

**Advancing age is not associated with greater exercise-induced muscle damage: A systematic review, meta-analysis, and meta-regression.**

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1 **Advancing age is not associated with greater exercise-induced muscle damage: A**  
2 **systematic review, meta-analysis, and meta-regression.**

3  
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1 **Advancing age is not associated with greater exercise-induced muscle damage: A**  
2 **systematic review, meta-analysis, and meta-regression.**

3  
4 **Abstract**

5 Objective: The aim of this paper was to undertake a PRISMA-accordant meta-analysis  
6 comparing exercise-induced muscle damage (EIMD) in older and younger adults. Methods:  
7 Google Scholar, PubMed and Sport Discus were searched in June 2023 for the terms “ageing”  
8 OR “age” OR “middle-aged” OR “old” OR “older” OR “elderly” OR “masters” OR “veteran” AND  
9 “muscle damage” OR “exercise-induced muscle damage” OR “exercise-induced muscle  
10 injury” OR “contraction-induced injury” OR “muscle soreness” OR “delayed onset muscle  
11 soreness” OR “creatine kinase”. From 1092 originally identified titles, 36 studies were included  
12 which had an exercise component comparing a younger against an older group. The outcome  
13 variables of EIMD were muscle function, muscle soreness, and creatine kinase (CK). A meta-  
14 analysis was conducted on change to EIMD after exercise in older vs younger adults using  
15 standardised mean difference (SMD) and an inverse-variance random effects model. Results:  
16 Change after 24 and 72 hours, and peak change, in muscle function was not different between  
17 old and young (SMD range = -0.16 to -0.35). Muscle soreness was greater in younger than  
18 older adults for all comparisons (SMD range= -0.34 to -0.62). CK was greater in younger than  
19 older adults at 24 hours (SMD= -0.32), as was peak change (SMD= -0.32). A relationship  
20 between sex and peak muscle function change was evident for males (SMD= -0.45), but not  
21 females (SMD= -0.44). All other meta-regression were non-significant. Conclusion: Advancing  
22 age is not associated with greater symptoms of EIMD. Implications: Older adults can pursue  
23 regular physical activity without concern for experiencing greater EIMD.

24  
25 **Key words**

26 Muscle function; muscle soreness; creatine kinase; eccentric exercise; fatigue; recovery;  
27 meta-analysis

28  
29 **Key points**

- 30 1. Exercise-induced muscle damage (EIMD) can negatively affect sport and exercise  
31 performance and reduce adherence to exercise.
- 32 2. Older adults exhibit smaller post-exercise increases in muscle soreness and creatine  
33 kinase, and similar muscle function decrements, compared to their younger counterparts.
- 34 3. Those working with older adults should use these data to inform the planning and  
35 programming of physical activity, and to improve exercise adherence.

36  
37 **Introduction**

1 Between 2017 and 2050, the number of people aged over 60 years is expected to double, and  
2 to triple by 2100 (United Nations, 2017). Improvements in medical care, a greater appreciation  
3 for longevity, and a decline in the leading causes of mortality contribute to the ageing  
4 population (Baker & Tang, 2010). The ageing population has driven interest in ‘successful’  
5 ageing (Elliott, Hayes, Hughes, & Burtcher, 2020; Geard, Reaburn, Rebar, & Dionigi, 2017;  
6 Hayes, Burtcher, & Elliott, 2022), which comprises physical, psychological, social, and  
7 cognitive domains (Garai et al., 2021; Stenbäck et al., 2019; Steptoe et al., 2015; Urtamo et  
8 al., 2019). Whilst ageing is associated with reduced muscle strength and power (Dodds et al.,  
9 2014; Fernandes et al., 2018b, 2018a, 2019, 2021), alterations in body compositions  
10 (Fernandes et al., 2018a; Lexell et al., 1988) and declines in aerobic fitness (Tanaka & Seals,  
11 2008; Valenzuela et al., 2020; Yasar et al., 2021), physical activity, changes in appetite-related  
12 hormones (Johnson et al., 2020) and exercise can offset and ameliorate these declines (Cruz-  
13 Jentoft et al., 2014; Hayes, Elliott, et al., 2021; Hayes et al., 2020; Hayes, Herbert, et al.,  
14 2021a, 2021b; Herbert et al., 2021a, 2021b; Johnson et al., 2021; Sellami et al., 2017; Yasar  
15 et al., 2023; Zouhal et al., 2022). Therefore, physical activity is core to successful ageing, and  
16 as such is included in national and international health guidelines (Izquierdo et al., 2021).

17

18 Despite the benefits of physical activity, an acute consequence is exercise-induced muscle  
19 damage (EIMD), particularly if the mode or intensity is novel, includes eccentric muscle  
20 contractions, or is of high volume (Fernandes et al., 2023; Owens et al., 2018; Reaburn &  
21 Fernandes, 2023; Wilson et al., 2018, 2019). According to the “popping-sarcomere  
22 hypothesis” (Morgan & Proske, 2004), increased stress per myofiber during eccentric  
23 contractions causes non-uniform lengthening whereby weaker sarcomeres extend beyond  
24 their myofilament overlap and fail to re-interdigitate (Hyldahl & Hubal, 2014; Morgan & Proske,  
25 2004). Thereafter, disruptions to calcium homeostasis leads to excitation–contraction  
26 uncoupling and a prolonged loss of muscle strength and other associated symptoms (Damas  
27 et al., 2016; Hyldahl & Hubal, 2014; Morgan & Proske, 2004). Regardless of age, EIMD  
28 manifests as reductions in muscle function (e.g. strength and power), increased muscle  
29 soreness and pain, and intramuscular enzymes ‘leaking’ into circulation (e.g. creatine kinase;  
30 CK). Typically, these symptoms peak between 24 and 48 hours after the initial bout of physical  
31 activity and are recovered (i.e. returned to baseline) by seven days (Damas et al., 2016;  
32 Hyldahl & Hubal, 2014; Reaburn & Fernandes, 2023; Wilson et al., 2018, 2019). These  
33 symptoms are highly individualised, not synchronous (Damas et al., 2016; Hubal et al., 2007;  
34 Machado & Willardson, 2010) and appear to differ between sexes (e.g. (Kendall & Eston,  
35 2002)) and exercising limb (e.g. (Chen et al., 2011)).

36

1 Ageing is associated with a reduction in muscle protein synthesis in response to exercise  
2 (Kumar et al., 2009) and protein ingestion (Cuthbertson, 2004), reductions in satellite cell  
3 count (Ballak et al., 2015), and impaired proliferation of existing satellite cells (Pietrangelo et  
4 al., 2009). Theoretically, this would result in an impaired ability to activate regenerative  
5 pathways and repair muscle damage. Although it has previously been reported that older  
6 adults display greater symptoms of EIMD after aerobic (Easthope et al., 2010) and intermittent  
7 activity (Borges et al., 2018), a recent review of 11 studies suggested alterations in muscle  
8 function, muscle soreness/pain, and CK after resistance exercise-induced muscle damage are  
9 comparable between older and younger males (Fernandes, Lamb, Norris, et al., 2020). This  
10 could indicate that the exercise modality might influence the EIMD response between age-  
11 groups.

12  
13 Divergent EIMD responses between ages remains an important and contentious consideration  
14 in exercise and health science (Fernandes et al., 2023; Fernandes et al., 2020; Hayes et al.,  
15 2023). For example, EIMD symptoms are likely to reduce physical activity adherence and  
16 could result in discontinuation (Farias-Junior et al., 2019). Given the benefit of physical activity  
17 to health outcomes (Ashton et al., 2020; Sprung et al., 2013), strategies that maintain exercise  
18 adherence in older adults remain fundamental, including programming of physical activity.  
19 Though recommendations have been provided for resistance EIMD (Fernandes, Lamb, Norris,  
20 et al., 2020), none have been provided for other exercise modalities (e.g., aerobic exercise).  
21 If EIMD symptoms increase with age, then it is also important to develop an understanding of  
22 the influence of sex and the exercising limb. Such information can guide practitioners working  
23 with adults to appropriately plan and programme physical activity regimes and recovery  
24 strategies.

25  
26 Recent work has meta-analysed indirect symptoms of EIMD in youths compared to young  
27 adults (Fernandes et al., 2023) but there is a need to establish how these symptoms differ  
28 across the adult lifespan. Despite the interest in EIMD across the adult lifespan, there was no  
29 meta-analysis to provide pooled analysis of published studies to date. Therefore, the aim of  
30 this investigation was to conduct meta-analyses on the effect of a single exercise bout on  
31 muscle function, muscle soreness/pain and CK between two different adult age groups. A  
32 secondary aim was to investigate study characteristics (exercise modality, sex, and involved  
33 limb) and whether this influenced the effect of age on EIMD markers.

34

## 35 **Methods**

36 This systematic review with meta-analysis was conducted according to the Preferred  
37 Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) guidelines (Page et al.,

1 2021). The literature search was performed by three authors with the data extraction and  
2 verification performed by two authors.

3

#### 4 **Information sources**

5 On the 15<sup>th</sup> June 2023 a systematic search, with no date restrictions, was performed on Google  
6 Scholar, PubMed and Sport Discus.

