Comparison of the symptoms of exercise-induced muscle damage after an initial and repeated bout of plyometric exercise in men and boys

Vicky Marginson,1 Ann V. Rowlands,2 Nigel P. Gleeson,2 and Roger G. Eston2

1Cardiac Rehabilitation Department, Glan Clwyd Hospital, Rhyl; and 2Children’s Health and Exercise Research Centre, School of Sport and Health Sciences, University of Exeter, Exeter, United Kingdom

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Marginson, Vicky, Ann V. Rowlands, Nigel P. Gleeson, and Roger G. Eston. Comparison of the symptoms of exercise-induced muscle damage after an initial and repeated bout of plyometric exercise in men and boys. J Appl Physiol 99: 1174–1181, 2005—The purpose of this study was to compare symptoms of exercise-induced muscle damage after an initial and repeated bout of plyometric exercise in men and boys. Ten boys (9–10 yr) and 10 men (20–29 yr) completed two bouts of eight sets of 10 plyometric jumps, 2 wk apart. Perceived soreness (0–10, visual analog scale), isometric strength of the quadriceps at six knee flexion angles, and countermovement jump and squat jump height were assessed before and at 30 min, 24 h, 48 h, and 72 h after each bout. All variables followed the expected patterns of change in men, with soreness peaking at 24–48 h (5.8 ± 1.7) and decrements in muscle function peaking at 30 min after the first bout (73–85% of baseline scores). Symptoms remained for 72 h after the first bout in men. In boys, symptoms were much less severe and peaked at 30 min (visual analog scale = 2.1 ± 1.8, functional decrements 87–92% of baseline) and, with the exception of soreness, returned to baseline after 24 h. After the second bout of plyometric exercise, the level of soreness and decrements in countermovement jump, squat jump, and isometric strength were lower, although the effect was stronger in men, in all cases. The results of this study suggest that although children may experience symptoms of muscle damage after intensive plyometric exercise, they are much less severe. A prior bout of plyometric exercise also appears to provide children with some protection from soreness after a subsequent bout of plyometric exercise. Explanations for milder symptoms of exercise-induced muscle damage in children include greater flexibility leading to less overextension of sarcomeres during eccentric exercise, fewer fast-twitch muscle fibers, and greater and perhaps more varied habitual physical activity patterns.

repeated-bout effect; muscle function; children; flexibility; delayed-onset muscle soreness

STRENUOUS, UNACCUSTOMED ECCENTRIC exercise leads to muscle damage in adults (2, 26, 27, 38, 40, 41). The plethora of symptoms resulting from exercise-induced muscle damage (EIMD), particularly that caused by eccentric muscle activity in adults, is well documented (e.g., for reviews see Refs. 2, 10, 14, 15, 44, among others). Symptoms include delayed-onset muscle soreness (27, 39), presence of intramuscular proteins in the blood (42), and prolonged decrements in muscle function as evidenced by reductions in strength (13, 16), power output (7, 47), range of motion (16), and rapid dynamic muscle function, such as jumping, rebounding, and intermittent maximal intensity exercise (8, 10, 51).

The symptoms associated with exercise-induced muscle damage are substantially reduced after a second bout of uncustomed eccentric exercise (32, 38, 43, 46). This effect is commonly referred to as “the repeated-bout effect” and is attained even if the symptoms after the first bout are mild (6). Explanations for the apparent prophylactic effect of a prior bout of EIMD have been reviewed recently (31, 32).

There have been few studies on EIMD in children, and no study has examined the repeated-bout effect in this group. Webber et al. (52) reported no difference in soreness and creatine kinase (CK) activity in children and adults after a downhill run. Their study suggested that the severity of damage was similar after an initial bout of damaging exercise. In contrast, Soares et al. (49) reported that boys appeared to suffer less damage compared with young men after a weight training protocol, based on measurements of soreness, CK, and isometric strength. Duarte et al. (17) observed that symptoms of damage in boys increased when the duration of the eccentric contraction in a stepping protocol was doubled, although no adult group was included for comparison.

