

## **Aging and recovery after resistance-exercise-induced muscle damage: Current evidence and implications for future research**

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**1 Ageing and recovery after resistance exercise-induced muscle damage:**

**2 Current evidence and implications for future research**

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**1 Abstract**

2 Ageing is anecdotally associated with a prolonged recovery from resistance training,  
3 though current literature remains equivocal. This brief review considers the effects of  
4 resistance training on indirect markers of muscle damage and recovery (i.e. muscle  
5 soreness, blood markers and muscle strength) in older males. With no date  
6 restrictions, four databases were searched for articles relating to ageing, muscle  
7 damage and recovery. Data from 11 studies was extracted for review. Of these four  
8 reported worse symptoms in older compared to younger populations, while two have  
9 observed the opposite, and the remaining studies (n = 6) proposing no differences  
10 between age groups. It appears that resistance training can be practiced in older  
11 populations without concern for impaired recovery. To improve current knowledge,  
12 researchers are urged to utilise more ecologically valid muscle damaging bouts and  
13 investigate the mechanisms which underpin the recovery of muscle soreness and  
14 strength after exercise in older populations.

**15 Key words**

16 Fatigue, muscle soreness, muscle strength, sarcopenia, dynapenia

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## 1 **Introduction**

2 It is predicted that the global population will grow to 11.18 billion by the year 2100  
3 (United Nations, 2017). This growth will incorporate an increasing proportion of  
4 people classified as older adults, with those over the age of 60 expected to increase  
5 from 0.91 billion in 2015 to 3.14 billion (United Nations, 2017). Improvements in  
6 medical care, a decline in the leading causes of mortality and a better appreciation of  
7 the factors that enhance longevity contribute to such demographic transformations  
8 (Baker & Tang, 2010; Ferrucci, Giallauria, & Guralnik, 2008). Despite these  
9 demographic transformations, the ageing process remains associated with losses in  
10 muscle mass (i.e. sarcopenia) (Lexell, Taylor, & Sjöström, 1988), and strength and  
11 power (i.e. dynapenia) (Fernandes, Lamb, & Twist, 2018a). In addition, these losses  
12 are not uniform with strength and power declining faster than muscle mass into older  
13 age (Clark & Manini, 2008, 2012), and lower-body regions displaying greater rates of  
14 sarcopenia and dynapenia than the upper-body (Fernandes et al., 2018a; Frontera et  
15 al., 2000). For the general population, sarcopenia and dynapenia have a negative  
16 impact on quality of life and daily functioning (Cruz-Jentoft et al., 2010) and, for the  
17 growing numbers of ageing athletes (Lepers, Rüst, Stapley, & Knechtle, 2013;  
18 Tanaka & Seals, 2008), are likely contributors to age-related declines in athletic  
19 performance (Baker & Tang, 2010; Pantoja, Saez De Villarreal, Brisswalter, Peyré-  
20 Tartaruga, & Morin, 2016). Resistance training provides a potent method of offsetting  
21 these age-associated changes (Bottaro, Machado, Nogueira, Scales, & Veloso,  
22 2007; Kongsgaard, Backer, Jørgensen, Kjær, & Beyer, 2004; Newton et al., 2002;  
23 Sayers & Gibson, 2010, 2014) and, as such, is included in national physical activity  
24 guidelines (Department of Health and Social Care, 2019). However optimal

1 management of resistance training dosing for older populations remains challenging  
2 given concerns around impaired recovery.

