%, and the ICC was 0.98 (CI: 0.96-0.98).

10 m Walking Speed Test

Walking speed time was recorded on an indoor wooden track. The participants were instructed to start one meter behind the starting line and finish one meter after the 10 m to attenuate the acceleration and deceleration phases. After instruction, they walked 10 m as fast as possible, without running (Marques et al., 2020; Pereira et al., 2012a). During the test, a coach walked alongside the participants to verbally encourage them and ensure safety. The time was measured to the nearest 0.01 s using pairs of photoelectric cells (RaceTime Kit 2, Microgate, Bolzano, Italy) attached to tripods, raised to a height of 0.5 m, and placed in pairs at 0 and 10 m. Three trials separated by 3 min rest were recorded, and the best time was analyzed. The mean velocity (MV) in T_{10} (T_{10}-MV) was calculated by dividing the distance by the time ($m \cdot s^{-1}$). The CV was 2.95%, and the ICC was 0.95 (CI: 0.92-0.96).

Five-Repetition Sit-to-Stand Test

Seated on an armless chair (0.49 m) with the back straight and the arms crossed over the chest, the participants were instructed to stand up and sit down as fast as possible five times (Alcazar et al., 2018; Marques et al., 2020). During the test, a coach stood alongside the participants to verbally encourage them and ensure safety. The time was measured to the nearest 0.01 s using a digital stopwatch (Casio HS-3V-1R, Tokyo, Japan). Two trials, separated by 2-min rest, were conceded, and the best one was kept for analysis (Alcazar et al., 2018; Marques et al., 2020). The STS-MV ($m \cdot s^{-1}$) and the STS mean power (STS-MP) (Watts, W) were calculated using the equations proposed by Alcazar et al. (Alcazar et al., 2018). The CV was 2.36%, while the ICC was 0.97 (CI: 0.96-0.98).

Resistance Training Program

The training program's design was like a previous study conducted by our research team (Marques et al., 2020). The RT sessions lasted 45 min and were performed at a fitness health club, at the same time (2:00-3:00 p.m.), with a room temperature between 22-24 °C. After a general warm-up of 10 min walking on a treadmill (2-4 km/h) or pedaling on a stationary bicycle (50-70 rpm; resistance levels: 1-5), the participants performed the following exercises: horizontal leg-press; seated chest-press; MBT; chair-squat with a weight-vest. Between sets and exercises, the participants rested for 2-3 min. The cool-down consisted of 5 min walking or pedaling at low intensity. The relative loads in the leg-press and chest-press progressed from 40-65% 1RM. This load range is appropriate for inexperienced RT practitioners and improves strength and functional capacity in older adults (Fragala et al., 2019; Marques et al., 2020, 2013). The training volume consisted of 2-3 sets with a velocity loss of 10%. The sets ended when the participants reached the relative velocity loss of 10%. We verbally encouraged the participants to perform the concentric phase at the maximal intended velocity during all exercises. In the leg-press, coaches controlled the eccentric phase by standing alongside the participants and placing their hands on the platform handle. In the chest-press, coaches were behind the participants and controlled the eccentric phase by placing their hands on the machine's arms. Table 2 shows the characteristic of the velocity-monitored RT program.

Table 2. Velocity-monitored resistance training program.

	Week 1		Week 2		Week 3		Week 4		Week 5	
Exercises	**TS1**	**TS2**	**TS3**	**TS4**	**TS5**	**TS6**	**TS7**	**TS8**	**TS9**	**TS10**
LP & CP (S x VL [%])	2 x 10%	2 x 10%	3 x 10%	3 x 10%	2 x 10%	2 x 10%	3 x 10%	3 x 10%	2 x 10%	1RM Mid-test Load Adjustment
1RM (%)	40%	40%	40%	40%	50%	50%	50%	50%	55%	
Chair-Squat (S x R x kg)	1 x 10 x 3	1 x 10 x 3	2 x 10 x 3	2 x 10 x 3	2 x 10 x 3	2 x 10 x 3	3 x 10 x 3	3 x 10 x 3	3 x 10 x 3	
MBT (S x R x kg)	1 x 10 x 1	1 x 10 x 1	2 x 10 x 1	2 x 10 x 1	2 x 10 x 1	2 x 10 x 1	3 x 10 x 1	3 x 10 x 1	3 x 10 x 1	
	Week 6		**Week 7**		**Week 8**		**Week 9**		**Week 10**	
Exercises	**TS11**	**TS12**	**TS13**	**TS14**	**TS15**	**TS16**	**TS17**	**TS18**	**TS19**	**TS20**
LP & CP (S x VL [%])	2 x 10%	2 x 10%	3 x 10%	3 x 10%	2 x 10%	2 x 10%	3 x 10%	3 x 10%	2 x 10%	1RM Post-test
1RM (%)	55%	55%	60%	60%	60%	60%	65%	65%	65%	
Chair-Squat (S x R x kg)	4 x 8 x 3	4 x 8 x 3	4 x 8 x 3	4 x 8 x 3	4 x 8 x 3	4 x 8 x 3	4 x 8 x 3	4 x 8 x 3	2 x 8 x 3	
MBT (S x R x kg)	4 x 8 x 1	4 x 8 x 1	4 x 8 x 1	4 x 8 x 1	4 x 8 x 1	4 x 8 x 1	4 x 8 x 1	4 x 8 x 1	2 x 8 x 1	

1RM = one-repetition maximum; CP = chest-press; LP = leg-press; MBT = medicine ball throw; R = repetitions; S = sets; TS = training session; VL = velocity loss.

Data Collection

Except for the 1RM tests, in every RT session, the MV of each repetition performed in the horizontal leg-press and seated chest-press was recorded in real-time using a linear velocity transducer (T-Force Dynamic Measurement System, Ergotech Consulting, Murcia, Spain). The T-Force consists of a transducer interfaced to a computer that samples the instantaneous vertical velocity at 1000 Hz (González-Badillo & Sánchez-Medina, 2010). This device is valid and reliable for measuring the movement velocity during resistance exercises (Courel-Ibáñez et al., 2019). The procedure to connect the T-Force to the resistance machines was already described elsewhere by our research team (Marques et al., 2020). Briefly, the transducer's tethered cable was attached to the resistance machines' weight stack pin through a steel snap hook and a nylon cable tie. The data were displayed in real-time in custom software (T-Force v2.36), enabling the variables' monitorization. In every session, we analyzed the following variables: total repetitions (sum of all repetitions completed), repetitions per set (average of repetitions performed in each set), fastest MV (maximum value of MV attained), average MV (average MV of all repetitions) and velocity loss (average of the percent change from the fastest to the slowest repetition in each set). In the software, we selected the option to identify the fastest MV in the first three repetitions. In the leg-press, the fastest MV was attained, on average, in repetition 2.5 ± 0.3, while in the chest-press, in repetition 1.8 ± 0.1.

Statistical Analysis

The sample size was estimated using a Microsoft Office Excel® spreadsheet available online (Arifin, 2017). To detect a final difference between-groups of ~20 kg in the 1RM leg-press (Marques et al., 2020) with a baseline standard deviation (SD) of 15.75 kg, and using an alpha of 5%, a sample size of 13 participants was needed to obtain a power of 80%. A drop-out rate of 20% was also considered. Data are presented as mean ± SD unless otherwise indicated. The normality and homogeneity of variances were calculated and confirmed using the Shapiro-Wilk and Levene's tests, respectively. The ICC (95% CI) was calculated using a two-way random-effects, absolute agreement, single rater/measurement model ($ICC_{2,1}$) (Koo & Li, 2016), while the CV as (SD/mean) x 100. Independent-samples t-test analyzed the differences between groups at baseline and between the variables collected in the leg-press and chest-press. A mixed design 2 × 2 factorial analysis of variance (ANOVA) analyzed the differences between groups (RT group, CG) and time (pre-test, post-test) in all variables. Paired samples t-tests compared the differences within-groups from pre- to post-test. A repeated-measures ANOVA (within subject-factor: 3 and 4 levels) with post hoc Bonferroni adjustments analyzed the differences in the number of repetitions per set and the fastest MV attained against the same relative load (e.g., repetitions per set at 65% 1RM in session 17 vs. session 18 vs. session 19; fastest MV at 40% 1RM in session 1 vs. session 2 vs. session 3 vs. session 4). The percent change was calculated with a 90% CI. The Hegde's *g* effect size calculated the magnitude of differences between and within-groups. The effect size (*g*) was interpreted as follows: trivial, 0.0-0.2; small, 0.2-0.6; moderate, 0.6-1.2; large, 1.2-2.0; very large, 2.0-4.0; extremely large, > 4.0) (Hopkins et al., 2009). The alpha level was set at $p < 0.05$. The SPSS v27 (SPSS Inc., Chicago, USA) was used to analyze the data, while the GraphPad Prism v7 (GraphPad Inc., San Diego, USA) to design the figures.

Results

At baseline, no significant differences were observed between groups in any of the variables analyzed. Table 3 shows the changes in strength-related variables from pre- to post-test in both groups. At post-test, significant differences between groups ($p < 0.05$-0.001) in the 1RM leg-press, 1RM chest-press, MBT-1kg, T_{10}, T_{10}-MV, STS, STS-MV, and STS-MP were observed. In the RT group, there were significant improvements in the 1RM leg-press (p<0.001), 1RM chest-press (p<0.001), MBT-1kg (p=0.004), T_{10} (p=0.019), T_{10}-MV (p=0.007), STS (p<0.001), STS-MV (p<0.001) and STS-MP (p<0.001) after the velocity-monitored RT program. In the CG, there was a significant increase in T_{10} (p=0.024) and a significant decrease in T_{10}-MV (p=0.030) after the intervention.

Table 3. Changes in strength-related variables from pre- to post-test in the RT group and CG.

	RT Group				CG				RT vs. CG	
Variable	**Pre-test**	**Post-test**	**Δ (90% CI)**	**ES**	**Pre-test**	**Post-test**	**Δ (90% CI)**	**ES**	***p***	**ES**
1RM LP (kg)	72.19 ± 15.66	81.38 ± 16.35 ***	13.86 (9.58 to 18.14)	0.57	67.29 ± 15.82	67.24 ± 15.27	0.14 (-1.44 to 1.72)	0.00	<0.001	0.88
1RM CP (kg)	29.91 ± 9.66	37.24 ± 9.90 ***	28.71 (21.40 to 36.01)	0.74	29.86 ± 9.90	29.71 ± 9.08	0.57 (-1.99 to 3.12)	-0.01	<0.001	0.78
HGS (kg)	23.38 ± 6.69	24.08 ± 7.05	3.35 (-0.51 to 7.22)	0.10	24.43 ± 5.75	24.32 ± 5.74	-0.18 (-2.67 to 2.31)	-0.02	0.197	-0.04
MBT-1kg (m)	3.12 ± 0.48	3.25 ± 0.48 **	4.42 (2.10 to 6.73)	0.26	2.88 ± 0.54	2.85 ± 0.59	-1.07 (-3.79 to 1.66)	-0.05	0.014	0.72
MBT-3kg (m)	2.31 ± 0.39	2.35 ± 0.36	1.96 (-0.38 to 4.31)	0.10	2.13 ± 0.34	2.15 ± 0.41	0.82 (-2.15 to 3.79)	0.06	0.754	0.49
T_{10} (s)	6.26 ± 0.96	5.99 ± 0.84 *	-3.97 (-6.37 to -1.57)	-0.30	6.47 ± 0.89	6.59 ± 0.86 *	1.97 (0.61 to 3.32)	0.13	0.002	-0.69
T_{10}-MV (m·s-1)	1.63 ± 0.23	1.70 ± 0.23 **	4.63 (1.97 to 7.29)	0.29	1.57 ± 0.21	1.54 ± 0.19 *	-1.81 (-3.04 to -0.58)	-0.15	<0.001	0.74
STS (s)	9.09 ± 1.45	7.85 ± 1.52 ***	-13.72 (-17.02 to -10.43)	-0.82	9.58 ± 1.39	9.69 ± 1.40	1.53 (-1.27 to 4.32)	0.08	<0.001	-1.24
STS-MV (m·s-1)	0.30 ± 0.06	0.35 ± 0.08 ***	16.74 (12.42 to 21.06)	0.73	0.30 ± 0.06	0.30 ± 0.05	-1.00 (-3.82 to 1.82)	-0.11	<0.001	0.85
STS-MP (W)	182.64 ± 50.55	209.38 ± 64.76 ***	14.43 (9.40 to 19.46)	0.45	186.15 ± 56.43	181.34 ± 50.14	-1.37 (-4.15 to 1.40)	-0.09	<0.001	0.48

Δ = percent change; 1RM = one-repetition maximum; CG = control group; CI = confidence interval; CP = chest-press; *g* = Hedge’ s *g* effect size; HGS = absolute handgrip strength; LP = leg-press; MBT = medicine ball throw; MP = mean power; MV = mean velocity; RT = resistance training; STS = five-repetition sit-to-stand; T_{10} = 10 m walking speed; Data are mean ± SD.* p-value < 0.05; *** p-value < 0.01; *** p-value < 0.001.

Table 4 presents an overall description of the acute RT variables in the leg-press and chest-press. The total repetitions, repetitions per set, average MV, and fastest MV in the leg-press exercise were significantly higher than the chest-press. Significant differences between the fastest MV and the average MV in the LP ($p < 0.001$; $g = 0.49$) and CP ($p < 0.001$; $g = 0.46$) were observed. The velocity loss in the LP was significantly lower than the CP.

Table 4. Overall description of the acute resistance training variables in the leg-press and chest-press.

	Leg-press	**Chest-press**	***p*-value**	**Effect Size**	
Variable	**Mean (95% CI)**	**Mean (95% CI)**	**between**	***g***	**Magnitude**
Total repetitions	230.12 (215.75 to 244.49)	164.46 (154.49 to 174.44)	<0.001	2.23	Very large
Repetitions per set	5.13 (4.61 to 5.65)	3.65 (3.25 to 4.04)	<0.001	1.35	Large
Fastest MV ($m \cdot s^{-1}$)	0.44 (0.42 to 0.47)	0.38 (0.35 to 0.40)	<0.001	1.08	Moderate
Average MV ($m \cdot s^{-1}$)	0.41 (0.39 to 0.44) [a]	0.35 (0.32 to 0.37) [b]	<0.001	1.10	Moderate
Velocity loss (%)	12.11 (11.70 to 12.52)	12.43 (11.94 to 12.92)	0.02	-0.30	Small

CI = confidence interval; g = Hedge's g effect size; MV = mean velocity; [a] Denotes a significant difference ($p < 0.001$) between the fastest MV and the average MV in the leg-press exercise; [b] Denotes a significant difference ($p < 0.001$) between the fastest MV and the average MV in the chest-press exercise.

The repetitions per set in the leg-press were significantly different from session 3 to 4 at 40% 1RM, from session 11 to 12 at 55% 1RM, from session 14 to 15 at 60% 1RM, and from session 18 to 19 at 65% 1RM (Figure 3). The fastest MV in the leg-press was significantly different from session 2 to 3 and session 3 to 4 at 40% 1RM, from sessions 5 and 6 to session 7 at 50% 1RM, from session 6 to 8 at 50% 1RM, from session 9 to 11 at 55% 1RM, and from sessions 17 and 18 to session 19 at 65% 1RM (Figure 3). The fastest MV in the CP was significantly different from session 1 to sessions 3 and 4 at 40% 1RM, from sessions 5 and 6 to sessions 7 and 8 at 50% 1RM, from session 13 to 15 at 60% 1RM, and from sessions 17 and 18 to session 19 at 65% 1RM (Figure 4).

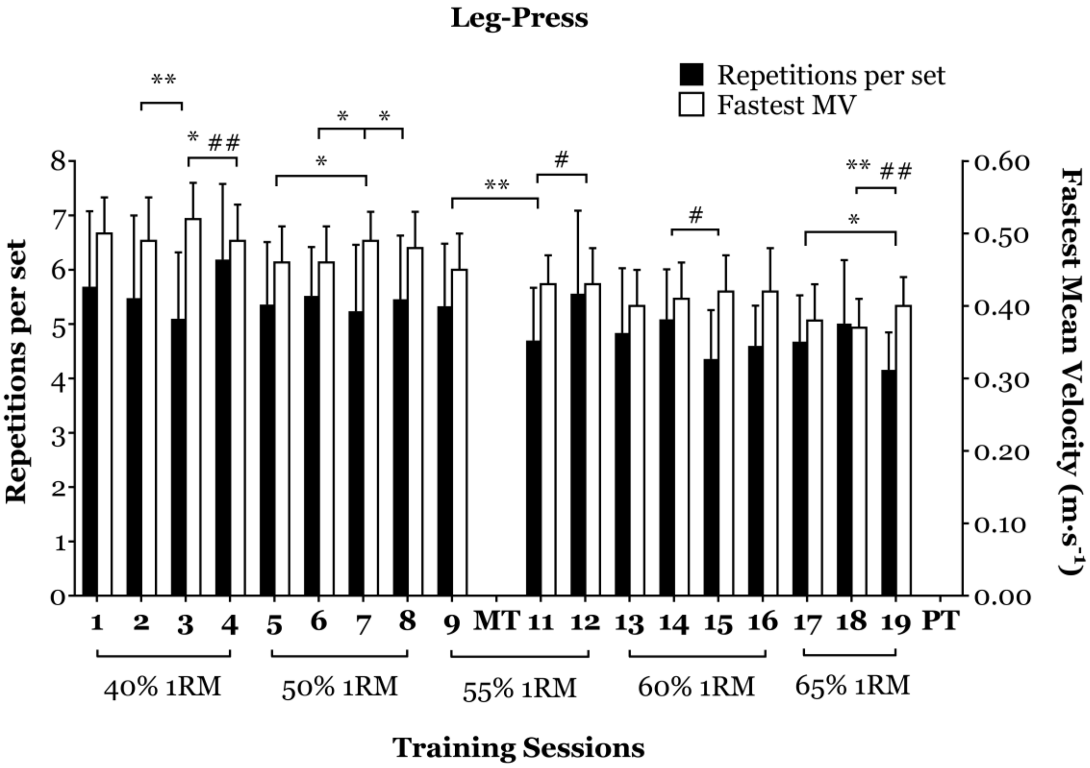

Figure 3. Repetitions per set and fastest MV (mean ± SD) in the leg-press exercise throughout the RT program. 1RM = one-repetition maximum; MT = 1RM mid-test load adjustment; MV = mean velocity; PT = post-test; * p-value < 0.05 in the fastest MV; ** p-value < 0.01 in the fastest MV; # p-value < 0.05 in the number of repetitions per set; ## p-value < 0.01 in the number of repetitions per set.

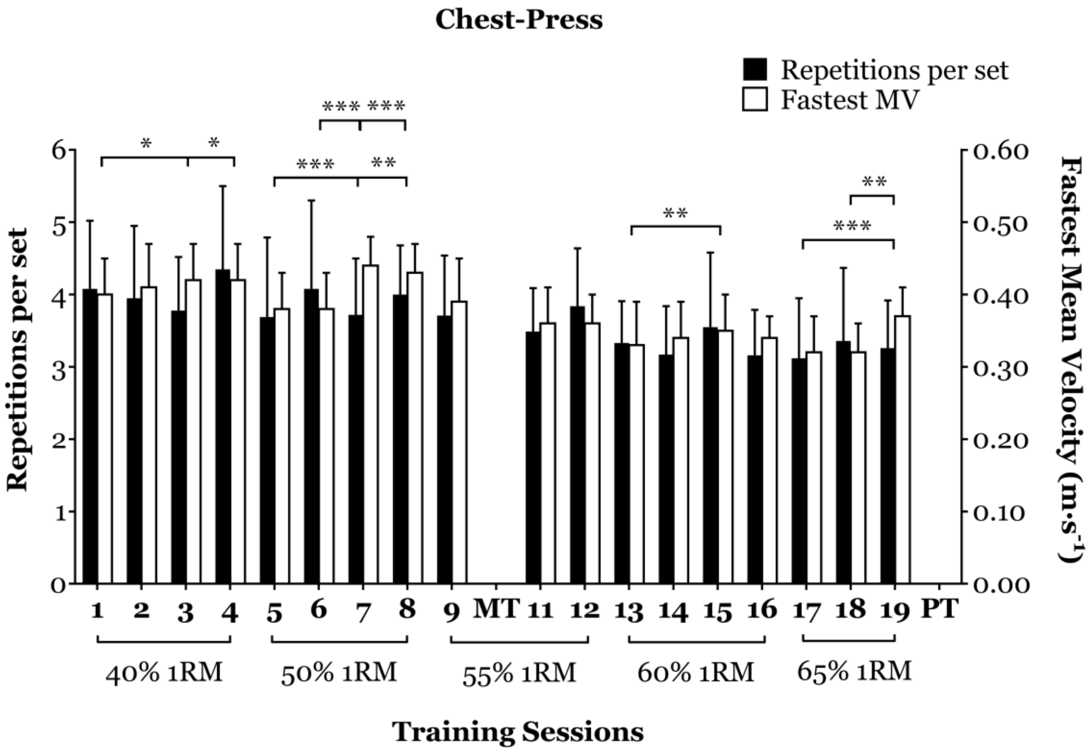

Figure 4. Repetitions per set and fastest MV (mean ± SD) in the chest-press exercise throughout the RT program. 1RM = one-repetition maximum; MT = 1RM mid-test load adjustment; MV = mean velocity; PT = post-test; * p-value < 0.05 in the fastest MV; ** p-value < 0.01 in the fastest MV; *** p-value < 0.001 in the fastest MV.

Discussion

We aimed to analyze the effects of velocity-monitored RT with a velocity loss of 10% on strength and functional capacity in older adults. Our data revealed that despite the low repetitions per set in the leg-press and chest-press, a velocity loss of 10% was enough to improve older adults' strength and functional capacity, thus confirming our central hypothesis.

After 10-weeks, the participants significantly increased the 1RM load in the leg-press and chest-press. The gains and the effect size in both exercises were similar to those reported in a previous velocity-monitored RT study with older adults (leg-press: 15.07%; g = 0.43; chest-press: 31.35%; g = 0.58) (Marques et al., 2020). Nonetheless, in that study, the participants performed the repetitions until reaching a velocity loss of 20%, resulting in almost double the repetitions per set than the current study (leg-press: 9.7 ± 2.9; chest-press: 6.6 ± 2.4). Previous velocity-monitored RT studies with young adults also found that performing half or even less than half the number of possible repetitions (velocity losses between 5-20%) is enough to achieve similar strength gains compared to repetitions up to or near to failure (velocity losses between 30-40%) (Galiano et al., 2020; Pareja-Blanco et al., 2017a, 2017b, 2020b, 2020a; Rodiles-Guerrero et al., 2020; Rodríguez-Rosell et al., 2020). Thus, taken together, these data suggest that a low-velocity loss (i.e., few repetitions per set) allows achieving similar physical performance gains compared to a high-velocity loss in both young and older adults.

Our results found a reverse trend between the repetitions per set and the fastest MV in the leg-press after two consecutive sessions with the same load. The repetitions per set significantly increased from session 3 to 4 at 40% 1RM, and the fastest MV significantly decreased. In comparison, from session 18 to 19 at 65% 1RM, the repetitions per set significantly decreased, and the fastest MV significantly increased. According to these results, it seems that when the fastest MV increased against the same absolute load, the repetitions per set tended to decrease, and vice-versa. Probably the high or low intensity of effort in the first repetitions might have dictated this inverse trend. However, future studies should compare the influence of achieving the fastest MV in the first, second, and the third repetition in the number of repetitions per set in the leg-press with older adults.

There were significant differences in the fastest MV attained against the same relative load in both exercises in some consecutive sessions. In the leg-press, we found significant increases in the fastest MV between sessions at 40, 50, and 65% 1RM, as well as a significant decrease at 55% 1RM, which was associated with an increase in the absolute loads after the 1RM mid-test (Marques et al., 2020). In the chest-press, we found significant increases in the fastest MV between sessions at 40, 50, 60, and 65% 1RM. Although an increase in the fastest MV against the same weight is an indicator of performance improvement (Rodríguez-Rosell et al., 2020), it also indicates that the loads must be adjusted. Otherwise, the effort made by the participants will not match the programmed effort (González-Badillo et al., 2017). However, to adjust the loads, it would be necessary to identify the MV associated with each relative load in both exercises, which to our knowledge, has not yet been analyzed in older adults of ~80 years old. Future research should establish the load-velocity relationship in the horizontal leg-press and seated chest-press in older adults to provide coaches and researchers guidelines during velocity-monitored RT.

Despite the significant gains in 1RM strength, the HGS values did not change. This result agrees with a previous velocity-monitored RT with older adults, where after 10-weeks, no significant differences were found on the HGS (Marques et al., 2020). These data reinforce that the HGS might not be a sensitive test to detect physical performance changes after RT with older adults (Tieland et al., 2015). Possible reasons might be related to the lack of exercises targeting the forearm muscles (Marques et al., 2020). Nonetheless, future studies should analyze the effects of these exercises on the HGS in older adults.

At post-test, our results revealed significant gains on MBT-1kg and a non-significant gain on MBT-3kg. Although a previous velocity-monitored RT study with older adults corroborates these results (Marques et al., 2020), both tests' gains were ~60% lower in our study. Since the training program's duration and the exercises were similar to that study, the differences for these results might be associated with the total volume performed in the chest-press. In that study, the participants performed on average a total number of repetitions of 296.4 ± 78.9 (Marques et al., 2020), which was almost more than half (~55%) of the total repetitions performed by our participants. Thus, taken together, these results suggest that a velocity loss of 20% seems more effective than 10% to increase the ball throwing distance in older adults. Future studies should test if velocity losses higher than 20% are practical approaches to increase the ball throwing distance with heavier weights in older adults.

Contrary to a previous hypothesis that high volumes and more than one lower body exercise would be necessary to improve the T_{10} in older adults (Marques et al., 2020), our results demonstrated that 10% of velocity loss during the leg-press increased the T_{10}. Previous studies with older women found significant gains on T_{10} (-18% to -6%) after high-velocity RT programs (Pereira et al., 2012a; Ramírez-Campillo et al., 2014, 2017, 2018). Based on the study duration, sessions per week, sets, and repetitions performed in only one lower body exercise, a total volume between 576-864 repetitions was completed (Pereira et al., 2012a, 2012b; Ramírez-Campillo et al., 2014, 2017, 2018), which on average, corresponds to ~30% more than the total repetitions performed in our study. However, considering that in three studies (Ramírez-Campillo et al., 2014, 2017, 2018), the participants performed the leg-press, leg-curl, and leg-extension, the total repetitions increases to ~2592. This number is 11 times higher than the total repetitions completed in our study. Thus, our results suggest that in older adults (~80 years old), a low number of repetitions per set in the leg-press seems enough to increase the T_{10}. On the other hand, the CG significantly decreased their ability during the T_{10}, which agrees with a previous study with institutionalized older adults (Marques et al., 2020). Therefore, older adults living in community-dwelling centers should be encouraged to participate in RT to avoid the loss of walking speed and maintain physical autonomy (Marques et al., 2020).

After the RT program, our data revealed significant improvements in the STS time. In a previous velocity-monitored RT with older adults, the authors also found significant improvements in the STS test after 10-weeks (Marques et al., 2020). However, these participants performed in the leg-press 437.6 ± 66.1 total repetitions, which corresponds to more than half (~53%) of the total repetitions completed in our study. Therefore, these results suggest that a low-velocity loss, which eventually will cause lower mechanical and metabolic fatigue than a higher velocity loss (González-Badillo et al., 2017; Rodríguez-Rosell et al., 2018; Sánchez-Medina & González-Badillo, 2011; Weakley et al., 2020), seems as significant as a velocity loss of 20% to improve the ability to rise from a chair in older adults.

The current study presents some limitations. Firstly, although the sample size statistics considered 13 participants sufficient to obtain a power of 80%, a larger number of participants would allow extrapolating the data to other older populations. Secondly, the randomization process would determine this novel approach's effectiveness with a high evidence level. Thirdly, different experimental groups would help compare the effects of different velocity loss thresholds on older adults' physical performance. Finally, establishing the load-velocity relationship in the leg-press and chest-press would allow estimating the real level of effort developed during each set and adjust the absolute loads whenever needed. Also, analyzing the peak power using a wide range of relative loads (30-90% 1RM) would help understand if the RT program promoted shifts in the load-power curve (Ni & Signorile, 2017). Therefore, future randomized studies with larger sample sizes should analyze older adults' physical responses to different velocity losses. Simultaneously, crossover designs should establish the load-velocity and load-power relationship in the leg-press and chest-press in aged populations to define coaches' and researchers' guidelines.

Conclusions

We provide evidence that 10% of velocity loss in each set during the horizontal leg-press and seated chest-press is an effective and efficient approach to significantly improving strength and functional capacity in institutionalized older adults. When using a velocity measurement device, strength and conditioning coaches can prescribe velocity-monitored RT with a velocity loss of 10% in each set and relative loads progressing from 40-65% 1RM to improve strength and functional capacity in this population. When it is not possible to use a velocity measurement device, prescribing 2-3 sets of ~5 and 4 repetitions per set in the leg-press and chest-press, respectively, seems to be a sufficient stimulus to increase physical performance in institutionalized older women and men without RT background.

Study 5. Load-velocity relationship in the horizontal leg-press exercise in older women and men

Abstract

Objectives: This study analyzed the predictive ability of movement velocity to estimate the relative load (i.e., % of one-repetition maximum [1RM]) during the horizontal leg-press exercise in older women and men. **Methods:** Twenty-four women and fourteen men living in community-dwelling centers volunteered to participate in this study. All participants performed a progressive loading test up to 1RM in the horizontal leg-press. The fastest peak velocity (PV) and mean velocity (MV) attained with each weight were collected for analysis. Linear regression equations were modeled for women and men. **Results:** We observed very strong linear relationships between both velocity variables and the relative load in the horizontal leg-press in women (PV: r^2 = 0.93 and standard error of the estimate (SEE) = 5.96% 1RM; MV: r^2 = 0.94 and SEE = 5.59% 1RM) and men (PV: r^2 = 0.93 and SEE = 5.96% 1RM; MV: r^2 = 0.94 and SEE = 5.97% 1RM). The actual 1RM and the estimated 1RM using both the PV and MV presented trivial differences and very strong relationships (r = 0.98-0.99) in both sexes. Men presented significantly higher (p < 0.001-0.05) estimated PV and MV against all relative loads compared to women (average PV = 0.81 vs. 0.69 $m \cdot s^{-1}$ and average MV = 0.44 vs. 0.38 $m \cdot s^{-1}$). **Conclusions:** Our data suggest that movement velocity accurately estimates the relative load during the horizontal leg-press in older women and men. Coaches and researchers can use the proposed sex-specific regression equations in the horizontal leg-press to implement velocity-monitored resistance training with older adults.

Keywords: regression equations, predictive ability, lifting velocity, relative load, leg-press, elderly

Introduction

In humans, the aging-related loss of muscle function and strength (i.e., *dynapenia*) compromises the functional ability to produce force during daily living activities and increases the risk of physical disability and death (Clark & Manini, 2012; Mitchell et al., 2012). Scientific literature states that muscle power, defined as the product of force and velocity, declines at a much faster rate over the years than muscle strength (Reid & Fielding, 2012). As a result, older adults gradually decrease their ability to walk, climb stairs, stand up from a chair or bed, resulting in a loss of functional independence and increased fall risk (Phelan et al., 2015). Therefore, to decelerate or reverse the deleterious effects of aging, public and private health services need to implement adequate preventive strategies.