7

#### 8 **Search strategy**

9 Only peer-reviewed articles written in English were considered. Using Boolean logic  
10 combinations of the following search terms were used; “ageing” OR “age” OR “middle-aged”  
11 OR “old” OR “older” OR “elderly” OR “masters” OR “veteran” AND “muscle damage” OR  
12 “exercise-induced muscle damage” OR “exercise-induced muscle injury” OR “contraction-  
13 induced injury” OR “muscle soreness” OR “delayed onset muscle soreness” OR “creatine  
14 kinase”. When selecting studies for inclusion, all relevant article titles were reviewed before  
15 an examination of article abstracts and, then, full published articles. After the formal systematic  
16 searches, additional searches of the reference lists were conducted. The search process is  
17 outlined in Figure 1.

18

19 INSERT FIGURE 1 HERE

20

#### 21 **Eligibility criteria**

22 The following criteria were used to determine the eligibility of studies for the meta-analysis  
23 using the PICO framework (Participants [P], Intervention [I], Comparator [C], Outcomes [O]:  
24 P) An older adult human group and a younger comparison, I) An acute exercise bout without  
25 provision of a recovery aid (e.g., cold-water immersion), C) An older versus younger  
26 comparison O) Measure of muscle function (e.g., strength, power), muscle soreness/pain, or  
27 CK beyond  $\geq 24$  hours.

28

#### 29 **Selection process, data collection process, and data items**

30 Data extraction was conducted independently by two reviewers (JFTF and LJW) using a  
31 standardised Microsoft Excel form. Any disagreement between both reviewers was discussed  
32 in a consensus meeting, and unresolved items were addressed by a third independent  
33 reviewer for resolution (LJH). Where data were not numerically reported, and only visualised,  
34 authors were contacted. In the case of authors not responding (up to 6 weeks response time  
35 was allowed), ImageJ software was used to manually extract data from figures (Schneider et  
36 al., 2012). Data were extracted on baseline and post-EIMD measures of muscle strength,  
37 muscle soreness/pain, and CK. Anthropometric and physical activity characteristics of the

1 participants, as well as the exercise bout were also extracted. As there is no consensus for  
2 what is deemed a 'young' and 'old' adult (Fernandes et al., 2020) the age comparisons are  
3 based upon the criteria set in each individual study. The EIMD bout was categorised as  
4 resistance (i.e. exercise performed against an external load) or aerobic (i.e. continuous and  
5 rhythmic movement of the body for a sustained period) in nature. Muscle function data from  
6 Fell et al. (2008) was only presented for the whole groups, thus only the muscle soreness data  
7 was extracted. Similarly, CK data from Lavender and Nosaka (2006) could not be accurately  
8 extracted, so only muscle function and soreness data were extracted from this study. In both  
9 cases the data were excluded from analysis. The 24 hours standard deviation data for CK in  
10 Lavendar and Nosaka (2006) could not be extracted. Therefore, results are presented with  
11 the standard deviations values at 48 hours and with the removal of these data. Importantly,  
12 the results were identical and did not affect the main analysis. Any data reported as standard  
13 error were converted to standard deviation for analysis. As differences at baseline were  
14 expected between youths and adults for muscle strength, the peak percentage change from  
15 baseline was entered for analysis. Where standard deviation of the change was not reported  
16 (merely pre- and post-EIMD SDs), the standard deviation of the change was calculated thusly:

$$17 \quad SD \text{ of the change} = \sqrt{(a^2 + b^2) - (2correl. \times a \times b)}$$

18  
19 *Equation 1. a = baseline SD; b = peak SD; and correl. = the Pearson's correlation between*  
20 *baseline and 24h post-EIMD muscle strength (r = 0.94) in Fernandes et al. (2020).*

21  
22 One study (Lavender & Nosaka, 2007) included multiple age group comparisons (e.g.,  
23 younger adults versus both middle-aged and old adults) and both were included for analysis.  
24 Previous work (Kadlec et al., 2022) has raised concerns that including multiple groups from  
25 the same study within a meta-analysis could ignore the within-study correlation. However, the  
26 differences in biometric characteristics of the groups (see Table 2) in Lavender and Nosaka  
27 (2007) indicate distinct physical and physiological differences which warrant their inclusion.  
28 Trivisonno et al. (2021) analysed data from both upper- and lower-body. As the upper- and  
29 lower-body respond differently to EIMD (Chen et al., 2011; Jamurtas et al., 2005; Saka et al.,  
30 2009), and under-go differing sarcopenic (i.e., loss of muscle mass) and dynapenic (i.e., loss  
31 of muscle strength) responses (e.g. (Abe et al., 2011; Fernandes et al., 2018a)) both data  
32 were included in the meta-analysis. As per the suggestion of Kadlec et al. (2022) multiple  
33 variables were not included in the same analysis, e.g. both concentric and isometric strength  
34 into the muscle strength analysis.

35

## 36 **Analysis and interpretation of results**

1 Jamovi (version 2.3.0.0, MAJOR package) was used to conduct the meta-analyses. Means  
2 and standard deviations of baseline and post-exercise markers of EIMD were used to calculate  
3 the standardised mean difference (SMD). Standardised mean difference expressed the  
4 intervention effect within each study using a restricted maximum-likelihood model estimate  
5 (Langan et al., 2017). An inverse-variance random effects model for meta-analyses allocated  
6 a proportionate weight to trials based on the standard error and accounted for heterogeneity  
7 between studies (Deeks et al., 2019). Effect sizes are reported as SMD and 95% confidence  
8 intervals (CIs). The following qualitative criteria were used to interpret the SMD; 0.2 = trivial;  
9 0.2–0.59 = small, 0.6–1.19 = moderate, 1.2–1.99 = large, 2.0–3.99 = very large, > 4.0 =  
10 extremely large (Hopkins et al., 2009). To assess the degree of heterogeneity amongst the  
11 included studies, the  $I^2$  statistic was employed. This represents the proportion of effects that  
12 are due to heterogeneity as opposed to chance (Liberati et al., 2009). Low, moderate, and  
13 high heterogeneity correspond to  $I^2$  values of 25, 50, and 80%, respectively. Random-effects  
14 meta-regressions tested the influence of sex (i.e. female or male), the involved limb segment  
15 (i.e. upper- or lower-limb) and the exercise type (i.e., resistance or aerobic) on the SMD.  
16 Studies which included a mixed sex sample ( $k = 6$ ) or did not state the sex of their sample ( $k$   
17 = 1) or used plyometric exercise ( $k = 1$ ) were not included in the regression analysis.

18

### 19 **Quality assessment and risk of bias assessment**

20 The quality of the included studies was determined using the National Institute of Health's  
21 Quality Assessment Tool for Before-After ([pre-post](#)) Studies with No Control Group (National  
22 Health Lung and Blood Institute, 2023). The assessment tool analyses the following domains  
23 1) study question was clearly stated; 2) eligibility was prespecified and clearly described; 3)  
24 study subjects were representative of those who would be of interest; 4) eligible subjects were  
25 enrolled; 5) sample size was sufficiently large; 6) intervention was clearly described and evenly  
26 applied to subjects; 7) outcome measures prespecified, clearly defined, valid, reliable; 8)  
27 assessors were blind to the intervention/outcomes; 9) subject attrition was less than 20%; 10)  
28 statistical measures assessed pre to post changes; 11) outcome measures were taken  
29 multiple times; 12) statistical analysis took into account group level data. Two reviewers  
30 conducted the quality assessment independently with any disputes settled by a third reviewer.

31

## 32 **Results**

### 33 **Study selection**

34 Results from the three database searches identified 1092 articles, 121 of which were  
35 duplicates (Figure 1). A total of 650 articles were removed after the screening of abstracts,  
36 leaving 321 articles available for full text inspection. After manual screening of reference lists  
37 and review articles 10 studies were added. One study (Manfredi et al., 1991) reported CK



1 values relative to creatinine, which no other study did. As this is not typical within the EIMD  
2 literature the study was removed. Therefore, data was retrieved from all 36 studies identified  
3 for analysis.

4

### 5 **Study characteristics**

6 The NIH Quality Assessment Tool resulted in a mean score of  $9.2 \pm 0.5$ . Individual  
7 assessments can be found in Table 1, with study characteristics found in Table 2. On  
8 completion of data pooling, 38 comparisons (from 36 individual studies) were included in the  
9 analysis; 29 included a marker of muscle function, 23 included a marker of muscle soreness  
10 and 26 measured CK. A total of 389 younger adults and 390 older adults were included in the  
11 meta-analysis. As Easthope et al. (2010) did not include the sex of participants, the number  
12 of males and females is unknown. However, 6 comparisons include females only, 25 males  
13 only and 6 both female and male. Nine comparisons investigated EIMD in the upper-limb, with  
14 the remaining 29 reporting on EIMD in the upper-limbs.

