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ORIGINAL ARTICLE

The effect of acute low-load resistance exercise with the addition of blood flow occlusion on muscle function in boys and men

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Abstract

Purpose In adults, low-load resistance training with blood flow occlusion (BFO) mimics strength increases that occur from high-load training, without the need to experience high mechanical stress. In view of child–adult differences in exercise responses, this study examined whether BFO during exercise elicits differential changes in maximal voluntary contraction (MVC) and electromyographical (EMG) activity in children and adults.

Methods Sixteen men (24.4 ± 2.5 years) and 14 boys (10.7 ± 2.0 years) performed low-load resistance exercise (25 repetitions at 35% MVC) of the wrist flexors with and without BFO. MVC wrist flexor force and EMG activity of the flexor carpi radialis (FCR) were obtained at the beginning and end of the exercise.

Results Both groups demonstrated a larger decrease in MVC force following BFO ($-18.6 \pm 12.5\%$) than the control (without BFO) condition ($-6.2 \pm 15.0\%$; $p < 0.001$). Whereas the men's EMG amplitude increased $16.3 \pm 20.5\%$ ($p = 0.005$) during BFO, the boys' EMG amplitude did not change over time or between conditions. In both groups, the mean power frequency (MPF) of the EMG signal decreased more during BFO ($-20.1 \pm 9.6\%$; $p < 0.001$) than the control condition ($-5.6 \pm 9.7\%$; $p = 0.002$).

Conclusions Low-load exercise with BFO resulted in similar neuromuscular responses between boys and men, except for an observed increase in the EMG amplitude in men but not boys. While this result might suggest that men relied on a greater activation of higher-threshold motor units during BFO, it does not explain why there were similar decreases in MPF between groups. Therefore, it remains unclear whether the effectiveness of BFO training is similar for children and adults.

Keywords Blood flow occlusion · Children · Electromyography · Resistance exercise · Strength

Abbreviations

BFO	Blood flow occlusion
EMG	Electromyography
MPF	Mean power frequency
MVC	Maximal volitional contraction
RE	Resistance exercise
RMS	Root mean square
RPE	Rating of perceived exertion

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Introduction

Loads that are higher than the intensity to which a muscle is accustomed must be used to enhance muscular strength and hypertrophy. However, some individuals, such as those undergoing rehabilitation, are unable to withstand the high mechanical stress placed on the joints and muscles that may be required to induce these muscle adaptations. To compensate for this, researchers have suggested that replacing high-load resistance training with low-load resistance training in combination with blood flow occlusion (BFO) achieves a similar increase in muscle strength (Loenneke et al. 2010). For example, Yasuda et al. (2008) found that repeated sessions of resistance exercise with BFO resulted in greater strength and hypertrophy gains than would otherwise be seen from non-occluded low-load training. Others have observed that strength and hypertrophy gains following low-load BFO resistance training could be comparable to that of non-occluded high-load training (Cook et al. 2007, 2018; Manimmanakorn et al. 2013; Manini and Clark 2009; Takarada et al. 2000).

It is suggested that the increases in strength and hypertrophy observed following low-load BFO resistance training are due to BFO reducing oxygen availability and increasing metabolite accumulation during low-load exercise. These processes may lead to changes in motor unit recruitment, with greater activation of higher-threshold motor units (Loenneke et al. 2010; Moritani et al. 1992). That is, trapped metabolites from glycolytic metabolism reliance and BFO result in lower intramuscular pH (acidic milieu) and are hypothesized to be responsible for acute fatigue and increased higher-threshold motor unit recruitment (Wernbom et al. 2012). This has been supported by findings of a ~ 50% increase in motor unit firing rate (Moritani et al. 1992) and a 60–100% increase in EMG amplitude during exercise with BFO (Moritani et al. 1992; Person and Golubovich 1960; Takarada et al. 2000; Yasuda et al. 2009).

