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Youths Are Less Susceptible to Exercise-Induced Muscle Damage Than Adults: A Systematic Review With Meta-Analysis

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1 **Title:** Youths are less susceptible to exercise-induced muscle damage than adults; a
2 systematic review with meta-analysis

3 **Running head:** Youth versus adult EIMD

4

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39 Abstract

40 Purpose; This meta-analysis aimed to 1) provide a comparison of peak changes in indirect
41 markers of EIMD in youths versus adults and 2) determine if the involved limb moderated
42 this effect. Method; Studies were eligible for inclusion if they 1) provided a human youth
43 versus adult comparison, 2) provided data on muscle strength, soreness or creatine kinase
44 (CK) markers beyond ≥ 24 hours, 3) did not provide a recovery treatment. Effect sizes
45 (ES) were presented alongside 95% confidence intervals. Results; EIMD exhibited larger
46 effects on adults than in youths for muscle strength (ES=-2.01; $P<0.001$), muscle
47 soreness (ES=-1.52; $P<0.001$) and CK (ES=-1.98; $P<0.001$). The random effects meta-
48 regression examined the effects of upper- and lower-limb exercise in youths and adults
49 was significant for muscle soreness (coefficient estimate =1.11; $P< 0.001$) but not muscle
50 strength or CK ($P>0.05$). As such, the between-group effects for muscle soreness (ES=-
51 2.10 versus -1.03; $P<0.05$) were greater in the upper- than lower-limb. Conclusion; The
52 magnitude of EIMD in youths is substantially less than their adult counterparts, and this
53 effect is greater in upper- than lower-limbs for muscle soreness. These findings help guide
54 practitioners who may be concerned about the potential impact of EIMD when training
55 youth athletes.

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68 **1. Introduction**

69 There is a considerable volume of evidence recommending that youths engage in physical
70 activity and long-term athletic development programs (29,46,47). Current guidelines
71 suggest that youths **should** perform an average of 60 minutes of moderate to vigorous
72 daily physical activity (61). Engaging in physical activity can improve health related
73 outcomes, reduce injury risk, and positively influence fitness variables (1,2,29,57). For
74 youth athletes, fitness variables are, for the most part, positively influenced by the
75 maturation process (57,58) and can be further enhanced by engagement in a variety of
76 strength, hypertrophy, power, speed, and agility training methods (47).

77

78 Notwithstanding the positive adaptations that can occur through training, exercise-induced
79 muscle damage (EIMD) occurs if the exercise mode or intensity is novel, high in volume,
80 or eccentrically biased (8,21,30,31,76,77). **Though greater in more mature individuals,**
81 EIMD occurs irrespective of the maturity status in youths (20,36,73). The “popping-
82 sarcomere hypothesis” (59) proposes that an increased stress per myofibre during
83 eccentric contractions causes non-uniform lengthening of the sarcomeres whereby weaker
84 ones extend beyond their myofilament overlap and fail to re-interdigitate (38,59).
85 Thereafter, disruptions to calcium homeostasis lead to excitation–contraction coupling
86 failure and a prolonged loss of muscle strength and other associated symptoms
87 (15,38,59). Independent of age and maturity, EIMD can manifest in its symptoms which
88 include reductions in muscle function (e.g., strength and power), elevated muscle soreness
89 and pain, and increased intramuscular enzymes in the blood (e.g., creatine kinase; CK;
90 (15)). These symptoms frequently peak between 24 and 48 hours after the initial exercise
91 bout and are recovered (i.e., returned to baseline values) by seven days post-exercise
92 (15,30,31,38,76,77). Moreover, symptoms are highly individualised, not synchronous
93 (35,50), and have been suggested to differ according to age and maturity status (3,12,44).

94

95 The magnitude of EIMD is attenuated when individuals possess prior experience of
96 eccentric exercise (37,54). This protection is known as the repeated bout effect (RBE) and

97 is underpinned by neural, mechanical, and biomechanical adaptation after an initial bout
98 of exercise (37,54) and can last up to 6 months (63). Although the RBE has been
99 demonstrated across the lifespan, its effect appears more evident in adults than youths
100 (32,51). This is likely because extent of the RBE is related to the initial magnitude of EIMD
101 with several studies reporting that adults experience greater EIMD than youths
102 (3,12,17,19,32,44,51,72,74). A recent narrative review (26) also concluded that
103 practitioners working with youths populations need not have undue concerns about EIMD
104 due to the lower magnitude they experience. Drury et al. (26) proposed that eccentric
105 training, [which induces the most severe EIMD](#), in youths should be considered a necessity
106 due to the performance-related and injury-protecting benefits. However, strength and
107 conditioning coaches deem scheduling as the most frequent barrier to the implementation
108 of eccentric exercise in youths (25), perhaps due to the perception that EIMD may occur
109 as consequence or the practicalities of implementing such training.

110

111 Previous studies in adults have repeatedly shown that the upper-limb is more susceptible
112 to EIMD than the lower-limb (11,13,39,49,62,70). The greater susceptibility of fast-twitch
113 muscle fibres to EIMD, and greater percentage of this fibre type in upper-limbs compared
114 to lower-limb might explain these differences (39,70). Moreover, the daily use of the
115 lower-limb is greater than the upper-limb, and these muscles (i.e., the lower-limb)
116 habitually undergo more eccentric contractions (e.g., downhill walking, walking
117 downstairs), thus a greater protective RBE is elicited (37). Regardless of the mechanism,
118 it is unknown whether the protective effect is greater in adults compared to youth. Such
119 information would be useful to applied practitioners when scheduling upper- and lower-
120 limb exercise that is novel, eccentrically biased, or high-volume. However, whilst individual
121 investigations comparing EIMD in youths and adults exist, a systematic and rigorous
122 pooled statistical analysis of these data has not been conducted. This is an important issue
123 when planning and programming training for youth, as the distinct biological differences
124 mean that youths cannot be treated the same as adults. That EIMD impairs markers of
125 sports performance (e.g., strength and power, change of direction; (31,33) might also

126 have implications for training and competition (22). Therefore, the present paper sought
127 to meta-compare indirect markers (muscle strength, muscle soreness/pain and CK) of
128 EIMD in youths and adults. A secondary aim was to determine if peak changes in EIMD
129 were different between the upper- and lower-limb in youths versus adults.