15

16 INSERT TABLES 1 AND 2 HERE

17

### 18 **The effect of advancing age on muscle function after an exercise bout**

19 EIMD as determined by muscle function per age group at 24, 48, 72 hour, and peak  
20 comparisons changes are displayed in Figure 2. There were no differences between age  
21 groups at 24 (SMD = -0.28; 95% CI = -0.63, 0.08; Z = -1.54; P = 0.124), 48 (SMD = -0.35;  
22 95% CI = -0.71, 0.01; Z = -1.89; P = 0.059), or 72 hours (SMD = -0.16; 95% CI = -0.69, 0.38;  
23 Z = -0.58; P = 0.561), or for the peak change (SMD = -0.26; 95% CI = -0.59, 0.08; Z = -1.50;  
24 P = 0.132). Heterogeneity was moderate to high which justified the use of a random effects  
25 model ( $I^2 = 74$  to  $83\%$ ). No publication bias was detected for 48 and 72 hours comparisons.  
26 For 24 hour and peak comparisons 2 and 4 studies, respectively, needed to be removed to  
27 negate publication bias according to the Trim and Fill method (Rothstein et al., 2005). The  
28 removal of Lavender and Nosaka (2006) and Lavender and Nosaka (2007) (which fell outside  
29 of the funnel) for the 24 hours comparison removed the publication bias but did not alter the  
30 interpretation (SMD = -0.15; 95% CI = -0.46, 0.16; Z = -0.952; P = 0.341). The removal of four  
31 studies (Arroyo et al., 2017; Gorianovas et al., 2013; Lavender & Nosaka, 2006, 2007) that  
32 fell outside the funnel for peak comparison resulted in a similar observation as the original  
33 analysis (SMD = -0.04; 95% CI = -0.29, 0.22; Z = -0.278; P = 0.781) and removed the  
34 publication bias. We also noted that the study by Ploutz-Snyder et al. (2001) was an outlier as  
35 it repeatedly fell outside the funnel plot. The removal of the study at 24 hours (SMD = -0.36;  
36 95% CI = -0.67, -0.05; 0.14; Z = -2.25; P = 0.024) and for peak alterations (SMD = -0.33; 95%

1 CI = -0.63, 0.02; Z = -2.10; P = 0.036) achieved a Trim and Fill statistic of 0 in both cases and  
2 indicated greater losses in muscle function in the younger than older group.

3  
4 INSERT FIGURE 2 HERE

### 6 **The effect of advancing age on muscle soreness after an exercise bout**

7 EIMD as determined by muscle soreness for 24, 48, 72 hour and peak alterations are  
8 displayed in Figure 3. Muscle soreness was smaller in older adults than their younger  
9 counterparts at 24 (SMD = -0.61; 95% CI = -0.81, -0.41; Z = -6.04; P < 0.001), 48 (SMD = -  
10 0.34; 95% CI = -0.63, -0.06; Z = -2.34; P = 0.019) and 72 hours (SMD = -0.62; 95% CI = -0.98,  
11 -0.26; Z = -3.38; P < 0.001) and at its peak value (SMD = -0.42; 95% CI = -0.67, -0.18; Z = -  
12 3.40; P < 0.001). Heterogeneity was low for the 24-hour comparison (I<sup>2</sup>= 77%), but moderate  
13 for all other comparisons (I<sup>2</sup>= 46 to 57%). For all analyses the Trim and Fill method suggested  
14 no publication bias.

15  
16 INSERT FIGURE 3 HERE

### 18 **The effect of advancing age on creatine kinase after an exercise bout**

19 EIMD as determined by CK for 24, 48, 72 hour and peak concentrations are displayed in  
20 Figure 4. Creatine kinase at 24 hours after exercise (SMD = -0.28; 95% CI = -0.63, -0.08; Z =  
21 -2.54; P = 0.011) and for peak magnitude (SMD = -0.26; 95% CI = -0.59, 0.08; Z = -2.56; P =  
22 0.010) was smaller in older than younger adults. Differences between groups at 48 (SMD = -  
23 0.35; 95% CI = -0.71, 0.01; Z = -1.29; P = 0.197) and 72 (SMD = -0.16; 95% CI = -0.69, 0.38;  
24 Z = -1.78; P = 0.076) hours did not reach the P < 0.05 level. Heterogeneity was moderate for  
25 all comparisons (I<sup>2</sup>= 46 to 52%), justifying the use of a random effect model. For 24 and 72  
26 hours and peak analysis the Trim and Fill method suggested that no studies needed to be  
27 removed to reduce publication bias. According to the 48 hours comparison Trim and Fill  
28 statistic three studies needed to be removed; the removal of eradication of publication bias  
29 (removal of Borges et al. (2018), Gorianovas et al. (2013) and Nikolaidis et al. (2013)) did not  
30 alter interpretation (SMD = -0.02; 95% CI = -0.27, 0.23; Z = -0.177; P = 0.859). Therefore, we  
31 are confident results from the initial meta-analysis are robust against the analysis decisions.

32  
33 INSERT FIGURE 4 HERE

### 35 **Meta-regressions**

36 A random effects meta-regression revealed a significant relationship between sex and SMD  
37 (coefficient estimate = -0.12; 95% CI = -2.30, -1.14; P = 0.027), but no relationship of limb

1 involved (coefficient estimate = 0.09; 95% CI = -0.68, 0.86;  $P = 0.817$ ), or exercise type  
2 (coefficient estimate = 0.34; 95% CI = -0.39, 1.07;  $P = 0.367$ ). A random effects meta-  
3 regression examined the effects of limb involved (coefficient estimate = 0.40; 95% CI = -0.12,  
4 0.93;  $P = 0.131$ ), sex (coefficient estimate = -0.72; 95% CI = -0.91, 0.43;  $P = 0.475$ ), and  
5 exercise type (coefficient estimate = 0.07; 95% CI = -0.69, 0.56;  $P = 0.828$ ) on muscle  
6 soreness SMD and indicated no relationship. Similarly, the relationships between limb  
7 involved (coefficient estimate = -0.21; 95% CI = -0.91, 0.49;  $P = 0.554$ ), sex (coefficient  
8 estimate = -0.23; 95% CI = -0.42, 0.88;  $P = 0.491$ ), and exercise type (coefficient estimate = -  
9 0.14; 95% CI = -0.63, 0.36;  $P = 0.587$ ) on CK SMD were not significant. Subgroup analysis  
10 can be found in Table 3.

11

12 INSERT TABLE 3 HERE

13

#### 14 **Sensitivity analysis**

15 A *post-hoc* sensitivity analysis was performed by individually removing these comparisons  
16 from the main analysis. For muscle function, the removal of the Lavender and Nosaka's (2007)  
17 middle-aged versus young (SMD = -0.25;  $P = 0.161$ ), Lavender and Nosaka (2007) old versus  
18 young (SMD = -0.20;  $P = 0.218$ ), Trivisonno et al. (2021) upper-limb (SMD = -0.26;  $P = 0.149$ )  
19 and finally Trivisonno et al. (2021) lower-limb (SMD = -0.27;  $P = 0.138$ ) resulted in similar  
20 SMDs as the original analysis (SMD = -0.26;  $P = 0.132$ ). For muscle soreness, the removal of  
21 Trivisonno et al. (2021) upper-limb (SMD = 0.42;  $P = 0.001$ ) and Trivisonno et al. (2021) lower-  
22 limb (SMD = 0.42;  $P = 0.001$ ) did not change the interpretation of the original analysis (SMD  
23 = 0.42;  $P < 0.001$ ). The results of this sensitivity check justifies the inclusion of these  
24 comparisons in the main analysis.

25

#### 26 **Discussion**

27 This was the first study to 1) meta-analyse and systematically review the effect of age on  
28 markers of EIMD and 2) determine if sex, exercising limb and exercise modality moderated  
29 findings. Our results indicate that 1) muscle soreness is smaller in *older* compared to younger  
30 individuals after muscle damaging exercise, 2) *older* individuals present lower peak CK values,  
31 and lower values acutely (i.e., at 24 hours after exercise) compared to younger individuals, 3)  
32 there are no differences in muscle function responses between older and younger adult age  
33 groups 4) in the moderator analysis, sex affected muscle function SMD only. These data show  
34 that ageing is not associated with greater EIMD and should provide encouragement to those  
35 looking to increase physical activity habits in older adults.

36

1 Whilst some of the mechanisms which underpin [ageing holistically](#) suggest greater EIMD and  
2 impaired recovery (i.e., reduced muscle protein synthesis rates (Cuthbertson, 2004; Kumar et  
3 al., 2009), satellite cell count and proliferation (Ballak et al., 2015; Pietrangelo et al., 2009) in  
4 older adults, this is not reflected in the EIMD studies' findings. Indeed, the present investigation  
5 reveals there were no differences in acute strength decrements with [advancing](#) age. The lack  
6 of agreement between mechanistic and empirical EIMD findings might be explained, in part,  
7 by changes in skeletal muscle fatigability with age. Systematic reviews and meta-analyses  
8 have reported that older adults can experience greater muscular fatigue during dynamic  
9 contractions than younger adults (Christie et al., 2011; Krüger et al., 2018). Given all studies  
10 in this meta-analysis used dynamic contractions to initiate muscle damage, it is possible that  
11 older adults exhibit a reduced absolute load (e.g. work, force, torque, power), despite working  
12 at the same relative load, thereby reducing tissue damage compared younger individuals.  
13 Increases in cross linking, collagen content and advanced glycation end products with age  
14 can increase muscle stiffness (Haus et al., 2007; Kjær, 2004; Olson et al., 2021). Conversely,  
15 tendon degradation with ageing; could cause a decline in stiffness (Narici & Maganaris, 2007).  
16 Regardless, it is plausible that these changes result in altered dynamic stiffness during the  
17 eccentric component, thus improving the sarcomeres' ability to withstand lengthening.