While the benefits of BFO have been investigated in adults, the effects of exercise with BFO in children are currently unknown. It cannot be assumed that children will respond to BFO in a similar manner as adults due to differences in muscle function and physiological responses to resistance training and exercise. For example, children have previously been shown to have lower muscle (Eriksson et al. 1971) and blood lactate levels during exercise, and may experience lower metabolite accumulation (Dotan et al. 2003; Hebestreit et al. 1993; Ratel et al. 2002; Zafeiridis et al. 2005). This may be due to children having a greater proportion of type I and lower type II (~ 10%) muscle fibres than adults (Jansson 1996; Lexell et al. 1992). Furthermore, children recruit less of their available motor unit pool, as reflected by lower volitional activation, compared with adults (O'Brien et al. 2010). It has also been hypothesized that children specifically recruit less of their type II motor units during high-intensity contractions (Dotan et al. 2012; Long et al. 2017; Pitt et al. 2015; Woods et al. 2019, 2020). Together, these factors might suggest that children are less affected by resistance exercise with BFO, as they rely less on higher-threshold motor unit recruitment and display a smaller decrease in functional working capacity than adults.

The purpose of this study was to determine whether a low-intensity (35% MVC) resistance exercise session combined with BFO increases children's muscle activity more than resistance exercise without BFO, and whether this increase is comparable to adults. It was hypothesized that both boys and men would demonstrate greater muscle activity when performing low-load contractions with BFO compared to without. However, due to children's hypothesized lower recruitment of high-threshold motor units, it was expected that the increase in muscle activity would be lower in boys compared with men. It was also hypothesized that both boys and men would demonstrate a larger decrease in maximal force from pre- to post-exercise with BFO, compared to without, but the relative decrease in maximal force would be smaller in boys than in men.

Methods

Participants

Healthy, recreationally active boys ($n = 14$, 10.7 ± 2.0 years) and men ($n = 16$, 24.4 ± 2.5 years) participated in this study. All boys self-assessed as maturational stages 1–3 based on secondary sex-characteristics (Tanner 1981), and were before the age of peak height velocity (− 2.47 ± 1.5 years) (Mirwald et al. 2002). Detailed participant characteristics are presented in Table 1. All participants and children's parents/guardians provided written informed consent or assent. All procedures were cleared by the Brock University Research Ethics Board.

Experimental procedure and measurements

Participants visited the Biomechanics and Motor Control Laboratory at Brock University on two separate days, approximately 1 week apart. On the first visit, anthropometric measurements including height, seated height (boys only), forearm skinfold thickness, and forearm length were obtained. Habitual physical activity was assessed using the Godin–Shephard Leisure-Time Exercise Questionnaire (Godin and Shephard 1985), and pubertal stage (boys only) was self-assessed. Next, participants completed a familiarization protocol, whereby they became accustomed to the equipment, the required wrist contractions, and the BFO. Participants placed their right forearm and hand into a custom-built isometric wrist flexion dynamometer (Fig. 1) which was adjusted to each participant's forearm length and width. A strain gauge transducer was attached to the custom-built dynamometer to measure the exerted wrist flexion force at a sampling rate of 1000 Hz (micro1401, Cambridge Electronics Design, Cambridge, UK). Participants completed

Table 1 Participant characteristics.

Variables	Men	Boys
Age (y)*	24.4 ± 2.0	10.7 ± 2.0
Height (cm)*	180.0 ± 5.9	148.6 ± 13.8
Mass (kg)*	82.9 ± 13.7	39.9 ± 9.5
Volar skinfold (mm)	3.9 ± 2.9	2.7 ± 1.6
Body Fat (%)*	18.2 ± 6.5	11.3 ± 4.6
Resting Systolic BP (mmHg)*	124.9 ± 5.1	107.2 ± 7.6
MVC Systolic BP (mmHg)*	135.4 ± 2.8	115.8 ± 4.3
Physical Activity Score	53.8 ± 27.3	68.1 ± 28.6

*indicates a significant difference between the men and the boys

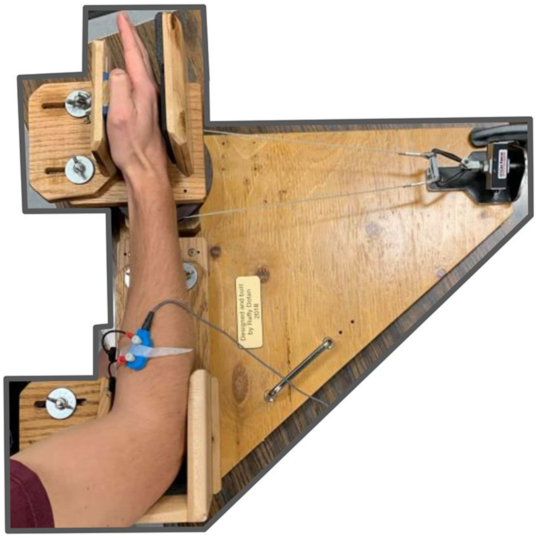

Fig. 1 Overhead view of a custom-built isometric wrist flexion dynamometer with the participant's ulnar styloid process above the device's axis of rotation. Wrist flexion force applied to the left was recorded using the attached strain gauge transducer