130

131 **2. Methods**

132 This systematic review with meta-analysis was conducted according to the Preferred
133 Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) guidelines (66). The
134 literature search was performed by three authors (JFTF, LJW and AFD) with the data
135 extraction and verification performed by two authors (JFTF and LJW).

136

137 *2.1 Literature search*

138 A systematic search, with no date restrictions, was performed on Google Scholar, PubMed,
139 and Sport Discus in July 2022. Only peer-reviewed articles written in the English language
140 were considered. Using Boolean logic the following terms were searched for in article title,
141 abstracts and keywords; "paediatric" OR "youth" OR "children" OR "adolescent" OR
142 "maturation" AND "muscle damage" OR "exercise-induced muscle damage" OR "exercise-
143 induced muscle injury" OR "contraction-induced injury" OR "muscle soreness" OR "delayed
144 onset muscle soreness" OR "creatine kinase". When selecting studies for inclusion, all
145 relevant article titles were reviewed before an examination of article abstracts and then,
146 full published articles. After the formal systematic searches, additional searches of the
147 eligible papers were conducted. The search process is outlined in Figure 1.

148

149 *2.2 Eligibility criteria*

150 The following criteria were used to determine the eligibility of studies for the meta-
151 analysis; 1) provided a youths (<18 years) versus adult (\geq 18 years) comparison, 2)
152 provided muscle strength, muscle soreness/pain or CK markers to at least 24 hours post-
153 exercise, 3) did not provide a recovery aid or strategy (e.g. cold-water immersion; [control
154 groups were included providing they did not receive treatment]) and 4) was conducted in

155 humans. Alterations within 24 hours of exercise could be due to transient fatigue (7),
 156 therefore studies were only included if they provided indirect markers of EIMD \geq 24 hours
 157 after the exercise bout.

158

159 *2.3 Data extraction*

160 Using a standardised form in Microsoft Excel, data were extracted by two reviewers (LJW
 161 and JFTF). Any disagreements were resolved via consensus. Where data were not
 162 numerically reported, and only visualised, authors were contacted. In the case of authors
 163 not responding, ImageJ software was used to manually extract the data (71). Data were
 164 extracted on any baseline and post-EIMD measures of muscle strength, muscle
 165 soreness/pain and CK. Biometric and physical activity characteristics of the participants,
 166 as well as the EIMD bout were also extracted. Note that it was not possible to extract or
 167 retrieve CK data from Chen et al. (12). Muscle soreness data in Dos Santos et al. (23)
 168 were presented as median values and it was not possible to retrieve the data. Any data
 169 reported as standard error were converted to standard deviation for analysis. As
 170 differences at baseline were expected between youths and adults for muscle strength, the
 171 peak percentage change from baseline was entered for analysis. The standard deviation
 172 of the change was calculated as:

$$173 \quad SD \text{ of the change} = \sqrt{(a^2 + b^2)} - (2 \text{correl.} \times a \times b)$$

174

175 *Equation 1. a = baseline SD; b = peak SD; and correl. = the Pearson's correlation between*
 176 *baseline and 24h post-EIMD muscle strength (r = 0.94) in Fernandes et al. (30).*

177

178 Where studies implemented multiple youths groups, both were included for analysis
 179 (12,44). Previous work (40) has raised concerns that including multiple groups from the
 180 same study within a meta-analysis could ignore the within-study correlation. However, the
 181 differences in age and maturity of the groups (see Table 2) in Chen et al. (12) and Lin et
 182 al. (44) indicate distinct physical and physiological differences which warrant their
 183 inclusion. As per the suggestion of Kadlec et al. (40) multiple variables were not included

184 in the same analysis, e.g., both concentric and isometric strength into the muscle strength
185 analysis. Finally, a *post-hoc* 'quality check' (i.e., a sensitivity analysis) was performed by
186 individually removing the younger/less mature and then older/more mature groups from
187 each indirect EIMD marker analysis. For muscle strength the removal of the younger/less
188 mature group resulted in a minimal qualitative (i.e., the magnitude, not the direction)
189 effect size change (from -2.01 to -1.78), whilst the removal of the older/more mature
190 group did not alter effect size. For muscle soreness and CK the removal of each group did
191 not change the magnitude of the effect. The authors believe this justifies the inclusion of
192 these groups.

193

194 *2.4 Analysis and interpretation of results*

195 Jamovi (version 2.3.0.0, MAJOR package) was used to conduct the meta-analysis. Means
196 and standard deviations of baseline and post-exercise markers of EIMD were used to
197 calculate the standardised mean difference (SMD). SMDs expressed the intervention effect
198 within each study using a restricted maximum-likelihood model estimate (42). An inverse-
199 variance random effects model for meta-analyses was used as it allocates a proportionate
200 weight to trials based on the size of their standard errors (16) and facilitates analysis
201 whilst accounting for heterogeneity across studies. Effect sizes are given as SMD and 95%
202 confidence intervals (CIs). The following qualitative criteria were used to interpret the ES;
203 0.2 = trivial; 0.2–0.59 = small, 0.6–1.19 = moderate, 1.2–1.99 = large, 2.0–3.99 = very
204 large, > 4.0 = extremely large (34). To assess the degree of heterogeneity amongst the
205 included studies, the I^2 statistic was employed. This represents the proportion of effects
206 that are due to heterogeneity as opposed to chance (43). Low, moderate, and high
207 heterogeneity correspond to I^2 values of 25, 50, and 80%, respectively. A random-effects
208 meta-regression with moderator analysis was employed to establish the influence of the
209 involved limb segment (i.e., upper- or lower-limb) on the magnitude of indirect markers
210 in adult and youth. Alpha was set at ≤ 0.05 .