Theoretically, it may be expected that the severity of symptoms of exercise-induced muscle damage would be decreased in children. McHugh et al. (33) observed greater symptoms of damage (strength, tenderness, CK activity) in men and women who were classified as having greater levels of passive stiffness in the hamstring muscles, compared with those who were classified as “compliant.” It was suggested that the reduced amount of stretch in the noncontractile component of the muscle in the stiffer muscles resulted in greater overstretching of the sarcomeres during exercise and hence more damage. It is well documented that flexibility is correlated with muscle stiffness (22) and decreases with age (1). Marginson and Eston (30) have already observed that the extensibility (passive flexibility) of the quadriceps muscle is significantly greater in boys compared with men. The greater flexibility and extensibility of children’s muscle may explain why the torque-joint angle curve of the knee extensors is shifted slightly to the right of the corresponding adult curve. In other words, peak torque occurs at a higher joint angle (longer muscle length) in children than adults (30). This study also observed a significantly greater decrement in peak torque beyond the optimal peak joint angle in adults. Recently it has been shown in adults that this decrement in torque beyond the optimal angle for torque production in the knee extensors, measured before eccentric exercise, is predictive of strength loss and pain after a bout of eccentric exercise (34, 35). This further supports the hypothesis

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that the rightward shift of the children’s torque-joint angle curve relative to the adult curve may mean children are less susceptible to damage.

It may be hypothesized that, in exercising at a given joint angle, the increased compliance of the child’s muscle would lead to differences in sarcomere lengths and affect the relative force that is capable of being exerted at a given joint angle. One of the most prominent explanations for the extent of damage caused by eccentric contractions involves the overextension of sarcomeres that fail to return to their normal length on relaxation of the muscle (36, 37). This effect is exacerbated during eccentric contractions at long muscle length (9, 12, 48) and moderated by the initial passive stiffness of the muscle group (33). Some researchers have reported a shift in the length-tension relationship toward longer muscle lengths after eccentric contractions (5). This adaptation is believed to be due to a shortening of some sarcomeres as compensation for the overstretched and irreversibly damaged sarcomeres in series after eccentric exercise (37). Reduced sarcomere overextension in children’s muscle may lead to reduced levels of muscle damage resulting from eccentric contractions.

There is also evidence to suggest that fast-twitch fibers are particularly susceptible to exercise-induced muscle damage (19, 20, 25). Because children have a lower proportion of fast-twitch fibers (28), the symptoms of exercise-induced muscle damage in children may be expected to be milder than those reported by adults.

Therefore, we hypothesized that the severity of symptoms of exercise-induced muscle damage after an initial bout of plyometric exercise would be milder in boys than in men. As a consequence, we also hypothesized that the repeated-bout effect would be less evident in boys than in men.

METHODS

Participants

Ten boys [age (mean ± SD) 9.9 ± 0.3 yr, height 138.2 ± 5.4 cm, mass 32.2 ± 6.3 kg] and 10 men (age 22.2 ± 2.7 yr, height 183.5 ± 5 cm, mass 71.8 ± 6.3 kg) participated in this study. All participants gave written consent. In the case of the children, parents or guardians gave written consent and children gave verbal assent to participate in this study. The study was approved by the North West Wales National Health Service Trust Ethics Committee. Before any participation in this study, all participants completed health questionnaires to screen for any potential health risk. Reports of any history of knee pain or injury would have led to exclusion from the study. At the onset of the study, participants attended the laboratory for a familiarization session. This session also served to obtain target values for strength and jump height that the participant was encouraged to exceed during all subsequent testing.

Procedure

After familiarization procedures, which took place 2–3 days before, all participants performed two bouts of damage-inducing exercise separated by a 2-wk break. Before each bout, each participant followed a standardized warm-up. This consisted of five submaximal and five maximal continuous jumps and a standardized stretch of the quadriceps muscles, whereby the foot was raised to the buttocks. After the warm-up, participants performed eight sets of 10 continuous maximal plyometric jumps. Participants stood with feet shoulder width apart and hands on hips. Assuming this posture, they were asked to jump as high as possible on each jump after a preparatory downward eccentric movement, to a knee bend of ~90°, which was performed as fast as possible. Verbal guidance and encouragement were given throughout by the experimenter (V. Marginson). Each set of 10 jumps was separated by a 1-min rest period, in which the participant was allowed to walk around. Measures of isometric strength, countermovement jump height, squat jump height, and soreness were taken before each damaging protocol and at 30 min, 24 h, 48 h, and 72 h after each of the two bouts of damaging exercise.