a series of sub-maximal wrist contractions as a warm-up before completing three MVCs of the wrist flexors. Each MVC was held for 3 s and contractions were separated by 1 min of rest. Resting and MVC systolic blood pressure were measured from the participant's right upper arm prior to the first MVC and during the first two MVCs, respectively. Subsequently, practice contractions with and without BFO over a range of different intensities were performed. The practice continued until the participants were comfortable and capable of performing sub-maximal and maximal contractions with and without concurrent BFO.

The second visit included the control and BFO protocols, in random order. It began by preparing the participant's skin for the placement of EMG electrodes. The skin of the right forearm directly over the flexor carpi radialis (FCR) was shaved when necessary, abraded with a conductive gel (NuPrep, Weaver and Company, Aurora, CO, USA), and cleansed with alcohol before two surface electrodes (N-00-S, Ambu BlueSensor N, Malaysia) were placed on the skin with an interelectrode distance of 1.25 cm. A single ground electrode (H124SG, Covidien Kendall, Minneapolis, MN, USA) was placed on the right styloid process of the radius. The EMG signal was amplified 350 times (Motion Lab Systems, Baton Rouge, LA, USA) and recorded using a data acquisition program (Spike2, Cambridge Electronics Design, Cambridge, UK) at a sampling rate of 2000 Hz (micro1401, Cambridge Electronics Design, Cambridge, UK). The EMG data were filtered offline using a 4th order, 30–500 Hz band-pass filter prior to analysis.

Participants completed the same warm-up, MVCs (MVC_{pre}) and blood pressure recording procedures as the first visit. The highest force from the three MVC trials was used to determine the target force during the repeated contractions protocol. They then completed two experimental conditions in a randomized order (Fig. 2). For the occlusion condition, participants performed 25 wrist flexions at 35% MVC while concurrently experiencing BFO, at 50 mmHg above MVC systolic blood pressure. An intensity of 35% MVC was chosen based on pilot testing data and previous research using low-loads with BFO (Moritani et al. 1992; Takarada et al. 2000; Yasuda et al. 2009). Each contraction was held for 3 s, followed by 3 s of relaxation. Online feedback of the participant's force was provided on a screen situated in front of the participant. Following the 25th contraction, participants rated their perceived level of exertion (RPE) using the Omni-Resistance Exercise Scale of Perceived Exertion (Robertson et al. 2005), in which 1 is the lowest and 10 is the highest score, and completed one MVC (MVC_{post1}) before the blood pressure cuff was deflated and removed. A second MVC (MVC_{post2}) was conducted two

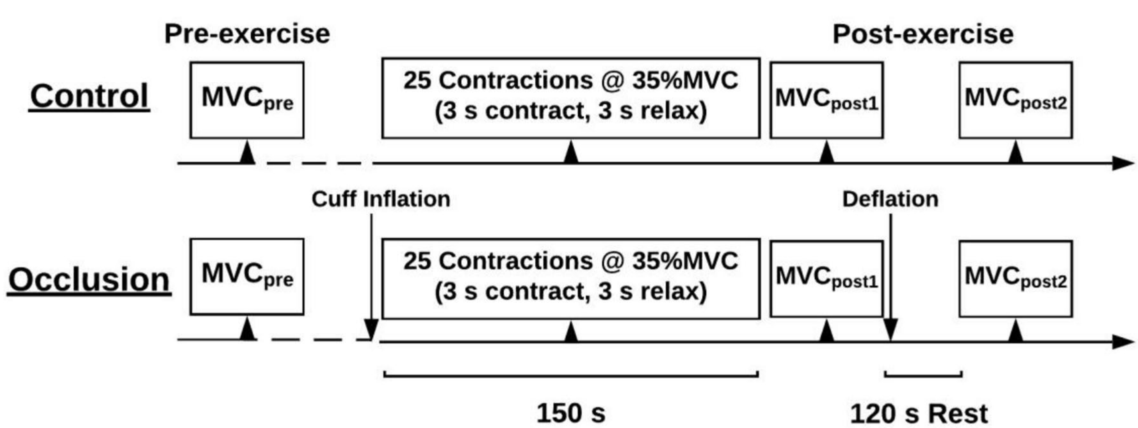

Fig. 2 Timeline of both experimental conditions completed during the second visit. The two conditions were performed in a randomized order