18

19 Although there was no difference between the older and younger adults for muscle function  
20 changes after muscle-damaging exercise, there was a small effect of sex. SMDs were similar,  
21 but only the male comparison was significant, indicating a difference between older and  
22 younger males but not females. For a given protocol, even after accounting for fat free mass,  
23 men perform more work, are subjected to greater loads, and experience greater muscle  
24 damage than women (Heavens et al., 2014). [Additionally, oestrogen is thought to have a  
25 protective effect against skeletal muscle damage \(Kendall & Eston, 2002\). Oestrogen exhibits  
26 a high antioxidant capacity which could attenuate metabolic damage; cell membrane  
27 stabilising properties that could protect the structural integrity of muscle fibre units; and a gene  
28 regulatory effect that might inhibit the inflammatory response after muscle damage \(Kendall &  
29 Eston, 2002; Hayes et al., 2024\). Although the processes underpinning muscle damage are  
30 complex, it is possible that one, or a combination, of these factors could play a role in the  
31 reduction of muscle damage, and the maintenance of muscle function in females.](#) Given this  
32 pronounced disparity in sex responses, it might be that the age effect reported herein is  
33 diminished in females. Another consideration is the role of tendon stiffness, and the potential  
34 'mechanical buffer' this can provide during eccentric contractions (Hicks et al., 2016). Males  
35 exhibit greater patella tendon stiffness than females, and this results in greater vastus lateralis  
36 fascicle lengthening and potential structural damage in males during eccentric contractions  
37 (Hicks et al., 2013). However, when examining sex differences in fascicle lengthening, tendon

1 properties and the impact on function, Hicks and colleagues (Hicks et al., 2016) reported no  
2 differences between sexes for knee extension torque loss after EIMD. Another important factor  
3 is that [age associated losses in muscle mass](#) might also influence sex effects between  
4 younger and older individuals. The aetiology of skeletal muscle mass loss is complex, and  
5 factors such as declining anabolic hormone concentrations, nutritional deficiencies, chronic  
6 inflammation, insulin resistance and a reduction in physical activity have all been implicated  
7 (Abe et al., 2011). Several large-scale studies (Abe et al., 2011; Gallagher et al., 1997;  
8 Janssen et al., 2014) report that despite greater muscle mass in males compared to females  
9 at all ages, muscle mass loss with age was greater in men than in women. This could explain  
10 the sex-related disparity in age effects between the older and younger adults in that women  
11 maintain a greater proportion of their lean mass as they age, whereas older males will  
12 experience a much greater mechanical load per muscle fibre unit than their younger  
13 counterparts for a given protocol due to sarcopenic changes. The considerable heterogeneity  
14 in participant cohorts might have further confounded any potential age-effect in females. Some  
15 studies reported menstrual cycle phase information and whether older females were post-  
16 menopausal (Romero-Parra et al., 2021) others included oral contraceptive users (Conceição  
17 et al., 2012), or simply reported chronological age (Ploutz-Snyder et al., 2001). Lastly, four  
18 studies compared female muscle function changes, and 19 male muscle function changes.  
19 Given the female and male SMDs were similar, despite differences in significance, it is  
20 possible that this comparison was underpowered.

21

22 Increases in muscle soreness are because of the complex interaction of damage to the muscle  
23 structure and connective tissue, disrupted calcium homeostasis, sensitization of nociceptors  
24 from inflammatory cell infiltrates, and reductions in range of motion (Hlydahl & Hubal, 2014;  
25 Jamurtas et al., 2005; Nogueira et al., 2014; Nosaka et al., 2002). Our findings indicate that  
26 muscle soreness was small to moderately lower for older than younger adults from 24 to 72  
27 hours post-exercise and that the previously stated mechanisms were less severe in older than  
28 younger adults. Ageing leads to increased collagen concentrations in skeletal muscle  
29 connective tissues (Haus et al., 2007) which can stiffen both the muscle and connective tissue.  
30 In the same way that muscle undergoes an adaptation to EIMD, ageing might cause  
31 mechanical changes which improve dynamic and passive muscle stiffness (Hlydahl et al.,  
32 2017; McHugh, 2003). These age-related changes might offer some protection against  
33 structural damage and resultant soreness because of an improvement in dissipating  
34 myofibrillar stresses (Lapier et al., 1995). This is an important finding as muscle soreness can  
35 have negative effects on physical activity adherence, particularly for older individuals who  
36 perceive typical EIMD and soreness responses as causing 'more harm than good' (Hayes,  
37 Stevenson, Sayer, Granic, & Hurst, 2023; Schutzer & Graves, 2004). Moreover, recent work

1 has indicated the need to educate older adults on the post-exercise symptoms of soreness  
2 (Hurst et al., 2022). Thus, the message to older adults should be a positive one, in that muscle  
3 soreness is not worse than when they were younger or at least not worse than for their younger  
4 counterparts. Importantly, the peak magnitude of soreness experienced was not affected by  
5 sex, involved limb, or exercise type. The finding that there was no difference in soreness  
6 responses between males and females after EIMD, irrespective of exercise limb or type, is a  
7 novel addition to the literature. Thus, older adults can engage in physical activity that might  
8 induce muscle damage irrespective of their sex, the involved limb or exercise type, without  
9 fear of an 'increased' soreness response compared to younger individuals. Practically, this  
10 finding should provide encouragement to older adults and practitioners/clinicians working with  
11 those older populations who need to engage in physical activity.

12  
13 CK at 24 h after exercise, and at peak magnitude was smaller in older than younger adults.  
14 EIMD increases membrane permeability and causes muscle proteins to leak into the blood  
15 (Sorichter et al., 1999). However, CK demonstrates a poor temporal relationship with muscle  
16 function, a high intra- and interindividual variability (Damas et al., 2016; Fridén & Lieber, 2001),  
17 and most likely reflects only the occurrence of tissue damage rather than the magnitude  
18 (Fernandes, Lamb, Norris, et al., 2020; Owens et al., 2018). These data suggest that older  
19 adults exhibit less structural damage than their younger counterparts after muscle damaging  
20 exercise. It is plausible that many of the mechanisms mentioned above (e.g., changes in tissue  
21 stiffness) would explain the lower CK leakage in older adults. Nonetheless, CK demonstrates  
22 high interindividual variability, and there are differential responses between 'high' and 'low'  
23 responders (Clarkson & Dedrick, 1988). Thus, it is unsurprising that there was no effect of sex,  
24 involved limb, or exercise type on peak CK perturbations. Whilst these findings are important  
25 to report given the prevalence of CK as a marker to indicate the presence of muscle tissue  
26 damage, readers should interpret these data cautiously when other markers offer a more valid  
27 assessment of the EIMD magnitude.

28  
29 Whilst this study provides new insight into EIMD responses across the adult lifespan, it also  
30 highlights key areas for future research. Much like sport and exercise science research in  
31 general (Cowley et al., 2021), there remains a paucity of literature examining female  
32 responses to EIMD (Hayes et al., 2023). Such observations are likely to reflect the patriarchal  
33 nature of sport and exercise research (Caven et al., 2020; O'Malley & Greenwood, 2018).  
34 Previous work has suggested that there are sex-specific differences in the symptoms of EIMD  
35 (Hyldahl & Hubal, 2014), meaning future work should ensure that women are benefitting from  
36 the same quality and quantity of research on the topic (Cowley et al., 2021). Researchers must  
37 now improve equity in the literature and future studies must consider the cyclical (i.e.,

1 menstrual cycle), exogenous (i.e., oral contraceptives) and age-related (i.e., menopause)  
2 changes in female sex hormones on EIMD between age groups (Hayes et al., 2023). With  
3 more older athletes and increased interest in 'successful ageing', further studies investigating  
4 the efficacy of recovery strategies in older individuals are also warranted. Though some  
5 symptoms of EIMD are attenuated with ageing, older adults still experience muscle damage.  
6 Moreover, the implications of reduced muscle strength, and muscle soreness, after muscle-  
7 damaging exercise could have more severe negative consequences for older adults than their  
8 younger counterparts (e.g. increasing fall risk). Therefore, improved understanding of recovery  
9 strategies in older populations might increase exercise adherence and long-term health  
10 benefits. Thirdly, there appears to be a perception that ageing is associated with greater EIMD,  
11 particularly muscle soreness (Fernandes, Lamb, Norris, et al., 2020; Reaburn & Fernandes,  
12 2023), although this is not reflected in the intervention studies presented here. Therefore,  
13 future studies should seek to both understand why older adults perceive muscle damage to  
14 be greater and establish methods to effectively disseminate the current evidence. This would  
15 be particularly useful for those using physical activity to improve their health. If future research  
16 in older adults is concerned with lifelong physical activity, it would be useful if this was reflected  
17 in the muscle damaging protocols employed (Hayes et al., 2024). For example, using protocols  
18 that mirror activities of daily living will provide benchmarks from which to investigate damage  
19 and recovery responses, rather than those solely designed to induce greater magnitudes of  
20 muscle damage. Lastly, one of the emergent themes here was that older adults might  
21 experience less muscle damage because the external load during exercise is less, due to  
22 dynapenia and age-related increases in exercise fatigue. A study which standardises the  
23 external load during muscle-damaging exercise or investigates the recovery from a set force  
24 decrement between age groups would help determine the extent to which external load is  
25 mediating muscle damage and recovery between age groups.