Resistance training is an effective tool to improve older adults' musculoskeletal system (Aagaard et al., 2010; Fragala et al., 2019; Hakkinen et al., 2001). Regular practice increases muscle strength, power, functional capacity and decreases the incidence of falls in older adults (Csapo & Alegre, 2016; Fragala et al., 2019; Marques et al., 2013; Straight et al., 2016). In a geriatric context, coaches and researchers commonly determine the load (intensity) based on the direct or indirect measurement of the one-repetition maximum (1RM) (Niewiadomski et al., 2008). The direct measurement consists of performing a single repetition with the maximum weight possible (González-Badillo et al., 2011). The indirect method consists of completing repetitions to fatigue with submaximal weights using the number of repetitions to estimate the 1RM through regression equations (Knutzen et al., 1999; Tan et al., 2015; Wood et al., 2002).

Although the direct method is reliable when administered correctly in older adults with and without limitations (LeBrasseur et al., 2008), coaches should guarantee additional precautions with naïve practitioners to prevent injuries (Shaw et al., 1995). The direct measurement of 1RM is also time-consuming (unpractical with large groups) and may cause muscle soreness in older adults (Niewiadomski et al., 2008; Shaw et al., 1995). In contrast, although the predictive equation method might be a suitable alternative to estimate the 1RM in middle-aged and older adults (Knutzen et al., 1999; Tan et al., 2015; Wood et al., 2002), coaches and researchers must consider several limitations. Firstly, the use of predictive equations developed in studies with young populations might significantly underestimate the 1RM in older women and men of ~70 years old (Knutzen et al., 1999). Secondly, when used with middle-aged women and men of ~54 years old, these same regression equations might induce substantial error when the number of repetitions exceeds ten (Wood et al., 2002). Thirdly, to date, only one study validated predictive equations to estimate the 1RM based on repetitions to failure in the biceps curl, bench press, and squat exercises in healthy older women and men of ~63 years old (Tan et al., 2015). Therefore, these equations might not be suitable for older adults of other ages and different health conditions and other resistance exercises, such as the leg-press, chest-press, and knee-extension. Considering the limitations of both the direct and indirect methods to determine the training load in older populations, coaches and researchers need to identify valid and reliable alternatives.

In the last decade, a groundbreaking work by González-Badillo & Sánchez-Medina (2010) showed that the measurement of movement velocity allowed to estimate with high accuracy the relative load (%1RM) in the bench-press exercise in trained young adults. This novel procedure demonstrated that it is possible to estimate the 1RM without applying direct or indirect methods (González-Badillo & Sánchez-Medina, 2010). From that period to now, several studies proposed regression equations based on the load-velocity relationship in different resistance exercises, such as the full, parallel, and half squat (Martínez-Cava et al., 2019; Sánchez-Medina et al., 2017), 45º inclined leg-press (Conceição et al., 2016), prone-bench pull (Sánchez-Medina et al., 2014) pull-up (Sánchez-Moreno et al., 2017), deadlift (Benavides-Ubric et al., 2020), and shoulder press (Hernández-Belmonte et al., 2020). However, all predictive equations are specific for trained young adults, which means that they might not be accurate to estimate the 1RM in other populations, such as older adults.

To date, only one study analyzed the load-velocity relationship in the free-weight bench-press and 45º inclined leg-press in strength-trained older women (at least two years of experience) with ~68 years old (Marcos-Pardo et al., 2019). Here, the authors observed that it is also possible to establish regression equations based on the load-velocity relationship in older adults, although with lower accuracy than those observed with younger adults (Marcos-Pardo et al., 2019). Moreover, the velocities associated with submaximal loads were lower than those found in younger populations (Marcos-Pardo et al., 2019). Although that study presented insightful findings, the equations proposed might only be applicable for trained older women when using the inclined leg-press and free-weight bench-press exercises. Consequently, future research with older adults of both sexes and different physical conditions without previous resistance training background is needed to analyze the load-velocity relationship in other resistance exercises.

Therefore, in the current research, we aimed to analyze the predictive ability of movement velocity to estimate the relative load during the horizontal leg-press exercise in older women and men without previous resistance training experience. On this, we formulated two hypotheses. First, we expected to identify a very strong relationship between velocity and relative load in the horizontal leg-press exercise in both sexes, as observed in previous research using a similar movement pattern (Conceição et al., 2016; Marcos-Pardo et al., 2019). Second, we conjectured that men would present higher peak and mean velocities than women against most relative loads in the horizontal leg-press, except with the 1RM load. This hypothesis was based on a previous study that observed higher lifting velocities in men than women against submaximal loads, except with the 1RM load, in a lower body exercise (Pareja-Blanco et al., 2020). Furthermore, considering the larger and stronger muscle fibers and larger whole muscle cross-sectional area of the quadriceps in older men than women (Barnouin et al., 2017; Frontera et al., 2000), higher movement velocities are expected in older men compared to older women.

Methods

Participants

The participant's recruitment was performed by the clinicians of several community-dwelling centers in collaboration with our research team. Participants were included if they were 65 years or older, male or female, able to walk at least 10 m, standing up from a chair with the arms crossed over the chest five times, willing to participate in the study, and collaborate with the researchers. Exclusion criteria included severe physical dependency (Barthel Index score < 60) and cognitive decline (Mini-Mental State Examination [MMSE] cut-off scores for Portuguese older adults: participants without years of schooling, <15 points; 1 to 11 years of school completed, <22 points; and >11 years of school completed, <27 points (Mendes et al., 2017)), musculoskeletal injuries in the previous three months, and terminal illness. The clinicians of the community-dwelling centers conducted the initial screening tests, which included the 10-m walking speed test (Marques et al., 2020), five-repetition sit-to-stand test (Alcazar et al., 2018b), handgrip strength test (Marques et al., 2020), Barthel Index (Mahoney & Barthel, 1965) and MMSE (Folstein et al., 1975). After screening, thirty-eight older adults (24 women and 14 men) fulfilling the inclusion criteria volunteered to participate in this study. Table 1 shows the characteristics of the participants. All of them received detailed information regarding the study procedures and signed a written informed consent. The Ethical Committee of the University of Beira Interior approved this study (code: CE-UBI-Pj-2019-019). All experimental procedures followed the recommendations of the Declaration of Helsinki.

Table 1. Participant's characteristics.

Variable	Women (n = 24)	Men (n = 14)	Total (n = 38)
Age (years)	79.0 ± 7.7	78.6 ± 7.1	78.9 ± 7.4
Body Mass (kg)	65.2 ± 9.6	73.5 ± 13.0	68.3 ± 11.5
Height (m)	1.51 ± 0.05	1.64 ± 0.07	1.55 ± 0.09
BMI (kg/m^2)	28.7 ± 4.0	27.5 ± 4.6	28.3 ± 4.2
Education (years)	2.3 ± 2.1	2.6 ± 2.3	2.4 ± 2.2
Barthel Index score	92.5 ± 11.1	95.4 ± 10.1	93.6 ± 10.7
MMSE score	22.0 ± 3.9	23.8 ± 4.4	22.6 ± 4.1
10-m Walking test (s)	6.2 ± 1.0	6.6 ± 2.3	6.4 ± 1.6
5STS test (s)	8.9 ± 1.8	8.9 ± 2.0	8.9 ± 1.9
HGS left hand (kg)	20.0 ± 5.8	31.0 ± 8.2	24.1 ± 8.6
HGS right hand (kg)	21.2 ± 6.2	30.8 ± 8.5	24.7 ± 8.4
HGS absolute (kg)	20.6 ± 5.9	30.9 ± 7.9	24.4 ± 8.3
1RM Leg-Press (kg)	69.8 ± 14.0	84.4 ± 16.9	75.2 ± 16.5
Relative Strength (Leg-Press kg/BM kg)	1.07 ± 0.18	1.16 ± 0.19	1.10 ± 0.18

Data are mean ± SD; 1RM: one-repetition maximum; 5STS: five-repetition sit-to-stand test; BM: body mass; BMI: body mass index; HGS: handgrip strength (the absolute handgrip strength corresponds to the average result of the left and right hands score); MMSE: mini-mental state examination; Relative Strength = 1RM Leg-Press (kg) / Body Mass (kg).

Study Design

In a cross-sectional study design, we analyzed the predictive ability of movement velocity to estimate the relative load in the horizontal leg-press exercise in older women and men. All participants went to a fitness health club five times for three weeks, at the same time (2-4 p.m.), with a room temperature of 22-24 ºC. In general, two weeks were dedicated to familiarization sessions and a third week for the horizontal leg-press progressive loading test up to 1RM. More specifically, in the first week, all participants underwent two sessions, separated by 48 hours' rest, to familiarize themselves with the testing procedures and ensure a proper adaptation to the fitness health club facilities and coaches. We also performed anthropometric measurements during this period and identified everyone's correct position in the horizontal leg-press machine, adjusting the seat carriage to a 90º knee flexion. In the first session of the second familiarization week, all participants performed two sets of five repetitions with 20.5 and 29.5 kg at the maximal intended velocity. After 48 hours' rest, they performed a second familiarization session constituted by one set of three repetitions at the maximal intended velocity with 20.5, 29.5, and 39.9 kg and rested three minutes between sets.

We instructed the participants to focus on the movement velocity and the technique of the exercise. After five days of rest (week 3), all participants completed a progressive loading test session in the horizontal leg-press up to 1RM. An experienced researcher and two senior coaches' specialists supervised all testing procedures. Figure 1 illustrates the study design.

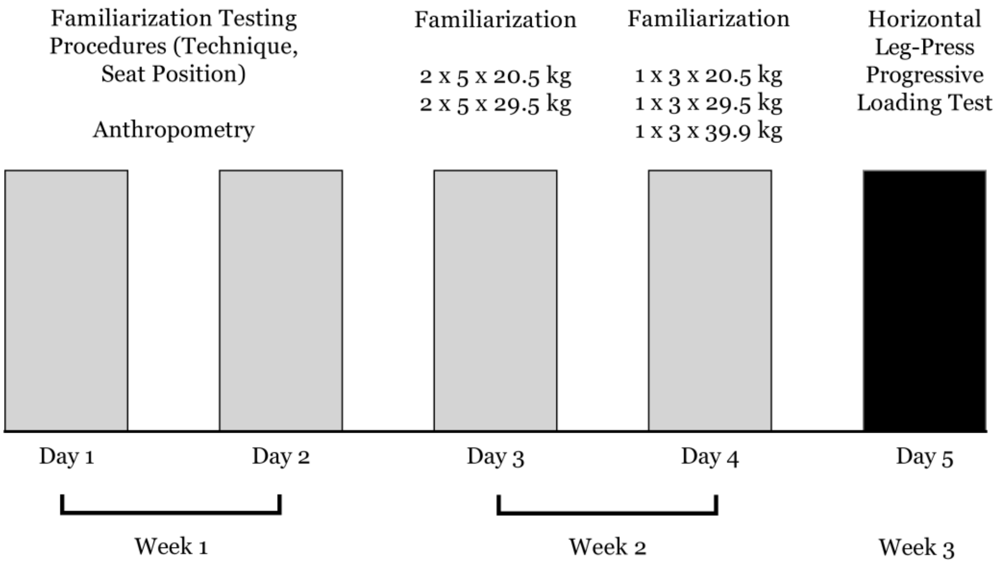

Figure 1. Illustration of the study design. Sets x repetitions x absolute load (kg).

Horizontal Leg-Press Progressive Loading Test

Before the evaluations, all participants performed a general warm-up of 10 min walking on a treadmill (2-4 km/h) or pedaling on a stationary bicycle (50-70 rpm; resistance levels: 1-5). Following this, they performed a progressive loading test up to 1RM in the horizontal leg-press exercise (Ribeiro et al., 2020). All participants initiated the test in a seated position with the lower back in contact with the seat, feet placed on the platform at shoulder-width apart, knees flexed at 90º, and hands placed on the side handles. After instruction, they performed a purely concentric action and slowly returned to the initial position before performing the next repetition. Both the concentric and eccentric phases were controlled by an experienced researcher, who placed his hands on the platform handle. This procedure enabled the participants to maintain the feet in contact with the platform, especially when performing repetitions against lightweights, and control the eccentric phase avoiding a fast descent. Between the eccentric and concentric phases, there was a 1 s pause. All participants received verbal encouragement to perform the concentric phase as fast and forcefully as possible against all weights. The test's warm-up consisted of two sets of seven and five repetitions with weights of 20.5 and 29.5 kg, respectively. Then, the test started with a weight of 29.5 kg and progressively increased by 10 kg. Whenever possible, the participants performed three repetitions for each load to enable correct data collection. We carried out this procedure until they were able to perform only one correct repetition. If the participants could not perform a single lift, we decreased the weight by 1-5 kg until they could achieve the 1RM. We provided a 3 min rest for three repetitions and 5 min rest for two repetitions between sets. The average number of sets was 5.13 ± 1.60 for women (total repetitions = 123 [5.13 x 24 participants]) and 6.50 ± 2.10 for men (total repetitions = 91 [6.50 x 14 participants]).

Measurement Equipment and Data Collection

The anthropometric measurements included body mass (TANITA BC-601, Japan) and height (Portable Stadiometer SECA, Germany). A horizontal leg-press machine (Leg-Press G3, Matrix, USA), coupled with a linear velocity transducer (T-Force System, Ergotech, Murcia, Spain), was used to perform the test. The T-Force collects data at a sampling frequency of 1000 Hz and is a valid and high reliable device to measure the lifting velocity during resistance exercises (Courel-Ibáñez et al., 2019; Martínez-Cava et al., 2020). To connect the T-Force to the resistance machine, we followed the procedures described elsewhere (Marques et al., 2020). During each repetition, the peak velocity (i.e., the maximum instantaneous velocity value reached during the concentric phase) and the mean velocity (i.e., the average velocity from the start of the concentric phase until the weight stack plate reached the maximum height) were displayed in real-time by custom software (T-Force v2.36). The fastest peak velocity and mean velocity values attained with each weight were analyzed, including the load of 20.5 kg, which was displaced at the maximal intended velocity.

Statistical Analysis

The sample size was estimated using the t-test for two independent groups (Hulley et al., 2013). Eighteen participants were required to ensure a statistical power of 80%, based on an effect size of 0.60, assuming a standard deviation (SD) of 1 (according to the SD of the average number of sets during the leg-press testing procedure in Marcos-Pardo et al. (2019)), and a significance level of 0.05. Considering a proportion of 63% in the women's group, 11 women and 7 men were required. Data are presented as mean ± SD and 95% confidence intervals (CI). We conducted a regression analysis to examine the relationship between the peak/mean velocity and relative load in the horizontal leg-press in older women and men. After creating a scatter plot with the independent (peak or mean velocity) and dependent (relative load) variables, we considered the regression model (linear or quadratic) according to the one that provided the best fit curve to the data. The coefficient of determination (r^2) assessed the predictive ability of the regression equations, and the standard error of the estimate (SEE) (SD of the residuals) assessed the prediction accuracy. Pearson's correlation coefficient (r) assessed the relationship between variables. The magnitude of correlation was interpreted as: 0.00-0.10, negligible; 0.10-0.39, weak; 0.40-0.69, moderate; 0.70-0.89, strong; 0.90-1.00, very strong (Schober et al., 2018). Checking the assumptions of normality, independence, and homoscedasticity of the residuals enabled us to analyze the regression model's effectiveness and appropriateness (Casson & Farmer, 2014). The normality was examined using the histograms, normal P-P plots, and Q-Q plots of the standardized residuals, coupled with the Kolmogorov-Smirnov test. The independence was analyzed using the Durbin-Watson test, while the homoscedasticity by inspecting the scatter plots of the standardized residuals against the standardized predicted values. The assumption of no extreme values was verified after the outlier's removal. The regression equations were cross validated to test if there was no overfitting. We split the data into two equal-sized subsets, and cross-validation, considering the holdout method, was conducted. To estimate the peak and mean velocity values associated with each relative load, we established individual regression equations for each participant. Normality and homogeneity of the data (i.e., estimated peak and mean velocity for each relative load) were evaluated by the Shapiro-Wilk test and Levene's test, respectively. Independent samples t-test analyzed the differences between sexes in the estimated peak and mean velocity for each relative load. The Hedge's g effect size compared the magnitude of differences between sexes in the estimated peak and mean velocity values for each relative load. The effect size (g) was interpreted as: trivial, 0.0-0.2; small, 0.2-0.6; moderate, 0.6-1.2; large, 1.2-2.0; very large, 2.0-4.0; extremely large, > 4.0 (Hopkins et al., 2009). The intraclass correlation coefficient (ICC) with the two-way mixed effects, consistency, single rater/measurement model ($ICC_{3,1}$) analyzed the relative reliability of the actual and estimated 1RM (Koo & Li, 2016). The coefficient of variation (CV) assessed the absolute reliability (CV = (SD/Mean) x 100). ICC values were interpreted as: < 0.50, poor; 0.50-0.75, moderate; 0.75-0.90, good; > 0.90, excellent (Koo & Li, 2016). CV values were interpreted as: > 10%, poor; 5-10%, moderate; < 5%, excellent (Banyard et al., 2017). The significance level was set at $p < 0.05$. Statistical analyses were performed in Microsoft Office Excel® (Microsoft Inc., Redmond, WA, USA) and SPSS v27 (SPSS Inc., Chicago, IL, USA). The figures were designed in GraphPad Prism v7 (GraphPad Inc., San Diego, CA, USA).

Results

Relationship Between Movement Velocity and Relative Load in Both Sexes

In both sexes, the model that provided the best curve fitting was the linear regression. The results revealed a very strong significant linear relationship between the relative load and the peak and mean velocity in both women (r = -0.96-0.97) and men (r = -0.96-0.97). Figures 2 and 3 show the regression equations to estimate the peak and mean velocities values associated with each relative load, respectively.

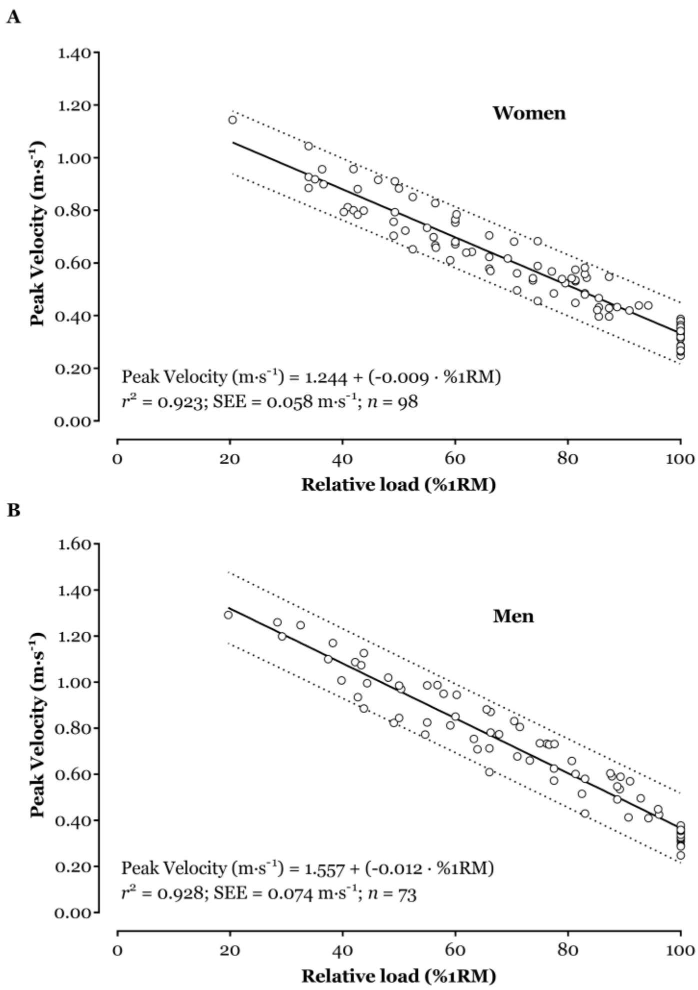

Figure 2. Regression equations to estimate the peak velocity based on the relative load (%1RM) in the horizontal leg-press exercise in older women (A) and men (B). r^2: coefficient of determination; SEE: standard error of the estimate; n: number of observations; Dotted lines indicate the 95% prediction bands.

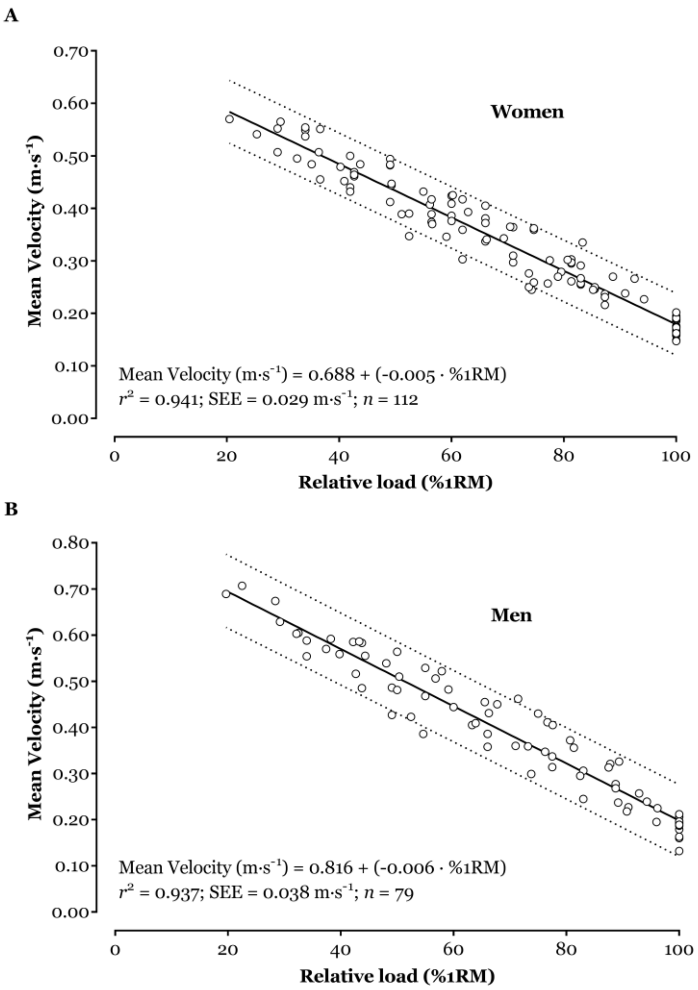

Figure 3. Regression equations to estimate the mean velocity based on the relative load (%1RM) in the horizontal leg-press exercise in older women (A) and men (B). r^2: coefficient of determination; SEE: standard error of the estimate; n: number of observations; Dotted lines indicate the 95% prediction bands.

Differences Between Sexes in the Estimated Peak and Mean Velocity for all Relative Loads

Tables 2 and 3 show the differences between sexes in the estimated peak and mean velocities for each relative load, respectively. The estimated peak and mean velocities for all relative loads were significantly higher in men than women.

Table 2. Estimated peak velocity for each relative load in the horizontal leg-press exercise for older women and men, derived from the individual load-velocity relationships.

Load (% 1RM)	**Women ($m \cdot s^{-1}$)**	**Men ($m \cdot s^{-1}$)**	***p-value***	**Difference ($m \cdot s^{-1}$)**	**Hedge's *g* (classification)**
20	1.04 ± 0.14	1.24 ± 0.13	< 0.001	0.20	1.45 (large)
25	1.00 ± 0.13	1.19 ± 0.12	< 0.001	0.19	1.46 (large)
30	0.95 ± 0.12	1.14 ± 0.12	< 0.001	0.18	1.47 (large)
35	0.91 ± 0.11	1.08 ± 0.11	< 0.001	0.17	1.48 (large)
40	0.87 ± 0.11	1.03 ± 0.11	< 0.001	0.16	1.49 (large)
45	0.82 ± 0.10	0.97 ± 0.10	< 0.001	0.15	1.50 (large)
50	0.78 ± 0.09	0.92 ± 0.09	< 0.001	0.14	1.51 (large)
55	0.73 ± 0.08	0.86 ± 0.09	< 0.001	0.13	1.52 (large)
60	0.69 ± 0.07	0.81 ± 0.08	< 0.001	0.12	1.52 (large)
65	0.64 ± 0.07	0.75 ± 0.07	< 0.001	0.11	1.52 (large)
70	0.60 ± 0.06	0.70 ± 0.07	< 0.001	0.10	1.52 (large)
75	0.55 ± 0.05	0.64 ± 0.06	< 0.001	0.09	1.49 (large)
80	0.51 ± 0.05	0.59 ± 0.06	< 0.001	0.08	1.45 (large)
85	0.47 ± 0.05	0.53 ± 0.05	< 0.001	0.07	1.37 (large)
90	0.42 ± 0.04	0.48 ± 0.05	< 0.001	0.06	1.71 (large)
95	0.38 ± 0.04	0.42 ± 0.05	< 0.01	0.05	1.08 (moderate)
100	0.33 ± 0.04	0.37 ± 0.05	< 0.05	0.04	0.86 (moderate)
Average	0.69 ± 0.07	0.81 ± 0.08	< 0.001	0.12	1.52 (large)

Data are mean ± SD. 1RM: one-repetition maximum.

Table 3. Estimated mean velocity for each relative load in the horizontal leg-press exercise for older women and men, derived from the individual load-velocity relationships.

Load (% 1RM)	**Women ($m \cdot s^{-1}$)**	**Men ($m \cdot s^{-1}$)**	***p-value***	**Difference ($m \cdot s^{-1}$)**	**Hedge's *g* (classification)**
20	0.57 ± 0.07	0.67 ± 0.05	< 0.001	0.10	1.57 (large)
25	0.55 ± 0.06	0.64 ± 0.05	< 0.001	0.10	1.58 (large)
30	0.52 ± 0.06	0.61 ± 0.05	< 0.001	0.09	1.60 (large)
35	0.50 ± 0.06	0.59 ± 0.05	< 0.001	0.09	1.62 (large)
40	0.47 ± 0.05	0.56 ± 0.04	< 0.001	0.08	1.64 (large)
45	0.45 ± 0.05	0.53 ± 0.04	< 0.001	0.08	1.66 (large)
50	0.43 ± 0.04	0.50 ± 0.04	< 0.001	0.07	1.69 (large)
55	0.40 ± 0.04	0.47 ± 0.03	< 0.001	0.07	1.72 (large)
60	0.38 ± 0.04	0.44 ± 0.03	< 0.001	0.06	1.75 (large)
65	0.35 ± 0.03	0.41 ± 0.03	< 0.001	0.06	1.77 (large)
70	0.33 ± 0.03	0.38 ± 0.03	< 0.001	0.05	1.80 (large)
75	0.30 ± 0.02	0.35 ± 0.03	< 0.001	0.05	1.82 (large)
80	0.28 ± 0.02	0.32 ± 0.02	< 0.001	0.04	1.82 (large)
85	0.25 ± 0.02	0.29 ± 0.02	< 0.001	0.04	1.80 (large)
90	0.23 ± 0.02	0.26 ± 0.02	< 0.001	0.03	1.71 (large)
95	0.20 ± 0.01	0.23 ± 0.02	< 0.001	0.03	1.54 (large)
100	0.18 ± 0.01	0.20 ± 0.02	< 0.001	0.02	1.29 (large)
Average	0.38 ± 0.04	0.44 ± 0.03	< 0.001	0.06	1.75 (large)

Data are mean ± SD. 1RM: one-repetition maximum.

Estimating the Relative Load from Peak and Mean Velocity

To estimate the relative load from the measurement of peak velocity during the horizontal leg-press, the following linear regression equations were obtained for both sexes:

Women: Load (%1RM) = 131.651 + (-101.293 · Peak Velocity)
($r = -0.963$; $r^2 = 0.928$; SEE = 6.094% 1RM)

Men: Load (%1RM) = 126.448 + (-77.928 · Peak Velocity)
($r = -0.963$; $r^2 = 0.928$; SEE = 5.963% 1RM)

When using the mean velocity to estimate the relative load during the horizontal leg-press, the following equations can be used for both sexes:

Women: Load (%1RM) = 131.382 + (-185.059 · MV)
($r = -0.970$; $r^2 = 0.941$; SEE = 5.590% 1RM)

Men: Load (%1RM) = 128.265 + (-151.843 · MV)
(r = -0.968; r^2 = 0.937; SEE = 5.974% 1RM)

Table 4 presents the cross-validation method considering the regression equations when using the peak and mean velocity. The results suggest no overfitting in both models since the correlation coefficients are positive and high (0.953 to 0.970) and do not present a big difference between both subsets.

Table 4. Cross-validation using the holdout method.

	Relative load (% 1RM)	Testing set#	Training set#
Peak velocity	Women	0.953	0.953
	Men	0.970	0.959
Mean velocity	Women	0.970	0.970
	Men	0.953	0.975

Pearson correlation coefficient between predicted and observed values.

Relationship between Actual and Estimated 1RM

Table 5 shows the relationship between the actual and estimated 1RM leg-press for women and men. The estimated 1RM was calculated from the general equations using the 1RM weight and the associated peak and mean velocity. The actual and estimated 1RM using the peak and mean velocity presented trivial differences (g = -0.003 to -0.101) and very strong relationships (r = 0.98 to 0.99) in both sexes. In all cases, the ICC and CV values presented excellent reliability.

Table 5. Differences between the actual and estimated 1RM in both sexes using the peak and mean velocity and reliability between both methods.

	Sex	**Actual 1RM (kg) (mean ± SD)**	**Estimated 1RM (kg) (mean ± SD)**	**Difference (kg) (95% CI)**	**Hedge's *g* (classification)**	***r* (classification)**	**ICC $_{(3,1)}$ (95% CI)**	**CV (%) (95% CI)**
PV	Women	69.81 ± 13.95	71.29 ± 14.71	-1.48 (-2.98-0.03)	-0.101 (trivial)	0.98 (very strong)	0.98 (0.95-0.99)	2.77 (1.93-3.60)
PV	Men	84.39 ± 16.95	82.90 ± 18.42	1.48 (-0.20-3.17)	0.081 (trivial)	0.99 (very strong)	0.98 (0.95-1.00)	2.43 (1.20-3.65)
MV	Women	69.81 ± 13.95	70.44 ± 14.01	-0.62 (-1.66-0.42)	-0.044 (trivial)	0.99 (very strong)	0.99 (0.98-1.00)	1.62 (1.00-2.23)
MV	Men	84.39 ± 16.95	84.44 ± 17.98	-0.05 (-1.35-1.25)	-0.003 (trivial)	0.99 (very strong)	0.99 (0.97-1.00)	1.55 (0.76-2.33)

1RM: one-repetition maximum; CV: coefficient of variation; ICC (3,1): intraclass correlation coefficient model; MV: mean velocity; PV: peak velocity *r*: Pearson's correlation coefficient.