minutes following the cuff removal. Due to time restrictions, only a single MVC trial could be collected at each of MVC_{post1} and MVC_{post2}. However, relying on a single trial for determining MVC has been performed by others (Yasuda et al. 2009). Further, no differences in force were observed between the three pre-exercise MVC trials ($p = 0.150$ across all participants; $p = 0.274$ for boys only). The test–retest reliability coefficient of these three contractions ranged between $r = 0.965$–0.977 when data from both men and boys were combined, and $r = 0.873$–0.913 for boys' data only. These results suggest that participants, and particularly the boys, were well accustomed to the experiment's MVC protocol and that the reported MVC values at each time point are likely to be reliable.

The control condition involved the same procedures and timeline as the occlusion condition but without BFO. Participants were provided 15 min of rest between conditions. The duration of rest was determined based on pilot testing, where no changes in EMG amplitude were observed when two control conditions were performed 10 min apart (see Fig. 2 for protocol).

Data analyses

Of the 25 sub-maximal contractions performed during each of the occlusion and control conditions, the 2nd to the 5th as well as the last 4 trials were included for analyses (Fig. 3). For these contractions, the period during which the raw force signal was nearest to 35% MVC and most stable (i.e., the lowest SD) over a 1.5 s window was determined. Data obtained during this time period was then used to calculate the average force, the EMG RMS amplitude and the EMG MPF. The two EMG outcome measures were chosen as they have been suggested to indirectly reflect motor unit activation (Wernbom and Aagaard 2019).

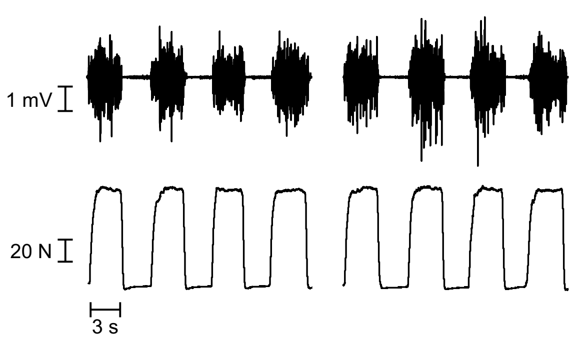

Fig. 3 EMG and force traces from a representative adult male during the occlusion condition. The first four contractions represent trials 2–5 and the last four contractions represent trials 22–25. These two blocks of trials were used for comparing the average force as well as the EMG RMS amplitude and MPF between the occlusion and control conditions

Statistical analyses

Physical characteristics were compared between boys and men using independent samples t-tests. The effect of BFO on EMG and trial force were analyzed using separate 2 (age: boys vs. men) × 2 (condition: control vs. occlusion) × 2 (time: start vs. end) mixed model ANOVAs. The effect of BFO on MVC was analyzed using separate 2 (age: boys vs. men) × 3 (MVC_{pre} vs. MVC_{post1} vs. MVC_{post2}) ANOVAs for the occlusion and control conditions. These analyses were performed for each condition separately because the MVC_{pre} value was obtained once, only at the beginning of the second visit. The effect of BFO on RPE was analyzed using a 2 (age: boys vs. men) × 2 (condition: control vs. occlusion) ANOVA. Note that the reported ANOVAs were also performed with "condition order" as a between-subject factor. This was to examine whether there were any potential order effects from participants having to complete the control and occlusion trials on the same day. However, since no main or interaction effects involving condition order were significant, these results are not presented in this paper.

Assumptions of normality were confirmed prior to all statistical analyses. Post-hoc two-way ANOVAs and/or Bonferroni-corrected *t* tests were conducted where appropriate. All statistical analyses were performed using IBM SPSS Statistics (version 24, Armonk, NY, USA). A significance value of $p \leq 0.05$ was used for all tests. The Greenhouse–Geisser correction was interpreted when the assumption of sphericity was violated (i.e. $p \leq 0.05$ for Mauchly's statistics). Unless otherwise stated, all results are reported as the mean ± one SD.