26

27 The studies included within this manuscript compared two different age groups, rather than  
28 investigating ageing directly. Readers should therefore be aware of the cross-sectional nature  
29 of the studies included. Whilst this could provide a direction for future research, conducting  
30 studies over the course of ~20+ years is challenging. We did not utilise age thresholds  
31 because of differences in chronological and biological age (Balcombe & Sinclair, 2001) and  
32 the changing nature of terms such as 'middle-aged' or 'old' (Orimo et al., 2006). Moreover, as  
33 this study sought to examine the effects of **advancing** age (i.e. and older group compared to  
34 a younger group) on EIMD responses, it was not deemed necessary to define specific age  
35 category thresholds for included studies. However, future **studies** may seek to clarify the  
36 definitions of different age groups and determine the effects of EIMD on distinct age groups.

37



1 **Conclusion**

2 The findings from this meta-analysis suggest **advancing** age is not associated with greater  
3 muscle damage and a prolonged recovery from EIMD. Indeed, we demonstrated that there  
4 were no differences in muscle function changes between older and younger adults, but that  
5 older adults exhibited smaller increases in muscle soreness and CK after exercise. Generally,  
6 there did not appear to be any effect of sex, involved limb, or exercise type on the observed  
7 results. These findings indicate that older adults can, and should, pursue regular physical  
8 activity without concerns for experiencing greater EIMD compared to younger counterparts.  
9 Given a lack of female participants included in the pooled analysis for all EIMD markers, future  
10 research should focus on understanding EIMD and recovery responses in older females.  
11 These findings should provide confidence to older adults engaging in physical activity and  
12 those practitioners and clinicians who work with them.

13

14 **Disclosure of interests**

15 There are no conflicts of interest.

16

17 **References**

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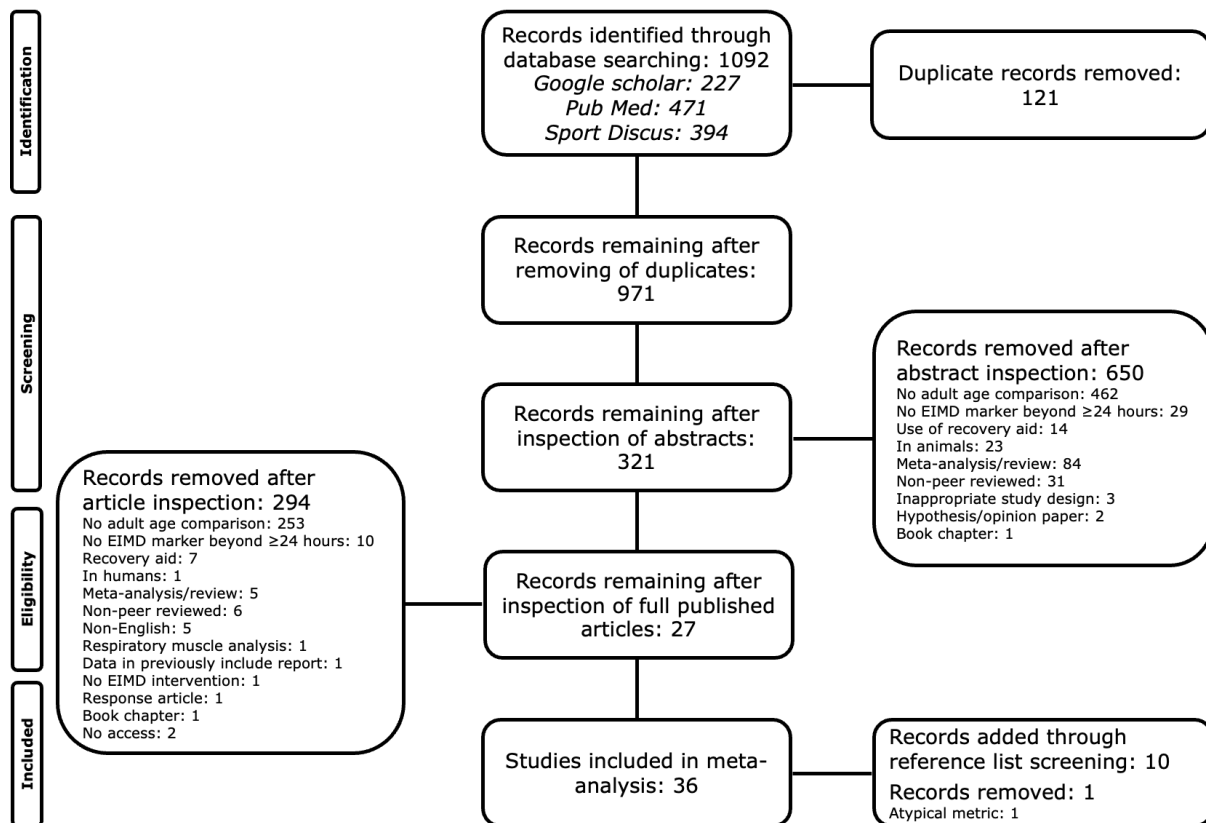
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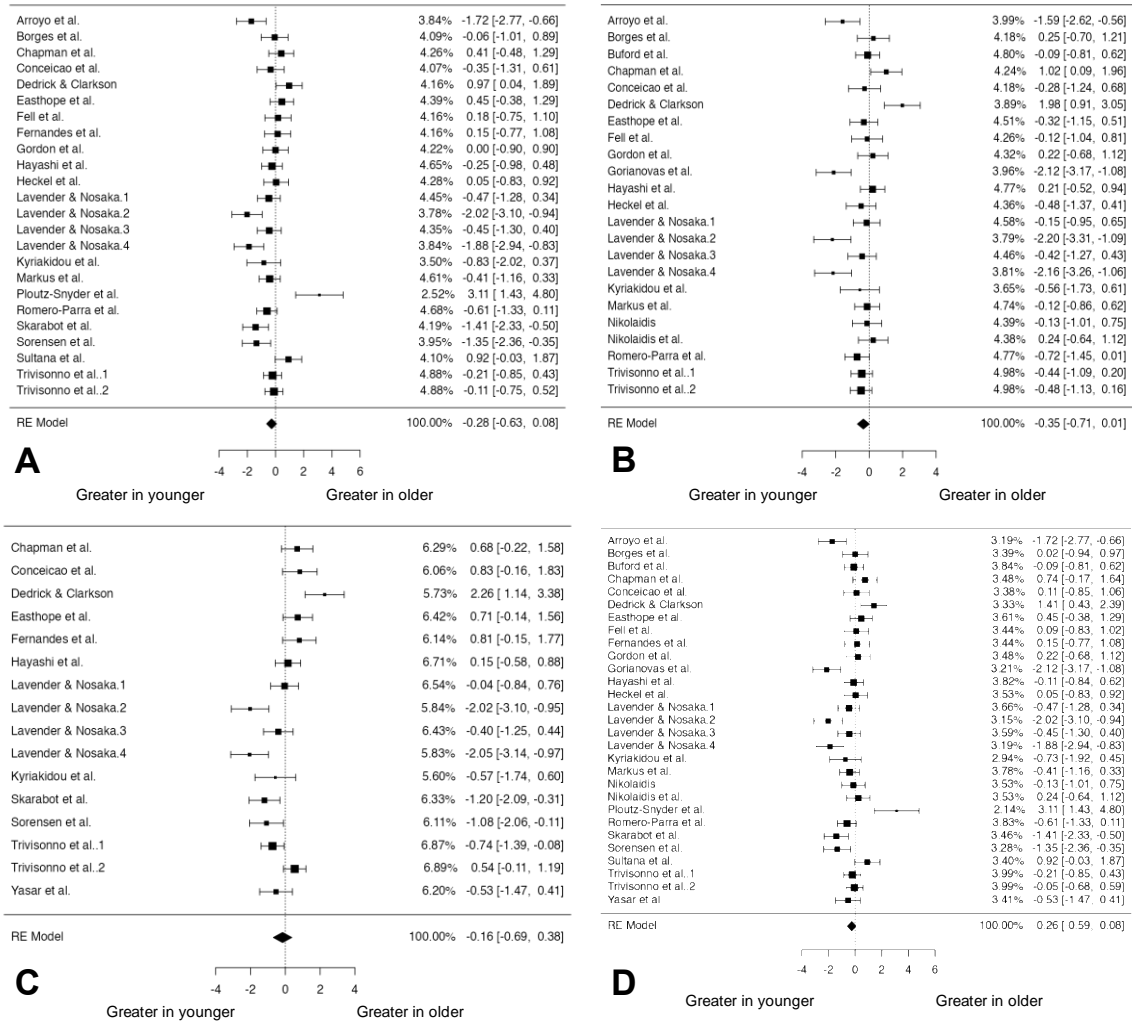
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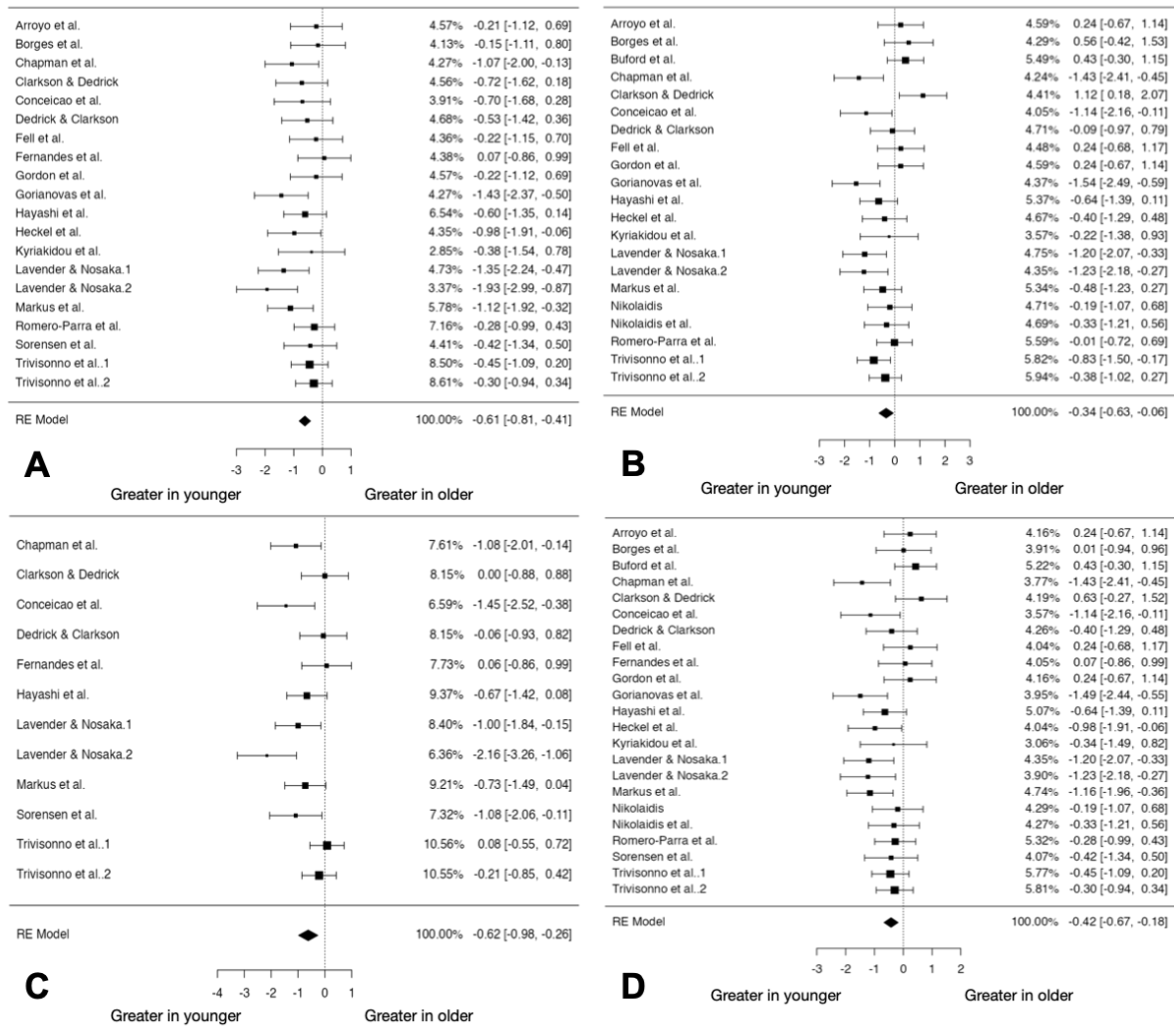
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**Figure 1.** PRISMA Flow diagram displaying inclusion and exclusion of studies. EIMD = exercise-induced muscle damage.