Discussion

In the present study, we analyzed the predictive ability of movement velocity to estimate the relative load in the horizontal leg-press exercise in older women and men. Our results confirmed a very strong relationship between the movement velocity and relative load in the horizontal leg-press in older women and men, which corroborates our first hypothesis. The load-velocity relationship is well studied in several resistance exercises in trained young adults (Benavides-Ubric et al., 2020; González-Badillo & Sánchez-Medina, 2010; Pareja-Blanco et al., 2020; Sánchez-Medina et al., 2017). However, the measurement of lifting velocity to predict the relative load in older adults is a scarcely investigated topic. To our knowledge, the unique study that proposed a load-velocity regression equation was conducted with trained older women (Marcos-Pardo et al., 2019). In that study, the authors analyzed the load-velocity relationship in the 45° inclined leg-press, and the r^2 was 0.91, while the SEE was 5.63%. These values were like those observed in our study for both sexes, which reveals that it is also possible to establish a high accurate load-velocity relationship in untrained older adults. In fact, when we compared the values of the actual 1RM with the estimated 1RM using both the peak and mean velocity values, the results presented trivial differences and very strong relationships between both methods, thus revealing an excellent level of agreement. Therefore, these outcomes suggest that the proposed sex-specific equations can be used in geriatric settings to predict the relative load accurately. These findings might have critical practical applications in clinical settings because they will enable coaches and researchers to estimate and monitor 1RM changes daily through submaximal loads and avoid using the direct method, which might present disadvantages in older adults.

Our results revealed that men presented significantly higher estimated peak and mean velocity values for all relative loads than women, which partially confirms our second hypothesis. A previous study that analyzed the load-velocity relationship in the full-back squat with adult women and men observed that men exhibited significantly higher estimated mean velocity values for almost all relative loads than adult women, except with the maximal load (Pareja-Blanco et al., 2020). These results suggest that, in general, both young and older men displace submaximal loads during lower body exercises at faster velocities than young and older women, respectively. Nevertheless, as observed in our study, when the relative loads increase near the maximum, the differences between sexes in lifting velocity tend to decrease (Pareja-Blanco et al., 2020). Possible reasons might be associated with a higher strength deficit in women than men, which means a higher percentage of maximal strength that is not used during a specific movement (Pareja-Blanco et al., 2020; Siff, 2000). Besides, larger and stronger muscle fibers and larger whole muscle cross-sectional area of the quadriceps in older men than women (Barnouin et al., 2017; Frontera et al., 2000) might also contribute to these differences in force-generating capacity and lifting velocity. Therefore, these data suggest that load-velocity regression equations should be sex-specific to obtain better predictive models in young (García-Ramos et al., 2019; Pareja-Blanco et al., 2020; Torrejón et al., 2019) and older adults.

Previous studies with older women and men analyzed the peak velocity values against a wide range of relative loads during the horizontal leg-press using a pneumatic machine (Ni & Signorile, 2017; Sayers & Gibson, 2010). However, the type of machine used and the pooled results for both sexes do not allow comparisons with our data. Moreover, in Sayers and Gibson (2010), the authors only presented the load-peak velocity relationship data in the knee extension exercise. Therefore, future studies with older women and men should analyze the load-peak velocity relationship in the horizontal leg-press for plausible comparisons with the current research data.

Our female participants attained, on average, lower mean velocities (~0.06 $m \cdot s^{-1}$) than those found in a previous study with strength-trained older women (Marcos-Pardo et al., 2019). Possible explanations for these differences might be associated with age (on average ~11 years' difference), training background (trained vs. untrained), and type of leg-press machine used (45° inclined vs. horizontal). Conversely, when comparing the estimated mean velocity values for each relative load in men against strength-trained older women, they seem to be very close (~0.002 $m \cdot s^{-1}$ difference). Despite the differences in age, training background, and type of resistance machine, these results suggest that untrained older men have similar strength levels to strength-trained older women, younger on average ~10 years old. Therefore, this information reinforces the importance of developing regression equations according to age, sex, training background, and type of equipment used.

In line with previous findings (Marcos-Pardo et al., 2019), our data show that older adults attain lower lifting velocities for each relative load in the leg-press than trained young adults in the 45° inclined leg-press (Conceição et al., 2016) and full-back squat exercises (Pareja-Blanco et al., 2020; Sánchez-Medina et al., 2017). When analyzing the differences between young and older adults in velocity values in load increments of 5%, on average, the range of velocities is narrower in older adults (peak velocity: ~0.05 m·s-

^{1}; mean velocity: ~0.03 m·s^{-1}) than in strength-trained young adults (peak velocity: ~0.07 to 0.13 m·s^{-1}; mean velocity: ~0.06 to ~0.09 m·s^{-1}) (Conceição et al., 2016; Pareja-Blanco et al., 2020; Sánchez-Medina et al., 2017). These results highlight the differences between young and older adults regarding power production (Korff et al., 2014) and reinforce the importance of older individuals engaging in resistance training to improve strength, muscle power, and functional capacity (Fragala et al., 2019; Marques et al., 2013).

The current research presents critical practical applications for strength and conditioning coaches and researchers to implement velocity-monitored resistance training with older adults. Besides the possibility to estimate the 1RM from lifting velocity using submaximal loads, knowing the velocity associated with each relative load will enable prescribing the training based on a target velocity instead of a percentage of 1RM (González-Badillo & Sánchez-Medina, 2010; González-Badillo et al., 2011). A recent velocity-monitored resistance training study with older adults observed that prescribing the relative loads based on a percentage of 1RM resulted in significant differences between the mean velocities attained in the leg-press against the same absolute loads after consecutive sessions (Marques et al., 2020). According to the authors, these results might suggest that the participant's level of effort in some sessions did not correspond to the programmed one (Marques et al., 2020). Therefore, coaches and researchers will now have the possibility to adjust the absolute loads in real-time whenever the peak or mean velocity attained in the leg-press does not match the programmed ones and ensure that all participants train at the desired level of effort.

Besides the study strengths, we identified several limitations in the current research. Firstly, although the cross-validation analyses suggest that the equations can be generalized, a larger sample size would allow us to extrapolate the equations to other older populations with high confidence. Secondly, although a minimum of two familiarization sessions seems required for valid and reliable measurements (Alcazar et al., 2019), a more extended period could also guarantee a better adaptation to testing procedures. Thirdly, a standardized progressive loading test protocol with untrained older women and men would allow us to decide the number of repetitions and rest periods based on the peak or mean velocity attained with each load. In a previous study with strength-trained older women, the participants performed the number of repetitions based on the mean velocity attained (Marcos-Pardo et al., 2019). For example, the participants could perform three repetitions in the 45° inclined leg-press when the mean velocity was > 1.00 $m \cdot s^{-1}$. However, no older women could attain a mean velocity > 0.62 $m \cdot s^{-1}$ in the horizontal leg-press in our study. Therefore, the reference velocity values provided in the study of Marcos-Pardo et al. (Marcos-Pardo et al., 2019) do not apply to our sample and similar ones, which means that further research on this topic is needed. Finally, analyzing the load-velocity relationship in upper-body resistance exercises, such as the seated chest-press, would contribute to training prescription purposes and help understand the differences in lifting velocity between different body regions in older adults.

Conclusions

The present study's findings demonstrated that the movement velocity accurately estimates the relative load during the horizontal leg-press exercise in older women and men. Considering that the leg-press is widely used in geriatric research (Alcazar et al., 2018a), the proposed sex-specific equations will enable coaches and researchers to estimate and monitor 1RM changes from lifting velocity measurement. Implementing this method in clinical practice with proper supervision will also avoid submitting the participants to the direct or indirect (repetitions to failure) assessments, which present several disadvantages in older adults (e.g., time-consuming, muscle soreness, injury risk). Finally, by knowing the peak or mean velocity associated with each relative load in the horizontal leg-press, coaches and researchers can now prescribe and monitor older adults' training load based on lifting velocity measurement.

Study 6. Estimating the relative load from movement velocity in the seated chest press exercise in older adults

Abstract

Objectives: This study examined i) the load-velocity relationship in the seated chest press exercise in older women and men and ii) the differences between sexes in movement velocity for each relative load in the chest press. **Methods:** Thirty-two older adults (17 women; 79.6±7.7 years) performed the chest press progressive loading test up to one-repetition maximum (1RM). A linear velocity transducer collected the fastest peak and mean velocity attained with each weight. Quadratic regression equations were developed for women and men. We analyzed the regression model's effectiveness by checking the residuals' normality, independence, and homoscedasticity. The regression equations were cross-validated, considering the holdout method. Independent samples t-test analyzed the differences between sexes in the estimated peak and mean velocity for each relative load. **Results:** The data demonstrated a very strong quadratic load-velocity relationship in the chest press in women (peak velocity: r^2 = 0.97, standard error of the estimate (SEE) = 4.5% 1RM; mean velocity: r^2 = 0.96, SEE = 5.3% 1RM) and men (peak velocity: r^2 = 0.98, SEE = 3.8% 1RM; mean velocity: r^2 = 0.98, SEE = 3.8% 1RM). The results suggested no overfitting in both models since the correlation coefficients were positive and high (r = 0.98-0.99) and did not present a big difference between subsets. Men presented higher ($p < 0.001$) estimated peak and mean velocity values than women against almost all relative loads, except with 95 and 100% of 1RM ($p > 0.05$). **Conclusions:** The results suggest that movement velocity can estimate the relative load in the seated chest press in older women and men. In addition, given the velocity differences between older women and men against submaximal loads, we recommend using sex-specific equations to estimate the 1RM and prescribe the relative loads in older adults.

Keywords: regression analysis, load-velocity relationship, upper-limb strength, aging

Introduction

Human aging is a continuous process characterized by a progressive loss of muscle mass and reduced ability to produce and apply force in motor tasks such as walking, climbing stairs, and rising from a chair (Demontis et al., 2013; Rolland et al., 2008). Therefore, scientific literature recommends resistance training as a practical and effective approach to counteract the age-related decline of functional capacity and the incidence of falls in older adults (Fragala et al., 2019; Marques et al., 2013).

In a geriatric setting, a common practice to determine the resistance training load (intensity) is through the direct measurement of the one-repetition maximum (1RM), which consists of displacing the maximum weight possible in a single lift (Niewiadomski et al., 2008; Tan et al., 2015). Although reliable, this is time-consuming and may cause muscle soreness due to the high physical stress imposed, especially in naïve practitioners (Shaw et al., 1995; Tan et al., 2015). Consequently, coaches may seek safer and time-efficient procedures to estimate the 1RM, such as regression equations based on repetitions-to-failure (Shaw et al., 1995; Tan et al., 2015; Wood et al., 2002). However, considering the paucity of equations to estimate the 1RM in older adults, using these formulas might not be accurate with individuals of different ages, health conditions, and resistance training backgrounds (Tan et al., 2015). Therefore, alternative approaches to assess the 1RM in older adults are needed.

Recently, two studies suggested regression equations to estimate the relative load from movement velocity in older adults (Marcos-Pardo et al., 2019; Marques et al., 2021). For example, Marcos-Pardo et al. (2019) developed load-velocity equations in the free weight bench press and 45° inclined leg press with strength-trained older women of ~68 years old. In another study, Marques et al. (2021) established sex-specific load-velocity equations in the horizontal leg press with untrained older women and men of ~79 years old. As observed in both studies, the proposed equations for the leg press demonstrated a very high accuracy level (r^2: ~0.91-0.94; standard error of the estimate (SEE): ~5.7% 1RM), suggesting that load-velocity regression equations are reliable in geriatric settings (Marcos-Pardo et al., 2019; Marques et al., 2021). However, Marcos-Pardo et al. (2019) did not find the same accuracy level for the free weight bench press (r^2: 0.83; SEE: 6.10% 1RM). According to the authors, possible reasons for these results might be the lack of a more extended familiarization period and using free weights instead of resistance machines (Marcos-Pardo et al., 2019). Indeed, using free weights may increase the variation in the exercise technique because it requires more stabilization and balance than resistance machines (Schwanbeck et al., 2020). Therefore, future studies with older women and men proposing load-velocity equations in upper-body exercises performed in resistance machines must be developed.

Previous research verified that men attained higher velocity values than women for almost all relative loads in the horizontal leg press in older adults (Marques et al., 2021) and the full-back squat in young adults (Pareja-Blanco et al., 2020). However, the authors observed that the higher the relative load, the lower the differences between sexes in movement velocity (Marques et al., 2021; Pareja-Blanco et al., 2020). These data suggest that women present a higher strength deficit than men, regardless of age. This deficit is the percentage of maximal strength potential not used in a motor task (Marques et al., 2021; Pareja-Blanco et al., 2020; Siff, 2000). In addition, other reasons might be associated with larger and stronger type II muscle fibers in the quadriceps in older men than older women (Barnouin et al., 2017; Frontera et al., 2000), enabling the former to displace submaximal loads with higher velocities. Nevertheless, it remains unclear if these differences between older women and men in movement velocity for the same relative loads also occur in upper-body resistance exercises.

Given the considerations mentioned above, the aim of the current study was twofold. First, we aimed to analyze the predictive ability of the movement velocity to estimate the relative load in the seated chest press exercise in older women and men. A second aim was to compare the differences between older women and men in movement velocity for each relative load in the seated chest press exercise. We expected to identify a relationship between movement velocity and relative load in the seated chest press in both sexes, as observed in previous studies with younger populations (García-Ramos et al., 2019; Pareja-Blanco et al., 2020; Torrejón et al., 2019). In addition, we hypothesized that men would present higher velocities than women against almost all relative loads in the seated chest press. However, as observed in previous research with younger populations, these differences would decrease as the relative load increases (García-Ramos et al., 2019; Pareja-Blanco et al., 2020; Torrejón et al., 2019).

Methods

Participants

Thirty-two older adults (seventeen women and fifteen men) from residential care facilities and day centers volunteered to participate in this study. Inclusion criteria were age ≥ 65, male and female, walking and standing up from a chair independently, willing to participate in the study, and collaborating with the researchers. Exclusion criteria included severe physical dependency (Barthel Index score < 60) and cognitive decline (Mini-Mental State Examination [MMSE] cut-off scores: participants without years of schooling, <15 points; 1 to 11 years of school completed, <22 points; and >11 years of school completed, <27 points (Mendes et al., 2017)), musculoskeletal injuries in the previous three months, and terminal illness. The clinicians of the centers conducted the initial screening tests, which included the 10-m walking speed (Marques et al., 2020), five-repetition sit-to-stand (Alcazar et al., 2018), handgrip strength (Marques et al., 2020), Barthel Index (Mahoney & Barthel, 1965), and MMSE (Folstein et al., 1975). Table 1 shows the characteristics of the participants. All participants received detailed information regarding the study procedures and signed written informed consent. The Ethical Committee of the University of Beira Interior (code: CE-UBI-Pj-2019-019) approved this study, which follows the recommendations of the Declaration of Helsinki.

Table 1. Participant's characteristics.

Variable	Women (n = 17)	Men (n = 15)	Total (n = 32)
Age (years)	81.5 ± 7.7	77.5 ± 7.4	79.6 ± 7.7
Body Mass (kg)	65.4 ± 10.5	78.3 ± 15.6	71.5 ± 14.5
Height (m)	1.49 ± 0.06	1.66 ± 0.08	1.57 ± 0.11
BMI (kg/m^2)	29.5 ± 4.2	28.4 ± 4.9	29.0 ± 4.5
Barthel Index score	89.1 ± 12.3	90.7 ± 12.9	89.8 ± 12.4
MMSE score	20.9 ± 3.6	24.8 ± 4.7	22.7 ± 4.5
10-m Walking test (s)	6.6 ± 1.1	6.9 ± 2.4	6.7 ± 1.8
5STS test (s)	8.0 ± 1.9	8.7 ± 1.8	8.3 ± 1.9
HGS absolute (kg)	19.5 ± 4.9	32.9 ± 9.5	25.8 ± 10.0
1RM Chest press (kg)	27.2 ± 6.4	43.3 ± 11.6	34.7 ± 12.2
Relative Strength (kg/BM)	0.42 ± 0.11	0.56 ± 0.13	0.49 ± 0.14

Data are mean ± SD; 1RM: one-repetition maximum; 5STS: five-repetition sit-to-stand test; BM: body mass; BMI: body mass index; HGS: handgrip strength (the absolute handgrip strength corresponds to the average result of the left and right hands score); MMSE: mini-mental state examination; Relative Strength = 1RM Chest press (kg) / Body Mass (kg).

Study Design

In a cross-sectional study design, untrained older adults went to a fitness health club five times for three weeks, at the same time (2-4 p.m.), with a room temperature of 22-24 °C. We dedicated four sessions (two each week) for familiarization and one to implement the test. Therefore, in the first week, the participants underwent two sessions, separated by 48 hours, to adapt to the testing procedures (focus on the exercise technique). We also performed anthropometric measurements during this period and identified the correct position in the seated chest press machine for every participant. In the second week's first session, all participants performed two sets of five repetitions with 5.7 and 10.2 kg at the maximal intended velocity (focus on movement velocity). After 48 hours of rest, they performed a second session constituted by one set of three repetitions at the maximal intended velocity with 5.7, 10.2, and 14.8 kg and rested three minutes between sets. Finally, in week 3, all participants performed the chest press progressive loading test. An experienced researcher and two senior coaches' specialists supervised all sessions and testing procedures. Figure 1 illustrates the study design.

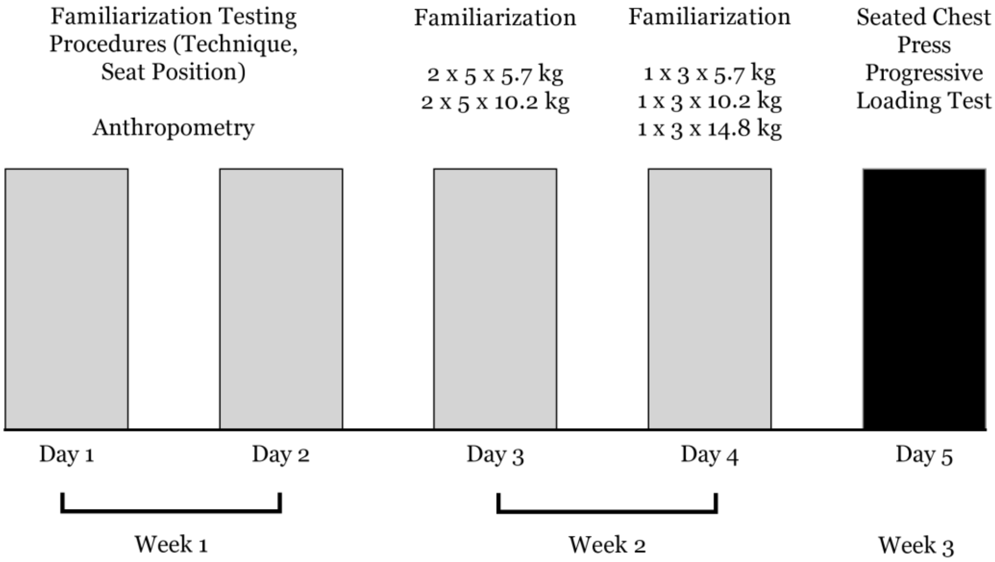

Figure 1. Illustration of the study design. Sets x repetitions x absolute load (kg).

Seated Chest press Progressive Loading Test

Before the evaluations, all participants performed a general warm-up of 10 min walking on a treadmill (2-4 km/h) or pedaling on a stationary bicycle (50-70 rpm; resistance levels: 1-5), followed by 5 min of joint mobility exercises for the upper extremity in a seated position (i.e., shoulders and wrists circular rotation back and forth; shoulders, elbows, and wrists flexion and extension). Then, all participants initiated the test in a seated position with the handgrips at mid-chest, shoulders abducted, elbows flexed at 90°, handles grabbed with a full grip, and wrists in a neutral position. All participants received verbal encouragement to perform the concentric phase as fast and forcefully as possible. An experienced researcher controlled the eccentric phase by placing his hands on the machine's arms to control the descending phase. There was a pause between the eccentric and concentric phases of ~2 s. The test's warm-up consisted of two sets of seven and five repetitions with weights of 5.7 and 10.2 kg, respectively. Then, the test started with 10.2 kg and progressively increased by 5 kg. Whenever possible, the participants performed three repetitions for each load to enable correct data collection (Marques et al., 2021). We carried out this procedure until they could perform only one correct repetition. If the participants could not perform a single lift, we decreased the weight by 1 to 2.5 kg until they could achieve the 1RM. We provided a 3 min rest for three repetitions and 5 min rest for two repetitions between sets. The average number of sets was 5.41 ± 1.23 for women (total repetitions = 92 [5.41 x 17 participants]) and 7.33 ± 1.88 for men (total repetitions = 110 repetitions [7.33 x 15 participants]).

Measurement Equipment and Data Collection

The anthropometric measurements included body mass (TANITA BC-601, Japan) and height (Portable stadiometer SECA, Germany). A seated chest press machine (Chest press G3, Matrix, USA), coupled with a linear velocity transducer (T-Force System, Ergotech, Murcia, Spain), was used to perform the test. The T-Force collects data at a sampling frequency of 1000 Hz and is a valid and high reliable device for measuring the movement velocity during resistance exercises (Courel-Ibáñez et al., 2019). We followed the procedures described elsewhere to connect the T-Force to the resistance machine (Marques et al., 2020). During each repetition, the T-Force software (v2.36) calculated and displayed in real-time the peak velocity (i.e., the maximum instantaneous velocity value reached during the concentric phase) and the mean velocity (i.e., the average velocity from the start of the concentric phase until the weight stack plate reached the maximum height). We analyzed the fastest peak and mean velocities attained with each weight.

Statistical Analysis

The sample size was estimated using the t-test for two independent groups (Hulley et al., 2013). Twenty-five participants were required to ensure a statistical power of 80%, based on an effect size of 0.60, assuming a standard deviation (SD) of 0.5 (according to the SD of the average number of sets during the free weight bench press test in Marcos-Pardo et al. (2019)), and a significance level of 0.05. Considering a proportion of 53% in the women's group, 13 women and 12 men were required. Data are presented as mean ± SD and 95% confidence intervals (CI). We conducted a regression analysis to examine the relationship between the movement velocity and relative load in the seated chest press in both sexes. After creating a scatter plot with the independent (peak or mean velocity) and dependent (relative load) variables, we considered the regression model (linear or quadratic) according to the one that provided the best fit curve to the data. The coefficient of determination (r^2) assessed the predictive ability of the regression equations, the SEE (SD of the residuals) calculated the prediction accuracy, and Pearson's correlation coefficient (r) assessed the relationship between variables. The magnitude of correlation was interpreted as: 0.00-0.10, negligible; 0.10-0.39, weak; 0.40-0.69, moderate; 0.70-0.89, strong; 0.90-1.00, very strong (Schober et al., 2018). Checking the assumptions of the residuals' normality, independence, and homoscedasticity enabled us to analyze the regression model's effectiveness and appropriateness (Casson & Farmer, 2014). The normality was examined using the histograms, normal P-P plots, and Q-Q plots of the standardized residuals, coupled with the Kolmogorov-Smirnov test. The independence was analyzed with the Durbin-Watson test, while the homoscedasticity by inspecting the scatter plots of the standardized residuals against the standardized predicted values. The assumption of no extreme values was verified after the outlier's removal. The regression equations were cross validated to test if there was no overfitting. We split the data into two equal-sized subsets, and cross-validation was conducted considering the holdout method. We established individual regression equations for each participant to estimate the peak and mean velocity associated with each relative load. The normality and homogeneity of the data (i.e., estimated peak and mean velocity values for each relative load) were evaluated by the Shapiro-Wilk test and Levene's test, respectively. Independent samples t-test analyzed the differences between sexes in the estimated peak and mean velocity for each relative load. The Hedge's g effect size compared the magnitude of differences between sexes in the estimated peak and mean velocity for each relative load. The effect size (g) was interpreted as: trivial, 0.0-0.2; small, 0.2-0.6; moderate, 0.6-1.2; large, 1.2-2.0; very large, 2.0-4.0; extremely large, > 4.0 (Hopkins et al., 2009). The significance level was set at $p < 0.05$. Statistical analyses were performed in Microsoft Office Excel® (Microsoft Inc., Redmond, WA, USA) and SPSS v27 (SPSS Inc., Chicago, IL, USA). The figures were designed in GraphPad Prism v7 (GraphPad Inc., San Diego, CA, USA).

Results

Relationship Between Movement Velocity and Relative Load in Both Sexes

The quadratic regression was the model that provided the best curve fitting in both sexes. The results revealed a very strong quadratic relationship between the relative load and the peak and mean velocity in both women (r = -0.98-0.99) and men (r = -0.99). Figures 2 and 3 show the regression equations to estimate the peak and mean velocity values associated with each relative load, respectively.

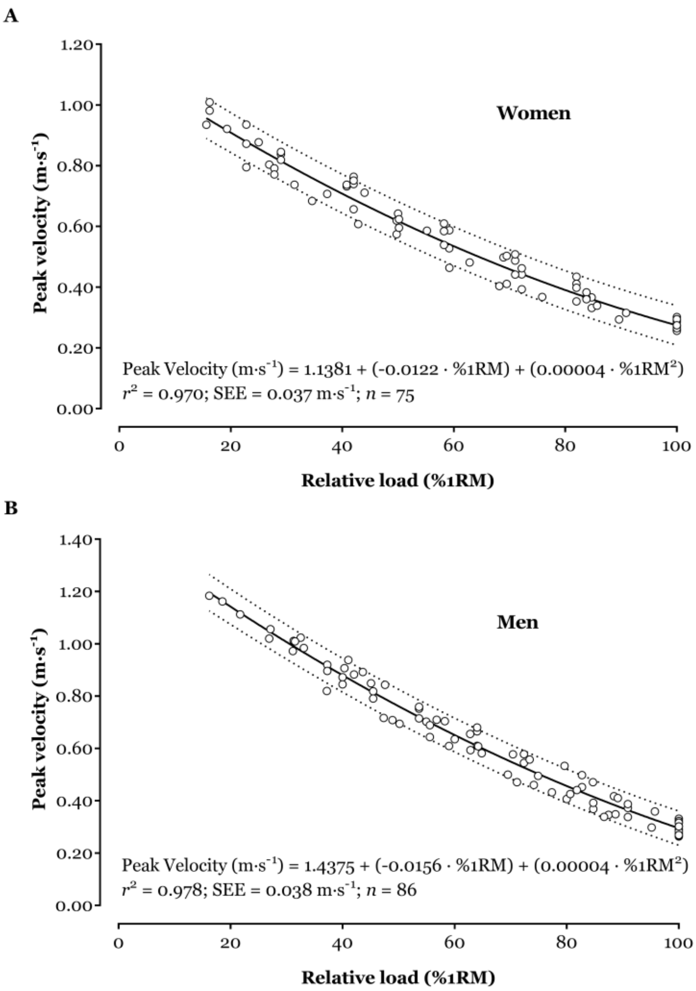

Figure 2. Regression equations to estimate the peak velocity based on the relative load (%1RM) in the seated chest press exercise in older women (A) and men (B). r2: coefficient of determination; SEE: standard error of the estimate; n: number of observations; Dotted lines indicate the 95% prediction bands.

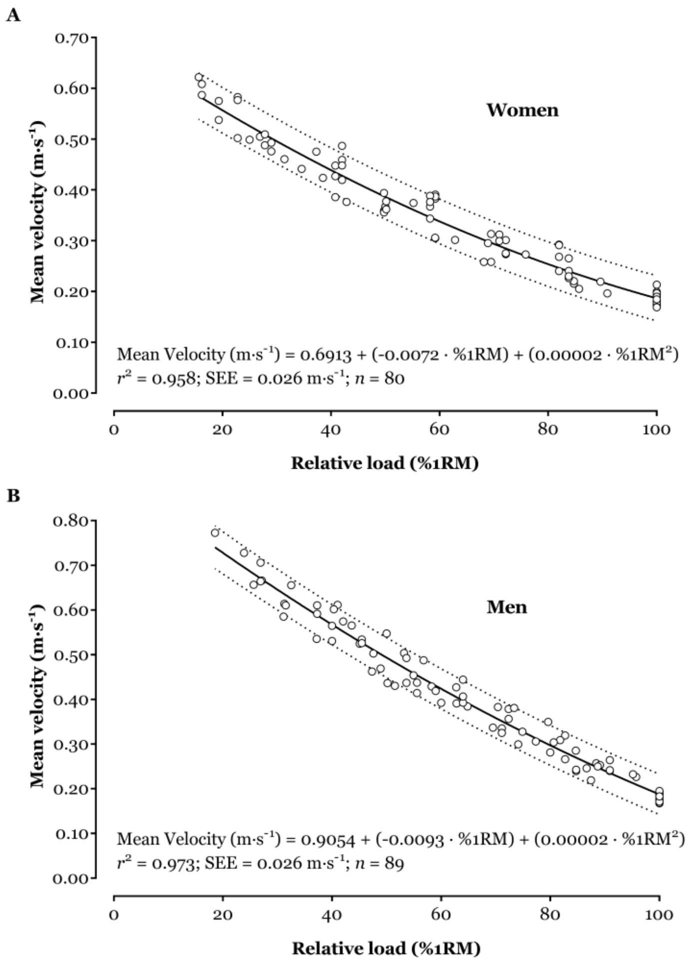

Figure 3. Regression equations to estimate the mean velocity based on the relative load (%1RM) in the seated chest press exercise in older women (A) and men (B). r2: coefficient of determination; SEE: standard error of the estimate; n: number of observations; Dotted lines indicate the 95% prediction bands.

Differences Between Sexes in the Estimated Peak and Mean Velocity for all Relative Loads

Tables 2 and 3 show the differences between sexes in the estimated peak and mean velocity for each relative load in increments of 5% derived from the individual regression equations, respectively. Men presented higher estimated peak and mean velocity values than women for almost all relative loads ($p < 0.001$), except with 95 and 100% of 1RM ($p > 0.05$).

Table 2. Estimated peak velocity for each relative load in the seated chest press exercise for older women and men, derived from the individual load-velocity relationships.

Load (% 1RM)	**Women ($m·s^{-1}$)**	**Men ($m·s^{-1}$)**	***p-value***	**Difference ($m·s^{-1}$)**	**Hedge's *g* (classification)**
20	0.88 ± 0.08	1.10 ± 0.17	< 0.001	0.22	1.66 (large)
25	0.84 ± 0.07	1.03 ± 0.15	< 0.001	0.20	1.73 (large)
30	0.79 ± 0.06	0.97 ± 0.13	< 0.001	0.18	1.80 (large)
35	0.75 ± 0.06	0.91 ± 0.11	< 0.001	0.17	1.86 (large)
40	0.70 ± 0.06	0.85 ± 0.10	< 0.001	0.15	1.91 (large)
45	0.66 ± 0.05	0.80 ± 0.08	< 0.001	0.14	1.95 (large)
50	0.62 ± 0.05	0.74 ± 0.07	< 0.001	0.12	1.96 (large)
55	0.58 ± 0.05	0.69 ± 0.06	< 0.001	0.11	1.94 (large)
60	0.54 ± 0.04	0.64 ± 0.06	< 0.001	0.10	1.88 (large)
65	0.51 ± 0.04	0.59 ± 0.05	< 0.001	0.08	1.79 (large)
70	0.47 ± 0.04	0.54 ± 0.05	< 0.001	0.07	1.66 (large)
75	0.43 ± 0.04	0.50 ± 0.04	< 0.001	0.06	1.51 (large)
80	0.40 ± 0.03	0.45 ± 0.04	< 0.01	0.05	1.32 (large)
85	0.37 ± 0.03	0.41 ± 0.04	< 0.01	0.04	1.10 (moderate)
90	0.34 ± 0.03	0.37 ± 0.04	0.03	0.03	0.85 (moderate)
95	0.31 ± 0.03	0.33 ± 0.04	0.13	0.02	0.58 (small)
100	0.28 ± 0.04	0.29 ± 0.04	0.38	0.01	0.33 (small)
Average	0.56 ± 0.04	0.66 ± 0.06	< 0.001	0.10	1.97 (large)

Data are mean ± SD. 1RM: one-repetition maximum.