Passive extensibility of the hip flexors (hip extension with knee flexion). During the familiarization period, passive hip extension was measured. Participants were placed in the prone position on a portable treatment couch (Darley, Cornwall, UK). A restraining strap was placed across the pelvis, and a partner stabilized the hips to prevent any extraneous movement. A Leighton flexometer (Leighton, Spokane, WA) was attached 2 cm proximal to the lateral malleolus. The knee was flexed to 120° (0° = full extension) and splinted to lengthen the quadriceps muscle. The Leighton flexometer was then transferred to the lateral epicondyle of the femur. The experimenter placed one hand under the hip, to ensure that the hip was not lifting off the couch, and the other hand under the thigh, proximal to the knee. The participant was asked to relax while the experimenter lifted the participant’s thigh to extend the hip to its maximum range of motion. Maximum hip extension was indicated by the participant saying “stop” (Fig. 1). The mean of three trials was taken as the performance measure (23).

Plyometric exercise protocol for inducing muscle damage. Power output was assessed by use of an infrared jump system (Optojump, Microgate, Bolzano, Italy) interfaced with a Hi Grade AMD K2 366-mHz laptop computer. Participants stood between two infrared sensor bars to perform the eight sets of 10 plyometric jumps. A visual display showed power output in real time. Participants were asked to try to beat or maintain target values that were based on their maximal countermovement jump height. Power output was recorded for each of the eight sets of 10 jumps for both bouts using the following equation, adjusted to obtain absolute power output in watts (4):

$$PO = BM \cdot \frac{g^2 \cdot \Sigma t_{flight} \cdot (\Sigma t_{flight} + \Sigma t_{contact})}{4 \cdot N_{jump} \cdot \Sigma t_{contact}}$$

where PO is absolute power output (W), BM is body mass, g is the acceleration of gravity (≈9.8065 m/s²), t_{flight} is flight time (ms), t_{contact} is contact time (ms), and N_{jump} is number of jumps.

Torque-joint angle relationship and isometric strength. The torque-joint angle relationship associated with the knee joint extensor musculature was assessed before and 30 min after each bout of damage-inducing exercise on an isokinetic dynamometer (Kin Com, 500H...
The power output (W) elicited by each group during the damage-inducing jumping exercise was calculated for each of the eight sets of 10 jumps, for bout 1 and bout 2. A three-factor mixed-model analysis of covariance, with repeated measures on bout (2) and set (8), was used to assess group differences across both bouts. Body mass was used as the covariate.

To address the question of whether boys suffered milder symptoms of muscle damage after a single plyometric exercise bout, a series of two-factor mixed-model ANOVAs, with repeated measures on time (5), were used. The symptoms examined were soreness, isometric strength at the optimal angle, squat jump, and countermovement jump. A three-factor mixed-model ANOVA, with repeated measures on angle and time, was used to assess group differences in the torque-joint angle relationship from predamage values and whether this curve shifted to the right after the first bout of damaging exercise.

To address the question of whether the repeated-bout effect was evident in each group, a series of two-factor ANOVAs, with repeated measures on bout (2) and time (5), was used for men and boys separately. The symptoms examined were soreness, isometric strength at the optimal angle, squat jump, and countermovement jump.

Where appropriate, the Greenhouse Geisser correction was used to account for violation of the assumption of sphericity in the ANOVA analyses. Post hoc Tukey’s tests, modified for mixed-model ANOVAs (50), were used to follow up significant results.

Correlational analyses were undertaken to assess whether there was a relationship between flexibility and the severity of symptoms of exercise-induced muscle damage. Correlations were computed separately for range of motion with soreness, isometric strength, countermovement jump height, and squat jump height at 30 min, 24 h, 48 h, and 72 h postdamage. Boys and men were assessed separately to avoid confounding the analysis because boys are typically more flexible and 72 h postdamage. Boys and men were assessed separately to avoid confounding the analysis because boys are typically more flexible than men and experience less severe symptoms of muscle damage. This resulted in 32 correlations (4 symptoms × 4 time points × 2 groups). To account for the increased risk of Type I error, the Bonferroni correction was used and alpha was reduced to 0.0016 (0.05/32). Alpha was set at 0.05, unless stated otherwise.