211

212 *2.5 Quality assessment and risk of bias*

213 The quality of the included studies was determined using the National Institute of Health's
214 Quality Assessment Tool for Before-After (Pre-Post) Studies with No Control Group (60).
215 The assessment tool analyses the following domains 1) study question is clearly stated;
216 2) eligibility is prespecified and clearly described; 3) study subjects are representative of
217 those who would be of interest; 4) eligible subjects were enrolled; 5) sample size is
218 sufficiently large; 6) intervention is clearly described and evenly applied to subjects; 7)
219 outcome measures prespecified, clearly defined, valid, reliable; 8) assessors were blind to
220 the intervention/outcomes; 9) subject loss was less than 20%; 10) statistical measures
221 assessed pre to post changes; 11) outcome measures were taken multiple times; 12)
222 statistical analysis took into account group level data. Two reviewers (LJW and JFTF)
223 conducted the quality assessment independently with any disputes settled by a third
224 reviewer (LDH).

225

226 **3. Results**

227 *3.1 Study selection*

228 Results from the three database searches identified 744 articles, 74 of which were
229 duplicates (Figure 1). A total of 414 articles were removed after the screening of titles and
230 abstracts, leaving 257 articles available for full text inspection. The authors attempted to
231 retrieve 257 studies and were successful in retrieving and assessing 255 for eligibility. Of
232 the 255 screened, 11 full text manuscripts were included within the final quantitative
233 synthesis. As Dos Santos et al (23) only presented the median data, this study was not
234 included within the meta-analysis.

235

236 **[INSERT FIGURE 1 HERE]**

237

238 **Figure 1.** PRISMA Flow diagram displaying inclusion and exclusion of studies

239

240 *3.2 Study characteristics*

241 The National Institute of Health Quality Assessment Tool resulted in a mean score of 9.5
242 \pm 0.5. Individual assessments can be found in Table 1 as can the study characteristics.
243 On completion of data pooling, 13 comparisons (from 11 individual studies) were included
244 in the analysis; nine included a marker of muscle function, 11 included a marker of muscle
245 soreness and nine measured creatine kinase. A total of 157 youths and 136 adults were
246 included in the meta-analysis consisting of 49 girls, 108 boys, 35 women and 101 men.
247 Nine comparisons included males only, three studies compared females only and one both
248 males and females. Eight comparisons investigated EIMD in the lower-limb, with the
249 remaining five reporting on EIMD in the upper-limbs. *The EIMD interventions included*
250 *were highly varied; five utilised dynamometry based resistance exercise, three jumping*
251 *based exercise, two traditional resistance exercise and one aerobic exercise.* For both
252 groups peak change in muscle strength occurred at 24 hours in seven of the nine
253 comparisons. In Soares et al. (72) peak muscle strength loss occurred at 48 hours for
254 adults and 72 hours for youth. Gorianovas et al. (32) reported peak muscle strength loss
255 in both groups at 48 hours. Both studies did not measure muscle strength at 24 hours.
256 Muscle soreness peaked at 24 hours in six of the 11 comparisons (for both groups) and at
257 48 hours in four comparisons (for both groups). In Soares et al (72) peak soreness
258 occurred at 48 hours for adults, and 72 hours for youth. For both groups, CK peaked at
259 24 hours in three studies, 72 hours in three studies and 96 hours in two studies. In Arnett
260 et al. (3) CK peaked at 24 hours in youths and 72 hours in adults.

261

262 **[INSERT TABLE 1 AND 2 HERE]**

263

264 *3.3 Exercise-induced muscle damage in youths versus adults*

265 The effects of exercise on muscle strength, muscle soreness and CK are shown in Figure
266 2. Exercise-induced muscle damage exhibited large and very large effects between adults
267 than in youths for muscle strength (ES = -2.01; 95%CI -2.95,-1.07; Z = -4.20; $P < 0.001$),
268 muscle soreness (ES = -1.52; 95%CI -2.15, -0.90; Z = -4.76; $P < 0.001$) and CK (ES = -
269 1.98; 95%CI -2.93, -1.04; Z = -4.13; $P < 0.001$), indicating greater changes in adults

270 than youths. Heterogeneity was high for all analyses ($I^2 = 79-89\%$), justifying the use of
271 a random effects model. For all analyses the trim and fill method suggested that no studies
272 needed to be removed to reduce publication bias.

273

274

[INSERT FIGURE 2 HERE]

275

276 **Figure 2.** Forest plot of studies examining peak changes in muscle strength (A), muscle
277 soreness (B), and creatine kinase (C) after EIMD in youths and adults. Data are presented
278 as the percentage weight each study contributes to the pooled SMD, individual SMD [95%
279 CIs]. Note that symbol size of individual studies is representative of the weighting for the
280 pooled standardised mean difference. The filled diamond indicates overall SMD. RE =
281 random effects. model.

282

283

[INSERT FIGURE 3 HERE]

284

285 **Figure 3.** Funnel plots for studies evaluating peak changes in muscle strength (A), muscle
286 soreness (B), and creatine kinase (C) after EIMD in youths and adults.