Table 3. Estimated mean velocity for each relative load in the seated chest press exercise for older women and men, derived from the individual load-velocity relationships.

Load (% 1RM)	**Women ($m \cdot s^{-1}$)**	**Men ($m \cdot s^{-1}$)**	***p-value***	**Difference ($m \cdot s^{-1}$)**	**Hedge's *g* (classification)**
20	0.55 ± 0.05	0.72 ± 0.09	< 0.001	0.17	2.49 (very large)
25	0.52 ± 0.04	0.68 ± 0.08	< 0.001	0.16	2.61 (very large)
30	0.49 ± 0.04	0.64 ± 0.07	< 0.001	0.15	2.71 (very large)
35	0.46 ± 0.04	0.60 ± 0.06	< 0.001	0.14	2.79 (very large)
40	0.44 ± 0.03	0.56 ± 0.05	< 0.001	0.13	2.85 (very large)
45	0.41 ± 0.03	0.52 ± 0.05	< 0.001	0.11	2.87 (very large)
50	0.38 ± 0.03	0.49 ± 0.04	< 0.001	0.10	2.86 (very large)
55	0.36 ± 0.03	0.45 ± 0.03	< 0.001	0.09	2.79 (very large)
60	0.34 ± 0.03	0.42 ± 0.03	< 0.001	0.08	2.69 (very large)
65	0.31 ± 0.03	0.38 ± 0.03	< 0.001	0.07	2.53 (very large)
70	0.29 ± 0.03	0.35 ± 0.02	< 0.001	0.06	2.33 (very large)
75	0.27 ± 0.03	0.32 ± 0.02	< 0.001	0.05	2.06 (very large)
80	0.25 ± 0.02	0.29 ± 0.02	< 0.001	0.04	1.72 (large)
85	0.23 ± 0.02	0.26 ± 0.02	< 0.001	0.03	1.32 (large)
90	0.21 ± 0.02	0.23 ± 0.02	0.02	0.02	0.87 (moderate)
95	0.19 ± 0.03	0.20 ± 0.02	0.24	0.01	0.43 (small)
100	0.18 ± 0.03	0.18 ± 0.03	0.86	0.002	0.07 (trivial)
Average	0.35 ± 0.03	0.43 ± 0.03	< 0.001	0.08	2.80 (very large)

Data are mean ± SD. 1RM: one-repetition maximum.

Estimating the Relative Load from Peak and Mean Velocity

The following equations were obtained for both sexes to estimate the relative load from the measurement of peak velocity during the seated chest press exercise:

Women: Load (% 1RM) = 149.37 + (-205.01 · Peak Velocity) + (70.871 · Peak Velocity^2)
(r = -0.986; r^2 = 0.972; SEE = 4.547% 1RM)

Men: Load (% 1RM) = 136.09 + (-136.88 · Peak Velocity) + (31.699 · Peak Velocity^2)
(r = -0.988; r^2 = 0.976; SEE = 3.808% 1RM)

When using the mean velocity to estimate the relative load during the seated chest press, clinicians and researchers can use the following equations for both sexes:

Women: Load (%1RM) = 156.36 + (-350.98 · Mean Velocity) + (196.04 · Mean Velocity^2)
(r = -0.988; r^2 = 0.960; SEE = 5.319% 1RM)

Men: Load (%1RM) = 136.58 + (-214.50 · Mean Velocity) + (79.025 · Mean Velocity^2)
(r = -0.988; r^2 = 0.975; SEE = 3.809% 1RM)

Table 4 presents the cross-validation method considering the regression equations using the peak and mean velocity. The results suggest no overfitting in both models since the correlation coefficients are positive and high (r = 0.977 to 0.990) and do not present a big difference between both subsets.

Table 4. Cross-validation using the holdout method.

	Relative load (% 1RM)	Testing set#	Training set#
Peak velocity	Women	0.984	0.988
	Men	0.988	0.990
Mean velocity	Women	0.977	0.981
	Men	0.990	0.985

Pearson correlation coefficient between predicted and observed values.

Discussion

This study analyzed the predictive ability of the movement velocity to estimate the relative load in the seated chest press exercise in older women and men. Our data showed a very strong load-velocity relationship in the seated chest press in both sexes, thus confirming our first hypothesis. In addition, men presented significantly higher velocities than women against almost all relative loads, except for 95 and 100% of 1RM, confirming our research's second hypothesis.

To our knowledge, only one study with older women established the load-velocity relationship in an upper-body resistance exercise, the free-weight bench press (Marcos-Pardo et al., 2019). The equation proposed in that study presented lower r^2 (0.83) and higher SEE (6.10% 1RM) values than the equations developed in our study. The authors stated that using free weights instead of resistance machines might have decreased the equation's predictive ability (Marcos-Pardo et al., 2019). However, since free weights demand more balance and resistance machines allow a linear movement pattern, the stabilization factor might have increased our study's reliability of velocity measurement. Therefore, our results suggest that the accuracy of the load-velocity regression equations is high in older adults when using resistance machines. Nevertheless, future research with older women and men should compare the load-velocity relationship's predictive ability of the seated chest press vs. free weight bench-press for plausible comparisons between both forms of exercise.

The current results demonstrated that older men presented higher movement velocity values than older women for almost all relative loads in the seated chest press, except for 95 and 100% of 1RM. Previous research with physically active young adults corroborates these results demonstrating that men present higher lifting velocity values than women against almost all relative loads in the bench-press, except for heavier loads (~80-100% 1RM) (García-Ramos et al., 2019; Pareja-Blanco et al., 2020; Torrejón et al., 2019). Therefore, these results suggest that the differences between sexes in movement velocity decrease as the relative loads increase in young and older adults. One reason might be associated with a higher strength deficit in women than men, restricting women from expressing all strength potential in a given motor task (Marques et al., 2021; Pareja-Blanco et al., 2020; Siff, 2000). However, since no study analyzed the differences between older women and men on the strength and size of type II fibers in the triceps brachii or pectoralis major, no speculations can be made about its influence on the movement velocity during the chest press. Therefore, these data reinforce the pertinence of modeling sex-specific load-velocity regression equations for young (García-Ramos et al., 2019; Pareja-Blanco et al., 2020; Torrejón et al., 2019) and older adults in the chest press.

In our study, older women attained, on average, lower mean velocities than those observed in a previous study with strength-trained older women (~0.07 $m \cdot s^{-1}$ difference) (Marcos-Pardo et al., 2019). These differences are probably related to age (~11 years' difference), training experience (trained vs. untrained), and form of exercise (free weight vs. resistance machine). On the other hand, our male participants attained, on average, similar mean velocities (~0.01 $m \cdot s^{-1}$ difference) than strength-trained older women for the same relative loads (Marcos-Pardo et al., 2019). Although in the leg press, similar findings were observed in previous research with older adults (Marques et al., 2021), suggesting that load-velocity regression equations should be established based on age, sex, training experience, and form of exercise.

In line with previous research (Marcos-Pardo et al., 2019), our results showed that older adults attain lower lifting velocities than trained young adults against the same relative loads in resistance exercises that recruit the chest muscles (e.g., bench press) (García-Ramos et al., 2019; González-Badillo & Sánchez-Medina, 2010; Pareja-Blanco et al., 2020; Torrejón et al., 2019). Furthermore, when analyzing the differences in velocity values in increments of 5% of the relative load, both older women and men present a narrower range of mean velocities (~0.03 $m \cdot s^{-1}$) than physically active young adult women (~0.07 $m \cdot s^{-1}$) and men (~0.08 $m \cdot s^{-1}$) (García-Ramos et al., 2019;

González-Badillo & Sánchez-Medina, 2010; Pareja-Blanco et al., 2020; Torrejón et al., 2019). These data might reflect an impaired force-generating capacity in older adults, which might be attributed to a reduction in type II muscle fibers size (Frontera et al., 2000; Miljkovic et al., 2015). Therefore, to mitigate the age-related loss of muscle fiber size and cross-sectional area, older adults should be encouraged to work out against external resistances to increase type II fibers size and improve the ability to apply force rapidly (Aagaard et al., 2010; Hakkinen et al., 2001; Lexell et al., 1995).

To our knowledge, only one study with strength-trained older women compared the mean velocity values attained against each relative load in the 45° inclined leg press and free-weight bench press exercises (Marcos-Pardo et al., 2019). The results showed no significant differences between exercises for mean velocities at loads ≤ 70% 1RM (~0.01 $m \cdot s^{-1}$ difference). However, for loads ≥ 80% 1RM, the results demonstrated significantly higher velocities in the leg press than in the bench press (~0.03 $m \cdot s^{-1}$ difference) (Marcos-Pardo et al., 2019). The authors attributed these differences to a higher strength deficit in the leg press than the bench-press against submaximal loads (Marcos-Pardo et al., 2019). When comparing our results with those presented in the horizontal leg press of previous research with older adults (Marques et al., 2021), on average, the velocities are higher in the leg press than in the chest press, but the differences are minimal (women: ~0.03 $m \cdot s^{-1}$ difference; men: ~0.01 $m \cdot s^{-1}$ difference). Therefore, these results suggest that in older adults, the mean velocity values associated with each relative load in the leg press and chest press are similar, at least when using resistance machines. On the other hand, the peak velocity values attained against each relative load, on average, are higher in the leg press than the chest press (women: ~0.13 $m \cdot s^{-1}$ difference; men: ~0.15 $m \cdot s^{-1}$ difference) (Marques et al., 2021). Therefore, when comparing the load-velocity profile between exercises in older adults, these data suggest that the peak velocity might be more representative than the mean velocity of the differences in the force-generating capacity. Nevertheless, future studies with older adults must compare the load-velocity relationship in the leg press and chest press to confirm or refute the latter observations.

This study presents several limitations. Firstly, a larger sample size would allow generalizing the proposed sex-specific regression equations to other older individuals. Secondly, a standardized progressive loading test protocol with older women and men would allow us to decide the number of repetitions performed and the recovery periods based on the peak and mean velocity values attained with each weight. Finally, comparing the load-velocity relationship in the horizontal leg press and seated chest press in both sexes would allow us to directly analyze the differences in the movement velocity against all relative loads in both exercises.

Conclusions

The current research demonstrates that it is possible to accurately determine the load-velocity relationship in the chest press in older adults, a widely used exercise in geriatric research. Therefore, this method is helpful for researchers and clinicians to implement velocity-monitored resistance training with older women and men. Researchers and clinicians can reliably estimate the relative load using sex-specific equations and monitor the daily training load and 1RM changes.

Study 7. Load-Power Relationship in Older Adults: The Influence of Maximal Mean and Peak Power Values and Their Associations with Lower and Upper-Limb Functional Capacity

Abstract

Objectives: This research aimed to i) analyze the load-mean and peak power relationships in the leg press and chest press in older adults, ii) examine the differences between mean $P_{max\text{-}load}$ ($MP_{max\text{-}load}$) and peak $P_{max\text{-}load}$ ($PP_{max\text{-}load}$) within resistance exercises, iii) identify the differences between resistance exercises in $MP_{max\text{-}load}$ and $PP_{max\text{-}load}$, and iv) explore the associations between MP_{max} and PP_{max} in the leg press and chest press with functional capacity indicators. **Methods:** Thirty-two older adults (79.3±7.3 years) performed the following tests: medicine ball throw (MBT), five-repetition sit-to-stand (STS), 10-meters walking (10W), and a progressive loading test in the leg press and chest press. Quadratic regressions analyzed i) the load-mean and peak power relationships and identified the $MP_{max\text{-}load}$, MP_{max}, $PP_{max\text{-}load}$, and PP_{max} in both exercises, ii) the associations between MP_{max} and PP_{max} in the chest press with MBT, and iii) the associations between MP_{max} and PP_{max} in the leg press with STS_{power} and $10W_{velocity}$. **Results:** In the leg press, the $MP_{max\text{-}load}$ was ~66% 1RM, and the $PP_{max\text{-}load}$ was ~62% 1RM, both for women and men ($p>0.05$). In the chest press, the $MP_{max\text{-}load}$ was ~62% 1RM, and the $PP_{max\text{-}load}$ was ~56% 1RM, both for women and men ($p>0.05$). There were differences between $MP_{max\text{-}load}$ and $PP_{max\text{-}load}$ within exercises ($p<0.01$) and differences between exercises in $MP_{max\text{-}load}$ and $PP_{max\text{-}load}$ ($p<0.01$). The MP_{max} and PP_{max} in the chest press explained ~48% and ~52% of the MBT-1kg and MBT-3kg variance, respectively. In the leg press, the MP_{max} and PP_{max} explained ~59% of STS_{power} variance; however, both variables could not explain the $10W_{velocity}$ performance (r^2~0.02). **Conclusions:** This study shows that the $P_{max\text{-}load}$ is similar between sexes, is resistance exercise-specific, and varies within exercises depending on the mechanical power variable used in older adults. Furthermore, this research demonstrates the influence of the MBT as an upper-limb power marker in older adults.

Keywords: muscle power, functional performance, medicine ball throw, chair stand, walking velocity, regression analysis, aging.

Introduction

As people age, a sharp decrease in muscle power (i.e., the product of force and velocity) contributes to the loss of functional independence and increases the risk of falls and death in older adults (Byrne et al., 2016; McKinnon et al., 2017; Reid & Fielding, 2012). Therefore, measuring muscle power levels is essential for detecting early signs of mobility disability and designing preventive strategies, such as resistance training (Alcazar et al., 2018a; Beaudart et al., 2019). According to several studies, the spectrum of relative loads (% of one-repetition maximum [1RM]) that maximize power output ($P_{max\text{-}load}$) in older people differs between resistance exercises (Potiaumpai et al., 2016; Strand et al., 2019). For example, the $P_{max\text{-}load}$ range in the leg press is around 50-70% 1RM, and in the chest press, between 40-60% 1RM (de Vos et al., 2005; Ni & Signorile, 2017; Potiaumpai et al., 2016; Strand et al., 2019). Interestingly, a study that modeled the load-peak power relationship in participants aged ~69 years did not observe differences between older women and men in the $P_{max\text{-}load}$ in several resistance machines (Strand et al., 2019). According to the authors, the faster muscle power losses in older male adults than female counterparts might contribute to a convergence in muscle power production with age (Strand et al., 2019). Nevertheless, more research on older adults of similar or older ages is needed to corroborate or refute these observations.

Most studies with older people that modeled the load-power relationship in resistance exercises have primarily prioritized the analysis of the peak power variable (de Vos et al., 2005; Ni & Signorile, 2017; Potiaumpai et al., 2016). However, according to several authors, researchers should also consider mean power values when testing muscle power due to their measurement reliability and potential association with functional capacity in older adults (Alcazar et al., 2017, 2018a). Furthermore, it is essential to understand the differences between mechanical power variables when modeling the $P_{max\text{-}load}$ for training prescription purposes. For example, regarding this matter, previous research with young trained adults observed that the $P_{max\text{-}load}$ is exercise-specific and differs according to the mechanical power variable measured (Martínez-Cava et al., 2019; Pallarés et al., 2014; Sánchez-Medina et al., 2014; Soriano et al., 2015, 2017). These differences indicate that it is essential to define beforehand what mechanical power variable will be measured and monitored during the training program (considering the features of the linear encoder) to avoid erroneous decisions regarding training prescription. Nevertheless, to our knowledge, no known studies compared the differences in the $P_{max\text{-}load}$ using the mean power ($MP_{max\text{-}load}$) and peak power ($PP_{max\text{-}load}$) values in lower and upper-limb resistance exercises in older people. Therefore, to improve the design of resistance training interventions, future research with older people must model the load-mean and peak power relationships in resistance exercises and examine eventual differences between $MP_{max\text{-}load}$ and $PP_{max\text{-}load}$ in the same exercise and the differences in $MP_{max\text{-}load}$ and $PP_{max\text{-}load}$ between resistance exercises.

In addition to analyzing the load-mean and peak power relationships to examine the pattern of mechanical power across a broad range of relative loads, it is also essential to examine the association between the maximal mean power (MP_{max}) and peak power (PP_{max}) values (Watts, W) with markers of functional capacity in older people. For example, several authors observed that the PP_{max} in the leg press and knee extension could explain 38% of the variance in the short physical performance battery test (i.e., balance, walk, and chair stand tests) in mobility-limited older adults aged 65 years or over (Bean et al., 2002). On the other hand, research with community-dwelling older people aged 70 years or over observed that leg press mean values could explain more of the short physical performance battery test variance than peak values (34% vs. 15%, respectively) (Alcazar et al., 2017). Nevertheless, research is scarce comparing the associations between MP_{max} and PP_{max} in the leg press with lower-limb functional capacity field tests, including chair stand and walking performance, meaning that this topic needs further investigation. Furthermore, to our knowledge, research is scarce regarding the associations between MP_{max} and PP_{max} in upper-limb resistance exercises, such as the chest press, with upper-limb functional capacity markers.

As suggested by some researchers, evaluating upper-limb muscle power can provide essential information regarding the functionality of older people due to its impact on performing the activities of daily living, such as standing up from a chair with the help of the arms and lifting and carrying groceries (Candow & Chilibeck, 2005; Harris et al., 2011; Macaluso & De Vito, 2004; Metter et al., 1997). In this matter, research with community-dwelling older adults aged ~72 years found associations between the peak force applied during a modified push-up (knees on the ground) and the medicine ball throw (MBT) with 1.5 kg (r = 0.64) and 3 kg (r = 0.61) (Harris et al., 2011). Nevertheless, since the authors did not report the associations between MP_{max} and PP_{max} produced during the modified push-up with MBT, this analysis still needs to be conducted. In addition, selecting a resistance exercise performed in a seated position, such as the chest press, might be more representative of MBT performance than push-ups. Nevertheless, to our knowledge, no studies have yet assessed the association between MP_{max} and PP_{max} in the seated chest press with MBT performance in older people, representing a gap in the literature. Therefore, analyzing these relationships will allow an understanding of the applicability of the MBT as a functional field test to evaluate upper-limb muscle power in older adults.

Given the above considerations, the current research aimed to i) analyze the load-mean and peak power relationships in the leg press and chest press in older women and men, ii) examine the differences between $MP_{max\text{-}load}$ and $PP_{max\text{-}load}$ within resistance exercises, iii) identify the differences between resistance exercises in $MP_{max\text{-}load}$ and $PP_{max\text{-}load}$, and iv) explore the associations between MP_{max} and PP_{max} in the leg press and chest press with functional capacity indicators. We hypothesized that the $P_{max\text{-}load}$ in the leg press and chest press would be similar between older women and men (Strand et al., 2019). In addition, we hypothesized that the $MP_{max\text{-}load}$ and $PP_{max\text{-}load}$ would differ within and between resistance exercises (Martínez-Cava et al., 2019; Pallarés et al., 2014; Sánchez-Medina et al., 2014). Finally, we hypothesized that the MP_{max} and PP_{max} in the chest press would explain the MBT performance variance, while the MP_{max} and PP_{max} in the leg press would explain the performance variability in functional field tests for the lower limbs, including standing up from a chair and short-distance walking.

Methods

Study Design

In this cross-sectional study, the participants went to a fitness health club for three consecutive weeks to perform two weekly sessions, separated by 48 hours of rest. We dedicated the first two weeks to familiarization and anthropometric measures. During this period, we emphasized the proper execution technique of each exercise and movement velocity. Afterward, in the first session of the third week, the participants performed the following tests: MBT with 1 kg (MBT-1kg) and 3 kg (MBT-3kg), 10-meters walking speed (10W), and five-repetition sit-to-stand (STS). After 48 hours of rest, the participants performed a second session constituted by a progressive loading test in the leg press and chest press. An experienced researcher involved in the study and two certified senior fitness coaches supervised the procedures to guarantee safety and proper supervision during each exercise. In addition, verbal encouragement was provided during each exercise to motivate the participants to give a maximal effort. Figure 1 illustrates the study design.

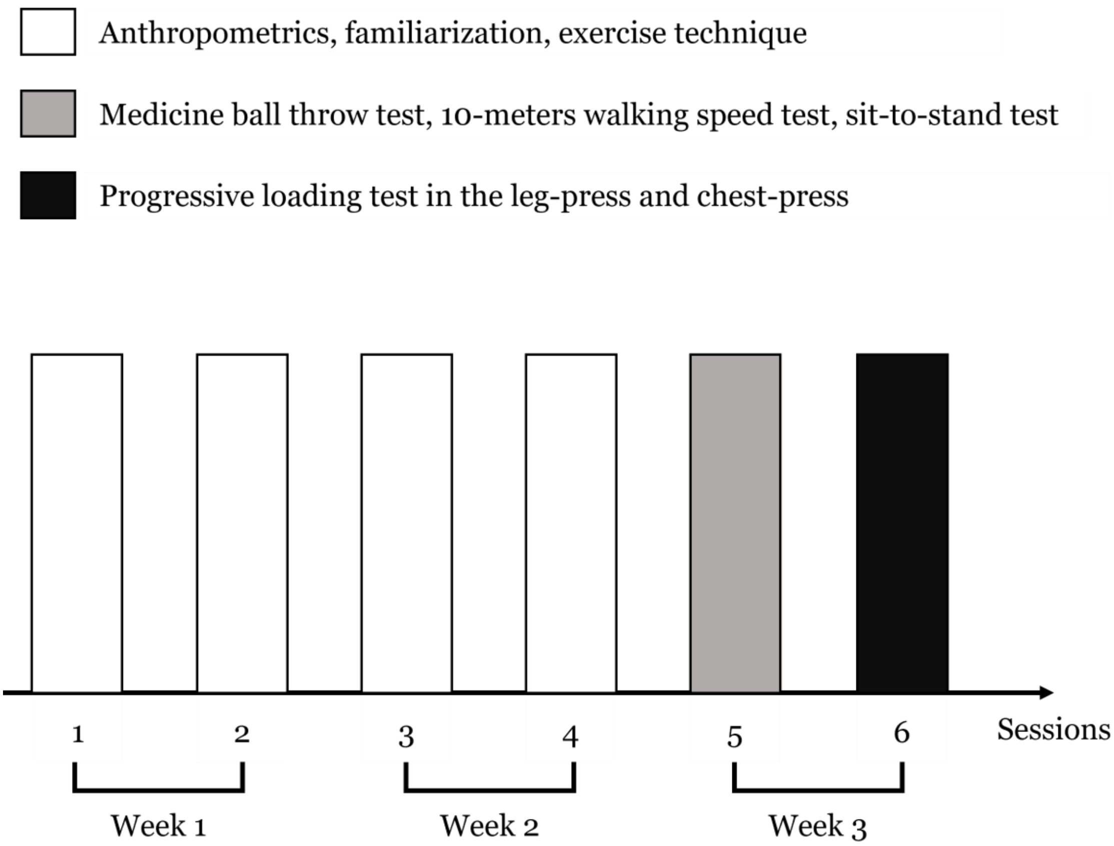

Figure 1. Illustration of the study design.

Participants

We estimated a sample size of twenty-three participants to achieve a power of 80%, considering an alpha level of 0.05, two predictor variables (MP_{max} and PP_{max}), and an r^2 of 0.38 based on the relationship between leg power and the short physical performance battery reported by Bean et al. (2002) (G*Power v3.1). Therefore, thirty-two older adults from residential care facilities and day centers were recruited to participate in this study (Table 1). We included male and female participants aged 65 years or more, able to walk and stand up from a chair independently, and willing to participate in the study. We excluded participants if they had physical dependency (Barthel Index score < 60), cognitive decline (Mini-Mental State Examination [MMSE] cut-off scores: no years of schooling, <15 points; 1-11 years of school, <22 points; and >11 years of school, <27 points (Mendes et al., 2017)), musculoskeletal injuries in the previous three months, and terminal illness. The clinicians of the centers conducted the initial screening tests, including the Barthel Index and MMSE. According to the clinicians, all participants had no records of risk factors (e.g., uncontrolled hypertension and arrhythmia) that could prevent them from performing the exercises included in the study. Furthermore, all participants were classified as sedentary since they had no records of participating in regular physical exercise programs in the last three months. All participants were informed of the study procedures and signed written informed consent. The Ethical Committee of the University of Beira Interior approved this study (CE-UBI-Pj-2019-019).

Table 1. Participants' characteristics.

Variable	Women (*n* = 17)	Men (*n* = 15)	Total (*n* = 32)
Age (years)	80.2 ± 7.8	78.3 ± 6.9	79.3 ± 7.3
Body Mass (kg)	65.7 ± 10.2	75.0 ± 13.9	70.1 ± 12.8
Height (m)	1.49 ± 0.06	1.64 ± 0.08	1.56 ± 0.10
BMI (kg/m^2)	29.5 ± 4.2	27.8 ± 4.6	28.7 ± 4.4
Barthel Index score	90.6 ± 12.0	95.7 ± 9.8	93.0 ± 11.1
MMSE score	21.1 ± 3.8	24.1 ± 4.3	22.5 ± 4.3
$10W_{velocity}$ (m·s^{-1})	1.6 ± 0.2	1.7 ± 0.4	1.6 ± 0.3
STS_{power} (W)	194.1 ± 53.6	259.7 ± 79.5	224.9 ± 73.8
MBT-1kg (m)	3.1 ± 0.5	3.6 ± 0.9	3.3 ± 0.7
MBT-3kg (m)	2.1 ± 0.3	2.6 ± 0.6	2.4 ± 0.5
1RM Chest Press (kg)	31.9 ± 6.4	44.4 ± 10.1	37.8 ± 10.4
1RM Leg Press (kg)	70.3 ± 14.7	87.5 ± 18.6	78.4 ± 18.6

Values are mean ± SD. Abbreviations: RM, repetition maximum; BMI, body mass index; MBT, medicine ball throw; MMSE, mini-mental state examination; STS, five-repetition sit-to-stand; 10W, 10-meters walking.

Measurements

Seated medicine ball throw

The participants held the ball on their chest and threw it as far as possible while seated on a chair (0.49 m) (Marques et al., 2020). They performed three trials with 1 and 3 kg balls, interspersed with 1-minute rest. We measured the distance (m) from the chest to where the balls landed using a tape measure and analyzed the best attempts.

Ten-meters walking speed

The participants walked 10-meters linearly at the maximal intended velocity on an indoor wooden track (Pereira et al., 2012). They performed three trials, separated by 3 minutes of rest. We measured the time (s) using photoelectric cells (Race Time Kit 2, Microgate, Italy) and estimated the mean velocity (10-meters divided by time; $10W_{velocity}$, in m·s^{-1};) of the best trial.

Five-repetition sit-to-stand

The participants stood up and sat down on a chair (0.49 m) with their arms crossed over the chest five times (Alcazar et al., 2018b). They performed two trials, separated by 2-minutes rest. We measured the time (s) using a stopwatch (Casio HS-3V-1R, Japan) and estimated the STS mean power (STS_{power}, in W) using a validated equation (Alcazar et al., 2018), and selected the best attempt.

Progressive loading test in the leg press and chest press

In the leg press (Leg press G3, Matrix, USA), the participants were seated on the bench with their hands on the side handles. They placed their feet on the platform shoulder-width apart, knees at 90°, and back in contact with the seat. In the chest press (Chest press G3, Matrix, USA), the participants were seated on the bench with the handgrips at mid-chest, shoulders abducted, elbows flexed at 90°, and handles grabbed with a full grip. The leg press warm-up consisted of seven repetitions with 20.5 kg plus five repetitions with 29.5 kg, while the chest press warm-up consisted of seven repetitions with 5.7 kg plus five repetitions with 10.2 kg. The initial weight was 29.5 kg and 10.2 kg in the leg press and chest press, respectively. We increased the weight by 10 kg in the leg press and 5 kg in the chest press until the participants achieved the 1RM. If they could not perform one correct repetition, we decreased the weight by 1-5 kg. The participants performed the repetitions at the maximal intended velocity, and we asked them to perform three repetitions whenever possible to guarantee proper data collection. The inter-set rest was 3 minutes for three repetitions and 5 minutes for two repetitions (Marques et al., 2021). Using the procedures described elsewhere (Marques et al., 2020), we coupled a linear velocity transducer (T-Force System, Ergotech, Spain) to the leg press and chest press machines to calculate each repetition's mean and peak power. We selected the maximal mean and peak power values attained with each weight for analysis. The set's average number was 6.4 ± 1.7 and 6.7 ± 1.5 in the leg press and chest press, respectively.

Statistical Analysis

We examined the assumption of normality of the data using the Kolmogorov-Smirnov test. We used standard statistical methods to calculate means, standard deviations (SD), 95% confidence intervals (CI), Pearson correlation coefficients (r), the adjusted coefficient of determination (r^2), and the standard error of the estimate (SEE).

Quadratic regressions analyzed i) the load-mean and peak power relationships in the leg press and chest press and identified the $MP_{max\text{-}load}$ (% 1RM), MP_{max} (W), $PP_{max\text{-}load}$ (% 1RM), and PP_{max} (W) in the leg press and chest press in women and men, ii) the associations between MP_{max} and PP_{max} in the chest press with MBT-1kg and MBT-3 kg, and iii) the associations between MP_{max} and PP_{max} in the leg press with $10W_{velocity}$ and STS_{power}. We used quadratic regressions to analyze the associations between MP_{max} and PP_{max} with functional capacity markers due to the curvilinear relationship between muscle power and functional capacity (Bean et al., 2002; Byrne et al., 2016; Cuoco et al., 2004; Marsh et al., 2006). Independent samples t-test analyzed i) the differences between sexes in absolute mean and peak power values (W) in the leg press and chest press for each relative load, including the $MP_{max\text{-}load}$ and $PP_{max\text{-}load}$, and ii) the differences between sexes in $MP_{max\text{-}load}$ and $PP_{max\text{-}load}$ in the leg press and chest press. A repeated-measures ANOVA with post hoc Bonferroni tests analyzed the differences between MP_{max}/PP_{max} in the leg press and chest press with absolute power values (W) at different relative loads in men and women. Paired samples t-test analyzed i) the differences between $MP_{max\text{-}load}$ and $PP_{max\text{-}load}$ within resistance exercises, and ii) the differences between resistance exercises in $MP_{max\text{-}load}$ and $PP_{max\text{-}load}$. We performed the statistical analyses in Microsoft Office Excel® (Microsoft Inc., Redmond, WA, USA) and SPSS v27 (SPSS Inc., USA) and set the significance level at $p < 0.05$. We designed the figures in GraphPad Prism v7 (GraphPad Inc., San Diego, CA, USA).

Results

Load-mean and peak power relationships in the leg press in women and men

Figure 2 shows the load-mean and peak power relationships in the leg press in older women and men. Men presented higher absolute peak power values than women at 35-95% 1RM (Figure 2A) and higher absolute mean power values at 30-100% 1RM (Figure 2B). The $PP_{max\text{-}load}$ in the leg press did not differ between men and women ($p = 0.59$). In men, the PP_{max} was not different from peak power values associated with loads at 60-65% 1RM ($p > 0.05$), while in women, the PP_{max} was not different from peak power values associated with loads at 60-70% 1RM ($p > 0.05$) (Figure 2A). The $MP_{max\text{-}load}$ in the leg press did not differ between men and women ($p = 0.62$). In men, the MP_{max} was not different from mean power values associated with loads at 60-70% 1RM ($p > 0.05$), while in women, the MP_{max} was not different from mean power values associated with loads at 65-70% 1RM ($p > 0.05$) (Figure 2B).