RESULTS

Descriptive statistics are presented in Table 1. Hip extension was significantly greater ($t_{18} = 4.52, P < 0.001$) in boys than in men.

<table>
<thead>
<tr>
<th>Angle (°)</th>
<th>Boys (n = 10)</th>
<th>Men (n = 10)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline isometric strength, N</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20°</td>
<td>97.4 ± 40.6*</td>
<td>434.0 ± 106.9</td>
</tr>
<tr>
<td>40°</td>
<td>251.8 ± 71.8*</td>
<td>879.2 ± 164.4</td>
</tr>
<tr>
<td>60°</td>
<td>427.1 ± 40.8*</td>
<td>1,407.2 ± 190.8</td>
</tr>
<tr>
<td>80°</td>
<td>601.1 ± 186.3*</td>
<td>1,615.8 ± 205.8</td>
</tr>
<tr>
<td>90°</td>
<td>623.5 ± 193.8*</td>
<td>1,404.3 ± 194.0</td>
</tr>
<tr>
<td>100°</td>
<td>591.7 ± 171.9*</td>
<td>1,164.5 ± 160.2</td>
</tr>
<tr>
<td>Jump height, cm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Countermovement</td>
<td>23.0 ± 3.5*</td>
<td>36.3 ± 4.5</td>
</tr>
<tr>
<td>Squat</td>
<td>18.9 ± 2.4*</td>
<td>30.1 ± 3.4</td>
</tr>
<tr>
<td>Bout 2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Baseline isometric strength, N</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Optimal angle</td>
<td>636.4 ± 130.1*</td>
<td>1,630.6 ± 177.0</td>
</tr>
<tr>
<td>Jump height, cm</td>
<td>Countermovement</td>
<td>21.7 ± 2.5*</td>
</tr>
<tr>
<td>Squat</td>
<td>19.2 ± 2.4*</td>
<td>30.7 ± 3.5</td>
</tr>
</tbody>
</table>

Values are means ± SD. *Significant difference between groups, $P < 0.001$. 

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Power output during the plyometric exercise protocol. There were no interactions for power output or main effects for bout or set. However, there was a main effect for group ($F_{1, 17} = 5.4, P < 0.05$) indicating that power output (adjusted for body mass) was higher in men than in boys (Fig. 2).

Symptoms of Exercise-Induced Muscle Damage

Comparison of symptoms of damage after one bout of damaging exercise in boys and men. There were group × time interactions for soreness ($F_{2.3, 42.0} = 17.0, P < 0.001$, Fig. 3), relative isometric strength ($F_{2.6, 42.8} = 4.9, P = 0.007$, Fig. 4), and relative squat jump height ($F_{2.6, 42.8} = 4.9, P = 0.007$, Figs. 5 and 6). Post hoc analysis showed that soreness was greater, and strength and jump height lower, in men than in boys 30 min postexercise and throughout the measurement period ($P < 0.05$). In men, all symptoms remained different from baseline at 30 min, 24 h, 48 h, and 72 h postexercise ($P < 0.05$). However, in boys, soreness was only elevated above baseline at 30 min and 24 h postexercise ($P < 0.05$), and strength and jump height were only lower than baseline 30 min postexercise ($P < 0.05$).

Torque-joint angle relationship. No time × angle × group interaction was evident (Fig. 7), but there was an angle × group interaction ($F_{2.5, 45.3} = 39.00, P < 0.001$). Post hoc analysis revealed that in boys relative isometric strength increased as angle increased (i.e., muscle length increased) up to 80°. Strength then plateaued and was not different between 80, 90, and 100°. However, in men isometric strength increased as angle increased up to a peak at 80°. Strength then decreased significantly at 90° and again at 100°. Relative torque was higher in men vs. boys at 20, 40, and 60°, but higher in boys at 100°. This was indicative of a leftward shift in the torque-joint angle curve in men relative to boys.
There was no main effect of time or interaction involving time, showing that the muscle damage did not result in any shift of the torque-joint angle curve in either group.