3 An acute consequence of unaccustomed resistance training is exercise-  
4 induced muscle damage (EIMD) which involves damage to the muscle ultrastructure,  
5 particularly when it comprises high-volume and/or eccentrically biased muscle  
6 actions (Hortobágyi et al., 1998; Roth et al., 1999). During the eccentric component  
7 of muscle actions, lengthening is non-uniform and weaker sarcomeres extend  
8 beyond their myofilament overlap and fail to re-interdigitate (Hyldahl & Hubal, 2014;  
9 Morgan & Proske, 2004). This causes an increased stress per myofibre that is  
10 consistent with eccentric contractions and is known as the 'popping-sarcomere  
11 hypothesis' (Morgan & Proske, 2004). Thereafter, a loss of calcium homeostasis  
12 leads to excitation-contraction (E-C) coupling dysfunction and a prolonged loss of  
13 muscle strength (Damas, Nosaka, Libardi, Chen, & Ugrinowitsch, 2016; Hyldahl &  
14 Hubal, 2014; Morgan & Proske, 2004). Irrespective of the mechanisms, indirect  
15 markers of EIMD such as muscle soreness, and intramuscular enzymes in the blood  
16 are commonly used to indicate EIMD (Damas et al., 2016; Fernandes, Lamb, &  
17 Twist, 2018b; Hyldahl & Hubal, 2014). These indirect markers are highly  
18 individualised and often do not reflect the magnitude of EIMD (Damas et al., 2016;  
19 Fridén & Lieber, 2001; Nosaka, Newton, & Sacco, 2002), such that quantifying  
20 changes in muscle function (i.e. strength and power) offers the most relevant marker  
21 of EIMD (Damas et al., 2016). This notwithstanding, best practice, from a research  
22 and practitioner perspective often takes a holistic view and measures a variety of  
23 indirect markers when assessing EIMD.

24 Muscle damage is a natural response to resistance training leading to cellular,  
25 mechanical and neural changes that enhance muscle function, reduce damage in

1 subsequent bouts of resistance training (Burt, Lamb, Nicholas, & Twist, 2015;  
2 Hyldahl, Chen, & Nosaka, 2017; McHugh, 2003) and might be a key requirement for  
3 skeletal muscle hypertrophy (Schoenfeld, 2010). Exposure to muscle damage should  
4 therefore not be discouraged in older populations. However, ageing is anecdotally  
5 associated with an impaired recovery from resistance induced muscle damage. The  
6 responses to EIMD in older individuals remain equivocal, with some research  
7 reporting worse symptoms of EIMD in older compared to young populations  
8 (Chapman, Newton, McGuigan, & Nosaka, 2008; Fernandes, Lamb, & Twist, 2019;  
9 Nikolaidis, 2017; Nikolaidis et al., 2013), some suggesting worse symptoms in young  
10 compared to old (Lavender & Nosaka, 2006, 2007), and others proposing no age  
11 differences in EIMD (Arroyo et al., 2017; Buford et al., 2014; Gordon III et al., 2017;  
12 Heckel et al., 2019; Lavender & Nosaka, 2008). These discrepancies between  
13 studies might be attributable to factors such as different protocols (e.g. single- versus  
14 multi-jointed), muscle groups used (e.g. upper- versus lower-body), activity status of  
15 the participants (e.g. trained versus untrained) and large inter-individual variability in  
16 the indirect markers of muscle damage measured (Damas et al., 2016). Therefore, a  
17 review of the current literature is required to provide sport and clinical practitioners  
18 with a greater understanding of EIMD and recovery time course for older adults.  
19 Moreover, greater understanding of the fatigue and recovery time course with ageing  
20 would provide older populations, clinicians and practitioners with a framework to  
21 facilitate the prescription of appropriate targeted recovery strategies and  
22 periodisation of resistance training within a micro-cycle (Clifford, 2019). As such, the  
23 aim of this review was to explore the effects of resistance training on indirect  
24 markers of EIMD (i.e. muscle function, soreness and circulating proteins) throughout  
25 the recovery process in older males. Additionally, the review sought to describe the

1 current limitations within this area of investigation and subsequently provide scope  
2 for future research.

3

#### 4 **Outline of terms**

5 Establishing a definition of what encompasses 'young', 'middle-aged' and 'old' is  
6 problematic because chronological and biological age are not always the same  
7 (Balcombe & Sinclair, 2001). Moreover, as life expectancy increases and the quality  
8 of life of older populations improves, what constitutes these terms will likely change  
9 (Orimo et al., 2006). As such, the use of young, middle-aged and old in this  
10 manuscript are based upon the age groups used in the reviewed articles. Typically,  
11 this constitutes young, middle-aged and old age groups as 18-25, 35-60 and >60  
12 years, respectively. Whilst it would be advantageous to establish definitions of these  
13 groups it is beyond the scope of this article.