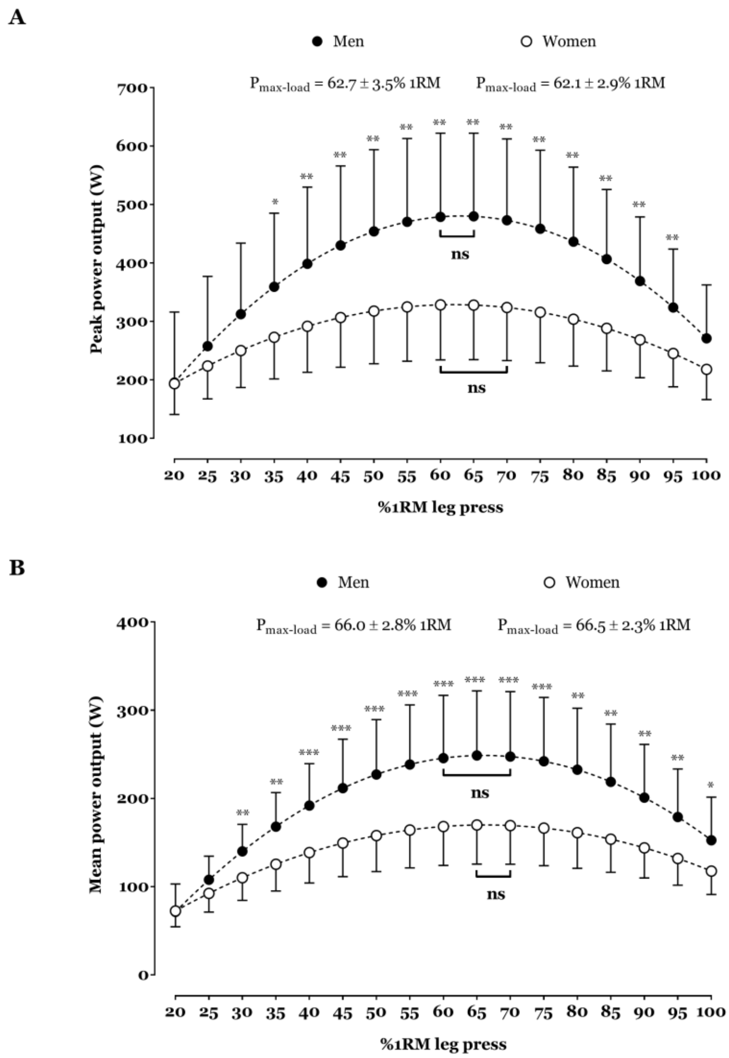

Figure 2. Load-peak (A) and mean power (B) relationships in the leg press for older women and men. * p < 0.05, ** p < 0.01, and *** p < 0.001 indicate significant differences between sexes in the absolute mean or peak power against the same relative load. Square brackets indicate the range of relative loads at which the power output was not statistically different (ns) than the $P_{max\text{-}load}$. Abbreviation: $P_{max\text{-}load}$, relative load that maximizes the power output; RM, repetition maximum.

Load-mean and peak power relationships in the chest press in women and men

Figure 3 shows the load-mean and peak power relationships in the chest press in older women and men. Men presented higher absolute peak and mean power values than women at 20-100% 1RM (Figures 3A and 3B, respectively). The $PP_{max\text{-}load}$ in the chest press did not differ between men and women (p = 0.09). In men, the PP_{max} was not different from peak power values associated with loads at 40-65% 1RM (p > 0.05), while in women, the PP_{max} was not different from peak power values associated with loads at 55-60% 1RM (p > 0.05) (Figure 3A). The $MP_{max\text{-}load}$ in the chest press did not differ between men and women (p = 0.41). In men, the MP_{max} was not different from mean power values associated with loads at 55-65% 1RM (p > 0.05), while in women, the MP_{max} was not different from mean power values associated with loads at 55-60% 1RM (p > 0.05) (Figure 3B).

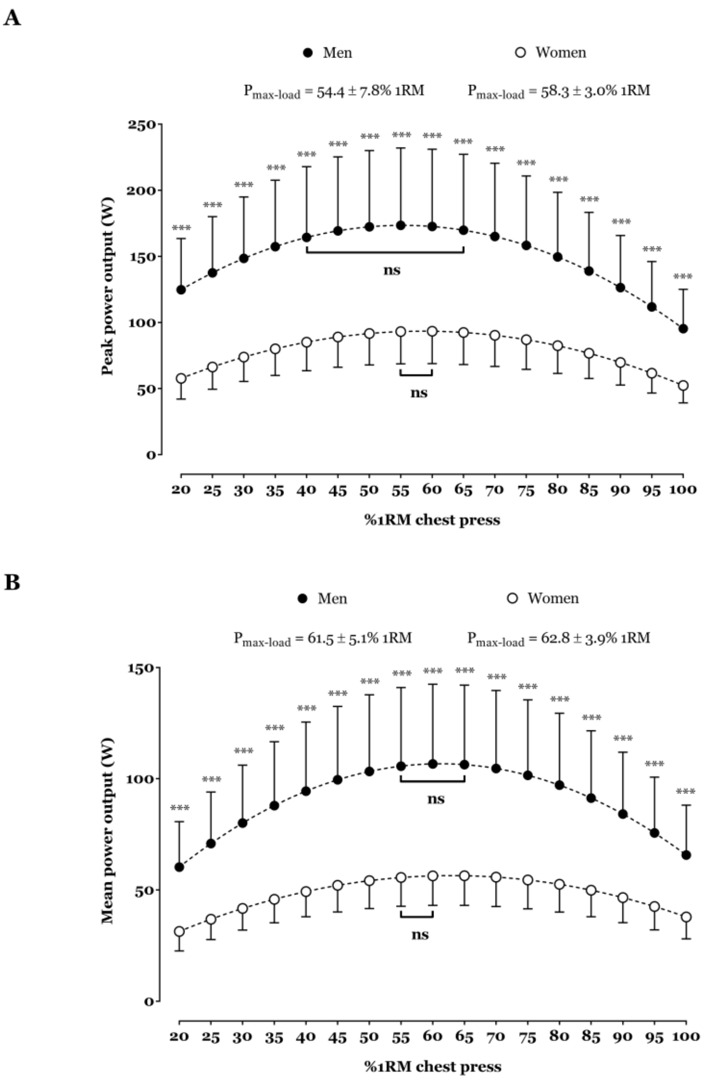

Figure 3. Load-peak (A) and mean power (B) relationships in the chest press for older women and men. * $p < 0.05$, ** $p < 0.01$, and *** $p < 0.001$ indicate significant differences between sexes in the absolute mean or peak power against the same relative load. Square brackets indicate the range of relative loads at which the power output was not statistically different (ns) than the $P_{max\text{-}load}$. Abbreviation: $P_{max\text{-}load}$, relative load that maximizes the power output; RM, repetition maximum.

Differences between leg press vs. chest press in mean $P_{max\text{-}load}$ and peak $P_{max\text{-}load}$

Table 2 shows differences between the leg press vs. chest press in $PP_{max\text{-}load}$ for men and women (p < 0.01). In addition, there were differences between the leg press vs. chest press in $MP_{max\text{-}load}$ for men and women (p < 0.01).

Table 2. Differences between leg press vs. chest press using the peak $P_{max\text{-}load}$ and mean $P_{max\text{-}load}$ in both sexes.

		Leg Press		Chest Press		
Sex	**Variable**	**Mean ± SD**	**95% CI**	**Mean ± SD**	**95% CI**	***p*-value***
Male	Peak $P_{max\text{-}load}$ (% 1RM)	62.7 ± 3.5	60.9-64.4	54.4 ± 7.8	50.5-58.3	0.004
Female	Peak $P_{max\text{-}load}$ (% 1RM)	62.1 ± 2.9	60.7-63.4	58.3 ± 3.0	56.9-59.7	< 0.001
Male	Mean $P_{max\text{-}load}$ (% 1RM)	66.0 ± 2.8	64.6-67.4	61.5 ± 5.1	58.9-64.1	0.004
Female	Mean $P_{max\text{-}load}$ (% 1RM)	66.5 ± 2.3	65.4-67.6	62.8 ± 3.9	61.0-64.7	0.009

Values are mean ± standard deviation (SD) with 95% confidence intervals (CI). * Paired samples t-test. Abbreviations: $P_{max\text{-}load}$, relative load that maximizes power-output; RM, repetition maximum.

Differences between mean $P_{max\text{-}load}$ vs. peak $P_{max\text{-}load}$ within resistance exercises

Table 3 shows differences between $PP_{max\text{-}load}$ vs. $MP_{max\text{-}load}$ in the leg press for men and women ($p < 0.01$). In addition, there were differences between $PP_{max\text{-}load}$ vs. $MP_{max\text{-}load}$ in the chest press for men and women ($p < 0.001$).

Table 3. Differences between peak $P_{max\text{-}load}$ vs. mean $P_{max\text{-}load}$ in the leg press and chest press in both sexes.

		Peak $P_{max\text{-}load}$		Mean $P_{max\text{-}load}$		
Sex	**Variable**	**Mean ± SD**	**95% CI**	**Mean ± SD**	**95% CI**	***p*-value***
Male	Leg press (% 1RM)	62.7 ± 3.5	60.9-64.4	66.0 ± 2.8	64.6-67.4	0.004
Female	Leg press (% 1RM)	62.1 ± 2.9	60.7-63.4	66.5 ± 2.3	65.4-67.6	< 0.001
Male	Chest press (% 1RM)	54.4 ± 7.8	50.5-58.3	61.5 ± 5.1	58.9-64.1	< 0.001
Female	Chest press (% 1RM)	58.3 ± 3.0	56.9-59.7	62.8 ± 3.9	61.0-64.7	< 0.001

Values are mean ± standard deviation (SD) with 95% confidence intervals (CI). * Paired samples t-test. Abbreviations: $P_{max\text{-}load}$, relative load that maximizes power-output; RM, repetition maximum.

Associations between maximal mean power and peak power in the leg press and chest press with functional capacity markers

Figure 4A indicates that the PP_{max} in the chest press explained 48% of MBT-1kg variance, while Figure 4B shows that the MP_{max} in the chest press explained 48% of MBT-1kg variance. In addition, Figure 4C reveals that the PP_{max} in the chest press explained 52% of MBT-3kg variance, while Figure 4D shows that the MP_{max} in the chest press explained 53% of MBT-3kg variance.

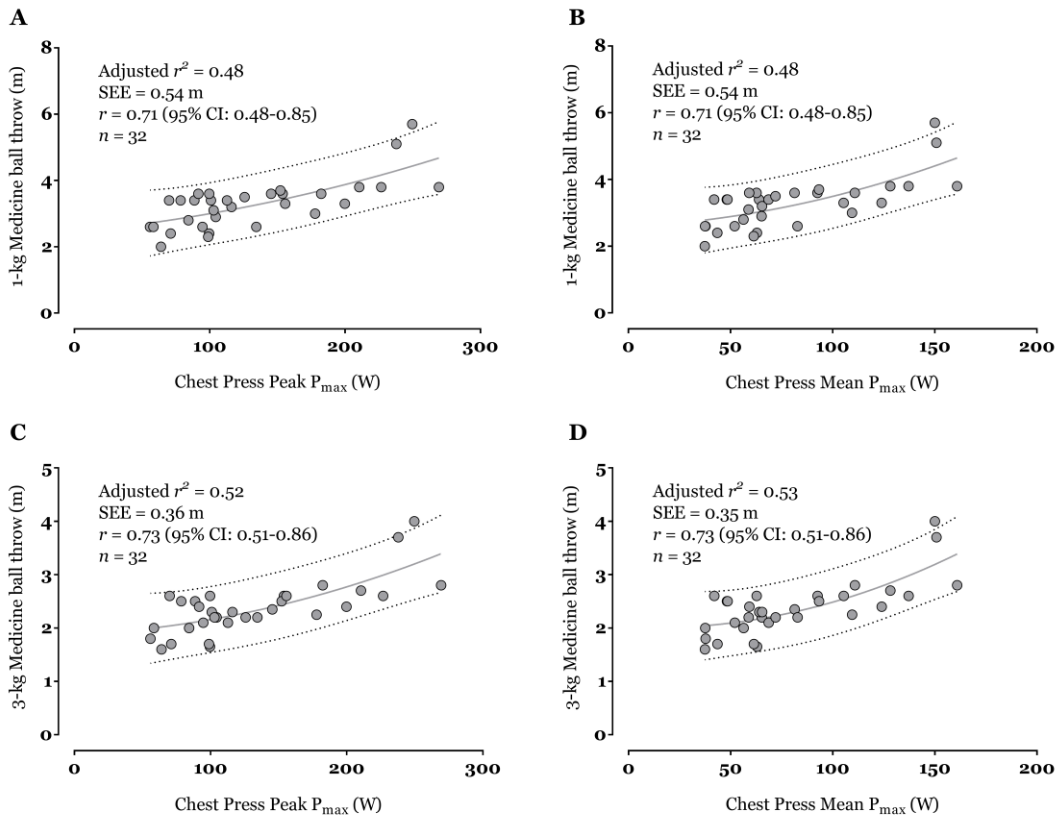

Figure 4. Associations between maximal peak power (A) and mean power output (B) in the chest press with 1-kg medicine ball throw and between peak power (C) and mean power output (D) with 3-kg medicine ball throw; Dotted lines indicate the prediction intervals. Abbreviation: CI, confidence interval; P_{max}, maximal power output; SEE, standard error of the estimate.

Figure 5A indicates that the PP_{max} in the leg press explained 61% of STS_{power} variance, while Figure 5B shows that the MP_{max} in the leg press explained 58% of STS_{power} variance. In addition, Figure 5C reveals that the PP_{max} in the leg press only explained 2% of $10W_{velocity}$ variance, while Figure 5D shows that the MP_{max} in the leg press only explained 1% of $10W_{velocity}$ variance.

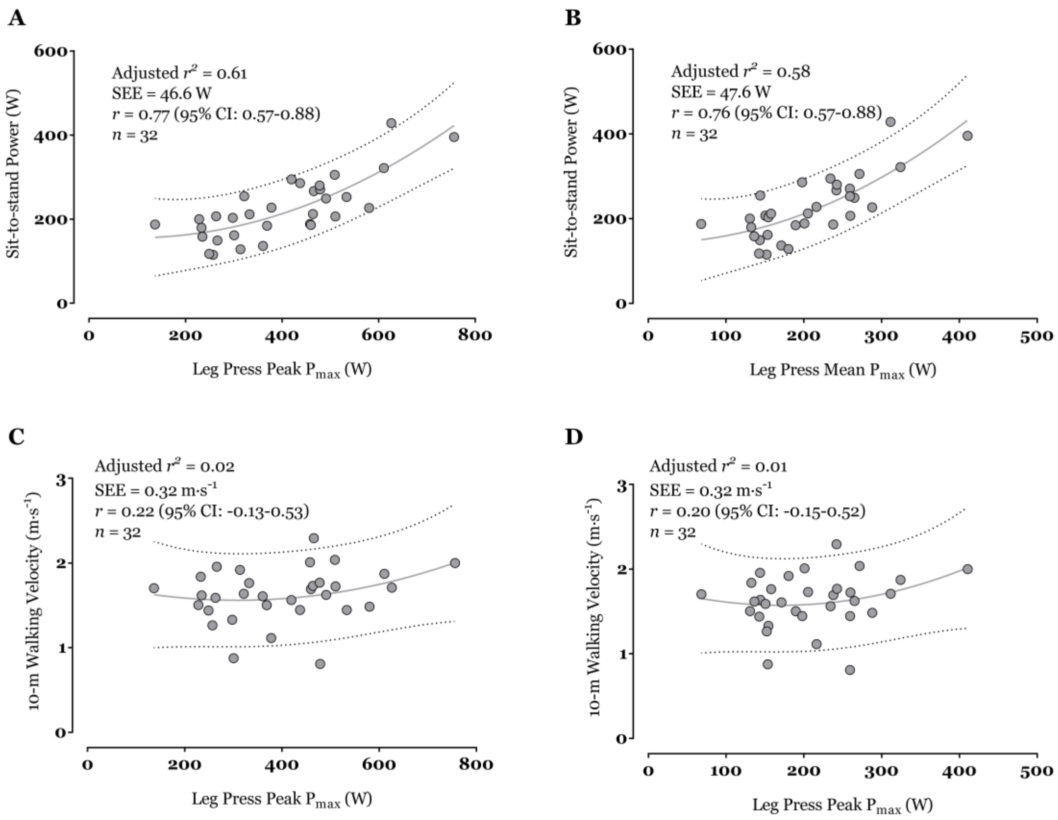

Figure 5. Associations between maximal peak power (A) and mean power output (B) in the leg press with sit-to-stand power and between peak power (C) and mean power output (D) with 10-meter walking velocity; Dotted lines indicate the prediction intervals. Abbreviation: CI, confidence interval; P_{max}, maximal power output; SEE, standard error of the estimate.

Discussion

Main Findings

The current study aimed to i) analyze the load-mean and peak power relationships in the leg press and chest press in older women and men, ii) examine the differences between $MP_{max\text{-}load}$ and $PP_{max\text{-}load}$ within resistance exercises, iii) identify the differences between resistance exercises in $MP_{max\text{-}load}$ and $PP_{max\text{-}load}$, and iv) explore the associations between MP_{max} and PP_{max} in the leg press and chest press with functional capacity indicators. The main findings of the current study were: i) the $MP_{max\text{-}load}$ and $PP_{max\text{-}load}$ in the leg press and chest press are similar between older women and men, ii) the $MP_{max\text{-}load}$ and $PP_{max\text{-}load}$ differ between resistance exercises, meaning that they are exercise-specific, iii) the $P_{max\text{-}load}$ varies in the same resistance exercise depending on the mechanical power variable chosen to measure, iv) the MP_{max} and PP_{max} in the chest press similarly explain the variability in MBT-1kg and MBT-3kg performance, and v) the MP_{max} and PP_{max} in the leg press similarly explain the STS_{power} variance; however both mechanical variables could not explain the variability in $10W_{velocity}$ performance.

Load-Mean and Peak Power Relationships in the Leg Press and Chest Press in Older Women and Men

The results of this study showed that the $MP_{max\text{-}load}$ and $PP_{max\text{-}load}$ in the leg press and chest press did not differ between older women and men, which agrees with previous findings, particularly for the peak power values (Strand et al., 2019). This convergence in muscle power production between sexes might be related to the more significant and faster age-related losses of muscle power in men than women during aging (Edwén et al., 2014; Strand et al., 2019). The results also showed that the load-power relationship in older adults is resistance exercise-specific, thus corroborating the results of previous observations (Strand et al., 2019). For example, the $PP_{max\text{-}load}$ in the leg press and chest press was around 60% and 55% 1RM, respectively, which agrees with previous findings (de Vos et al., 2008; Potiaumpai et al., 2016; Strand et al., 2019). On the other hand, the $MP_{max\text{-}load}$ in the leg press and chest press was unknown until the completion of our study. Compared to $PP_{max\text{-}load}$, the $MP_{max\text{-}load}$ in the leg press and chest press increased to around 66% and 62% 1RM, respectively. Despite its novelty in older populations, these data also indicate that the $P_{max\text{-}load}$ differs between mechanical power variables in older adults, as observed in young adults (Martínez-Cava et al., 2019; Pallarés et al., 2014; Sánchez-Medina et al., 2014). Although most studies with older adults analyzed the $P_{max\text{-}load}$ using the peak power variable (de Vos et al., 2005; Ni & Signorile, 2017; Potiaumpai et al., 2016; Strand et al., 2019), several authors observed higher reliability using mean values than peak values when conducting a progressive loading test in the leg press with this population (Alcazar et al., 2017). However, since no study had yet presented data concerning the $MP_{max\text{-}load}$ in resistance exercises, these results present preliminary evidence for clinicians and researchers who want to collect mean power values to estimate the $P_{max\text{-}load}$. In addition, these results also alert the importance of defining the mechanical power variable beforehand to be monitored during the intervention to avoid misinterpreting information during its course.

The current research also demonstrated that the $P_{max\text{-}load}$ range in the leg press (~60-70% 1RM) and chest press (~40-65% 1RM) was narrower than those observed for younger populations when using, for example, the squat or bench press exercises (~30-70% 1RM) (Soriano et al., 2015, 2017). These differences might be attributed to the progressive reduction in size and number of fast-twitch muscle fibers in the lower and upper limbs with aging, which negatively affects the elbow and knee extensor's power capacity (Candow & Chilibeck, 2005; Korff et al., 2014; Metter et al., 1997). In addition, as observed in our data, the $P_{max\text{-}load}$ range in the leg press was narrower than the chest press, which might be associated with the higher muscle power production losses in the lower limbs than in the upper limbs during aging (Candow & Chilibeck, 2005; Macaluso & De Vito, 2004). According to the literature, a significant reduction in physical activity with age and greater use of the upper limbs than the lower limbs to perform the activities of daily living (e.g., using arms to help to stand up from a chair) might contribute to higher decreases in lower limb's power than upper limb's power (Candow & Chilibeck, 2005; Macaluso & De Vito, 2004). Therefore, these results suggest a broad spectrum of relative loads to maximize the upper-limb muscle power and a narrow range of relative loads to maximize the lower-limb muscle power in older adults. Nevertheless, future research should analyze if training only with the $P_{max\text{-}load}$ improves older adults' muscle power to a greater extent than a broader range of relative loads.

Associations between Maximal Mean and Peak Power Values in the Leg Press and Chest Press with Functional Capacity Markers

The regression analysis showed that the MP_{max} and PP_{max} in the chest press could similarly explain the MBT-1kg and MBT-3kg performance. These data reinforce the influence of the MBT as an indicator of muscle power and functionality in older adults (Harris et al., 2011). Furthermore, although the relationship between the chest press power and functional capacity in older adults is scarce, earlier findings demonstrated a correlation between the chest press peak power and self-reported functional status (lower scores representing better functional status) (r = -0.35) in older women (Foldvari et al., 2000). Consequently, considering the associations between chest press muscle power with MBT, it can be suggested that the MBT seems an essential indicator of the capacity to perform the activities of daily living independently in older adults, such as lifting and carrying groceries and boxes, opening jars, rising from a chair with the help of the arms, and even catching oneself to prevent a fall (Adams et al., 2001; Candow & Chilibeck, 2005; Harris et al., 2011). Based on this information, clinicians, sport-related professionals, and researchers can administer the MBT test to analyze the upper-limb muscle power capacity and derive information regarding the functional ability of older adults.

As for the regression analysis in the lower limbs, the MP_{max} and PP_{max} in the leg press could similarly explain the variability in the STS_{power} performance. These results reinforce the substantial impact of lower-limb muscle power on explaining the variability during sit-to-stand transitions in older adults (Byrne et al., 2016). However, neither MP_{max} nor PP_{max} in the leg press could explain the variance in $10W_{velocity}$ performance. These results were surprising and unexpected since previous research found that leg press power could explain the variance in walking speed performance in older adults (Bean et al., 2002; Puthoff & Nielsen, 2007). Nevertheless, it is essential to note that the latter investigations that assessed the relationships between leg power and walking performance were conducted with mobility-limited older adults, unlike our study. Therefore, the impaired physical condition might have influenced the relationship between lower-limb muscle power with walking performance. Interestingly, research with community-dwelling older adults with similar maximal walking velocity values as our participants (1.6 – 2.0 $m \cdot s^{-1}$) found that hip and ankle muscle strength were better predictors of maximal walking speed than leg strength (Muehlbauer et al., 2018; Uematsu et al., 2014). Therefore, it is essential to consider that hip and ankle strength might better account for the variance in walking performance than leg strength in older adults without mobility impairments (Muehlbauer et al., 2018). Nevertheless, future large-scale research is necessary to determine the influence of leg, hip, and ankle power and strength on maximal walking performance in older adults with and without mobility limitations.

Of note, the range of r^2 values observed in our study is in line with previous research (Byrne et al., 2016), which indicates that a large part of the variance in functional capacity is to be explained by other outcomes (Puthoff & Nielsen, 2007). For example, aerobic endurance, balance, flexibility, agility, and even the fear of falling might explain the variance in functional capacity in older adults (Puthoff & Nielsen, 2007). Therefore, future research should examine, along with lower and upper-limb muscle power, what physiological and psychological indices play a significant role in explaining the variability in functional capacity in older adults.

Study Limitations and Future Research

The current study presents several limitations that we need to address. Firstly, a cross-sectional design does not allow us to establish causal relationships between muscle power with functional capacity in the tested population. In this perspective, future longitudinal studies with older adults should examine the effects of resistance training on muscle power and functional capacity and determine their relationships to support causal links. Secondly, although the sample size calculation determined that twenty-three participants were needed to obtain a statistical power of 80%, the actual number of participants is insufficient to generalize the results to other older adults. In addition, considering that our participants were functionally independent, caution should be taken when generalizing these results to mobility-limited older adults. Finally, including physiological and psychological outcomes would be helpful to examine if, along with lower and upper-limb muscle power measures, they could increase the capacity to explain the remaining part of the variance in functional capacity in older adults. Therefore, future research should consider the limitations mentioned above and conduct large-scale, longitudinal, and experimental studies to examine the physiological and psychological mechanisms that better explain the variability in functional capacity in older adults.

Conclusions

This study showed that the $P_{max\text{-}load}$ in the leg press and chest press are similar between older women and men. Nevertheless, the $P_{max\text{-}load}$ is exercise-specific and varies according to the mechanical power variable chosen for analysis. Therefore, from an applied perspective, this information can be helpful for clinicians, sport-related professionals, and researchers to design experimental interventions oriented to optimizing lower and upper-limb muscle power and functional capacity in older adults. In addition, the current research demonstrated the influence of the MBT exercise as a functional capacity field test for assessing upper-limb muscle power in older adults.

Study 8. Strength, power, and functional capacity changes following velocity-monitored resistance training with 10% and 20% velocity loss in older adults

Abstract

Objectives: We compared the effects of 10% vs. 20% velocity loss (VL) following velocity-monitored resistance training (RT) on older adults' strength, power, and functional capacity. **Methods:** We randomly assigned eighteen older adults to VL10 (n=10; 77.9±11.7 years) or VL20 (n=8; 72.5±10.4 years) to perform a 10-week velocity-monitored RT with 2-3 sets at ~40-65%1RM. The primary outcomes were the leg and chest press 1RM and load-velocity-power profiles, measured at pre, mid, and post-test. Secondary outcomes were the handgrip strength (HGS), medicine ball throw (MBT), ten-meters walking speed (T10), and five-repetition sit-to-stand (STS), measured at pre and post-test. **Results:** There were no differences (p>0.05) between groups in any outcome at any time. Both groups improved leg press 1RM and power and chest press velocity from pre to mid and post-test, while only VL20 improved chest press power from pre to mid-test (p<0.05). In addition, both groups improved STS, while only VL20 increased HGS and T10 at post-test (p<0.05). **Conclusions:** These findings suggest that VL10 and VL20 effectively improved leg press strength and power, chest press velocity, and STS in older adults, although VL10 was more efficient since it required less volume than VL20. Nevertheless, only VL20 improved chest press power, HGS, and T10.

Keywords: strength training, monitoring velocity, muscle strength, load-velocity-power profile, functional performance, aging

Introduction

The manipulation of the acute resistance training (RT) variables, such as volume (e.g., sets x repetitions), intensity (e.g., percentage of one-repetition maximum [% 1RM]), and movement velocity, is a crucial process to optimize sports performance and general health (Bird et al., 2005; Kneffel et al., 2021; Spiering et al., 2008). Therefore, how sport-related professionals and researchers manipulate these variables during training will influence the outcomes. For example, meta-analyses indicated that high loads (e.g., ≥ 70% 1RM) seem required to optimize 1RM gains in older adults (Csapo & Alegre, 2016; Peterson et al., 2010; Steib et al., 2010), while low-to-moderate loads (e.g., < 70% 1RM) displaced at maximal intended velocities seem to benefit muscle power and functional performance (Balachandran et al., 2022; Katsoulis et al., 2019; Marques et al., 2013).

Nevertheless, the amount of training volume required to optimize strength, power, and functionality in older adults seems more controversial (Borde et al., 2015; Polito et al., 2021; Santana et al., 2021). For example, experimental research comparing the effects of single vs. multiple sets observed that both sets effectively improved muscular and functional outcomes in older adults (Antunes et al., 2021; Cannon & Marino, 2010; Cunha et al., 2018, 2020; Galvão & Taaffe, 2005; Radaelli et al., 2013, 2018). Generally, these studies manipulated training volume based on a fixed number of repetitions per set for all participants, which could be maximal or not. Nevertheless, it is essential to notice that performing a maximal number of repetitions against a specific relative load produces high interindividual variability in older adults (Farinatti et al., 2013; Grosicki et al., 2014). Consequently, some older adults will tolerate more volume and others less, highlighting the need for approaches that account for the interindividual variability and enable an effective volume individualization.

To our best knowledge, two studies applied a velocity-monitored RT approach to prescribing the volume in older adults (Marques et al., 2020, 2021). In both studies, the researchers requested the participants to perform every repetition at the maximal intended velocity at 40-65% 1RM until reaching a velocity loss (VL) of 10% or 20%. In general, both VL thresholds effectively improved leg and chest press 1RM and functional capacity-related outcomes, regardless of the interindividual variability in the number of repetitions performed. Nevertheless, despite the findings and the novel approach, the authors observed several limitations. First, only one experimental group did not allow the authors to compare the training effects with a different VL group.

Second, the prescription based on % 1RM instead of target velocities did not let the authors know whether the participants trained according to the programmed intensity in every session. Knowing the velocities associated with each relative load would enable them to adjust the external loads whenever needed and guarantee that the velocities matched the programmed ones (Rodríguez-Rosell et al., 2020). Finally, the authors did not record the velocity and power during the 1RM test, which did not allow them to analyze the load-velocity-power profile changes during and after the intervention.

Therefore, based on the abovementioned limitations, we aimed to compare the effects of 10% vs. 20% VL on older adults' strength, power, and functional capacity. We hypothesized that VL10 and VL20 would effectively improve 1RM strength and power, although VL10 would be more efficient since it would require less volume than VL20 (Marques et al., 2020, 2021). In addition, we hypothesized that both VL thresholds would improve functional capacity-related outcomes, although VL10 would be more effective in increasing walking speed performance (Marques et al., 2021).

Methods

Participants

To achieve a power of 80%, considering an alpha level of 0.05, a Cohen's f of 0.29 (based on the Hedge's g of 0.57 in the leg press reported by Marques et al. (2021a)), two groups, and three measurements (pre, mid, and post-test for the primary outcomes), we needed a total sample size of twenty-two participants (G*Power v3.1.). Therefore, we included older women or men from residential care facilities or day centers aged 60 years or over, able to walk 10-meters and stand up from a chair, and willing to participate in the study. We excluded individuals with severe cognitive impairment and musculoskeletal injuries in the previous three months and those participating in another intervention. After screening, we selected twenty-four older adults without RT experience and randomly assigned them into two groups: VL10 (n = 12) or VL20 (n = 12). We excluded four participants who dropped out for personal reasons and two who missed the post-tests. Therefore, ten participants in VL10 (5 women and 5 men; 77.9 ± 11.7 years; 64.4 ± 11.0 kg; 1.55 ± 0.1 m) and eight in VL20 (4 women and 4 men; 72.5 ± 10.4 years; 70.1 ± 11.3 kg; 1.55 ± 0.1 m) remained for the final analysis. We informed all participants regarding the procedures, and all provided written informed consent to participate. The Ethical Committee of the University of Beira Interior approved this study (CE-UBI-Pj-2019-019).