Repeated-Bout Effect

Soreness. In boys there was a trend for a bout \times time interaction \((F_{1, 9} = 3.4, P = 0.06, \text{Fig. 3})\). There were main effects for bout \((F_{1, 9} = 5.8, P = 0.039)\) and time \((F_{1, 9} = 16.1, P < 0.001)\). Soreness was greater after the first bout than the second bout, indicating a repeated-bout effect, and post hoc analysis showed that soreness was elevated 30 min postexercise, then returned to baseline \((P < 0.05)\).

In men, there was a bout \times time interaction \((F_{1, 9} = 4.3, P = 0.037)\). Post hoc analysis showed a repeated-bout effect whereby soreness was greater after the first bout than the second bout 30 min, 24 h, 48 h, and 72 h postexercise \((P < 0.05)\). After bout 1, soreness increased 30 min postexercise and remained elevated for the entire measurement period. Soreness was elevated above baseline at 24 and 48 h after bout 2 \((P < 0.05)\).

Isometric strength. In boys there was no bout \times time interaction \((F_{4, 36} = 0.9, P < 0.498, \text{Fig. 4})\) or main effect for bout \((F_{1, 9} = 0.8, P = 0.402)\), indicating no repeated-bout effect, but there was a main effect for time \((F_{4, 36} = 9.1, P < 0.001)\). Post hoc analysis showed that strength decreased 30 min postexercise, then returned to baseline \((P < 0.05)\).

In men, there was a bout \times time interaction \((F_{4, 36} = 2.9, P < 0.001, \text{Fig. 4})\). Post hoc analysis showed a repeated-bout effect whereby strength decrement was lower after bout 2 than after bout 1 at 30 min, 24 h, 48 h, and 72 h postexercise \((P < 0.05)\). After bout 1, strength decreased at 30 min postexercise and remained below baseline for the entire measurement period. Strength decreased at 30 min after bout 2 but was returned to baseline by 72 h postexercise \((P < 0.05)\).

Squat jump. In boys, there was a bout \times time interaction \((F_{4, 36} = 2.7, P = 0.048, \text{Fig. 5})\). Post hoc analysis showed that jump height was higher after bout 1 than bout 2 at 48 h postexercise, but higher after bout 2 than bout 1 at 72 h \((P < 0.05)\). After both bouts, jump height decreased below baseline.
Fig. 7. Comparison of maximal torque at specific joint angles before and after the first bout of plyometric exercise in men and boys. *Significant group difference (P < 0.05).

examined in men, but only for soreness in boys. This may be due to the greater symptoms of damage evident in men after the first bout. There was no evidence of a rightward shift in the length-tension curve after damage, in either men or boys. It should be noted that the lack of evidence for a rightward shift in the length-tension curve does not mean a shift did not occur. The sample size was small (only 10 participants per group), limiting the power to detect such a shift. Furthermore, the only previous study to demonstrate a shift of the curve in the knee extensors (34) showed the effect at an angle of 110°. The present study assessed torque only up to 100°.

The results for the men confirm that the eccentric exercise protocol was sufficient to induce damage because the symptoms experienced were of a similar severity to those reported in the literature and showed the expected temporal pattern (8, 13, 27, 43). Furthermore, the repeated-bout effect, as demonstrated by reduced symptoms after the second bout of exercise, was evident. Therefore, we have confidence that the relatively mild symptoms experienced by the boys reflect group differences in the response to the exercise, as opposed to an exercise protocol that was not severe enough. Notably, all symptoms of damage peaked at 30 min after the first bout of exercise in boys and, with the exception of soreness, were back to baseline 24 h after exercise, supporting the findings of Soares et al. (49). Therefore, it is possible that decrements in muscle function may have been attributable to fatigue.

Previous research has reported that squat jump height is affected to a greater extent than countermovement jump height after EIMD in adults (8, 11). Similarly, in the present study the decrement in performance was greatest for the squat jump in men. The pattern of decline and recovery in squat and countermovement jump height in men concurs with previous findings after a single bout of eccentric exercise (8, 11). In boys, both jumps appeared to be affected to a similar extent after bout 1, although recovery was quicker for the squat jump. After the second bout of exercise, squat jump height did not deteriorate, and countermovement jump height decreased only slightly, in boys. In fact, the boys showed a trend for a supramaximal response in the countermovement jump after the second bout.