287

288 *3.4 Moderator analysis*

289 A random effects meta-regression examined the effects of upper- and lower-limb exercise
290 on muscle strength (coefficient estimate = -0.07; 95% CI range = -2.12 to 1.966; $P =$
291 0.945) and CK (coefficient estimate = 1.01; 95% CI range = -0.001 to 2.213; $P = 0.285$)
292 changes in youths and adults and indicated no relationship. As such the large difference
293 between groups was comparable for the upper- and lower-limbs (see Table 3) and
294 displayed high heterogeneity.

295

296 The random effects meta-regression comparing upper- and lower-limb exercise on muscle
297 soreness (coefficient estimate = 1.11; 95% CI range = -0.001 to 2.213; $P = 0.05$) in
298 youths and adults indicated significant relationships. As such, the between-group effects

299 for muscle soreness (SMD = -2.10 versus -1.03; both $P < 0.05$) were heterogenous and
300 greater in the upper- than lower-limb whilst still confirming the main analysis (i.e., greater
301 changes in adults than youth).

302 **[INSERT TABLE 3 HERE]**

303

304 **4. Discussion**

305 It is well documented that EIMD routinely occurs because of strenuous or novel exercise,
306 particularly after eccentrically biased actions. Whether a differential EIMD response is
307 evident in youths compared to adults is yet to be fully elucidated. Therefore, the aim of
308 this meta-analysis was to compare peak perturbations of indirect markers of EIMD in
309 youths and adults after muscle-damaging exercise, and to determine if these perturbations
310 between groups are different in the upper- and lower-limb. The key findings from this
311 study demonstrate that after EIMD; 1) youths experience smaller changes in peak indirect
312 markers of EIMD compared to adults and, 2) the age effect for muscle soreness and CK is
313 greater in the upper- than lower-limb. The present study adds meta-analytical
314 confirmation to the literature on the effect of age on EIMD. These data are encouraging
315 for practitioners concerned about the negative impact of EIMD on youth athletes'
316 performance and quality of training. A better understanding of the magnitude of EIMD
317 symptoms in youth athletes can help practitioners in managing these symptoms potentially
318 using recovery aids or changes in scheduling and programming of training.

319

320 While the finding that adults exhibit greater peak decrements in muscle strength than
321 youths after muscle-damaging exercise is not novel, our study is the first to offer a pooled
322 analysis on such data and a meta-analytical magnitude of effect (i.e., very large) to the
323 knowledge base. Unfortunately, we are unable to provide insight into the underpinning
324 physiological mechanism(s) evoking such age-related effects. In some studies, despite
325 standardised *relative* intensity (i.e., number of body mass vertical jumps), youths would
326 experience a reduced *absolute* mechanical stimulus because of a lower body mass
327 resulting in small symptoms of EIMD (32,51). Another possible explanation is that due to

328 the reduced body mass of youths compared to adults, less force is generated per muscle
329 fibre unit during concentric and eccentric contractions, resulting in a smaller amount of
330 structural muscle damage after exercise (18,32,51,74). This is supported by the finding
331 that although absolute strength decrements are larger in adults, this relationship is
332 attenuated or reversed when strength data are presented relative to body mass (18).
333 Youths also exhibit increased flexibility compared to adults (51). This leads to greater
334 relative strength at longer muscle lengths (51), suggesting the popping sarcomere
335 hypothesis of muscle damage would be less evident at a given joint angle for youths
336 compared to adults (52). Differential responses may also be related to muscle fibre
337 characteristics in that fast-twitch (i.e., type II) muscle fibres are proposed to be more
338 susceptible to damage and preferentially disrupted during eccentrically biased exercise
339 (44). Given that youths tend to have a higher proportion of slow-twitch muscle fibres and
340 fewer fast-twitch fibres, their skeletal muscles may be less susceptible to EIMD, resulting
341 in a smaller strength decrement post-exercise (51). A lower maximal volitional muscular
342 force in youths compared to adults, even when accounting for body- and muscle-size
343 differences (5) might reduce their capacity to recruit fast-twitch motor units (24) and thus
344 attenuates EIMD magnitude. Furthermore, within a group of youth athletes, maturity
345 status may also affect EIMD symptoms and recovery. In the present meta-analysis, six of
346 11 studies assessed maturity status, and only two studies compared maturity status
347 against adults (12,44). Given that maturation can result in significant changes in
348 physiology and physical qualities (e.g. increases in body mass, muscle mass, limb-lengths,
349 absolute strength) (1,2,56,58) this is something that future studies must consider.
350 Nonetheless, practitioners should be aware that youths exhibit reduced losses in muscle
351 strength after EIMD than their adult counterparts. These findings suggest that training
352 which requires high force contractions (e.g. resistance exercise, sprinting) should be
353 avoided in the presence of EIMD as the quality of these is likely to be reduced. Similarly,
354 the reductions in muscular strength with EIMD negatively affect markers of sports
355 performance ((31,33), thus novel or eccentrically biased exercise should be avoided close
356 to competitions.

357

358 Our meta-analysis indicates that youths experience lower peak increases in muscle
359 soreness than adults with EIMD, with the magnitude of the difference deemed large. In
360 addition to structural damage, muscle soreness can also result from connective tissue
361 damage and inflammation (38). Many of the mechanisms discussed above which are
362 responsible for smaller strength decrements are also likely to contribute to less muscle
363 soreness experienced by youths compared to adults. Youths may also experience less
364 soreness as they are less susceptible to microdamage of the connective tissue around the
365 working joints. It has been reported that musculo-tendinous stiffness is lower in youths
366 compared to adults (41). During exercise, the reduced musculo-tendinous stiffness leads
367 to a more 'compliant' tendon (51) that can then act as a buffer to reduce mechanical
368 strain on both fascicles and muscle fibres (44). This finding is practically meaningful as
369 increased muscle soreness can result in decreased physical activity adherence (55).
370 Indeed, physical activity has physical, mental, and social benefits of exercise (69) and
371 withdrawal from physical activity can negate these benefits. Given younger individuals
372 experience less muscle soreness with EIMD, they are more likely to continue with
373 subsequent physical activity and may require less recovery time between exercise bouts
374 compared to adults. This would be pertinent to applied practitioners developing periodised
375 training programmes for youth athletes, particularly during competition phases or when
376 in-season. However, the potential for negative consequences of exercise (e.g., non-
377 functional overreaching, overtraining) are still present in youths (53,75) and repeated
378 exposure to EIMD with insufficient recovery could lead to this. Practitioners should ensure
379 that youths' physical activity experiences are positive, so that their well-being and
380 adherence to long-term participation are maximised (64).