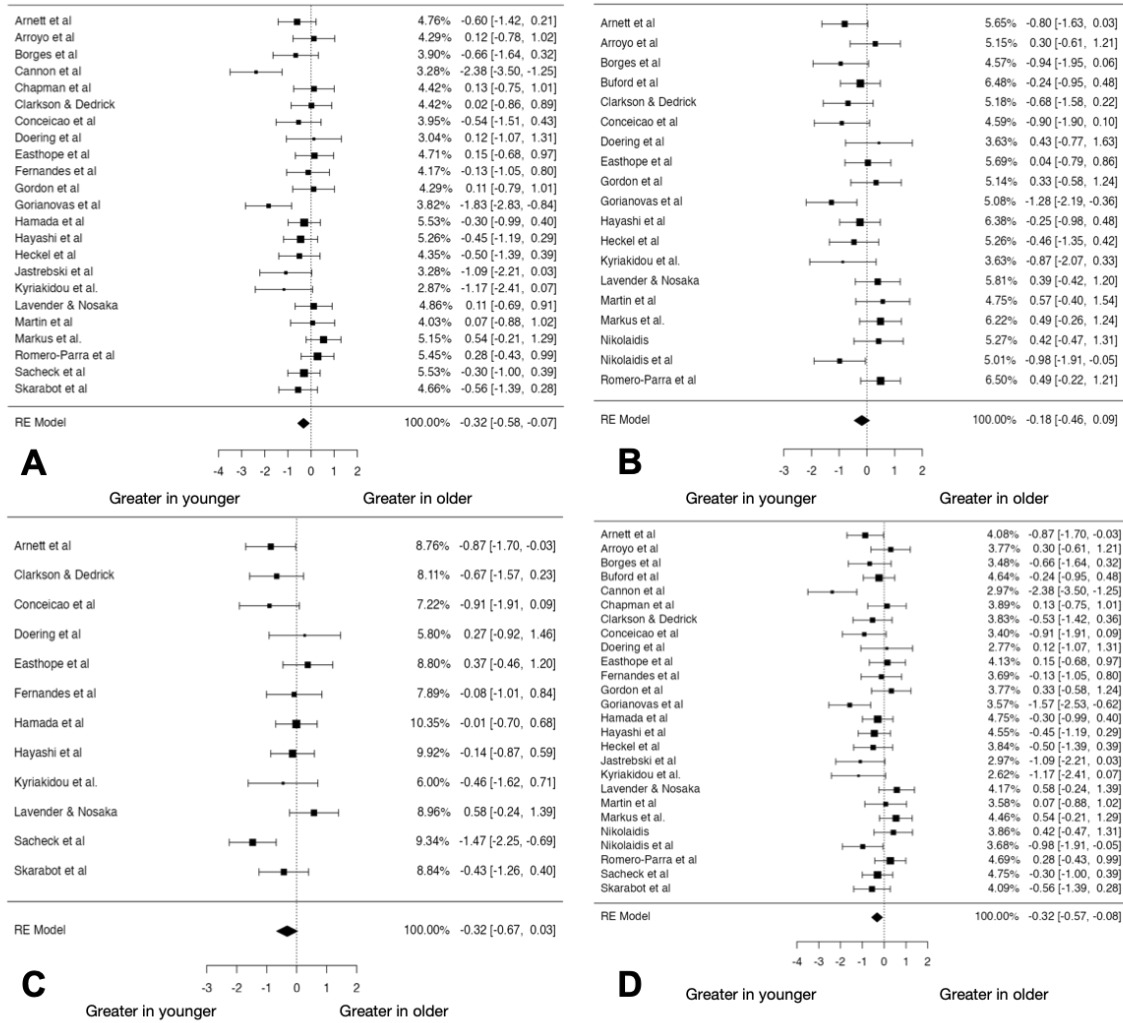
**Figure 2.** Forest plot of studies examining changes in muscle function at 24 (A), 48 (B) and 72 hours (C), and for peak changes (D) for older and young adults. Data are presented as the percentage weight each study contributes to the pooled standardised mean difference (SMD), and individual SMD [95% CIs]. Note that symbol size of individual studies is representative of the weighting towards the pooled SMD. The filled diamond indicates overall SMD. RE = random effects model. Lavender and Nosaka 1 and 2 are articles from (Lavender & Nosaka, 2008) and (Lavender & Nosaka, 2006), respectively. Lavender and Nosaka 3 and 4 are the young adult versus middle-aged and older adult comparisons (Lavender & Nosaka, 2007), respectively. Trivisonno et al. 1 and 2 are the upper- and lower-body comparisons, respectively (Trivisonno et al., 2021).