Study Design

We conducted a randomly assigned study for fourteen weeks (Figure 1). We dedicated the first two weeks to familiarizing the participants with the gym and exercises. In the third week, we assessed the medicine ball throw (MBT), 10-meters walking speed (T10), five-repetition sit-to-stand (STS), handgrip strength (HGS), and applied the leg and chest press progressive loading test. After the pre-test, the VL10 and VL20 performed a 10-week velocity monitored RT with two weekly sessions, interspersed with 48 hours of rest. They performed 18 sessions since we implemented the progressive loading tests in sessions 10 (mid-test) and 20 (post-test). In the last week, we conducted the last post-test assessments (MBT, T10, and STS). The test-retest intraclass correlation coefficients (ICC $_{(2,1)}$) and coefficients of variation (CV) for the outcome measures varied between 0.95-0.99 and 2.0-4.9%, respectively (Table A1 in Appendix II). One researcher and two coaches supervised all testing procedures and training sessions.

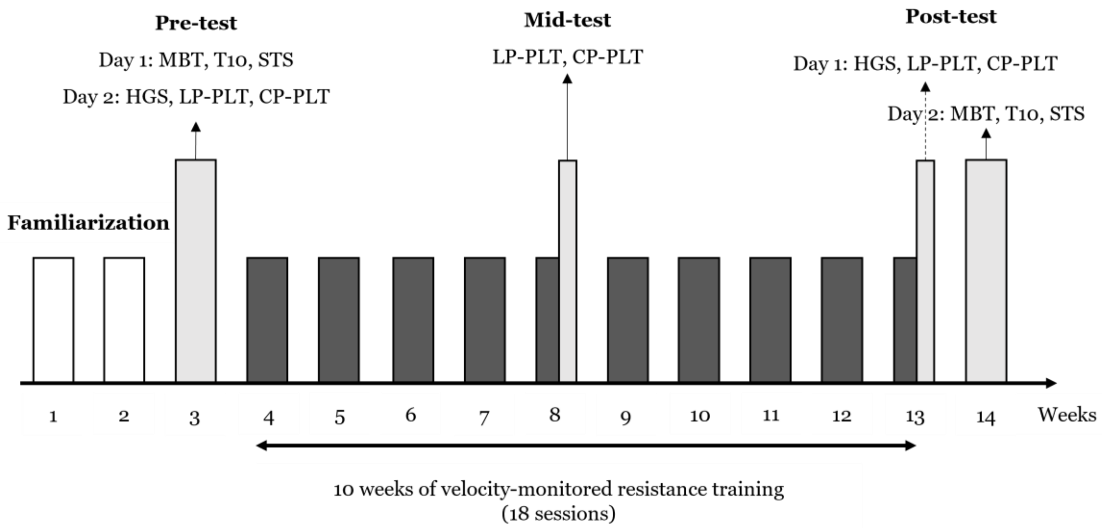

Figure 1. Study design. MBT: medicine ball throw; T10: 10-meters walking; STS: five-repetition sit-to-stand; HGS: handgrip strength; LP-PLT: leg press progressive loading test; CP-PLT: chest press progressive loading test.

Outcomes

Progressive Loading Test in the Leg and Chest Press

First, the participants performed the leg press (Leg press G3, Matrix, USA) starting in a seated position, knees flexed at 90°, and feet shoulder-width apart. Afterward, they performed the chest press (Chest press G3, Matrix, USA) starting in a seated position, handgrips at mid-chest, shoulders abducted, and elbows flexed at 90°. They performed a full knee or elbow extension at the maximal intended velocity and slowly returned (~3 s) to the initial position (Marques et al., 2021, 2022). The sessions started with a 10-minute general warm-up (walking on a treadmill or pedaling on a stationary bicycle), followed by a specific leg press warm-up (7 reps with 20.5 kg plus 5 reps with 29.5 kg). The chest press warm-up was 7 reps with 5.7 kg plus 5 reps with 10.2 kg. We set the initial load at 29.5 kg and 10.2 kg in the leg and chest press, respectively. After, we increased the load by 10 kg in the leg press until the participants attained a mean velocity of ~0.23 $m \cdot s^{-1}$ or ~0.26 $m \cdot s^{-1}$, corresponding to ~90% 1RM in older women and men, respectively (Marques et al., 2021). In the chest press, we increased the load by 5 kg until the participants attained a mean velocity of ~0.21 $m \cdot s^{-1}$ or ~0.23 $m \cdot s^{-1}$, corresponding to ~90% 1RM in older women and men, respectively (Marques et al., 2022). The participants performed three repetitions whenever possible and rested three minutes between sets. We recorded the mean velocity through a linear velocity transducer (T-Force System, Ergotech, Spain) coupled to the machines (Marques et al., 2020). To estimate the 1RM load, we used sex-specific load-velocity regression equations developed for older adults in the leg press (Marques et al., 2021) and chest press (Marques et al., 2022). Additionally, we recorded the highest mean velocity and mean power attained against each external load to model the individual load-velocity-power profiles.

Handgrip Strength

The participants squeezed a handheld dynamometer (Saehan, DHD-1, Japan) as hard as possible while seated on a chair with a 90° hip, knee, and elbow flexion (Marques et al., 2020). They performed three repetitions with both hands, interspersed with 1-minute rest. We averaged the six results to calculate the HGS (kg).

Medicine Ball Throw

After holding a 1-kg medicine ball on the chest in a seated position, the participants throw it as far as possible three times, with 1-minute rest between attempts (Marques et al., 2020). We measured the distance (m) from the chest to where the ball landed with a tape measure and analyzed the best attempt.

Ten-Meter Walking Speed

The participants walked 10-meters as fast as possible on an indoor wooden track (Marques et al., 2020). They performed three trials and rested 3 minutes between each one. We measured the time (s) using photoelectric cells (Race Time Kit 2, Microgate, Italy) and selected the best trial for analysis (T10, in $m \cdot s^{-1}$).

Five-Repetition Sit-to-Stand

The participants stood up and sat down on a chair (0.49 m) as fast as possible with their arms crossed over the chest five times (Alcazar et al., 2018). They performed two trials, separated by 2-minutes rest. We measured the time (s) using a stopwatch (Casio HS-3V-1R, Japan) and analyzed the best trial. We calculated the STS mean velocity (STS-MV, in $m \cdot s^{-1}$) and STS mean power (STS-MP, in W) using validated equations (Alcazar et al., 2018).

Resistance Training Program

The participants performed the sessions in a gym from 2:00-3:00 pm. All sessions started with the warm-up described for the testing sessions, followed by the leg press, chest press, seated medicine ball throw (1 kg), and chair squat (weight vest of 3 kg). In the latter two exercises, the participants performed the same volume (sets x reps) during the intervention (week 1: 1 x 10; weeks 2-3: 2 x 10; weeks 4-5: 3 x 10; weeks 6-9: 4 x 8; week 10: 2 x 8). In the resistance machines, the number of sets (2-3), relative loads (~40-65% 1RM), movement velocity (maximal intended concentric velocity), and inter-set rest (~3 min) were the same for both groups, except the velocity loss in each set (10% or 20%). We prescribed the relative loads through the leg and chest press load-velocity relationship in older adults (Marques et al., 2021, 2022). In the leg press, the target mean velocity to be attained in the first three repetitions of the first set was the following for women and men, respectively: ~0.47 $m \cdot s^{-1}$ and ~0.56 $m \cdot s^{-1}$ (average: ~0.52 $m \cdot s^{-1}$; ~40% 1RM); ~0.43 $m \cdot s^{-1}$ and ~0.50 $m \cdot s^{-1}$ (average: ~0.47 $m \cdot s^{-1}$; ~50% 1RM); ~0.40 $m \cdot s^{-1}$ and ~0.47 $m \cdot s^{-1}$ (average: ~0.44 $m \cdot s^{-1}$; ~55% 1RM); ~0.38 $m \cdot s^{-1}$ and ~0.44 $m \cdot s^{-1}$ (average: ~0.41 $m \cdot s^{-1}$; ~60% 1RM); ~0.35 $m \cdot s^{-1}$ and ~0.41 $m \cdot s^{-1}$ (average: ~0.38 $m \cdot s^{-1}$; ~65% 1RM). In the chest press, the target mean velocity was the following for women and men, respectively: ~0.44 $m \cdot s^{-1}$ and ~0.56 $m \cdot s^{-1}$ (average: ~0.50 $m \cdot s^{-1}$; ~40% 1RM); ~0.38 $m \cdot s^{-1}$ and ~0.49 $m \cdot s^{-1}$ (average: ~0.44 $m \cdot s^{-1}$; ~50% 1RM); ~0.36 $m \cdot s^{-1}$ and ~0.45 $m \cdot s^{-1}$ (average: ~0.41 $m \cdot s^{-1}$; ~55% 1RM); ~0.34 $m \cdot s^{-1}$ and ~0.42 $m \cdot s^{-1}$

(average: ~0.38 $m \cdot s^{-1}$; ~60% 1RM); ~0.31 $m \cdot s^{-1}$ and ~0.38 $m \cdot s^{-1}$ (average: ~0.35 $m \cdot s^{-1}$; ~65% 1RM). Before starting the main training sets, the participants performed a warm-up set of 5 repetitions at 80% of the external training load. During the first set, if the attained mean velocity in the first three repetitions did not match the programmed one (± 0.03 $m \cdot s^{-1}$), we stopped the set to adjust the load. Once adjusted, we maintained the load for all sets. We recorded each repetition's mean velocity using the T-Force System in all sessions. We also recorded the following variables: total repetitions, repetitions per set, fastest mean velocity, average mean velocity, and average velocity loss. Tables 1 and 2 present the characteristics of the leg and chest press velocity-monitored RT, respectively.

Table 1. Velocity-monitored leg press training program performed in both groups.

	Week 1		Week 2		Week 3		Week 4		Week 5	
	TS1	**TS2**	**TS3**	**TS4**	**TS5**	**TS6**	**TS7**	**TS8**	**TS9**	**TS10**
VL10 – MV (m·s⁻¹)	0.53 ± 0.07	0.54 ± 0.06	0.55 ± 0.04	0.54 ± 0.04	0.48 ± 0.04	0.48 ± 0.04	0.48 ± 0.03	0.49 ± 0.04	0.45 ± 0.02	Mid-Test
(% 1RM)	(~38%)	(~39%)	(~38%)	(~38%)	(~49%)	(~49%)	(~49%)	(~48%)	(~54%)	
VL20 – MV (m·s⁻¹)	0.52 ± 0.06	0.53 ± 0.06	0.55 ± 0.05	0.54 ± 0.03	0.50 ± 0.04	0.48 ± 0.02	0.48 ± 0.02	0.49 ± 0.02	0.45 ± 0.02	
(% 1RM)	(~43%)	(~41%)	(~38%)	(~39%)	(~45%)	(~49%)	(~50%)	(~47%)	(~54%)	
VL10 – VL (%)	13.6 ± 2.5	11.9 ± 1.4	12.3 ± 1.1	12.9 ± 2.5	12.7 ± 2.5	12.8 ± 2.0	13.2 ± 1.8	12.1 ± 1.2	12.4 ± 2.3	
VL20 – VL (%)	22.2 ± 1.4	22.7 ± 2.2	21.9 ± 1.3	23.3 ± 2.3	23.1 ± 3.3	22.5 ± 2.8	24.8 ± 1.2	21.6 ± 3.3	22.4 ± 2.6	
VL10 – Reps/Set	7.4 ± 1.4	8.0 ± 1.9	7.4 ± 2.0	7.1 ± 1.7	6.9 ± 2.2	6.4 ± 1.6	6.0 ± 1.3	6.1 ± 1.5	5.8 ± 0.9	
VL20 – Reps/Set	11.8 ± 1.9	11.6 ± 1.2	11.0 ± 1.4	11.3 ± 1.8	9.9 ± 1.4	9.6 ± 1.6	10.6 ± 1.3	10.0 ± 0.9	7.9 ± 1.2	

Table 1. Continue.

	Week 6		Week 7		Week 8		Week 9		Week 10		
	TS11	**TS12**	**TS13**	**TS14**	**TS15**	**TS16**	**TS17**	**TS18**	**TS19**	**TS20**	**Overall**
VL10 – MV ($m \cdot s^{-1}$)	0.48 ± 0.04	0.46 ± 0.04	0.43 ± 0.04	0.43 ± 0.02	0.44 ± 0.03	0.43 ± 0.03	0.40 ± 0.04	0.41 ± 0.02	0.41 ± 0.03	Post-Test	0.47 ± 0.03
(% 1RM)	(~49%)	(~51%)	(~56%)	(~57%)	(~55%)	(~57%)	(~62%)	(~62%)	(~61%)		(~50% 1RM)
VL20 – MV ($m \cdot s^{-1}$)	0.46 ± 0.01	0.46 ± 0.04	0.42 ± 0.03	0.43 ± 0.04	0.44 ± 0.05	0.43 ± 0.03	0.40 ± 0.03	0.39 ± 0.03	0.41 ± 0.03		0.47 ± 0.02
(% 1RM)	(~52%)	(~53%)	(~59%)	(~58%)	(~57%)	(~58%)	(~62%)	(~64%)	(~63%)		(~52% 1RM)
VL10 – VL (%)	12.7 ± 2.0	13.3 ± 2.1	12.6 ± 2.4	13.5 ± 1.7	13.5 ± 1.3	13.2 ± 1.5	13.2 ± 1.9	12.7 ± 1.8	12.7 ± 1.3		12.8 ± 0.6
VL20 – VL (%)	23.6 ± 1.7	23.2 ± 1.9	24.0 ± 3.1	21.9 ± 2.4	23.7 ± 1.8	23.0 ± 1.4	22.9 ± 2.2	21.8 ± 2.7	21.5 ± 2.8		22.7 ± 0.7***
VL10 – Reps/Set	5.4 ± 1.3	5.9 ± 0.9	5.1 ± 1.0	5.1 ± 0.7	5.1 ± 0.6	5.5 ± 0.9	5.3 ± 0.8	5.3 ± 0.8	4.6 ± 0.6		6.0 ± 0.8
VL20 – Reps/Set	9.2 ± 1.9	7.8 ± 1.6	7.3 ± 2.1	7.6 ± 1.2	7.6 ± 1.6	7.9 ± 1.2	6.8 ± 2.1	6.9 ± 1.7	6.7 ± 0.4		9.0 ± 0.8***

Data are mean ± SD; MV: fastest mean velocity attained in the session; RM: repetition maximum; TS: training session; VL: velocity loss; *** $p < 0.001$, significant differences between VL10 and VL20 in velocity loss and repetitions per set.

Table 2. Velocity-monitored chest press training program performed in both groups.

	Week 1		Week 2		Week 3		Week 4		Week 5	
	TS1	**TS2**	**TS3**	**TS4**	**TS5**	**TS6**	**TS7**	**TS8**	**TS9**	**TS10**
VL10 – MV ($m \cdot s^{-1}$)	0.50 ± 0.06	0.50 ± 0.07	0.49 ± 0.06	0.50 ± 0.06	0.42 ± 0.04	0.43 ± 0.04	0.44 ± 0.04	0.44 ± 0.04	0.39 ± 0.05	Mid-Test
(% 1RM)	(~38%)	(~40%)	(~40%)	(~39%)	(~51%)	(~50%)	(~48%)	(~49%)	(~56%)	
VL20 – MV ($m \cdot s^{-1}$)	0.50 ± 0.05	0.49 ± 0.06	0.52 ± 0.05	0.51 ± 0.05	0.43 ± 0.06	0.44 ± 0.05	0.45 ± 0.04	0.44 ± 0.06	0.41 ± 0.04	
(% 1RM)	(~41%)	(~42%)	(~37%)	(~39%)	(~52%)	(~50%)	(~48%)	(~50%)	(~54%)	
VL10 – VL (%)	13.2 ± 1.6	12.7 ± 1.6	12.4 ± 1.8	12.8 ± 2.3	12.7 ± 1.4	13.0 ± 1.0	12.9 ± 1.1	13.1 ± 1.9	12.9 ± 1.6	
VL20 – VL (%)	22.5 ± 1.0	23.5 ± 0.9	23.6 ± 1.7	23.0 ± 1.0	22.7 ± 0.9	21.3 ± 5.6	23.0 ± 2.2	24.0 ± 1.9	23.3 ± 2.6	
VL10 – Reps/Set	5.4 ± 1.3	4.7 ± 0.7	5.3 ± 0.8	5.2 ± 0.7	5.0 ± 1.2	5.0 ± 0.9	4.5 ± 0.7	4.4 ± 0.6	4.3 ± 0.9	
VL20 – Reps/Set	9.7 ± 0.7	9.2 ± 1.1	9.4 ± 0.8	9.5 ± 0.5	8.2 ± 0.4	8.1 ± 0.9	8.3 ± 0.6	7.8 ± 0.6	7.1 ± 1.2	

Table 2. Continue.

	Week 6		Week 7		Week 8		Week 9		Week 10		
	TS11	**TS12**	**TS13**	**TS14**	**TS15**	**TS16**	**TS17**	**TS18**	**TS19**	**TS20**	**Overall**
VL10 – MV ($m \cdot s^{-1}$)	0.40 ± 0.05	0.39 ± 0.04	0.38 ± 0.03	0.37 ± 0.05	0.38 ± 0.04	0.38 ± 0.03	0.35 ± 0.06	0.35 ± 0.04	0.36 ± 0.04	Post-Test	0.42 ± 0.04
(% 1RM)	(~54%)	(~56%)	(~59%)	(~59%)	(~58%)	(~59%)	(~66%)	(~65%)	(~64%)		(~52% 1RM)
VL20 – MV ($m \cdot s^{-1}$)	0.40 ± 0.05	0.41 ± 0.04	0.39 ± 0.04	0.39 ± 0.05	0.38 ± 0.04	0.39 ± 0.04	0.34 ± 0.06	0.33 ± 0.05	0.35 ± 0.04		0.42 ± 0.04
(% 1RM)	(~56%)	(~54%)	(~58%)	(~59%)	(~60%)	(~58%)	(~68%)	(~70%)	(~68%)		(~53% 1RM)
VL10 – VL (%)	12.4 ± 1.3	12.9 ± 1.6	13.2 ± 1.8	12.1 ± 1.0	12.8 ± 1.2	11.8 ± 1.2	12.5 ± 1.7	12.3 ± 1.9	12.2 ± 1.2		12.7 ± 0.3
VL20 – VL (%)	23.8 ± 2.2	23.9 ± 1.3	23.3 ± 1.4	22.4 ± 4.4	24.7 ± 1.7	23.3 ± 3.4	22.4 ± 2.2	22.4 ± 2.6	22.3 ± 2.9		23.1 ± 1.1***
VL10 – Reps/Set	4.4 ± 0.3	4.6 ± 0.6	4.9 ± 1.0	4.7 ± 0.8	4.2 ± 0.4	4.3 ± 0.5	4.3 ± 0.3	4.1 ± 0.6	4.0 ± 0.6		4.6 ± 0.4
VL20 – Reps/Set	7.9 ± 1.5	8.0 ± 1.4	6.8 ± 0.6	6.3 ± 0.9	7.0 ± 1.5	6.9 ± 1.2	6.6 ± 1.1	5.9 ± 1.0	6.1 ± 1.6		7.7 ± 0.5***

Data are mean ± SD; MV: fastest mean velocity attained in the session; RM: repetition maximum; TS: training session; VL: velocity loss; *** $p < 0.001$, significant differences between VL10 and VL20 in velocity loss and repetitions per set.

Statistical Analysis

The Shapiro-Wilk and Levene's test confirmed the normality and homogeneity of the data, respectively. The ICC $_{(2,1)}$, standard error of measurement (SEM = $SD_{pre\text{-}test}$ x $\sqrt{1}$ - ICC $_{(2,1)}$), and CV ((SEM / $Mean_{pre\text{-}test}$) x 100) analyzed the test-retest reliability. We calculated the percentage change with 90% CIs in all outcomes. Independent samples *t*-test analyzed the differences between groups at baseline and in the percentage change of outcomes. A repeated-measures ANOVA 3x2 (pre, mid, and post-test; VL10 and VL20) with post-hoc Bonferroni tests analyzed the differences between and within groups in the primary outcomes. Linear regressions modeled the load-velocity profiles, and quadratic regressions the load-power profiles. A repeated-measures ANOVA 2x2 (pre and post-test; VL10 and VL20) with post-hoc Bonferroni tests analyzed the differences between and within groups in the secondary outcomes. We calculated the Hedge's *g* effect size and interpreted it as small (0.20–0.49), moderate (0.50–0.79), or large (0.80) (Cohen, 1988). In addition, we calculated the minimal detectable change (MDC = $\sqrt{2}$ x SEM x 1.96) and MDC% ((MDC / $Mean_{pre\text{-}test}$) x 100) to estimate the sensitivity to change in the secondary outcomes. We set the significance level at $p < 0.05$ and used Microsoft Excel (Microsoft Inc., USA) and SPSS v28 (SPSS Inc., USA) to run the analysis and GraphPad Prism v9 (GraphPad Inc., USA) to plot the figures.

Results

There were no differences ($p > 0.05$) between groups at baseline and in the percentage change in any outcomes. The attendance rate was 91% in VL10 and 94% in VL20 ($p > 0.05$). There were no adverse events or injuries reported during the study.

Velocity-Monitored Resistance Training Program

Tables 1 and 2 show the overall training results in the leg and chest press, respectively. There were no differences ($p > 0.05$) between groups in the leg press fastest and average mean velocity (0.43 ± 0.02 $m{\cdot}s^{-1}$ vs. 0.40 ± 0.02 $m{\cdot}s^{-1}$ for VL10 and VL20, respectively), yet there were differences ($p < 0.001$) in the average VL, repetitions per set, and total repetitions (246.6 ± 40.7 vs. 378.5 ± 43.7 for VL10 and VL20, respectively). Likewise, there were no differences ($p > 0.05$) between groups in the chest press fastest and average mean velocity (0.38 ± 0.03 $m{\cdot}s^{-1}$ vs. 0.36 ± 0.04 $m{\cdot}s^{-1}$ for VL10 and VL20, respectively), yet there were differences ($p < 0.001$) in the average

VL, repetitions per set, and total repetitions (192.6 ± 20.7 vs. 326.0 ± 36.5 for VL10 and VL20, respectively).

Changes in Primary Outcomes

Table 3 shows the 1RM strength changes in both groups. There were 1RM leg press increases from pre to mid and post-test in VL10 and VL20, without differences (p > 0.05) between groups. In addition, there were no 1RM chest press increases (p > 0.05) at any time in both groups.

Table 3. Changes in 1RM strength in both groups.

Outcome	**Pre-test**	**Mid-test**	**Post-test**	**%Δ pre-mid**	**%Δ pre-post**	**%Δ mid-post**	***g***	***g***	***g***
	(mean ± SD)	(mean ± SD)	(mean ± SD)	(90% CI)	(90% CI)	(90% CI)	pre-mid	pre-post	mid-post
1RM-LP VL10 (kg)	74.5 ± 19.2	85.5 ± 17.8***	83.9 ± 18.9**	17.0 (9.9 to 24.1)	14.6 (6.3 to 22.9)	-1.9 (-6.4 to 2.5)	0.57	0.47	-0.09
1RM-LP-VL20 (kg)	80.2 ± 19.0	89.1 ± 18.5† † †	87.9 ± 19.4†	12.0 (8.2 to 15.8)	10.5 (3.0 to 18.1)	-1.4 (-6.1 to 3.2)	0.45	0.40	-0.06
1RM-CP-VL10 (kg)	32.1 ± 10.0	34.1 ± 11.4	33.4 ± 13.5	7.3 (-3.5 to 18.1)	3.0 (-7.3 to 13.2)	-3.8 (-8.7 to 1.1)	0.18	0.10	-0.05
1RM-CP-VL20 (kg)	33.3 ± 13.5	37.7 ± 11.3	33.9 ± 11.6	22.5 (1.7 to 43.4)	7.3 (-7.8 to 22.4)	-10.4 (-20.3 to -0.6)	0.34	0.05	-0.32

%Δ: percent change; CI: confidence interval; CP: chest press; LP: leg press; RM: repetition maximum; VL: velocity loss; ** $p < 0.01$, significant differences from pre- to post-test in VL10; *** $p < 0.001$, significant differences from pre- to mid-test in VL10; † $p < 0.05$, significant differences from pre- to post-test in VL20; † † † $p < 0.001$, significant differences from pre- to mid-test in VL20.

Figure 2 shows the resistance exercises load-velocity-power profile changes in both groups. There were no differences ($p > 0.05$) between groups in the leg and chest press mean velocity and power at any time. The VL10 increased leg press mean power at 25-90% 1RM from pre- to mid-test and at 35-65% 1RM from pre- to post-test ($p < 0.05$) (Figure 2A), while VL20 increased leg press mean power at 25-75% 1RM from pre- to mid-test ($p < 0.05$), and at 40-50% from pre- to post-test ($p < 0.05$) (Figure 2B). The VL10 increased chest press mean velocity at 20-70% 1RM from pre- to mid-test ($p < 0.05$) (Figure 2C), while VL20 increased chest press mean velocity at 20-45% 1RM from pre- to mid and post-test ($p < 0.05$) (Figure 2D). In addition, VL20 increased chest press mean power at 20-50% 1RM from pre- to mid-test ($p < 0.05$) (Figure 2B).

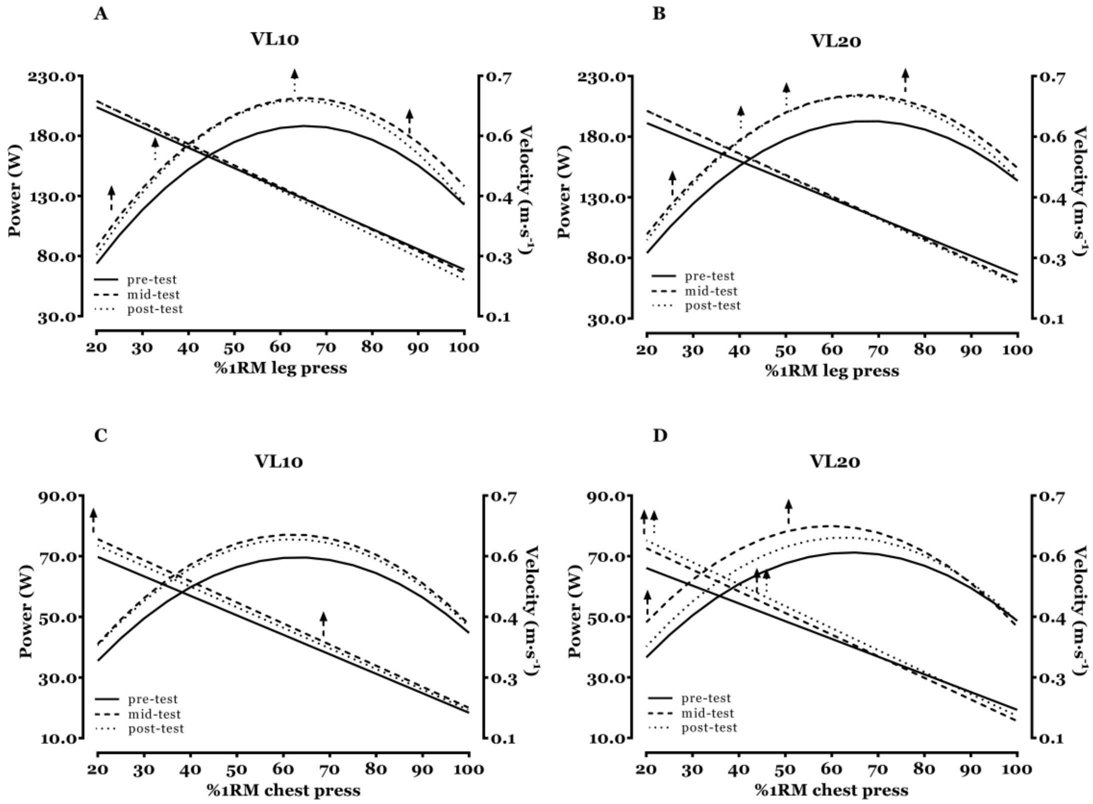

Figure 2. Load-velocity-power profile changes in the leg and chest press in both groups (A. leg press VL10; B. leg press VL20; C. chest press VL10; D. chest press VL20). Dashed arrows indicate the range of improvements in mean velocity or power against the relative loads from pre- to mid-test, while dotted arrows indicate the range of improvements from pre- to post-test. VL: velocity loss.

Changes in Secondary Outcomes

Table 4 presents the secondary outcome changes. There were no differences (p > 0.05) between groups on any measure at post-test. The VL20 improved the HGS, and the percent change was above the MDC. In addition, VL20 improved the T10, yet the percent change was below the MDC. Finally, VL10 and VL20 improved the STS-MV and STS-MP, and the percent change was above the MDC.

Table 4. Changes from pre to post-test in secondary outcome measures in both groups.

Outcomes	MDC	Pre-test (mean ± SD)	Post-test (mean ± SD)	Mean Diff (90% CI)	%Δ (90% CI)	*g* (interpretation)
HGS-VL10 (kg)	3.2 (13.6%)	23.2 ± 8.1	24.2 ± 8.0	0.9 (0.0 to 1.9)	4.8 (0.5 to 9.1)	0.11 (trivial)
HGS-VL20 (kg)	3.0 (12.8%)	23.1 ± 9.0	25.4 ± 8.8***	2.3 (1.7 to 2.9)	13.1 (6.8 to 19.3)	0.26 (small)
T10-VL10 ($m \cdot s^{-1}$)	0.1 (7.1%)	1.7 ± 0.2	1.7 ± 0.2	0.1 (0.0 to 0.1)	3.6 (0.3 to 6.9)	0.25 (small)
T10-VL20 ($m \cdot s^{-1}$)	0.1 (8.9%)	1.7 ± 0.3	1.8 ± 0.3*	0.1 (0.0 to 0.2)	5.8 (2.5 to 9.1)	0.29 (small)
STS MV-VL10 ($m \cdot s^{-1}$)	0.05 (12.3%)	0.4 ± 0.1	0.4 ± 0.1***	0.1 (0.0 to 0.1)	19.4 (11.8 to 27.1)	0.57 (moderate)
STS MV-VL20 ($m \cdot s^{-1}$)	0.03 (9.9%)	0.3 ± 0.1	0.4 ± 0.1***	0.1 (0.1 to 0.1)	26.2 (17.8 to 34.7)	1.09 (large)
STS MP-VL10 (W)	25.0 (11.8%)	211.6 ± 90.0	246.4 ± 84.7***	34.8 (24.2 to 45.4)	19.4 (11.8 to 27.1)	0.38 (small)
STS MP-VL20 (W)	19.9 (9.7%)	204.8 ± 29.5	258.4 ± 48.4***	53.6 (34.0 to 73.2)	26.2 (17.8 to 34.7)	1.26 (large)
MBT-VL10 (m)	0.2 (6.7%)	3.2 ± 0.5	3.3 ± 0.6	0.1 (0.0 to 0.3)	3.9 (-0.1 to 7.9)	0.25 (small)
MBT-VL20 (m)	0.2 (5.5%)	3.1 ± 0.6	3.1 ± 0.6	0.1 (-0.2 to 0.3)	2.2 (-5.9 to 10.4)	0.08 (trivial)

%Δ: percent change; CI: confidence interval; *g*: effect size; HGS: handgrip strength; MBT: medicine ball throw; MDC: minimal detectable change; STS: five-repetition sit-to-stand; T10: 10-meters walking speed; * $p < 0.05$, significant differences within group from pre- to post-test; *** $p < 0.001$, significant differences within group from pre- to post-test.