381

382 Increases in CK concentration are commonly used as proxy measures for structural
383 skeletal muscle damage (4). Findings from the present study reveal large differences in
384 CK after exercise with youths experiencing lower peak CK increases compared to adults.
385 However, it is well-reported that resultant CK is modified by several factors including sex,

386 ethnicity, maturation, and age (4), and exhibits large inter-individual variation (9).
387 Therefore, CK results reported herein should be interpreted with caution (6), although in
388 conjunction with the strength and soreness data it could be inferred that a lower CK activity
389 also reflects a smaller magnitude of EIMD observed in youths compared to adults after
390 eccentrically biased or novel exercise. Notwithstanding the issues surrounding CK's ability
391 to reflect the magnitude of damage experienced by an individual, increased CK represents
392 a greater cell membrane disruption after the initial insult (15,38). It is probable that youths
393 experience less cell membrane disruption for the reasons already outlined such as reduced
394 mechanical load, increased flexibility, greater proportion of slow-twitch muscle fibres, and
395 reduced muscle fibre activation. These factors would result in a reduced structural damage
396 and resultant cell membrane disruption, translating to a lower peak CK activity in youths
397 than adults. Whilst this finding is important to note from a mechanistic perspective, the
398 practical utility of these data is limited. It is unlikely that practitioners working with youth
399 athletes would routinely use invasive measures such as blood sampling to monitor training,
400 report on recovery status, or programme physical activity.

401

402 Moderator analysis revealed effects that were greater for the upper-limb for muscle
403 soreness than for the lower-limb. Essentially, although both youths and adults will be
404 experience EIMD, the magnitude of the difference between groups is larger after upper-
405 limb exercise than lower-limb exercise in adults than in youth. This finding supports
406 previous literature (13,39,70) however, no study has reported on the susceptibility to
407 upper- and lower-limb exercise between adults and youth. The mechanisms underpinning
408 these observations remain unclear. It is plausible that daily activities that youths engage
409 in include a greater amount of upper-limb activation than their adult counterparts. Indeed,
410 youth physical activity programmes regularly encourage the use of play type movements
411 that include animal shapes (e.g., bear crawls, alligator walks), hanging and swinging, all
412 of which active the upper-limbs (28,67); it is unlikely that untrained adults (included in
413 nine out of 13 comparisons) engage in such activities. A more physiological explanation
414 might be sought from the fibre type differences between youths and adults. Maturation is

415 associated with an increase in fast-twitch fibres (27,68), which are more susceptible to
416 EIMD (48) and of higher proportions in the upper-limb than lower-limb (39,70). Therefore,
417 youths might have a tissue makeup in the upper-limb that makes them less susceptible to
418 structural and connective tissue damage and inflammation, which underpin changes in
419 muscle soreness. Practitioners should be mindful that peak symptoms of EIMD will be
420 different in youths and adults, which is particularly important in scenarios where youths
421 and adults exercise concurrently (e.g. teams sport).

422

423 This meta-analysis has highlighted several avenues for future research. Firstly, other than
424 Webber et al. (74), no studies included in this review utilised an ecologically valid exercise
425 protocol, and instead predominantly focused on vertical jump or single joint resistance
426 training protocols. EIMD in youths has been investigated after competitive soccer match-
427 play (73), although no youth versus adult comparison has been reported. Future studies
428 should implement exercise protocols that better reflect a) the dynamic nature of physical
429 activity and/or competitive sport, such as self-directed play or simulated games and b)
430 the training methods used in strength and conditioning settings. Secondly, girls and
431 women accounted for 32.1 and 25.7% of the research participants, with only two studies
432 solely recruiting female participants (3,44), and one both combined males and females
433 without reporting sex-specific results (74). As is the case with sport and exercise science
434 research more generally, there is a dearth of EIMD literature in female youth athletes
435 which reflects the patriarchal nature of sport and exercise research (10,65). It has
436 previously been suggested that there are sex-specific differences in the susceptibility to,
437 and recovery from, symptoms of EIMD (38). Future work must ensure that girls and
438 women are benefiting from the same quality and quantity of EIMD research (14). Thirdly,
439 maturation may also impact EIMD symptoms and recovery (73) yet only two studies have
440 reported on the maturity status of participants in response to EIMD (12,44). Youths who
441 are the same chronological age can differ markedly in maturity status and biological
442 maturity influences the neural, muscular, and cardiorespiratory systems (45). As such, it
443 would be pertinent to directly compare males and females across the lifespan, to better

444 understand the physiological and performance related responses to EIMD. Finally, nine of
445 the 13 comparisons included untrained participants, and one which failed to describe the
446 training status. Although the RBE is less expressed in youths than adults (32,51) future
447 studies must determine how training status influences EIMD in youth. Indeed, recently
448 there has been an increase in the appreciation of physical activity and exercise for youth
449 physical development and long-term athletic development. Data on the EIMD response in
450 well-trained youths would be practically beneficial to those working with youth athletes in
451 high demanding environments. Such a study should include girls and EIMD protocols which
452 are ecologically valid.