14

#### 15 **Methods**

16 With no date restrictions a literature search was conducted between January 2019  
17 and March 2020 on PubMed, Google Scholar, SPORTDiscus and the host institution  
18 databases. Search terms included "ageing" OR "age" OR "middle-aged" OR "old" OR  
19 "masters" OR "older" OR "veteran" AND "eccentric exercise" OR "lengthening  
20 exercise" OR "muscle damage" OR "exercise-induced muscle damage" OR  
21 "exercise-induced muscle injury" OR "contraction-induced muscle injury" OR "muscle  
22 soreness" OR "delayed onset muscle soreness" OR "creatine kinase" OR  
23 "myoglobin" OR "exercise-induced muscle weakness" OR "fatigue" OR "recovery".  
24 Only articles in English were considered. Articles were only included if they 1)  
25 provided a young versus middle-aged or old comparison, 2) provided recovery

1 markers beyond  $\geq 24$  hours, 3) had an all-male sample and 4) did not provide a  
2 recovery aid (e.g. cold-water immersion). The reference list of the retrieved articles  
3 was examined to identify articles not found during the literature search. All article that  
4 were retrieved were included within the review, providing they met the inclusion  
5 criteria.

6

## 7 **The effects of ageing on indirect markers of EIMD**

### 8 *Muscle soreness*

9 Muscle soreness is the most commonly assessed marker of EIMD (Warren, Lowe, &  
10 Armstrong, 1999) though the mechanism for its appearance remains unclear.  
11 Sensations of muscle soreness could result from a complex interaction of damage to  
12 the muscle structure and connective tissue, disrupted calcium homeostasis,  
13 sensitisation of nociceptors from inflammatory cell infiltrates and reductions in range  
14 of motion (Hyldahl & Hubal, 2014; Jamurtas et al., 2005; Nogueira et al., 2014;  
15 Nosaka et al., 2002). Irrespective of the mechanisms, muscle soreness typically  
16 appears between 8 - 24 h after muscle-damaging exercise, peaks between 24 - 48 h  
17 and usually subsides within 96 h (Damas et al., 2016; Jones, Newham, & Torgan,  
18 1989). Although muscle soreness does not appear to reflect the magnitude of  
19 muscle damage (Damas et al., 2016; Nosaka et al., 2002), it might provide an  
20 indication of any physiological changes after exercise.

21 Several studies have presented equivocal findings on age-related differences  
22 in muscle soreness after muscle-damaging resistance training (Table 1). For  
23 example, older males (~64 to 70 years) have reported lower muscle soreness than  
24 young (~25 years) (Chapman et al., 2008; Lavender & Nosaka, 2006) and middle-  
25 aged males (~48 years) (Lavender & Nosaka, 2008) despite having greater force

1 losses after exercise (at 72 hours post) (Chapman et al., 2008) (Table 2). These data  
2 are in contrast to those studies reporting no differences in muscle soreness between  
3 age groups (Buford et al., 2014; Gordon III et al., 2017; Heckel et al., 2019), even in  
4 the presence of greater force losses in older males (Fernandes et al., 2019;  
5 Nikolaidis, 2017; Nikolaidis et al., 2013). Taken collectively, these findings suggest  
6 that the mechanisms which lead to soreness are comparable and *potentially*  
7 ameliorated after resistance training in older populations.