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2 **Figure 3.** Forest plot of studies examining muscle soreness at 24 (A), 48 (B) and 72 hours  
3 (C), and for peak changes (D) for older and younger adults. Data are presented as the  
4 percentage weight each study contributes to the pooled SMD, individual SMD [95% CIs]. Note  
5 that symbol size of individual studies is representative of the weighting toward the pooled  
6 SMD. The filled diamond indicates overall SMD. RE = random effects model. Lavender and  
7 Nosaka 1 and 2 are articles from (Lavender & Nosaka, 2008) and (Lavender & Nosaka, 2006),  
8 respectively. Trivisonno et al 1 and 2 are the upper- and lower-body comparisons  
9 (Trivisonno et al., 2021).

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2 **Figure 4.** Forest plot of studies examining changes in CK at 24 (A), 48 (B) and 72 hours (C),  
3 and for peak changes (D) for older and younger adults. Data are presented as the percentage  
4 weight each study contributes to the pooled SMD, individual SMD [95% CIs]. Note that symbol  
5 size of individual studies is representative of the weighting towards the pooled SMD. The filled  
6 diamond indicates overall SMD. RE = random effects model.

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**Table 1.** The National Institute of Health Quality Assessment Ratings

	Was the study question or objective clearly stated?	Were eligibility/selection criteria for the study population prespecified and clearly described?	Were the participants in the study representative of those who would be eligible for the test/service/intervention in the general or clinical population of interest?	Were all eligible participants that met the prespecified entry criteria enrolled?	Was the sample size sufficiently large to provide confidence in the findings?	Was the test/service/intervention clearly described and delivered consistently across the study population?	Were the outcome measures prespecified, clearly defined, valid, reliable, and assessed consistently across all study participants?	Were the people assessing the outcomes blinded to the participants' exposures/interventions?	Was the loss to follow-up after baseline 20% or less? Were those lost to follow-up accounted for in the analysis?	Did the statistical methods examine changes in outcome measures from before to after the intervention? Were statistical tests done that provided p values for the pre-to-post changes?	Were outcome measures of interest taken multiple times before the intervention and multiple times after the intervention?	If the intervention was conducted at a group level did the statistical analysis take into account the use of individual-level data to determine effects at the group level?	Criterion fulfilled
Arnett et al., (2000)	1	1	1	1	0	1	1	0	1	1	0	1	9 (64.3%)
Arroyo et al., (2017)	1	1	1	1	1	1	1	0	1	1	0	1	10 (71.4%)
Borges et al., (2015)	1	1	1	1	0	1	1	0	1	1	0	1	9 (64.3%)
Buford et al., (2014)	1	1	1	1	0	1	1	0	1	1	0	1	9 (64.3%)
Cannon et al., (1994)	1	1	1	1	1	1	1	0	1	1	0	1	10 (71.4%)
Chapman et al., (2008)	1	1	1	1	1	1	1	0	1	1	0	1	10 (71.4%)
Clarkson & Dedrick (1988)	1	1	1	1	0	1	1	0	1	1	0	1	9 (64.3%)
Conceição et al., (2012)	1	1	1	1	1	1	1	0	1	1	0	1	10 (71.4%)
Dedrick & Clarkson (1990)	1	1	1	1	0	1	1	0	1	1	0	1	9 (64.3%)
Doering et al., (2016)	1	1	1	1	0	1	1	0	1	1	0	1	9 (64.3%)
Easthope et al., (2010)	1	1	1	1	0	1	1	0	1	1	0	1	9 (64.3%)
Fell et al., (2006)	1	1	1	1	0	1	1	0	1	1	0	1	9 (64.3%)
Fell et al., (2008)	1	1	1	1	0	1	1	0	1	1	0	1	9 (64.3%)
Fernandes et al., (2019)	1	1	1	1	1	1	1	0	1	1	0	1	10 (71.4%)
Gordon III et al., (2017)	1	1	1	1	0	1	1	0	1	1	0	1	9 (64.3%)
Gorianovas et al., (2013)	1	1	1	1	1	1	1	0	1	1	0	1	10 (71.4%)
Hamada et al., (2005)	1	1	1	1	0	1	1	0	1	1	0	1	9 (64.3%)
Hayashi et al., (2019)	1	1	1	1	0	1	1	0	1	1	0	1	9 (64.3%)
Heckel et al., (2019)	1	1	1	1	0	1	1	0	1	1	0	1	9 (64.3%)
Jastrzębski et al., (2015)	1	1	1	1	0	1	1	0	1	1	0	1	9 (64.3%)
Kyriakidou et al., (2021)	1	1	1	1	0	1	1	0	1	1	0	1	9 (64.3%)
Lavender & Nosaka (2006)	1	1	1	1	0	1	1	0	1	1	0	1	9 (64.3%)
Lavender & Nosaka (2007)	1	1	1	1	0	1	1	0	1	1	0	1	9 (64.3%)
Lavender & Nosaka (2008)	1	1	1	1	1	1	1	0	1	1	0	1	10 (71.4%)
Markus et al., (2022)	1	1	1	1	1	1	1	0	1	1	0	1	10 (71.4%)
Martin et al., (2015)	1	1	1	1	1	1	1	0	1	1	0	1	10 (71.4%)
Nikolaidis et al., (2013)	0	1	1	1	1	1	1	0	1	1	0	1	9 (64.3%)
Nikolaidis (2017)	1	1	1	1	0	1	1	0	1	1	0	1	9 (64.3%)
Ploutz-Snyder et al., (2001)	1	1	1	1	0	1	1	0	1	1	0	1	9 (64.3%)
Romero-Parra et al., (2021)	1	1	1	1	0	1	1	0	1	1	0	1	9 (64.3%)
Sacheck et al., (2003)	1	1	1	1	0	1	1	0	1	1	0	1	9 (64.3%)
Škarabot et al., (2019)	1	1	1	1	1	1	1	0	1	1	0	1	10 (71.4%)
Sorensen et al., (2018)	1	1	1	1	0	1	1	0	1	1	0	1	9 (64.3%)
Sultana et al., (2012)	1	1	1	1	0	1	1	0	1	1	0	1	9 (64.3%)
Trivisonno et al., (2021)	1	1	1	1	0	1	1	0	1	1	0	1	9 (64.3%)
Yasar et al., (2021)	1	1	1	1	0	1	1	0	1	1	0	1	9 (64.3%)
<b>Studies fulfilled</b>	<b>35 (97.2%)</b>	<b>36 (100%)</b>	<b>36 (100%)</b>	<b>36 (100%)</b>	<b>11 (30.6%)</b>	<b>36 (100%)</b>	<b>36 (100%)</b>	<b>0 (0%)</b>	<b>36 (100%)</b>	<b>36 (100%)</b>	<b>0 (0%)</b>	<b>36 (100%)</b>	

**Table 2.** Characteristics of included studies

	Younger		Older		Sex	Activity level	Muscle	EIMD protocol	EIMD markers	
	Age	n	Exercise type	Age						n
Arnett et al., (2000)	23.4 ± 6.9	15	Resistance	59.4 ± 10.9	10	F	Untrained	KF	6 x 10 ECC at 110% CON 1RM	CK
Arroyo et al., (2017)	21.8 ± 2.2	9	Resistance	47.0 ± 4.4	10	M	Recreationally active	KE	8 x 10 CON-ECC at 60 deg°s <sup>-1</sup>	Strength, soreness, CK
Borges et al., (2015)	25.9 ± 3.0	8	Aerobic Intermittent	55.6 ± 5.0	9	M	Well trained	LB	6 x 30 s intervals at 175% peak aerobic power	Strength, soreness, CK
Buford et al., (2014)	22.5 ± 3.7	15	Resistance	75.8 ± 5.0	15	M & F	Physically active	PF	150 unilateral eccentrics at 110% 1RM	Strength, soreness, CK
Cannon et al., (1994)	20 – 32	9	Aerobic	61 – 72	12	M & F	Sedentary	LB	45mins eccentric cycling at 78 ± 5 max HR and downhill running (-16% slope) for 45 min at 77 ± 2% max HR	CK
Chapman et al., (2008)	25.0 ± 5.69	10	Resistance	64.0 ± 3.79	10	M	No prior resistance training	EF	5 x 6 eccentric at 210 deg°s <sup>-1</sup> from 60 to 180 deg° flexion	Strength, soreness, CK
Clarkson & Dedrick (1988)	23.6 ± 3.3	10	Resistance	67.4 ± 5.3	10	F	Mixed, all healthy	FF	24 unilateral eccentric contractions at 110% MIVC	Soreness, CK
Conceição et al., (2012)	23.9 ± 2.0	9	Resistance	51.1 ± 5.1	8	F	Healthy, no resistance training	EF	5 x 6 max eccentrics at 30 deg°s <sup>-1</sup>	Strength, soreness, CK
Dedrick & Clarkson (1990)	23.6 ± 3.3	10	Resistance	67.4 ± 5.2	10	F	Healthy & active	FA	24 unilateral eccentric contractions at 115% MIVC	Strength, soreness
Doering et al., (2016)	27.0 ± 2.0	6	Aerobic	53.0 ± 2.0	5	M	Well trained	LB	30 min downhill running (-10% slope) at 70% $\dot{V}O_{2max}$	CK
Easthope et al., (2010)	30.5 ± 7.0	10	Aerobic	45.9 ± 5.9	13	NS	Long distance runners	LB	55 km trail run	Strength, CK
Fell et al., (2006)	24.0 ± 5.0	9	Concentric Aerobic	45.0 ± 6.0	9	M & F	Well trained	LB	3 x 30 min TT on consecutive days	Strength
Fell et al., (2008)	24.0 ± 5.0	9	Aerobic	45.0 ± 6.0	9	M	Well trained	LB	3 x 30 min TT on consecutive days	Strength, soreness
Fernandes et al., (2019)	22.3 ± .7	9	Resistance	39.9 ± 6.2	9	M	Resistance trained	LB	10 x 10 eccentric squats at 60% 1RM, 3 s eccentric	Strength, soreness, CK
Gordon III et al., (2017)	21.8 ± 2.2	9	Resistance	47.0 ± 4.4	10	M	Recreationally trained	KE	8 x 10 CON-ECC at 60 deg°s <sup>-1</sup>	Strength, soreness, CK