453

454 **5. Conclusion**

455 The findings from this meta-analysis provide a clear overview of the responses of youth
456 athletes to EIMD. The data strongly indicates a lower EIMD magnitude in youths after
457 eccentric and/or novel exercise, when measured by changes in muscle strength, muscle
458 soreness and CK. The magnitude of this effect is also greater in the upper- than lower-
459 limbs. By understanding peak responses, and the potential performance impact,
460 practitioners can effectively programme for young athletes to ensure optimal training
461 adaptations, recovery between sessions, and performance outcomes. Practitioners should
462 be mindful that although youths experience less EIMD, it still occurs and that recovery
463 between bouts of exercise is necessary. Moreover, insufficient recovery can lead to non-
464 functional overreaching/overtraining which can have a negative effect on youths
465 performance and well-being. We therefore encourage practitioners to be cognisant of these
466 data and engage youths in physical activity that maximises their enjoyment and
467 development. Future research should explore EIMD in female youths by employing more
468 ecologically valid muscle-damaging protocols and accounting for both maturity and
469 training status.

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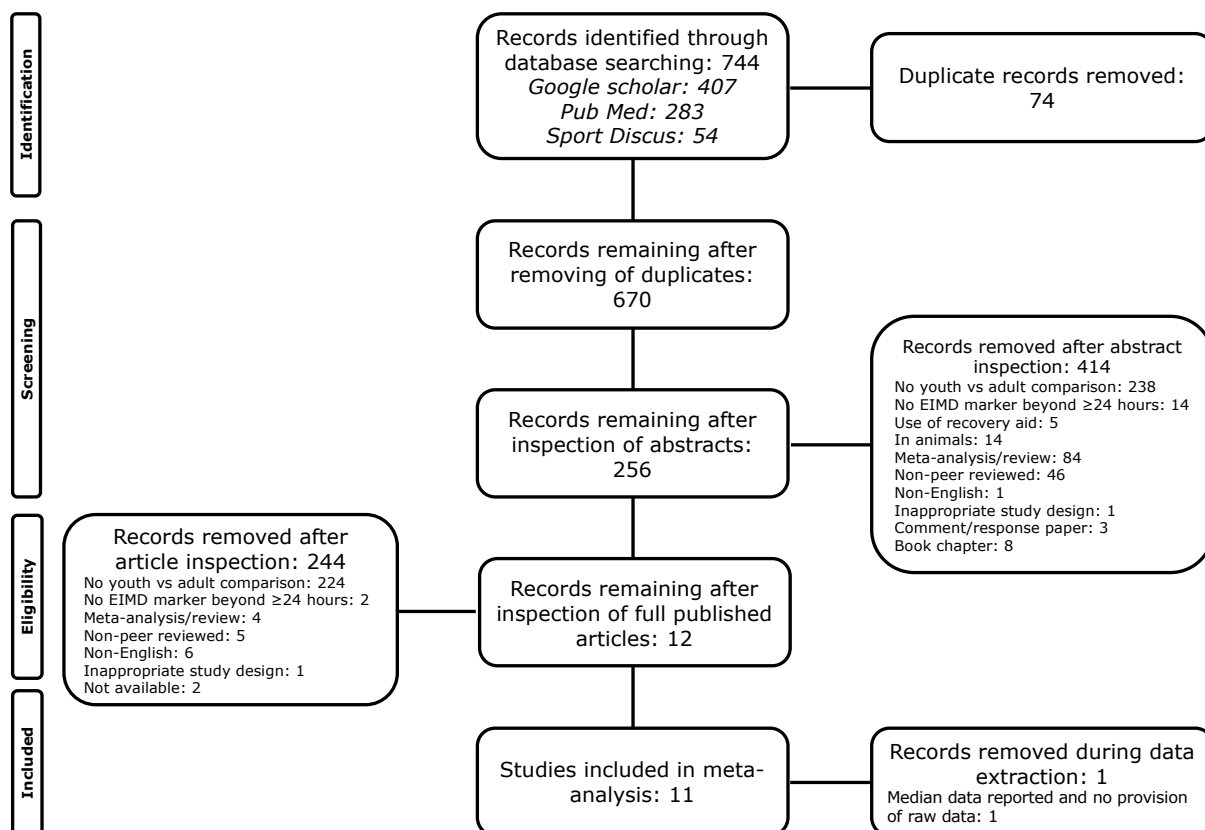
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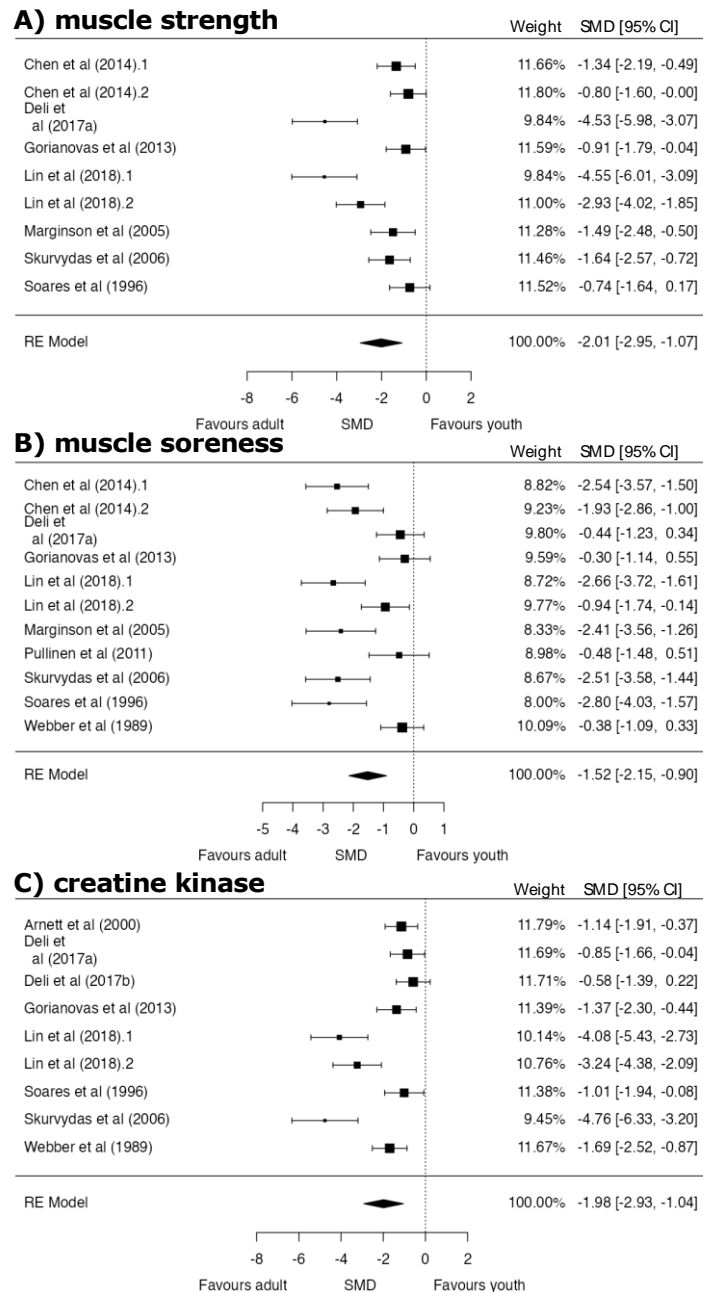
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Figure 1. PRISMA Flow diagram displaying inclusion and exclusion of studies