8

### 9 *Circulating proteins*

10 Monitoring of muscle-specific proteins, such as plasma creatine kinase (CK) and  
11 serum myoglobin (Mb), are typical when assessing EIMD and generally peak in  
12 concentration 2 to 6 days after exercise (Byrne, Twist, & Eston, 2004; Damas et al.,  
13 2016; Hyldahl & Hubal, 2014; Warren et al., 1999). Resistance training increases  
14 membrane permeability and subsequently leakage of muscle proteins into the blood  
15 (Sorichter, Puschendorf, & Mair, 1999). However, muscle-specific proteins  
16 demonstrate a poor temporal relationship with muscle function, a high intra- and  
17 inter-individual variability (Damas et al., 2016; Fridén & Lieber, 2001), and most likely  
18 reflect the occurrence of tissue damage rather than the magnitude (Owens, Twist,  
19 Cogley, Howatson, & Close, 2018).

20 CK (eight studies) and Mb (five studies) are the most frequently investigated  
21 muscle-specific proteins in studies of ageing and recovery (Table 1). Whilst several  
22 studies have examined the response of CK and Mb to resistance across age groups  
23 (Arroyo et al., 2017; Chapman et al., 2008; Fernandes et al., 2019; Gordon III et al.,  
24 2017; Lavender & Nosaka, 2006, 2008; Nikolaidis, 2017; Nikolaidis et al., 2013), only  
25 two have reported differences in the response of CK (Lavender & Nosaka, 2006) and

1 Mb (Heckel et al., 2019; Lavender & Nosaka, 2006) to resistance training between  
2 younger (~21 to 25 years) and older (~ 65 to 71 years) males (Table 2). Lavender  
3 and Nosaka (Lavender & Nosaka, 2006) noted higher CK and Mb activity in young  
4 males, after eccentric elbow flexor exercise, than in their older counterparts, whilst  
5 Heckel et al. (2019) observed elevated Mb in the older group after knee extension  
6 exercise. However, given the commentary above, CK and Mb concentrations were  
7 only increased from baseline (i.e. membrane permeability was increased) and do not  
8 provide an indication of the magnitude of EIMD between groups.

9

### 10 *Muscular strength*

11 Reduced muscle strength (e.g. force or torque) after resistance training is considered  
12 the most appropriate indirect marker of EIMD as it demonstrates the lowest inter-  
13 individual variability (Damas et al., 2016; Paulsen, Mikkelsen, Raastad, & Peake,  
14 2012; Warren et al., 1999). Depending on the type, intensity and duration of the  
15 initial exercise bout, strength can decrease by 15-60% after resistance training and  
16 can persist for up to ~2 weeks (Hlydahl & Hubal, 2014; Paulsen et al., 2012). The  
17 mechanisms that result in decreased force production include physical damage to  
18 the sarcomere and sarcolemma from eccentric lengthening and E-C coupling failure  
19 (Hlydahl & Hubal, 2014; Morgan & Proske, 2004).

20 Whether losses in muscle strength differ between age groups after resistance  
21 training is currently unclear. Of the 11 available studies (Table 1), four conclude that  
22 muscle strength loss after resistance training is greater in older (~40-67 years)  
23 compared to younger (~21-25 years) males (Chapman et al., 2008; Fernandes et al.,  
24 2019; Nikolaidis, 2017; Nikolaidis et al., 2013), two have reported greater  
25 decrements in young (~19 to 20 years) compared to old (~71 years) (Lavender &

1 Nosaka, 2006, 2007) and the remainder observed no differences between age  
2 groups (Arroyo et al., 2017; Buford et al., 2014; Gordon III et al., 2017; Heckel et al.,  
3 2019; Lavender & Nosaka, 2008) (Table 2). The reasons for the discrepancy  
4 between these studies are unclear but might be due to differences in physical activity  
5 and resistance training status of the participants. For example, when controlling for  
6 physical activity, Buford and colleagues (2014) observed similar recovery of  
7 isometric plantar flexion force in younger (~23 years) and older (~76 years) adults  
8 males after eccentric unilateral plantar flexion exercise. More recently, two studies  
9 have investigated the recovery profiles of young (~22 years) and middle-aged (~47  
10 years) recreationally resistance trained males (Arroyo et al., 2017; Gordon III et al.,  
11 2017), both of which reported no difference in the recovery profile of muscle strength  
12 markers (e.g. peak and mean knee extensor torque and power) after eccentric knee  
13 extension exercise (Arroyo et al., 2017; Gordon III et al., 2017). These studies  
14 suggest that when physical activity/training status is matched, recovery of muscle  
15 strength is similar between age groups. Conceptually, these data *might* suggest that  
16 impairments in the recovery of muscle strength can be attributed to a lack of training,  
17 rather than ageing.