Gorianovas et al., (2013)	20.8 ± 1.9	11	Plyometric	63.2 ± 3.6	11	M	Healthy, untrained	LB	100 intermittent drop jumps from 50cm box with 30 s rest between jumps	Strength, soreness, CK
Hamada et al., (2005)	26.3 ± 3.49	16	Eccentric aerobic	70.7 ± 3.87	16	M	Physically active	LB	3 x 15 min downhill running (-16% slope) at 75% $\dot{V}O_{2max}$	CK
Hayashi et al., (2019)	26.8 ± 6.97	15	Eccentric aerobic	57.5 ± 8.61	14	M & F	Aerobically trained	LB	3 x 15 min downhill running (-16% slope) at 65% $\dot{V}O_{2max}$	Strength, soreness, CK
Heckel et al., (2019)	25.1 ± 4.9	10	Resistance	64.5 ± 5.5	10	M	Physically active	KE	4 x 15 eccentric-concentric at 60 deg°s <sup>-1</sup> between 20 and 80 deg° range	Strength, soreness, CK
Jastrzębski et al., (2015)	32.0 ± 5.3	7	Aerobic	50.6 ± 9.7	7	M	Experienced ultra-marathon runner	LB	100 km run	CK
Kyriakidou et al., (2021)	27.0 ± 1.5	7	Resistance	63.0 ± 1.0	5	M	Habitually physically active	KE	5 x 10 leg press at 120% 1RM, 2 x 10 at 100% 1RM. All with 3-5 s eccentric	Strength, soreness, CK
Lavender & Nosaka (2006)	19.4 ± 1.26	10	Resistance	70.5 ± 4.74	10	M	Physically active no resistance training	EF	6 x 5 max eccentric at 40% MIVC from 90 to 180 deg° flexion	Strength, soreness, CK
Lavender & Nosaka (2007)	20.4 ± 2.0	10	Resistance	48.0 ± 7.3	12	M	Healthy, not resistance trained	EF	6 x 5 max eccentric at 40% MIVC from 90 to 180 deg° flexion	Strength
				70.5 ± 4.1	10					
Lavender & Nosaka (2008)	19.4 ± 1.39	12	Resistance	48.0 ± 7.27	12	M	Habitually active no resistance training	EF	6 x 5 max eccentric at 40% MIVC from 90 to 180 deg° flexion	Strength, soreness, CK
Markus et al., (2022)	26.1 ± 2.9	14	Aerobic	43.6 ± 4.1	14	M	Competitive runners/triathletes	KE	60 min downhill running (-10% slope) at 60% heart rate max	Strength, soreness, CK
Martin et al., (2015)	31.9 ± 5.0	9	Aerobic	63.1 ± 4.6	8	M	Marathon runners	LB	Marathon run	CK
Nikolaidis et al., (2013)	20.6 ± 1.58	10	Resistance	64.6 ± 3.48	10	M	Healthy, moderately inactive	KE	5 x 8 eccentric MVC 0 to 90 deg° range at 60 deg°s <sup>-1</sup> 2 min rest	Strength, soreness, CK
Nikolaidis (2017)	22.1 ± 3.9	10	Resistance	66.9 ± 5.4	10	M	Untrained, healthy	LB	5 x 15 eccentric biased squats with 2 min rest. 2 s eccentric phase	Strength, soreness, CK
Ploutz-Snyder et al., (2001)	23 ± 4	6	Resistance	66 ± 5	6	F	Sedentary	KE	10 x 10 eccentric knee extensions at 75% eccentric 1RM	Strength
Romero-Parra et al., (2021)	29.0 ± 6.0	19	Resistance	52.0 ± 4.0	13	F	Well trained	LB	10 x 10 eccentric squats at 60% 1RM, 4 s eccentric	Strength, soreness, CK
Sacheck et al., (2003)	26.4 ± 3.3	16	Aerobic	69.3 ± 3.5	16	M	Physically active	LB	3 x 15 min downhill running (-16% slope) at 75% $\dot{V}O_{2max}$	CK

Škarabot et al., (2019)	27.0 ± 5.0	12	Resistance	66.0 ± 4.0	11	M	Physically active	DF	10 x 6 eccentrics at 15 deg°s <sup>-1</sup> from 10 to 40° range	Strength, CK
Sorensen et al., (2018)	22.7 ± 2.3	11	Resistance	70.9 ± 7.5	8	M & F	Physically active	KE	30 x 10 maximal lengthening contractions at 120 deg°s <sup>-1</sup>	Strength, Soreness
Sultana et al., (2012)	28.4 ± 6.1	9	Aerobic	52.2 ± 10.0	10	M	Well trained	LB	Olympic distance triathlon	Strength
Trivisonno et al., (2021)	25.5 ± 3.4	19	Aerobic	50.3 ± 3.5	19	M	Resistance trained career firefighters	FB	8–10 and 4–6 repetitions with 1 min of rest between sets on 4 exercises.	Strength, Soreness
Yasar et al., (2021)	24 ± 3	9	Aerobic intermittent	70 ± 8	9	M & F	Physically active	LB	3 x 20 s maximal sprint efforts with 3 mins rest between	Strength

*Note*; NS = not stated; F = female; M = male; LB = lower body; KF = knee flexors; FF = forearm flexors; EF = elbow flexors; KE = knee extensors; EE = elbow extensors; DF = dorsiflexors; ECC = eccentric; CON = concentric; RM = repetition maximum; HR = heart rate; MIVC = maximal isometric voluntary contraction; CK = creatine kinase.



1 **Table 3.** Effect

		Younger (n)	Older (n)	Z	P	SMD (95% CIs)	I <sup>2</sup> (%)
<b>Muscle function</b>	<b><i>Involved limb</i></b>						
	Upper (k = 8)	90	91	-0.83	0.409	-0.33 (-1.11, 0.45)	84
	Lower (k = 21)	231	225	-1.27	0.203	-0.24 (-0.60, 0.13)	71
	<b>Sex</b>						
	Female (k = 4)	44	37	0.44	0.663	-0.44 (-0.89, 0.01)	88
	Male (k = 19)	191	192	-2.26	0.024	-0.45 (-0.85, -0.06)	73
	<b>Exercise type</b>						
	Resistance (k = 21)	212	202	-1.30	0.193	-0.28 (-0.70, 0.14)	79
	Aerobic (k = 7)	66	69	0.18	0.857	-0.03 (-0.32, 0.38)	14
<b>Muscle soreness</b>	<b><i>Involved limb</i></b>						
	Upper (k = 4)	41	40	0.45	0.657	-0.15 (-0.80, 0.50)	53
	Lower (k = 22)	246	238	-2.56	0.010	-0.36 (-0.63, -0.08)	53
	<b>Sex</b>						
	Female (k = 4)	53	46	-1.90	0.057	-0.44 (-0.89, 0.01)	34
	Male (k = 18)	185	183	-1.56	0.12	-0.22 (-0.51, -0.06)	44
	<b>Exercise type</b>						
	Resistance (k = 15)	166	153	-1.50	0.133	-0.21 (-0.49, 0.06)	33
	Aerobic (k = 10)	110	114	-1.62	0.106	-0.38 (-0.83, 0.08)	63
<b>Creatine kinase</b>	<b><i>Involved limb</i></b>						
	Upper (k = 4)	41	40	0.45	0.657	-0.15 (-0.80, 0.50)	53
	Lower (k = 20)	225	219	-2.72	0.007	-0.34 (-0.59, -0.09)	49
	<b>Sex</b>						
	Female (k = 4)	53	46	-1.90	0.057	-0.44 (-0.89, 0.01)	34
	Male (k = 16)	164	164	-2.29	0.022	-0.34 (-0.64, -0.05)	53
	<b>Exercise type</b>						
	Resistance (k = 24)	159	148	-1.22	0.223	-0.17 (-0.45, -0.10)	31
	Aerobic (k = 9)	96	100	-2.15	0.031	-0.48 (-0.92, -0.04)	54

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