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Figure 2. Forest plot of studies examining peak changes in muscle strength (A), muscle soreness (B), and creatine kinase (C) after EIMD in youths and adults. Data are presented as the percentage weight each study contributes to the pooled SMD, individual SMD [95% CIs]. Note that symbol size of individual studies is representative of the weighting for the pooled standardised mean difference. The filled diamond indicates overall SMD. RE = random effects. model.

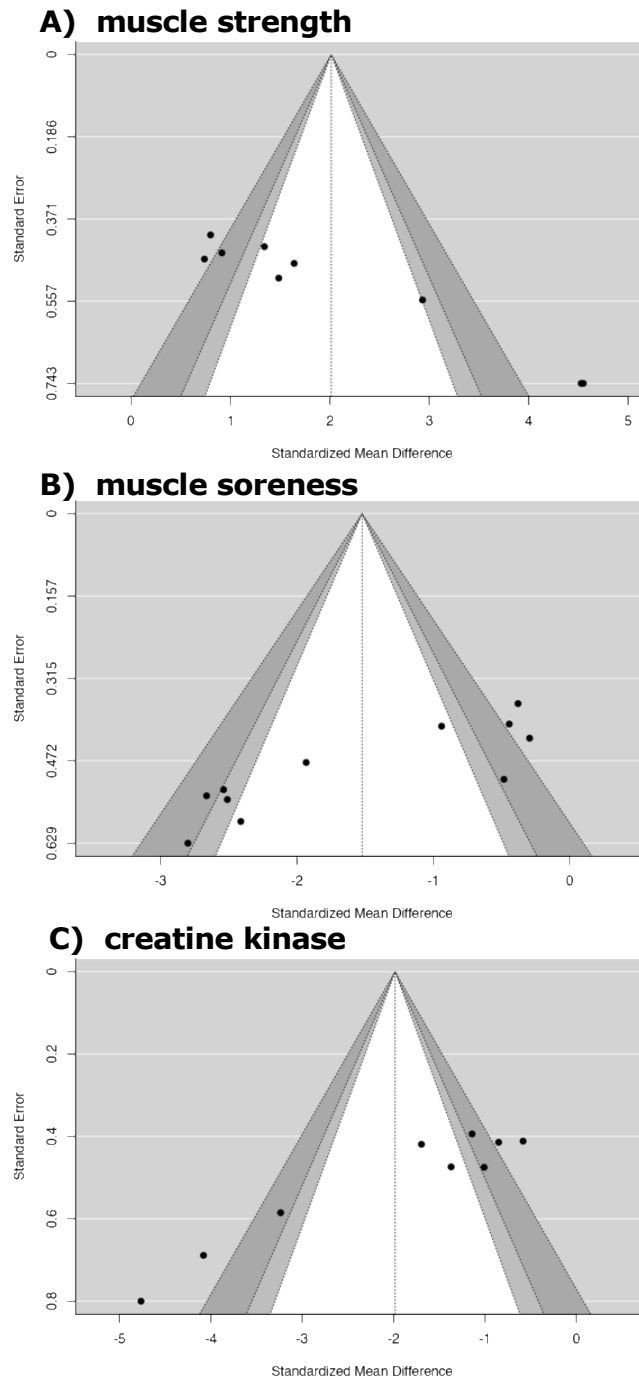


Figure 3. Funnel plots for studies evaluating peak changes in muscle strength (A), muscle soreness (B), and creatine kinase (C) after EIMD in youths and adults.

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747 **Table 1.** The National Institute of Health quality assessment ratings.