18 Another factor that could influence the time course of recovery between  
19 younger and older males after resistance training could be exercise selection. For  
20 healthy males, multi-jointed exercise (e.g. squats, bench press) are preferred to  
21 single-jointed exercises (e.g. knee extensions, bicep curls), especially in the strength  
22 and conditioning settings (Allison, Brooke-Wavell, & Folland, 2013; American  
23 College of Sports Medicine, 2002, 2009). When comparing the recovery of muscle  
24 function from squatting exercise (10 x 10 squats at 60% one repetition maximum  
25 (1RM)), Fernandes et al. (2019) reported greater losses in isometric force in

1 resistance trained middle-aged males (~40 years) compared to their younger (~22  
2 years) counterparts. These data are supported by Nikolaidis (2017) who observed  
3 greater isometric force loss in older males (~67 years) after squatting exercise than  
4 young males (~21 years). Uniquely, Fernandes and colleagues (2019) also noted  
5 moderately greater losses in squatting peak power at 20 and 80% 1RM after  
6 exercise for middle-aged males (~40 years) compared to younger participants (~22  
7 years) (Fernandes et al., 2019). Tentatively, these data *might* suggest that activity  
8 status and exercise type (e.g. single- versus multi-jointed) mediate the recovery of  
9 muscle strength loss between younger and older males after resistance training.  
10 Given the positive relationship between power and sporting tasks/playing standard  
11 (Cronin & Hansen, 2005; Fernandes, Daniels, Myler, & Twist, 2019; Hansen, Cronin,  
12 Pickering, & Douglas, 2011), middle-aged males should consider the potential  
13 implications of impaired recovery on performance after damaging exercise. However,  
14 the paucity of data makes it impractical to draw firm conclusions on muscle strength  
15 loss after resistance training.

16

### 17 *Age-dependant central and peripheral alterations in muscle function after resistance* 18 *training*

19 Impaired muscle function in the hours and days after resistance training might be the  
20 result of central (e.g. neural impairments and a reduction in excitability to the alpha  
21 motor-neuron (Avela, Kyröläinen, Komi, & Rama, 1999; Horita, Komi, Nicol, &  
22 Kyröläinen, 1999; Morton et al., 2005)) and/or peripheral perturbations (e.g.  
23 disruption of sarcomeres, impaired E-C coupling, accumulation/depletion of  
24 metabolites (Allen, Lamb, & Westerblad, 2008; Doguet et al., 2016; Hubal,  
25 Rubinstein, & Clarkson, 2007). For example, Macdonald, Button, Drinkwater and

1 Behm (2014) observed decrements in MVC after muscle-damaging squatting  
2 exercise that were accompanied by impairments in voluntary activation (VA; i.e.  
3 central alterations) and resting twitch force (i.e. peripheral alterations).