Because decreased muscle compliance has been linked with more severe symptoms of exercise-induced muscle damage (33), it was hypothesized that boys may experience milder symptoms owing to greater flexibility. The negative correlation between soreness and hip extension in men supports this hypothesis. No such relationship was present in boys, possibly because flexibility was consistently high among the boys and this homogeneity of performance capability may have tended to limit the extent of correlation, giving a ceiling effect. As expected, hip extension was greater in boys compared with men. This may have contributed to the difference in the length-tension curves, evidenced by greater relative strength in boys at long muscle lengths, as previously observed by Margison and Eston (30) in a separate group of men and boys.

Muscle length is an important moderating factor in the amount of muscle damage that is sustained, with exercise at longer muscle lengths leading to greater damage (9, 11, 46, 48). Morgan’s (36) popping sarcomere theory predicts a greater disruption to sarcomeres when the muscle functions at longer lengths corresponding to the plateau or descending portions of the torque-joint angle curve. Two recent studies
(34, 35) have shown that the decrease in torque beyond the optimal angle for torque production in the knee extensors, measured before eccentric exercise, is predictive of strength loss and pain on subsequent days in adults. As the angle-torque curve was shifted to the right in the boys in the present study, studies by McHugh at el. (34, 35) support the hypothesis and observation that children are less susceptible to exercise-induced muscle damage. With respect to the popping sarcomere theory, Morgan (36) proposed that there are always individual sarcomeres on the descending limb of the length-tension curve during eccentric contractions. The inherent nonuniformity of sarcomere length during eccentric contractions is explained by some sarcomeres being weaker than others. At longer muscle lengths, a greater number of sarcomeres would be operating on their descending limb. It is apparent from the torque-joint angle curves of the men and boys that the hypothesized phenomenon of sarcomere overstretching would be greater in men at any given muscle length. This may have induced more damage and hence more severe symptoms of exercise-induced muscle damage in the men.

During the bouts of eccentric exercise in the plyometric exercise protocol, power output (adjusted for body mass) was higher in men than in boys. The metabolic demands of the exercise protocol should not be ignored, particularly as the anaerobic glycolytic capacity increases with maturity (3, 18). This, in addition to the potentially greater proportion of fast-twitch fibers in adult muscle (28), is the most likely explanation for the greater power output observed in men. It is possible that the higher power output in the men resulted in a higher strain per muscle fiber, which induced greater muscle damage and led to the more severe symptoms present in men (29). Additionally, damage has been reported to occur predominantly in fast-twitch fibers (19, 20, 25). Because fast-twitch fibers are more susceptible to damage, a lower proportion of these fibers in boys may help explain the relatively mild symptoms of EIMD.

Children exhibit higher levels of habitual physical activity than adults (45). Children’s habitual activity typically involves hopping, jumping, and climbing activities, whereas adult’s activity tends to be of a lower intensity and restricted more to walking and running activities (24). Therefore, it is possible that, through the nature of their daily activity, children already have a protection from muscle damage, a prior repeated-bout effect, leading to the milder symptoms experienced when following the same damage-inducing protocol as adults.

In conclusion, boys experienced less severe symptoms of damage than men after a damage-inducing protocol. All functional measures were back to baseline 24 h after exercise, and soreness was back to baseline 48 h after exercise. Despite the relatively mild nature of the symptoms, there was a repeated-bout effect for soreness. Less muscle damage in boys may be explained by their greater flexibility and their ability to produce greater relative strength than the men at long muscle lengths, possibly leading to less overextension of sarcomeres during the damaging exercise bouts. Other possible explanations include the hypothesized greater reliance on slow-twitch muscle fibers during damage-inducing exercise in boys and greater and more varied habitual physical activity providing the boys with a prior repeated-bout effect. Future research should include girls and should investigate mechanisms for the reduced severity of symptoms of exercise-induced muscle damage in boys compared with men. The speed of recovery from the exercise bouts exhibited by the boys supports the use of plyometric training methods in boys.

REFERENCES