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Item	Arnett et al (2000)	Chen et al (2014a)	Deli et al (2017a)	Deli et al (2017b)	Gorianovas et al (2013)	Lin et al (2018)	Marginson et al (2005)	Pullinen et al (2011)	Skurvydas et al (2006)	Soares et al (1996)	Webber et al (1989)	Studies fulfilled
1) Was the study question or objective clearly stated?	1	1	1	1	1	1	1	1	1	1	1	11 (100%)
2) Were eligibility/selection criteria for the study population prespecified and clearly described?	1	1	1	1	1	1	1	1	1	1	1	11 (100%)
3) Were the participants in the study representative of those who would be eligible for the intervention in the general or clinical population of interest?	1	1	1	1	1	1	1	1	1	1	1	11 (100%)
4) Were all eligible participants that met the prespecified entry criteria enrolled?	1	1	1	1	1	1	1	1	1	1	1	11 (100%)
5) Was the sample size sufficiently large to provide confidence in the findings?	1	1	1	1	1	1	0	0	0	0	0	6 (54.5%)
6) Was the intervention clearly described and delivered consistently across the study population?	1	1	1	1	1	1	1	1	1	1	1	11 (100%)
7) Were the outcome measures prespecified, clearly defined, valid, reliable, and assessed consistently across all study participants?	1	1	1	1	1	1	1	1	1	1	1	11 (100%)
8) Were the people assessing the outcomes blinded to the participants' interventions?	0	0	0	0	0	0	0	0	0	0	0	0 (0%)
9) Was the loss to follow-up after baseline 20% or less? Were those lost to follow-up accounted for in the analysis?	1	1	1	1	1	1	1	1	1	1	1	11 (100%)
10) 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?	1	1	1	1	1	1	1	1	1	1	1	11 (100%)
11) Were outcome measures of interest taken multiple times before the intervention and multiple times after the intervention?	0	0	0	0	0	0	0	0	0	0	0	0 (0%)
12) 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?	1	1	1	1	1	1	1	1	1	1	1	11 (100%)
Criterion fulfilled	10 (83.3%)	10 (83.3%)	10 (83.3%)	10 (83.3%)	10 (83.3%)	10 (83.3%)	9 (75.0%)	9 (75.0%)	9 (75.0%)	9 (75.0%)	9 (75.0%)	

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Table 2. Characteristics of included studies

	Youth			Adult		Sex	Activity level	Muscle	EIMD protocol	EIMD markers
	Age	n	Maturity status	Age	n					
Arnett et al. (2000)	10.5 ± 1.1	15	NS	23.4 ± 6.9	15	F	Untrained	KF	6 x 10 ECC at 110% CON 1RM	CK
Chen et al. (2014)	9.4 ± 0.5	13	Tanner stage 1	22.6 ± 2.0	13	M	Untrained	EF	5 x 6 ECC at 90 deg°s ⁻¹	Strength, soreness
	14.3 ± 0.4	13	Tanner stage 3-4				Untrained			
Deli et al. (2017a)	11.0 ± 0.66	11	Tanner stage 2	35.3 ± 8.52	15	M	Untrained	KE	5 x 15 ECC at 60 deg°s ⁻¹	Strength, soreness, CK
Deli et al. (2017b)	11.0 ± 0.66	11	Tanner stage 2	34.9 ± 8.61	14	M	Untrained	KE	5 x 15 ECC at 60 deg°s ⁻¹	CK
Gorianovas et al. (2013)	11.8 ± 0.9	11	NS	20.8 ± 1.9	11	M	Physically active	KE	100 intermittent drop jumps	Strength, soreness, CK
Lin et al. (2018)	10.3 ± 0.7	13	BA = 9.9 ± 0.3	21.3 ± 1.3	13	F	Untrained	EF	5 x 6 ECC at 60% MIVC	Strength, soreness, CK
	14.4 ± 0.5	14	BA = 14.9 ± 0.3			F	Untrained			
Marginson et al. (2005)	9.9 ± 0.3	10	NS	22.2 ± 2.7	10	M	NS	KE	8 x 10 countermovement jumps	Strength, soreness
Pullinen et al. (2011)	14.0 ± 0.0	8	Tanner stage 3-5	31.0 ± 7.0	8	M	Physically active	KE	3 x max repetitions at 40% 1RM	Soreness
Skurvydas et al. (2006)	13.4 ± 0.6	12	NS	25.4 ± 1.7	12	M	Untrained	KE	5 x 10 countermovement jumps	Strength, soreness, CK
Soares et al. (1996)	12.1 ± 0.2	10	NS	28.3 ± 3.5	10	M	Untrained	EE	5 x max repetitions at 80% 1RM	Strength, soreness, CK
Webber et al. (1989)	10.4 ± 4.8	16	Pre-pubescent*	27.2 ± 8.91	15	M & F	Physically active	KE	30 mins running at -10% gradient	Soreness, CK

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756 *Note:* NS = not stated; BA= bone age; *=determined via maturity questions and paediatric cardiologist; F = female; M = male; KF =
757 knee flexors; EF = elbow flexors; KE = knee extensors; EE = elbow extensors; ECC = eccentric; CON = concentric; RM = repetition
758 maximum; MIVC = maximal isometric voluntary contraction; CK = creatine kinase.

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767 **Table 3.** Effect of moderator variables with 95% confidence intervals

		Youths (n)	Adult (n)	Z	P	SMD (95% CIs)	I ² (%)
Muscle strength	Upper limb (n=5)	63	62	2.84	0.004	-2.00 (-3.37, -0.62)	88.06
	Lower limb (n=4)	44	48	2.71	0.007	-2.06 (-3.55, -0.57)	89.91
Muscle soreness	Upper limb (n=5)	63	62	-5.47	<0.001	-2.10 (-2.82, -1.38)	61.80
	Lower limb (n=6)	68	71	-2.47	0.014	-1.03 (-1.84, -0.21)	79.63
Creatine kinase	Upper limb (n=3)	37	36	-2.94	0.003	-2.73 (-4.54, -0.91)	87.07
	Lower limb (n=6)	76	82	-3.01	0.003	-1.62 (-2.67, -0.56)	87.96

768 *Low, moderate, and high heterogeneity correspond to I² values of 25, 50, and 80%, respectively