4         The available data on resistance training induced central and peripheral  
5 fatigue alterations between age groups is limited to four studies investigating the  
6 immediate post-exercise alterations (Dalton, Power, Paturel, & Rice, 2015; Dalton,  
7 Power, Vandervoort, & Rice, 2012; Fernandes et al., 2018b) and one reporting on  
8 these alterations in the days after exercise (Fernandes et al., 2019). Dalton et al.  
9 (2012) observed no differences in VA or resting twitch torque between these groups  
10 (~25 vs 75 year old recreational active males) after slow ( $60^{\circ}\cdot\text{s}^{-1}$ ), moderate  
11 ( $180^{\circ}\cdot\text{s}^{-1}$ ) or unconstrained velocity knee extension exercise. Similarly, Dalton et al.  
12 (2015) and Fernandes et al. (2018b) noted a comparable reduction in VA after  
13 single- and multi-jointed RT, respectively, in young (~22 to 25 years) and older (~40  
14 to 74 years) recreational active and resistance trained males, respectively. Notably,  
15 the younger group was subject to greater losses in resting twitch torque after single-  
16 jointed resistance training (Dalton et al., 2015) but experienced inferior symptoms  
17 than the older males after multi-jointed exercise (Fernandes et al., 2018b). The  
18 reason for these discrepancies is unclear but might be owing to differences in the  
19 type of exercise (e.g. single- vs. multi-jointed), contraction type (e.g. isotonic versus  
20 isokinetic) and movement velocity (e.g. constrained versus unconstrained), such that  
21 the immediate central and peripheral fatigue responses might be task specific  
22 (Fernandes et al., 2018b; Petrella, Kim, Tuggle, Hall, & Bamman, 2005). In the only  
23 study of its kind, Fernandes and colleagues (2019) noted that the reductions in  
24 resting doublet force persisted for three days in resistance trained middle-aged  
25 males (~40 years), despite no difference in voluntary activation between age groups

1 (young = ~22 years), suggesting that force loss is peripherally mediated between  
2 these groups. Identifying the mechanism of force loss after resistance exercise might  
3 help practitioners when prescribing such exercise with athletes of different ages. For  
4 example, different mechanisms of force loss might determine appropriate recovery  
5 strategies after exercise, depending whether these are centrally or peripherally  
6 orientated (Minett & Duffield, 2014). Further work on the mechanisms of force loss  
7 after resistance training in different age groups is needed to confirm these findings.

8

### 9 **Gaps within the research literature and future directions**

10 Given that single-jointed, isolated dynamometry does not reflect common training  
11 practices, Gordon and colleagues (2017) proposed that future work should use more  
12 ecologically valid protocols (i.e. dynamic, constant resistance and multi-jointed  
13 exercises) to study the impact of EIMD and fatigue on older athletes. To date, only  
14 two studies have investigated the recovery response from multi-jointed dynamic RT  
15 in older participants (Fernandes et al., 2019; Nikolaidis, 2017). These studies  
16 reported greater losses in isometric force (Fernandes et al., 2019; Nikolaidis, 2017)  
17 and peak power (Fernandes et al., 2019) in middle-aged and older populations  
18 compared to younger ones. Given that the lower-body undergoes greater losses in  
19 muscle mass (Lexell, 1995), strength and power (Fernandes et al., 2018a) than the  
20 upper-body, these data have important implications for programming and periodising  
21 resistance training with older populations. However, such findings cannot be applied  
22 to the upper-body and currently data on the recovery from multi-jointed upper-body  
23 resistance training between age groups is lacking. Further investigations are  
24 required to understand the muscle damage response of different limbs in older  
25 participants, especially given that the upper-body is more susceptible to muscle

1 damage than the lower-body because of the daily exposure of the lower-body to  
2 eccentric contractions (i.e. the lower-body is afforded protection due to the repeated  
3 bout effect) (Chen, Lin, Chen, Lin, & Nosaka, 2011; Chen et al., 2019; Jamurtas et  
4 al., 2005; Saka et al., 2009).

5 A lack of data regarding the mechanistic basis for the muscle functional  
6 changes after resistance training in older populations remains a key omission. To  
7 date, only one study has provided such a comparison (Fernandes et al., 2019) with  
8 several studies investigating only the immediate (fatigue) central and peripheral  
9 response (Dalton et al., 2015, 2012; Fernandes et al., 2018b; Power, Dalton, Rice, &  
10 Vandervoort, 2012). Determining if losses in muscle function after resistance training  
11 are centrally or peripherally mediated is important for the provision of recovery  
12 modalities (Minett & Duffield, 2014). Researchers should, where possible, provide a  
13 mechanistic insight into the changes in muscle function across age groups after RT.  
14 When taking a holistic approach to muscle function recovery from resistance training,  
15 these studies might also employ methods such as the twitch interpolation technique  
16 or transcranial magnetic stimulation to examine the influence of peripheral and  
17 central alterations.