Discussion

Main Findings

The main findings of this study were: i) VL10 and VL20 increased leg press strength and power; ii) neither VL10 nor VL20 increased chest press strength, yet both improved chest press velocity, while only VL20 improved chest press power; iii) VL10 and VL20 improved STS, while only VL20 increased HGS and T10. Therefore, these results suggest that VL10 and VL20 were equally effective in improving leg press strength and power, chest press velocity, and STS performance in older adults. Nevertheless, VL10 was more efficient than VL20 since it required fewer repetitions per set. On the other hand, VL20 was more effective than VL10 in improving chest press power, HGS, and T10 in older adults.

Changes in Primary Outcomes

Although both groups improved 1RM leg press, VL10 only performed ~65% of the total repetitions completed by VL20, thus meaning a higher training efficiency. These results agree with studies showing 1RM leg press gains of ~14-15% following 10% and 20% VL in older adults (Marques et al., 2020, 2021). In addition, these studies reported an overall fastest mean velocity of ~0.44 $m \cdot s^{-1}$ (~55% 1RM), which is in line with our study, indicating that the participants trained at the programmed velocity. Furthermore, our study showed that both groups increased leg press power associated with a wide range of relative loads, reinforcing the importance of performing repetitions at maximal intended velocity (Balachandran et al., 2022; Marques et al., 2013; Rodriguez-Lopez et al., 2022). Indeed, the steeper load-velocity curves at weeks 5 and 10 suggest an improved capacity to displace light loads at higher velocities, despite the non-significant leg press velocity changes across the full spectrum of relative loads. Given these results, future studies should analyze whether RT durations longer than ten weeks can significantly increase the velocities associated with light loads in older adults.

Contrary to our hypothesis, both groups had no 1RM chest press increases. Previous findings showed 1RM chest press gains of ~28-30% following 10% and 20% VL in older adults (Marques et al., 2020, 2021). Nevertheless, the reported overall fastest mean velocity in these studies was lower than in our study (~0.38 $m \cdot s^{-1}$), indicating that these participants trained at higher relative loads (~60% 1RM). Therefore, the higher loading magnitude during the intervention might have triggered greater 1RM chest press gains, although this observation still needs to be examined in future research. Nevertheless, despite the non-significant chest press strength gains, both groups steeped the load-velocity curve, indicating a greater capacity to displace light loads at higher velocities. In addition, both groups showed chest press power improvements, although these were only significant for the VL20 against light loads. Therefore, performing 6-10 repetitions per set at relative loads that maximize chest press power (i.e., 40-60% 1RM) (Potiaumpai et al., 2016; Strand et al., 2019) might be more stimulating for upper-limb power development than 4-5 repetitions in older adults.

Changes in Secondary Outcomes

The results showed that VL20 produced small but meaningful HGS changes, which agrees with a meta-analysis showing that physical exercise produces small but meaningful HGS increases in older adults of similar ages as the VL20 group (~73 years) (Labott et al., 2019). On the other hand, a study that applied 20% VL did not observe HGS increases in older adults aged ~79 years (Marques et al., 2020). Although the age difference seems minor, this factor might have influenced the HGS gains. In fact, a meta-analysis including older adults aged 75 years or over did not observe significant differences between RT and control groups on HGS improvements (Grgic et al., 2020), suggesting attenuated HGS gains in advanced ages. Nevertheless, more studies are warranted to corroborate or refute these observations.

At post-test, VL20 significantly increased T10. Although the gains were not clinically meaningful, they indicate that more volume might be required to induce T10 gains in older adults, which contradict a study suggesting that 10% VL could be more efficient than 20% in improving T10 (Marques, 2021). Although the literature is scarce on this topic, a study observed higher fast walking speed gains following RT of six sets compared to three sets in older women (Nunes et al., 2017). Nevertheless, the differences in the test used (one-mile walk), RT duration (16 weeks), total volume (~1440-2880 repetitions), relative loads (70% 1RM), and participants' age (50-79 years) make comparisons with our results unfeasible. Therefore, more research is needed to compare the effects of different volumes on T10 in older adults.

Our findings showed STS gains in both groups higher than those observed in studies that applied 10% (14-17%) and 20% VL (14-15%) in older adults (Marques et al., 2020, 2021). Nevertheless, VL20 showed higher gains than VL10, indicating that more volume might be required to optimize lower-limb muscle power in older adults. On the other hand, neither VL10 nor VL20 significantly improved MBT. These results were unexpected since previous studies observed significant MBT-1kg gains of ~4% and 8% following 10% and 20% VL in older adults, respectively (Marques et al., 2020, 2021). Interestingly, although the gains in VL10 did not reach statistical significance, they were similar to the VL10 study (Marques, 2021). A plausible reason for this difference might be associated with the small sample size in the VL10 group, possibly increasing the chance of a type 2 error. Therefore, future studies should recruit large sample sizes to obtain more precise conclusions regarding the effects of VL10 and VL20 on MBT performance in older adults.

Limitations

This study presents limitations that we need to address. First, a larger sample size would allow us to get more accurate results, reduce the probability of a type II error, and increase the result's generalizability. Moreover, including a control group could give insights into whether the RT programs truly affected the participants in VL10 and VL20. Finally, increasing the RT duration would be beneficial to examine what VL threshold is more effective and efficient in the long term to improve strength, power, and functional performance in older adults. Therefore, future randomized controlled trials should include larger sample sizes and increase the RT duration to draw clear conclusions about the effects of 10% and 20% VL on older adults' strength, power, and functional capacity.

Conclusions

This study showed that VL10 and VL20 improved leg press strength and power, chest press velocity, and STS performance in older adults, although VL10 was more efficient since it required less volume than VL20. On the other hand, only VL20 produced improvements in chest press power, HGS, and T10. Therefore, 2-3 sets of 4-7 repetitions at 40-65% 1RM seem enough to increase lower-limb strength and power and upper-limb velocity in older adults. Nevertheless, 2-3 sets of 6-12 repetitions at 40-65% 1RM seem required to optimize lower-limb muscle power and upper-limb strength and power in older adults.

Chapter 4. General Discussion

The general purpose of the Ph.D. thesis was to analyze the effects of manipulating the volume of resistance training (RT) through monitoring the intra-set velocity loss on muscle strength, power, and functional capacity in older adults. In order to achieve that purpose, a sequence of studies was developed with the following specific aims:

i. Study 1 meta-analyzed the effects of single vs. multiple sets performed per exercise on muscle strength and size, muscle quality, and functional capacity in individuals aged 50 years and over;
ii. Study 2 compared the acute effects of three sets with a different number of repetitions per set (8 vs. 15) at 65% of one-repetition maximum (1RM) on hemodynamic, metabolic, and neuromuscular parameters in older adults;
iii. Study 3 analyzed the effects of a 10-week velocity-monitored RT program with 2-3 sets with 20% velocity loss at 40-65% 1RM on muscle strength, power, and functional capacity in older adults;
iv. Study 4 analyzed the effects of a 10-week velocity-monitored RT program with 2-3 sets with 10% velocity loss at 40-65% 1RM on muscle strength, power, and functional capacity in older adults;
v. Study 5 modeled the load-velocity relationship in the horizontal leg press exercise in older women and men;
vi. Study 6 modeled the load-velocity relationship in the seated chest press exercise in older women and men;
vii. Study 7 modeled the load-power relationship in the horizontal leg press and seated chest press exercises in older women and men;
viii. Study 8 compared the effects of 10% vs. 20% intra-set velocity loss thresholds on muscle strength, power, and functional capacity in older adults.

The first study showed that multiple sets (i.e., three sets) per exercise seem to optimize increases in lower-limb muscle strength and muscle quality, while single sets seem sufficient to increase upper-limb muscle strength, muscle size, and functional capacity in middle-aged and older adults. Moreover, both single and multiple sets similarly increase muscle strength and size for RT durations between 13-20 weeks in middle-aged and older adults. Despite these results, a critical finding that should be mentioned was that multiple sets consistently produced higher gains and effect sizes than single sets in all outcome measures. Therefore, based on this information, it was possible to understand that the prescription of three sets per exercise (eventually alternated with two sets) could be the ideal approach to be used in subsequent experimental studies to favor muscular and functional adaptations in older adults.

Importantly, considering that the volume of RT can also be defined as the product of sets and repetitions (Kraemer & Ratamess, 2004; Marston et al., 2017; Nunes et al., 2021; Straight et al., 2016), the identification of the required number of repetitions to optimize muscular and functional gains in older adults also seemed a relevant subject. However, the high heterogeneity in the included studies in the meta-analysis regarding the range of repetitions and methods prescribed (range: 6-20 repetitions; 80% of studies prescribed maximal repetitions) did not allow for drawing solid conclusions about this topic. Nevertheless, several key points were derived through a critical analysis of the literature on the use of maximal repetitions in older adults, which can be enumerated as follows: i) maximal repetitions do not produce significantly higher muscle strength, power, and functional gains than submaximal repetitions in older adults (Cadore et al., 2018; Silva et al., 2018; Teodoro et al., 2019); ii) maximal repetitions produce greater acute cardiovascular stress than lower RT volumes in older adults (Tajra et al., 2015; Vale et al., 2018); iii) maximal repetitions increase the interindividual variability in the number of repetitions performed in older adults (Farinatti et al., 2013; Grosicki et al., 2014; Jesus et al., 2018; Silva et al., 2009); iv) performing maximal repetitions in the first set decrease the number of repetitions completed in the following sets (Farinatti et al., 2013; Jambassi-Filho et al., 2019; Jesus et al., 2018; Silva et al., 2009). Therefore, taking into account these four premises, the focus of the subsequent experimental studies was: i) to compare the acute effects of low (3 sets of 8 repetitions at 65% 1RM) vs. high volume (3 sets of 15 repetitions at 65% 1RM) on hemodynamic, metabolic, and neuromuscular parameters in older adults, and ii) to analyze the effects of 10 weeks of prescribing and monitoring the number of repetitions using intra-set velocity loss thresholds on muscle strength, power, and functional capacity in older adults.

The results of the second study showed that the high-volume protocol (i.e., repetitions performed to (or close to) failure) elicited higher cardiovascular and metabolic stress and greater losses in neuromuscular function than the low-volume protocol in older adults. Moreover, the low-volume protocol acutely improved general strength (assessed using the handgrip strength test). Therefore, these findings revealed that prescribing 2–3 sets of 5–8 repetitions at 65% 1RM using a combination of resistance machines and free-weights seemed to be a sufficient stimulus to acutely enhance general strength without achieving high hemodynamic, metabolic, and neuromuscular stress in older people. Following these results and considering that repetitions to (or close to) failure increase the interindividual variability in the number of repetitions performed in older adults (Farinatti et al., 2013; Grosicki et al., 2014; Jesus et al., 2018; Silva et al., 2009), a novel approach for prescribing and monitoring the volume of RT was implemented during the following 10-week RT interventions.

The results of the first 10-week RT program (Study 3) found that an intra-set velocity loss of 20%, which resulted in a range of 8-11 repetitions in the leg press and 5-8 repetitions in the chest press, was effective in increasing dynamic strength, power, and functional capacity. Notably, it was observed that the total number of repetitions performed during the intervention (~438 in the leg press and ~296 in the chest press) was ~50% inferior to previous high-velocity RT interventions that used the chest press and leg press exercises (~600-1056 repetitions) with untrained older adults (Balachandran et al., 2014; Bottaro et al., 2007; Henwood & Taaffe, 2006; Marsh et al., 2009; Miszko et al., 2003; Nogueira et al., 2009; Ramírez-Campillo et al., 2014, 2017, 2018; Richardson et al., 2019a, 2019b). Therefore, these results agree with previous evidence indicating that a minimal dose of RT volume might be enough to increase muscle strength, power, and functional capacity in untrained older adults (Fragala et al., 2019; Fyfe et al., 2022; Radaelli et al., 2014). However, after this study, the following question was made: Can muscle strength, power, and functional capacity gains be induced in untrained older adults with a lower volume dose than that observed in the previous study? In this sense, a similar experimental intervention (Study 4) was conducted to answer that question. In general, the results from the fourth study demonstrated that an intra-set velocity loss of 10%, which resulted in few repetitions per set (5-6 in the leg press and 3-4 in the chest press), was sufficient to increase dynamic strength, power, and functional capacity in untrained older adults. Therefore, these results suggest that a low-velocity loss (10%), which eventually will cause lower mechanical and metabolic fatigue than a higher velocity loss, seems determinant to improving dynamic muscle strength, power, and functional capacity in older people.

Despite the novel approach used for prescribing and monitoring the RT volume and the findings indicating muscular and functional gains with a minimal dose of RT, several limitations were identified in both interventions. Firstly, the traditional prescription of relative loads based on percentages of 1RM instead of specific velocity values did not allow an understanding of whether the participants were training according to the prescribed relative loads in each session. Knowing the velocities associated with each relative load would enable adjusting the external loads whenever needed and guarantee that the velocities matched the programmed ones (González-Badillo & Sánchez-Medina, 2010; Rodríguez-Rosell et al., 2020; Sánchez-Medina et al., 2017). Therefore, identifying these relationships through the analysis of the load-velocity profiles in the leg press and chest press became needed after both experimental interventions. A second limitation was that the velocity and power-output values attained against each absolute load in the 1RM leg press and chest press tests were not recorded, which did not allow for analyzing the changes in the load-velocity-power curves after the RT programs. This analysis would help to examine if the training programs produced changes in the orientation of the slopes (e.g., if the x-axis represents the load and the y-axis the velocity, then a steeper slope means more efficiency in displacing light-to-moderate loads at greater velocities) (Giroux et al., 2016; Marques et al., 2010; Morin & Samozino, 2016). Finally, including only one experimental group in Studies 3 and 4 did not allow for comparing the effects with a different relative velocity loss group. Conducting this analysis would determine whether a velocity loss of 10% is more effective and efficient than 20% in inducing muscular and functional adaptations in older people. Therefore, four experimental studies were conducted to overcome the abovementioned limitations in the current paragraph.

In the following two studies, the modulation of the load-velocity relationship enabled the identification of the velocity values associated with each relative in the horizontal leg press (Study 5) and seated chest press (Study 6) in older women and men. These analyses opened up a possibility to prescribe the relative loads based on specific velocities and monitor them in real-time in future velocity-monitored RT programs with older adults. Moreover, sex-specific regression equations in the leg press (linear models) and chest press (quadratic models) were also proposed in both studies, thus enabling clinicians and researchers to estimate the 1RM from movement velocity using submaximal loads and monitor the 1RM changes over the intervention. Interestingly, a common point in both cross-sectional studies was that older men presented higher velocity values than older women for almost all relative loads, except for those near the maximum and maximal loads (i.e., ~90-100% 1RM). Indeed, similar findings were observed with strength-trained young adults in the full squat (Pareja-Blanco et al., 2020) and bench press exercises (García-Ramos et al., 2019; Pareja-Blanco et al., 2020; Torrejón et al., 2019), suggesting that the higher the relative loads, the lower the differences in velocity values between sexes and vice-versa. Possible explanations for these occurrences might be linked with an eventual higher strength deficit in women than men, which does not enable the former to express all their strength potential in a given motor task (Pareja-Blanco et al., 2020; Siff, 2000). In addition, the stronger muscle fibers and larger whole muscle cross-sectional area of the quadriceps observed in older men than women (Barnouin et al., 2017; Frontera et al., 2000) might also contribute to these differences, although these observations still need to be evidenced for the triceps brachii or pectoralis major. Therefore, these data reinforce the relevance of modeling sex-specific load-velocity regression equations in the leg press and chest press in older adults for more accurate results.

After conducting the previous two studies, the analysis of the load-power relationship in the leg press and chest press in older adults was the next topic of study (Study 7). Firstly, the results showed that the relative loads that maximize power output ($P_{max\text{-}load}$) in the leg press and chest press are similar between older women and men, either using mean ($MP_{max\text{-}load}$) or peak power values ($PP_{max\text{-}load}$). These data align with previous research showing that the $P_{max\text{-}load}$ in several resistance machines did not differ between older women and men aged ~69 years (Strand et al., 2019). It is speculated that the faster age-related losses of muscle power in men than in women during aging might contribute to these results (Edwén et al., 2014; Strand et al., 2019). A second finding of the seventh study was that the $MP_{max\text{-}load}$ and $PP_{max\text{-}load}$ differ between resistance exercises, meaning that they are exercise-specific, corroborating previous results with older people (Strand et al., 2019). In addition, the third finding indicated that the $P_{max\text{-}load}$ varies within the same resistance exercise depending on the mechanical power variable measured, which is in line with previous research conducted with strength-trained young adults (Martínez-Cava et al., 2019; Pallarés et al., 2014; Sánchez-Medina et al., 2014; Soriano et al., 2015, 2017). From a practical perspective, the second and third findings suggest that it is essential to define beforehand what mechanical power variable will be measured and monitored during the intervention to avoid erroneous decisions regarding RT prescription.

Finally, the seventh study also showed several associations between absolute maximal mean power (MP_{max}) and peak power (PP_{max}) (Watts, W) with markers of functional capacity in older people. First, it was observed that the MP_{max} and PP_{max} in the chest press similarly explained the performance variability in the medicine ball throw. Therefore, these results reinforced the influence of the MBT as a functional field test to evaluate upper-limb muscle power in older adults. Second, it was found that the MP_{max} and PP_{max} in the leg press could similarly explain the variance in the five-repetition sit-to-stand power test. However, neither MP_{max} nor PP_{max} in the leg press could explain the performance variability in walking velocity. A possible reason for the latter results might be related to mobility status, as most research that found associations between leg press power and walking performance conducted experiments with mobility-limited older adults (Bean et al., 2002; Puthoff & Nielsen, 2007), as opposed to the seventh study. In addition, previous research conducted with older adults with similar maximal walking velocity values as the participants of the seventh study found that hip and ankle strength were also significant predictors of maximal walking velocity (Muehlbauer et al., 2018; Uematsu et al., 2014). Therefore, besides leg power, these results suggest that hip and ankle strength should also be considered to explain the variance in walking performance in older adults without mobility impairments (Muehlbauer et al., 2018). However, given the paucity of research, future large-scale studies should determine the influence of leg, hip, and ankle power and strength on maximal walking performance in older adults with different mobility statuses to strengthen the scientific knowledge on this topic.

The final experimental research (Study 8) of the thesis incorporated the findings of the previous studies to compare the effects of 10% vs. 20% velocity loss thresholds with relative loads prescribed using target velocities on muscle strength, power, and functional capacity in older adults. It is essential to highlight that the mean velocity of each repetition performed in the leg press and chest press was recorded in every RT session, following the procedures described in Studies 3 and 4. However, the main difference between the current and previous studies was that the relative loads were prescribed based on the specific velocities identified in the leg press (Study 5) and chest press (Study 6) for older women and men. Therefore, if the attained mean velocity in the first three repetitions of the first set did not match the programmed one, the set was stopped, and the load (kg) was adjusted. Once adjusted, the load was maintained in all sets. In general, the results did not show differences between groups in the overall leg press fastest mean velocity (10% velocity loss: 0.47 ± 0.03 $m \cdot s^{-1}$; 20% velocity loss: 0.47 ± 0.02 $m \cdot s^{-1}$) and chest press mean velocity (10% velocity loss: 0.42 ± 0.04 $m \cdot s^{-1}$; 20% velocity loss: 0.42 ± 0.04 $m \cdot s^{-1}$). Consequently, these results indicated that both groups trained at the same average relative load (~50% 1RM in both exercises) during the 10-week RT program. However, the total repetitions performed over the intervention were different between groups. On average, the 10% velocity loss group completed ~65% of the total repetitions performed by the 20% velocity loss group in the leg press and ~59% in the chest press.

Regarding the changes in the outcome measures, the results showed that 10% and 20% velocity loss thresholds equally improved leg press strength (1RM) and power, chest press velocity, and sit-to-stand performance in older adults, although a velocity loss of 10% revealed more efficiency since it required less volume than a velocity loss of 20%. On the other hand, only a velocity loss of 20% produced increases in chest press power, handgrip strength, and walking velocity. Therefore, from a practical standpoint, the results of this study suggest that 2-3 sets with 10% velocity loss (i.e., 4-7 repetitions) at 40-65% 1RM seem a sufficient stimulus to increase lower-limb strength and power and upper-limb velocity in older adults. Nevertheless, 2-3 sets with 20% velocity loss (i.e., 6-12 repetitions) at 40-65% 1RM seem required to optimize lower-limb muscle power (i.e., walking velocity) and upper-limb strength and power in older adults.

Despite the inherent limitations of the eighth study, it is important to mention that the novel methods and preliminary results presented here should be seen as a step forward in optimizing the RT prescription in geriatric settings and improving muscle strength, power, and functional capacity in older adults.

The current Ph.D. thesis presents several limitations that should be addressed, namely:

i. Larger samples sizes would increase the statistical power and the accuracy and generalizability of the results, reduce the probability of type II errors, and help extrapolate the proposed regression equations to other older populations with high confidence;

ii. Considering that the included participants in the experimental studies were functionally independent, the results cannot be generalized to mobility-limited older adults;

iii. Performing additional measurements at different time points (e.g., 0-72h post-exercise) in Study 2 would be important to understand the pattern and time course of recovery of the different variables following both RT protocols;

iv. The randomization process in Studies 3 and 4 would be essential to prevent the risk of selection bias and increase the validity of the results. Moreover, incorporating blinding (or masking) of participants and personnel involved in data collection could also be an important strategy to prevent other risks of biases;

v. The nature of the cross-sectional designs does not allow for establishing causal relationships between markers of muscle power and functional capacity in the tested population;

vi. Measuring muscle size through imaging techniques (e.g., magnetic resonance imaging [MRI] or X-ray absorptiometry [DXA]) would provide deeper analyses of the changes in the skeletal muscle structure (e.g., cross-sectional area, muscle fibers, bone density) post-interventions;

vii. Assessing physiological and psychological outcomes would be helpful to determine if, along with lower and upper-limb muscle power measures, they could increase the capacity to explain the remaining part of the variability in functional capacity in older adults;

viii. Including a control group in the eighth study could give insights into whether the 10-week velocity-monitored RT programs truly improved muscle strength, power, and functional capacity of the participants included in the experimental groups;

ix. Increasing the RT duration in Studies 3, 4, and 8 would be beneficial to examine what velocity loss thresholds could be more effective in the long term to improve muscle strength, power, and functional performance in older adults.

Chapter 5. Overall Conclusions

The main finding of the doctoral thesis was that manipulating the volume of resistance training (RT) through monitoring the intra-set velocity loss was effective and efficient for improving muscle strength, power, and functional capacity in older adults. Therefore, this novel RT approach to prescribing the volume should be seen as a step forward in optimizing the designing of interventions and consequent improvement in muscular and functional capacity in older adults. Besides this overall finding, other conclusions were drawn during this thesis, namely:

i. Prescribing three sets per resistance exercise produces a higher magnitude of gains in muscle strength and size, muscle quality, and functional capacity than single sets in middle-aged and older adults;

ii. Performing submaximal repetitions (i.e., 3 sets of 8 repetitions at 65% of one-repetition maximum [1RM]) induces lower acute hemodynamic, metabolic, and neuromuscular stress than repetitions performed to (or close to) muscular failure (i.e., 3 sets of 15 repetitions at 65% 1RM) in older adults;

iii. A 10-week velocity-monitored RT program with 2-3 sets with 10% or 20% velocity losses and relative loads progressing from 40-65% 1RM improves muscle strength, power, and functional capacity in older adults;

iv. An intra-set velocity loss of 10% seems more efficient for inducing muscular and functional gains in older adults as it requires performing fewer repetitions per set than a 20% velocity loss;

v. Performing repetitions until reaching a 20% velocity loss in the set might be required to optimize increases in walking velocity, handgrip strength, and chest press power in older adults;

vi. The sex-specific load-velocity regression equations in the leg-press and chest press enable estimating with high accuracy the relative loads in older adults. In addition, the identification of the velocities associated with each relative load allows prescribing the relative loads based on specific/target velocities;

vii. Older men present higher lifting velocities than older women against most relative loads, especially low-to-moderate (20-70% 1RM). However, the higher the relative loads (>70% 1RM), the lower the differences in movement velocity between sexes;

viii. The relative loads that maximize power output ($P_{max\text{-}load}$) in the leg press and chest press are similar between older women and men but are exercise-specific and vary within resistance exercises depending on the mechanical power variable used;

ix. The maximal mean power (MP_{max}) and peak power (PP_{max}) values in the chest press similarly explain the variability in the medicine ball throw performance in older adults;

x. The MP_{max} and PP_{max} in the leg press explain the variance in the sit-to-stand performance but cannot explain the variance in maximal walking velocity in older adults without mobility impairments.

Chapter 6. Suggestions for Future Research

The results obtained in the thesis were just a first step toward a better understanding of the effects of manipulating the resistance training (RT) volume through monitoring movement velocity on muscle strength, power, and functional capacity in older adults. Therefore, as there is still a long way to go to better understand the RT volume required to produce the optimal muscular and functional adaptations in older adults, several suggestions should be made for future research, namely:

i. Compare the acute hemodynamic, metabolic, hormonal, and mechanical responses and the time course of recovery between different intra-set velocity loss configurations (e.g., 10% vs. 20% vs. 30%) and similar relative loads (e.g., 60% 1RM) in middle-aged and older adults;

ii. Analyze the long-term effects (e.g., ≥ 24 weeks) of velocity-monitored RT programs with different intra-set velocity loss configurations (e.g., 10% vs. 20% vs. 30%) and similar relative loads (e.g., 40-65% 1RM) on muscle strength and size, muscle power, and functional capacity in middle-aged and older adults;

iii. Examine the acute and chronic effects of velocity-monitored RT programs with similar intra-set velocity losses (e.g., 20%) and different relative loads (e.g., 40-60% 1RM vs. 70-90% 1RM) on muscle strength and size, muscle power, and functional capacity in middle-aged and older adults;

iv. Identify what combination between relative velocity loss and relative load promotes the optimal muscular and functional adaptations in middle-aged and older adults on an individual level;

v. Conduct large-scale studies to compare the differences in the load-velocity-power profiles between individuals of different age groups (e.g., 50-59 vs. 60-69 vs. 70-79 vs. 80-89 vs. ≥ 90 years) with and without mobility limitations, as well as those considered robust, pre-frail, and frail;

vi. Explore the influence of physiological (e.g., muscle size), mechanical (e.g., power output), and psychological (e.g., cognitive function) outcomes to explain the variability in functional capacity in middle-aged and older adults.

Chapter 7. References

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Chapter 1. General Introduction

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Appendices

Appendix I

Table A1. Data of the outcome measures associated with muscle strength.

Study	Outcome measure	Group	Mean Pre	SD Pre	*n* Pre	Mean Post	SD Post	*n* Post	Δ (%)	*p*-value within groups	*p*-value between groups	Favors
Abrahin et al. (2014)	10RM Deadlift (kg)	1 Set	10.0	3.8	11	16.5	3.6	11	65.0	≤0.001	>0.05	None
		3 Sets	13.3	3.8	8	20.5	4.1	8	54.1	≤0.001		
	10RM Bench Press (kg)	1 Set	13.8	1.7	11	21.6	3.2	11	56.5	≤0.001	>0.05	None
		3 Sets	14.3	3.5	8	22.0	4.0	8	53.8	≤0.001		
Antunes et al. (2021)	1RM Leg Extension (kg)	1 Set	51.5	13.3	20	51.6	13.5	20	0.2	>0.05	>0.05	None
		3 Sets	54.6	8.0	18	57.0	8.0	18	4.4	<0.05		
	1RM Chest Press (kg)	1 Set	42.4	9.9	20	46.4	9.5	20	9.4	<0.05	<0.05	3 Sets
		3 Sets	47.0	8.8	18	54.5	11.0	18	16.0	<0.05		
Correa et al. (2014)	1RM Leg Extension (kg)	1 Set	25.0[a]	NR[a]	12	35.6[a]	NR[a]	12	42.3	<0.05	>0.05	None
		3 Sets	26.0[a]	NR[a]	11	36.1[a]	NR[a]	11	39.0	<0.05		

Table A1. Continued.

Study	Outcome measure	Group	Mean Pre	SD Pre	*n* Pre	Mean Post	SD Post	*n* Post	Δ (%)	*p*-value within groups	*p*-value between groups	Favors
Correa et al. (2015)	1RM Leg Extension	1 Set	26.6	2.8	13	34.9	5.3	13	31.2	<0.05	>0.05	None
		3 Sets	27.0	4.4	12	37.1	3.6	12	37.4	<0.05		
Cunha et al. (2020)	1RM Leg Extension (kg)	1 Set	47.2	10.9	21	55.0	11.5	21	16.3	<0.05	>0.05	None
		3 Sets	44.4	9.9	20	54.1	9.7	20	21.7	<0.05		
	1RM Biceps Curl (kg)	1 Set	17.5	2.8	21	24.0	4.0	21	37.1	<0.05	>0.05	None
		3 Sets	17.9	3.2	20	22.8	3.7	20	27.4	<0.05		
Galvão & Taaffe (2005)	1RM Leg Press (kg)	1 Set	81.2	20.0	12	91.7	19.4	12	12.9	0.004	0.23	None
		3 Sets	89.3	21.9	16	104.0	24.6	16	16.5	<0.001		
	1RM Chest Press (kg)	1 Set	41.4	17.5	12	47.0	21.0	12	13.5	0.009	0.14	None
		3 Sets	40.6	14.9	15	49.7	17.8	15	22.4	<0.001		

Table A1. Continued.

Study	Outcome measure	Group	Mean Pre	SD Pre	*n* Pre	Mean Post	SD Post	*n* Post	Δ (%)	*p*-value within groups	*p*-value between groups	Favors
Polito et al. (2021a)	1RM Leg Extension (kg)	1 Set	56.2	10.1	14	71.3	12.2	14	26.9	<0.05	>0.05	None
		3 Sets	58.5	8.4	12	75.2	9.6	12	28.5	<0.05		
	1RM Chest Press (kg)	1 Set	36.7	7.2	14	48.1	6.3	14	31.1	<0.05	>0.05	None
		3 Sets	37.0	7.4	12	50.2	7.8	12	35.7	<0.05		
Radaelli et al. (2014a)	1RM Leg Extension	1 Set	47.0	15.0	11	64.5	14.4	11	37.2	≤0.001	≤0.01	3 Sets
		3 Sets	46.6	14.7	9	70.8	22.0	9	51.9	≤0.001		
	1RM Biceps Curl	1 Set	6.9	1.5	11	9.6	1.6	11	39.1	≤0.001	>0.05	None
		3 Sets	6.6	0.6	9	9.4	1.1	9	42.4	≤0.001		
Radaelli et al. (2013)	1RM Leg Extension (kg)	1 Set	47.7	15.0	11	61.1	12.8	11	28.1	≤0.001	>0.05	None
		3 Sets	46.6	14.7	9	64.4	20.0	9	38.2	≤0.001		

Table A1. Continued.