18 EIMD incurred from resistance training has the potential to impair sporting  
19 performance in the days after the initial bout (Highton, Twist, & Eston, 2009) and is  
20 therefore a potential concern for older athletes engaging in novel training  
21 approaches for the first time. Given the majority of studies examining the effects of  
22 EIMD in older participants have used relatively 'untrained' males (Buford et al., 2014;  
23 Lavender & Nosaka, 2006, 2007, 2008; Nikolaidis, 2017; Nikolaidis et al., 2013),  
24 what remains unclear is the recovery to unaccustomed exercise bouts in those aged  
25 participants that are habitually trained. Understanding how older athletes, who

1 continue to engage in frequent training to enhance athletic performance, respond to  
2 new or more intense training activities is important and has the potential to inform  
3 applied practice of those working with 'masters' athletes. Like Fell and Williams  
4 (2008) 12 years ago, we again encourage future work to examine the recovery  
5 profiles for those older athletes who habitually resistance train or regularly participate  
6 in competitive sport. These studies should use more ecologically valid exercise  
7 protocols and, where possible, provide a mechanistic underpinning.

8         To our knowledge, only three studies have investigated the muscle damage  
9 and recovery response in younger and older females (Clarkson & Dedrick, 1988;  
10 Dedrick & Clarkson, 1990; Ploutz-Snyder, Giamis, Formikell, & Rosenbaum, 2001).  
11 After both forearm flexor (Dedrick & Clarkson, 1990) and knee extensor (Ploutz-  
12 Snyder et al., 2001) exercise, the recovery of muscle strength appeared to be slower  
13 in older compared to younger females. However, to date, these remain the extent of  
14 our empirical understanding of recovery among older females after muscle-  
15 damaging exercise. Given the potential for differential responses to EIMD between  
16 males and females (Dannecker et al., 2012; Sayers & Clarkson, 2001; Sewright,  
17 Hubal, Kearns, Holbrook, & Clarkson, 2008; Stupka, Tarnopolsky, Yardley, &  
18 Phillips, 2017), the growing number of older females (United Nations, 2017) and  
19 female athletes (Lepers, 2019; Lepers et al., 2013; Lepers & Stapley, 2016), and the  
20 importance of resistance training in this group (Ploutz-Snyder et al., 2001), future  
21 work should seek to confirm and extend what is currently known about the muscle  
22 response to resistance training in older females.

23

24 **Conclusions**

1 The aim of this review was to compare the effects of resistance training on indirect  
2 markers of EIMD (i.e. muscle function, soreness and circulating proteins) throughout  
3 the recovery process in older trained and untrained males. The notion that ageing is  
4 associated with large changes in markers of muscle damage and a prolonged  
5 recovery time has not been reported consistently in the literature. In fact, more than  
6 half of the available studies have noted that older males experience similar, and  
7 even less severe, symptoms of muscle damage than their younger counterparts.  
8 Collectively, these data refute the anecdote that ageing is associated with an  
9 impaired recovery from exercise. It is therefore plausible to schedule recovery from  
10 resistance training among different age groups in a comparable manner. Considering  
11 both the mechanistic and performance-related outcomes, studies of muscle function  
12 recovery after multi-jointed resistance training in older athletes should be explored.  
13 We also encourage future research to consider how training history and sex  
14 influence the responses to training that cause symptoms of EIMD.

15

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**Table 1.** Characteristics of studies on ageing and in indirect markers of muscle damage and recovery (i.e. muscle soreness, blood markers and muscle strength) after resistance training.

	Young	Sample size	Old	Sample size	Activity level	Involved muscle	Exercise protocol	Time points
<i>Lavender &amp; Nosaka, 2006</i>	19.4 ± 0.4	10	70.5 ± 1.5	10	Non-RT	EF	6 x 5 ECC at 40% MIVC	Pre, 0, 24, 48, 72, 96, 120 h
<i>Lavender &amp; Nosaka, 2007*</i>	20.4 ± 2.0	10	48.0 ± 7.3 70.5 ± 4.1	12 10	Non-RT	EF	6 x 5 ECC at 40% MIVC	Pre, 0, 24, 48, 72, 96, 120, 144, 168 h
<i>Lavender &amp; Nosaka, 2008</i>	19.4 ± 0.4	12	48.0 ± 2.1	12	Non-RT	EF	6 x 5 ECC at 40% MIVC	Pre, 0, 24, 48, 72, 96 h
<i>Chapman et al. 2008</i>	25.0 ± 1.8	10	64.0 ± 1.2	10	Non-RT	EF	5 x 6 ECC at 210 degxs	Pre, 1, 24, 48, 72 and 96 h
<i>Nikolaidis et al 2013</i>	20.6 ± 0.5	10	64.6 ± 1.1	10	Non-RT	KE	5 x 8 ECC at 60 degxs	Pre, 0, 48
<i>Buford et al. 2014</i>	22.5 ± 3.7	15	75.8 ± 5.0	15	Non-RT	PF	150 ECC at 110% 1RM	Pre, 48, 168 h
<i>Gordon et al. 2017</i>	21.8 ± 2.0	9	47.0 ± 4.4	10	Rec. RT	KE	8 x 10 ECC-CON at 60 degxs	Pre, 0, 0.5, 1, 2, 24, 48 h
<i>Arroyo et al. 2017</i>	21.8 ± 2.2	9	47.0 ± 4.4	10	Rec. RT	KE	8 x 10 ECC-CON at 60 degxs	Pre, 0, 0.5, 1, 2, 24, 48 h
<i>Nikolaidis, 2017</i>	22.1 ± 3.9	10	66.9 ± 5.4	10	Non-RT	KE	5 x 15 ISOT at 75% 1RM	Pre, 48 h
<i>Fernandes et al. 2019</i>	22.3 ± 1.7	9	39.9 ± 6.2	9	RTd	KE	10 x 10 ISOT at 60% 1RM	Pre, 24, 72 h
<i>Heckel et al. 2019</i>	25.1 ± 4.9	10	64.5 ± 5.5	10	Non-RT	KE	4 x 15 ECC at 60 degxs	Pre, 24 48 h

\*study contained 3 age groups. RTd, resistance training; RT, resistance training; EF, elbow flexors; KE, knee extensors; PF, plantar flexors; 1RM, one-repetition maximum; MVC, maximal voluntary contraction; MIVC, maximal isometric voluntary contraction; ECC, eccentric contraction; CON, concentric contraction; ISOT, isotonic contraction; VAS, visual analogue scale; CK, creatine kinase; Mb, myoglobin

**Table 2.** Changes in indirect markers of muscle damage and recovery after resistance training in young and older age groups.

	Muscle damage marker			
	Soreness	Creatine kinase	Myoglobin	Strength
<i>Lavender &amp; Nosaka, 2006</i>	↑YG	↑YG	↑YG	↓YG
<i>Lavender &amp; Nosaka, 2007</i>	N/A	N/A	N/A	↓YG
<i>Lavender &amp; Nosaka, 2008</i>	↑YG	↔	↔	↔
<i>Chapman et al. 2008</i>	↑YG	↔	N/A	↓OG
<i>Nikolaidis et al. 2013</i>	↔	N/A	N/A	↓OG
<i>Buford et al. 2014</i>	↔	N/A	N/A	↔
<i>Gordon et al. 2017</i>	↔	↔	↔	↔
<i>Arroyo et al. 2017</i>	↔	↔	↔	↔
<i>Nikolaidis, 2017</i>	↔	↔	N/A	↓OG
<i>Fernandes et al. 2019</i>	↔	↔	N/A	↓OG
<i>Heckel et al. 2019</i>	↔	↔	↑OG	↔

↔ denotes similar response between groups; ↑ and ↓ denote greater group response in that direction; YG denotes young group; OG denotes old group.