Study	Outcome measure	Group	Mean Pre	SD Pre	*n* Pre	Mean Post	SD Post	*n* Post	Δ (%)	*p*-value within groups	*p*-value between groups	Favors
Radaelli et al. (2013)	1RM Biceps Curl (kg)	1 Set	6.9	1.5	11	8.5	1.5	11	23.2	≤0.001	>0.05	None
		3 Sets	6.6	0.6	9	8.4	0.5	9	27.3	≤0.001		
Radaelli et al. (2014b)	1RM Leg Extension (kg)	1 Set	49.5	16.4	14	56.5	15.5	14	14.1	≤0.05	>0.05	None
		3 Sets	50.8	16.4	13	60.3	17.8	13	18.7	≤0.05		
Radaelli et al. (2018)	1RM Leg Extension (kg)	1 Set	48.8	10.9	13	53.2	10.8	13	9.0	≤0.001	>0.05	None
		3 Sets	53.1	14.5	13	61.0	15.2	13	14.9	≤0.001		
Ribeiro et al. (2015)	1RM Leg Extension (kg)	1 Set	40.3	8.0	15	47.3	8.5	15	17.3	<0.05	<0.05	3 Sets
		3 Sets	39.3	3.9	15	49.3	3.7	15	25.5	<0.05		
	1RM Chest Press (kg)	1 Set	34.3	5.2	15	41.3	6.7	15	20.5	<0.05	<0.05	3 Sets
		3 Sets	35.3	4.4	15	44.3	4.8	15	25.5	<0.05		

Table A2. Data of the outcome measures associated with muscle size.

Study	Outcome measure	Group	Mean Pre	SD Pre	*n* Pre	Mean Post	SD Post	*n* Post	Δ (%)	*p*-value within groups	*p*-value between groups	Favors
Antunes et al. (2021)	LL-LST DXA (kg)	1 Set	11.6	1.5	20	11.8	2	20	1.7	>0.05	>0.05	None
		3 Sets	12.3	1.7	18	12.6	2	18	2.4	>0.05		
Correa et al. (2014)	MV Rectus Femoris USG (cm^3)	1 Set	621.0[a]	NR	12	792.2[a]	NR	12	27.6	<0.05	>0.05	None
		3 Sets	631.2[a]	NR	11	812.6[a]	NR	11	28.7	<0.05		
Correa et al. (2015)	MT Vastus Lateralis USG (mm)	1 Set	18.2	2.8	13	20.8	1.3	13	14.3	<0.05	<0.05	3 Sets
		3 Sets	18.9	2.3	12	22.3	1.2	12	18.0	<0.05		
Cunha et al. (2020)	LL-LST DXA (kg)	1 Set	12.7	1.9	21	13.4	2.0	21	5.6	<0.05	>0.05	None
		3 Sets	10.8	1.5	20	11.5	1.5	20	6.3	<0.05		
Cunha et al. (2017)	SMM DXA (kg)	1 Set	17.1	1.3	21	18.0	1.2	21	5.3	<0.05	>0.05	None
		3 Sets	16.9	1.5	20	18.0	1.9	20	6.5	<0.05		

Table A2. Continued.

Study	Outcome measure	Group	Mean Pre	SD Pre	*n* Pre	Mean Post	SD Post	*n* Post	Δ (%)	*p*-value within groups	*p*-value between groups	Favors
Galvão & Taaffe (2005)	Lean Mass DXA (kg)	1 Set	48.0	10.1	12	48.5	10.3	12	1.0	>0.05	>0.05	None
		3 Sets	47.9	9.0	16	48.6	8.8	16	1.5	>0.05		
Radaelli et al. (2014a)	MT Quadriceps USG (mm)	1 Set	64.6	18.4	11	72.3	15.7	11	11.9	≤0.001	≤0.05	3 Sets
		3 Sets	59.8	9.5	9	70.0	10.8	9	17.1	≤0.001		
Radaelli et al. (2013)	MT Quadriceps USG (mm)	1 Set	64.9[a]	14.7[a]	11	70.3[a]	14.6[a]	11	8.4	≤0.001	>0.05	None
		3 Sets	60.0[a]	9.2[a]	9	69.9[a]	8.8[a]	9	16.4	≤0.001		
Radaelli et al. (2014b)	MT Quadriceps USG (mm)	1 Set	55.8[a]	21.5[a]	14	58.6[a]	21.3[a]	14	5.0	≤0.05	>0.05	None
		3 Sets	55.1[a]	8.6[a]	13	61.0[a]	9.9[a]	13	10.6	≤0.05		
Radaelli et al. (2018)	MT Quadriceps USG (mm)	1 Set	61.7	10.4	13	64.7	10.8	13	4.9	≤0.05	>0.05	None
		3 Sets	63.1	15.7	13	67.8	16.1	13	7.4	≤0.05		

Table A2. Continued.

Study	Outcome measure	Group	Mean Pre	SD Pre	*n* Pre	Mean Post	SD Post	*n* Post	Δ (%)	*p*-value within groups	*p*-value between groups	Favors
Ribeiro et al. (2015)	Fat-Free Mass DXA (kg)	1 Set	37.9[a]	2.1[a]	15	38.3[a]	2.7	15	1.1	<0.05	>0.05	None
		3 Sets	37.0[a]	2.4[a]	15	37.6[a]	2.1	15	1.7	<0.05		

Table A3. Data of the outcome measures associated with muscle quality.

Study	Outcome measure	Group	Mean Pre	SD Pre	*n* Pre	Mean Post	SD Post	*n* Post	Δ (%)	*p*-value within groups	*p*-value between groups	Favors
Cunha et al. (2020)	1RM KE / LL-LST DXA (kg/kg)	1 Set	3.7	0.7	21	4.1	0.7	21	10.5	<0.05	>0.05	None
		3 Sets	4.1	0.8	20	4.7	0.8	20	15.4	<0.05		
Cunha et al. (2018)	Total Strength[a] / SMM DXA (kg/kg)	1 Set	5.4	0.9	20	6.1	0.9	20	12.1	<0.05	>0.05	None
		3 Sets	6.5	0.8	20	7.6	0.9	20	17.2	<0.05		
Radaelli et al. (2013)	1RM KE / MT Quadriceps USG (kg/mm)	1 Set	0.8	0.2	11	0.9	0.2	11	18.7	≤0.01	>0.05	None
		3 Sets	0.8	0.2	9	0.9	0.3	9	22.1	≤0.01		
Radaelli et al. (2019)	1RM KE / MT Quadriceps USG (kg/mm)	1 Set	0.4[b]	0.1[b]	14	0.4[b]	0.1[b]	14	16.3	<0.05	>0.05	None
		3 Sets	0.4[b]	0.1[b]	13	0.4[b]	0.1[b]	13	22.1	<0.05		

Table A4. Data of the outcome measures associated with functional capacity.

Study	Outcome measure	Group	Mean Pre	SD Pre	*n* Pre	Mean Post	SD Post	*n* Post	Δ (%)	*p*-value within groups	*p*-value between groups	Favors
Abrahin et al. (2014)	30-seconds Chair Stand (reps)	1 Set	19.0	3.2	11	21.0	3.8	11	10.5	<0.05	>0.05	None
		3 Sets	18.6	3.0	8	21.6	2.9	8	16.1	<0.05		
Galvão & Taaffe (2005)	6-meters Fast Walk (s)	1 Set	3.4	0.4	12	3.2	0.3	12	-5.9	0.08	0.94	None
		3 Sets	3.2	0.4	16	3.1	0.4	16	-3.1	0.73		
Radaelli et al. (2018)	Timed-up and Go (s)	1 Set	7.1	0.8	13	6.2	0.4	13	-13.0	<0.05	>0.05	None
		3 Sets	6.8	0.9	13	6.1	0.9	13	-9.3	<0.05		
Radaelli et al. (2019)	Timed-up and Go (s)	1 Set	8.4	0.8	13	8.2	0.7	13	-2.4	<0.001	0.023	3 Sets
		3 Sets	8.4	1.0	13	7.8	1.1	13	-7.1	<0.001		

Table A5. Effects of single vs. multiple sets on muscle strength and size according to training duration.

Outcome	**Training Duration**	***n***	**SMD, *g* (95% CI)**	***p*-value**	**MD, kg (95% CI)**	***p*-value**
Lower-limb muscle strength	≤ 12 Weeks	255	0.20 (-0.04, 0.45)	0.10	1.96 (-0.38, 4.30)	0.10
	> 12 Weeks	68	0.29 (-0.19, 0.77)	0.23	4.34 (-2.69, 11.37)	0.23
Upper-limb muscle strength	≤ 12 Weeks	154	0.19 (-0.13, 0.50)	0.25	1.05 (-0.73, 2.83)	0.25
	> 12 Weeks	67	0.22 (-0.26, 0.70)	0.37	2.02 (-2.36, 6.40)	0.37
Muscle size	≤ 12 Weeks	251	0.01 (-0.24, 0.26)	0.93	NA	NA
	> 12 Weeks	68	0.12 (-0.35, 0.60)	0.62	NA	NA

CI confidence interval, *MD* mean difference, *n* sample size, *NA* not applicable, *SMD* standardized mean difference.

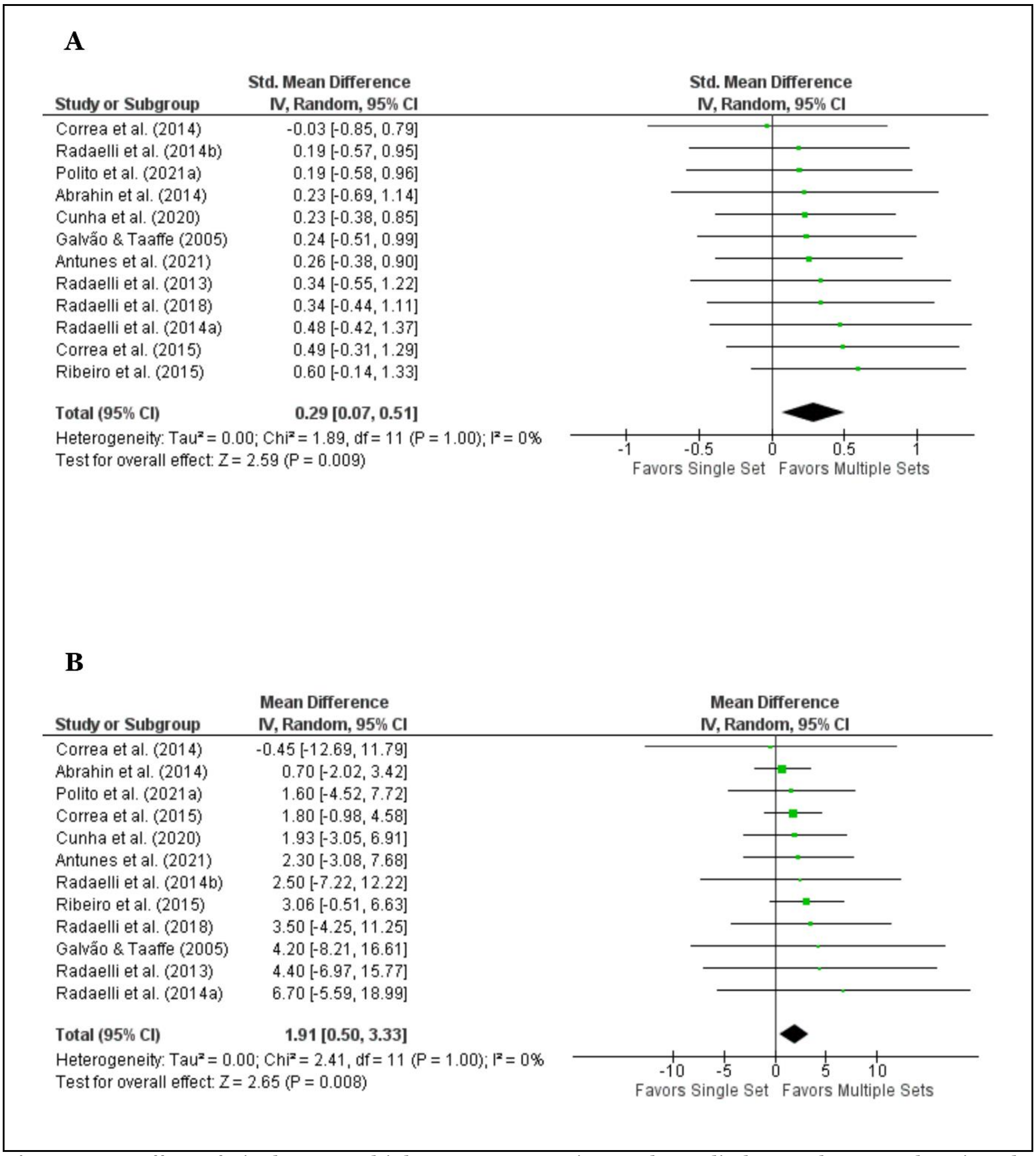

Figure A1. Effect of single vs. multiple sets per exercise on lower-limb muscle strength using the standardized mean difference (SMD, Hedge's *g*) (A) and mean difference (MD, kg) (B) with 95% confidence intervals (CI). *Chi²* chi-squared test, *I²* inconsistency test, *IV* inverse variance.

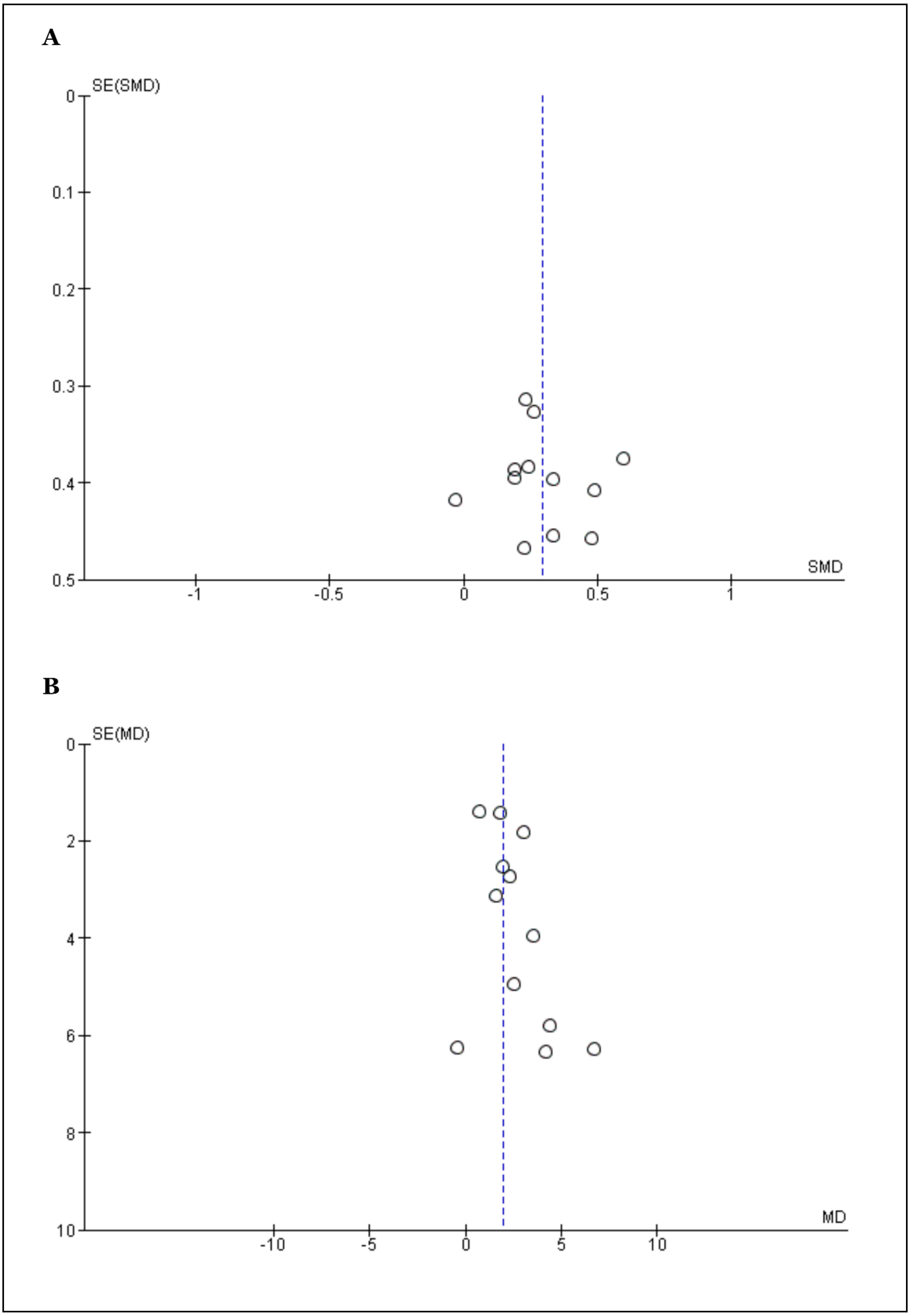

Figure A2. Funnel plot of the effect of single vs. multiple sets per exercise on lower-limb muscle strength using the standardized mean difference (SMD, Hedge's *g*) (A) and mean difference (MD, kg) (B); SE: standard error.

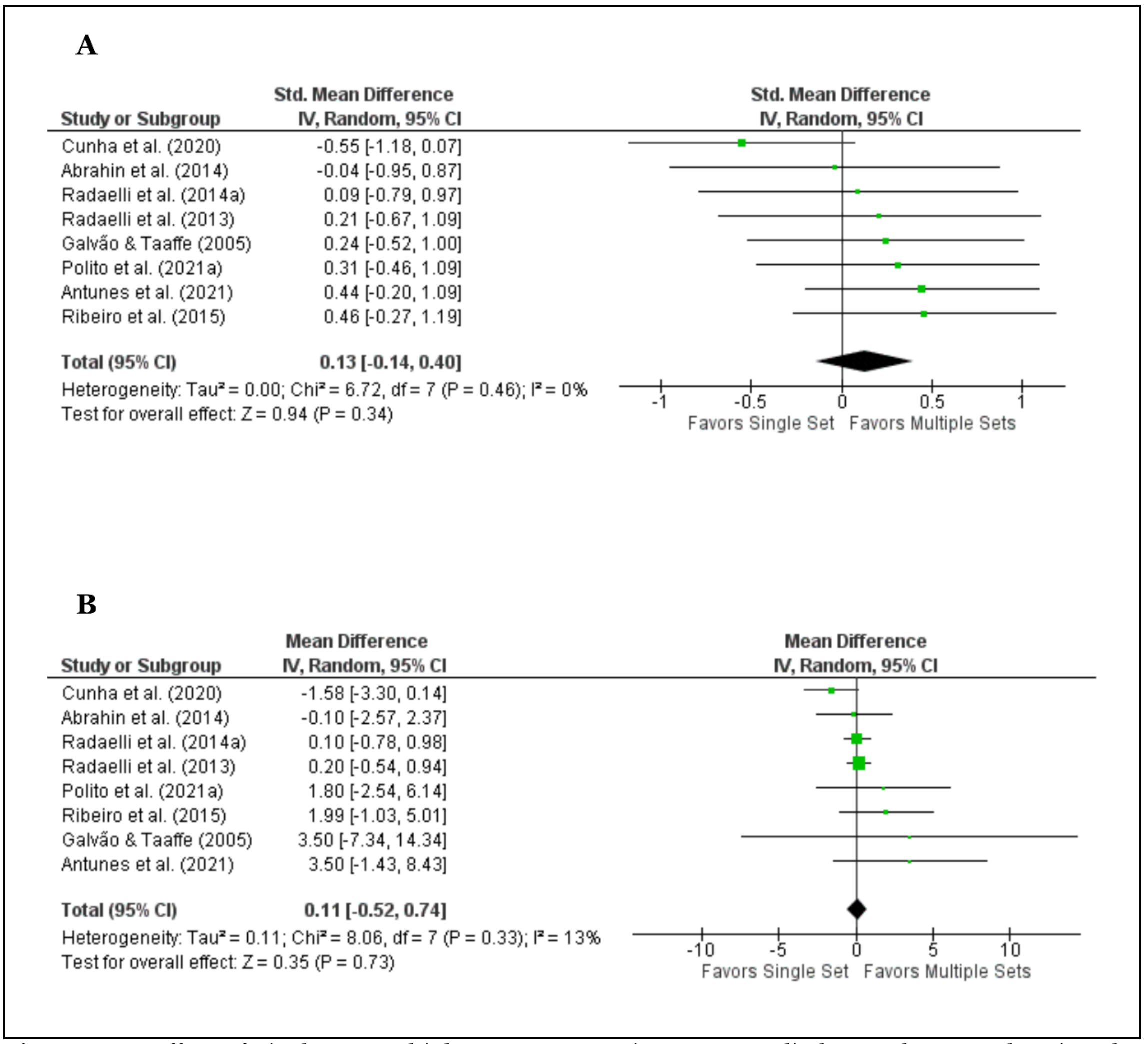

Figure A3. Effect of single vs. multiple sets per exercise on upper-limb muscle strength using the standardized mean difference (SMD, Hedge's *g*) (A) and mean difference (MD, kg) (B) with 95% confidence intervals (CI). *Chi*² chi-squared test, *I*² inconsistency test, *IV* inverse variance.

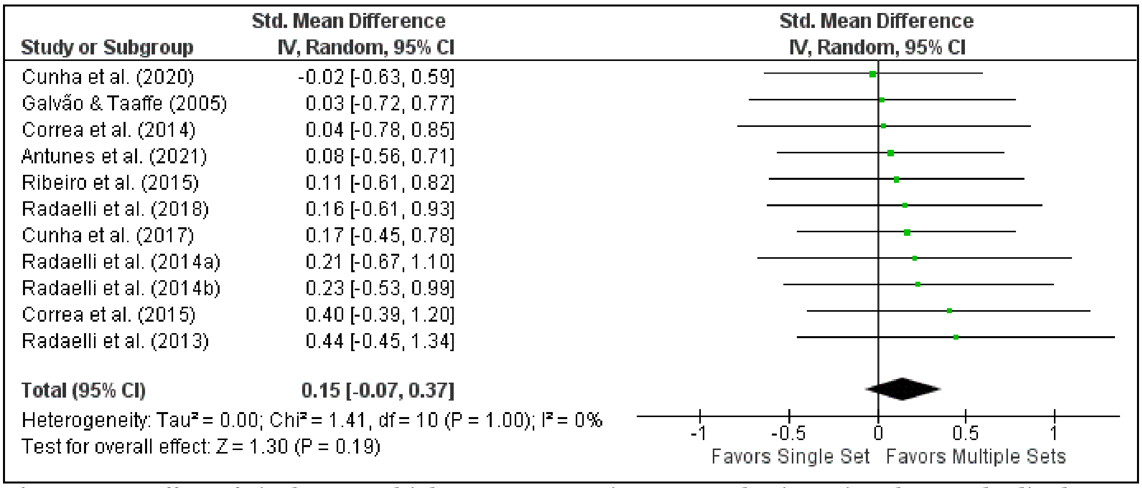

Figure A4. Effect of single vs. multiple sets per exercise on muscle size using the standardized mean difference (SMD, Hedge's *g*) with 95% confidence intervals (CI). *Chi*^{2} chi-squared test, I^2 inconsistency test, *IV* inverse variance.

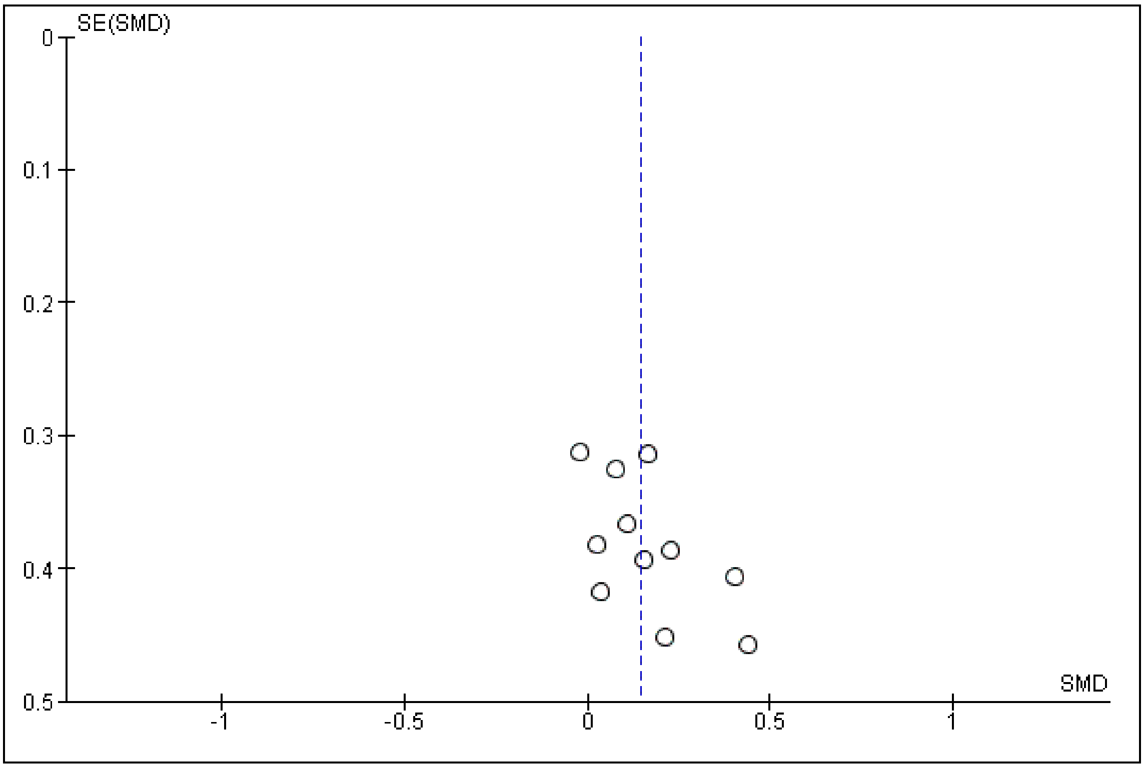

Figure A5. Funnel plot of the effect of single vs. multiple sets per exercise on muscle size using the standardized mean difference (SMD, Hedge's *g*); SE: standard error.

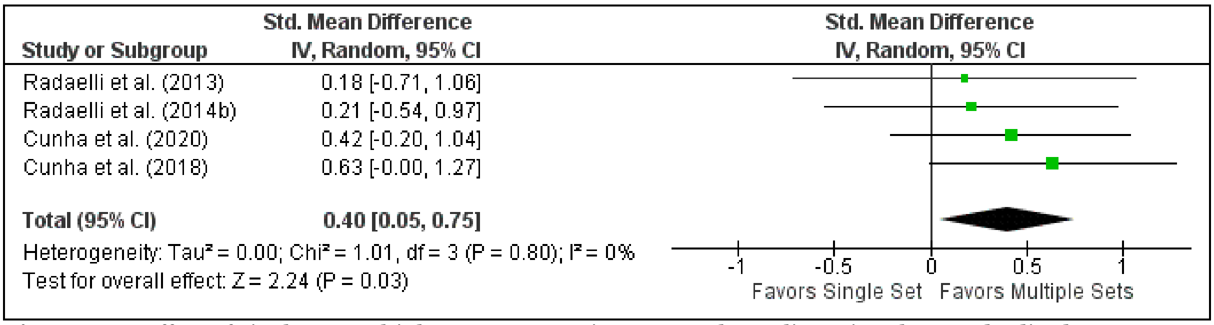

Figure A6. Effect of single vs. multiple sets per exercise on muscle quality using the standardized mean difference (SMD, Hedge's *g*) with 95% confidence intervals (CI). *Chi*² chi-squared test, *I*² inconsistency test, *IV* inverse variance.

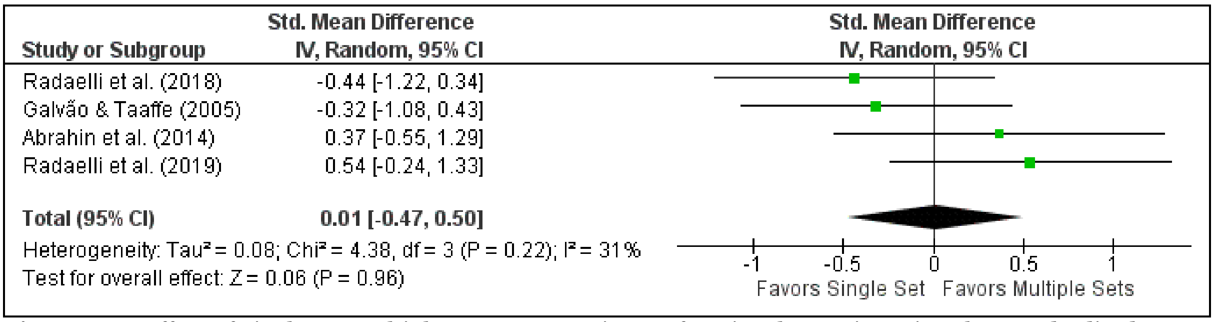

Figure A7. Effect of single vs. multiple sets per exercise on functional capacity using the standardized mean difference (SMD, Hedge's *g*) with 95% confidence intervals (CI). *Chi*² chi-squared test, *I*² inconsistency test, *IV* inverse variance.

Appendix II

Table A1. Test-retest reliability of the outcome measures in both groups.

Outcome	Group	ICC $_{(2,1)}$ (95% CI)	SEM	CV (%)	MDC	MDC (%)
HGS (kg)	VL10	0.98 (0.93 – 0.99)	1.1	4.9	3.2	13.6
	VL20	0.99 (0.95 – 0.99)	1.1	4.6	3.0	12.8
MBT (m)	VL10	0.97 (0.92 – 0.99)	0.1	2.4	0.2	6.7
	VL20	0.99 (0.97 – 0.99)	0.1	2.0	0.2	5.5
T10 (s)	VL10	0.95 (0.87 – 0.99)	0.2	2.9	0.5	8.0
	VL20	0.98 (0.91 – 0.99)	0.2	2.5	0.4	6.8
STS (s)	VL10	0.98 (0.92 – 0.99)	0.3	3.7	0.8	10.2
	VL20	0.95 (0.77 – 0.99)	0.3	3.6	0.8	10.0

CI: confidence interval; CV: coefficient of variation; HGS: handgrip strength; ICC: intraclass correlation coefficient; MBT: medicine ball throw; MDC: minimal detectable change; SEM: standard error of measurement; STS: five-repetition sit-to-stand; T10: 10-meters walking; VL: velocity loss.

Annexes

Annex I

UiA University of Agder

RESEARCH STAY CERTIFICATE

The undersigned hereby, Sveinung Berntsen, Professor and Head of the Department of Sport Science and Physical Education in the Faculty of Health and Sport Sciences at the University of Agder (Norway),

CERTIFIES that,

Diogo Luís Sequeira Torgal Marques (DNI 133894169ZY7), PhD student in the Department of Sport Sciences at the University of Beira Interior (Portugal), has conducted a research stay to support the development of his doctoral thesis from 4th April to 30th June 2022 in the Department of Sport Science and Physical Education at the University of Agder.

July 2022

Sveinung Berntsen
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