Results

Muscle activation

When normalized to MVC, the FCR EMG amplitude during the set of contractions at 35% MVC was influenced by a group × time × condition interaction effect ($F_{1,28} = 5.953$; $p = 0.021$) (Fig. 4). After separating by age, a time x condition interaction effect was observed in the men ($F_{1,15} = 14.329$; $p = 0.002$), where the men's EMG amplitude increased by 6.3 ± 7.7%MVC (95% CI [2.2, 10.4]) from the start (i.e., 2nd–5th contractions) to the end (i.e., 21st–25th contractions) of the occlusion condition ($t_{15} = 3.257$; $p = 0.005$). This represented a relative increase of 16.3 ± 20.5%. In contrast, no change (−0.1 ± 5.6%MVC (95% CI [−2.8, 3.1])) in the FCR EMG amplitude was

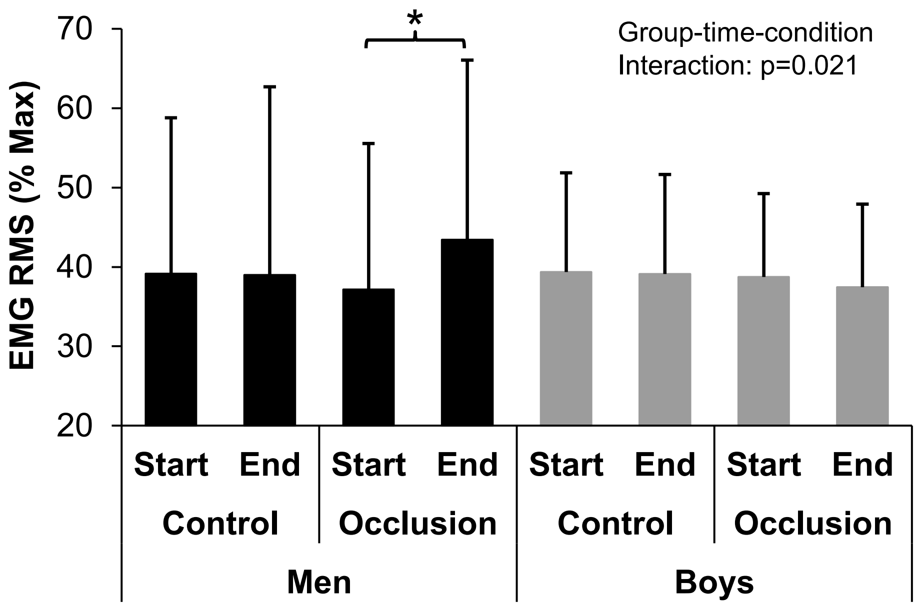

Fig. 4 The mean ± 1 SD EMG RMS amplitude, expressed as % of EMG RMS during MVC, from the beginning to the end of the control and occlusion experimental conditions. The asterisk (*) indicates a significant difference from the start to the end of the trial

observed from the start to the end of the control condition ($t_{15} = 0.103$; $p = 0.919$).

In contrast to the men, the boys' EMG amplitude was neither different over time ($F_{1,13} = 0.329$; $p = 0.576$) nor between conditions ($F_{1,13} = 0.378$; $p = 0.549$).

The MPF of the FCR EMG signal was influenced by a condition × time interaction effect ($F_{1,28} = 41.654$; $p < 0.001$) (Fig. 5). Post-hoc analyses revealed that both men and boys showed a larger decrease in MPF throughout the occlusion compared to the control condition. BFO resulted in a decrease of 24.2 ± 10.4 Hz (95% CI [20.3, 28.1]; $t_{29} = 12.793$; $p < 0.001$), representing a decrease of 20.1 ± 9.6%. In contrast, the control condition resulted in a decrease of only 6.9 ± 11.1 Hz (95% CI [2.7, 11.0]; $t_{29} = 3.383$; $p = 0.002$). This was equivalent to a relative decrease of 5.6 ± 9.7%**.** No differences in MPF were observed between boys and men.

Force

When normalized to body mass, the men's pre-exercise maximal force (3.2 ± 0.8 N/kg), was 27.6% higher than the boys' (2.6 ± 0.8 N/kg) ($t_{28} = 2.179$; $p = 0.038$). During the

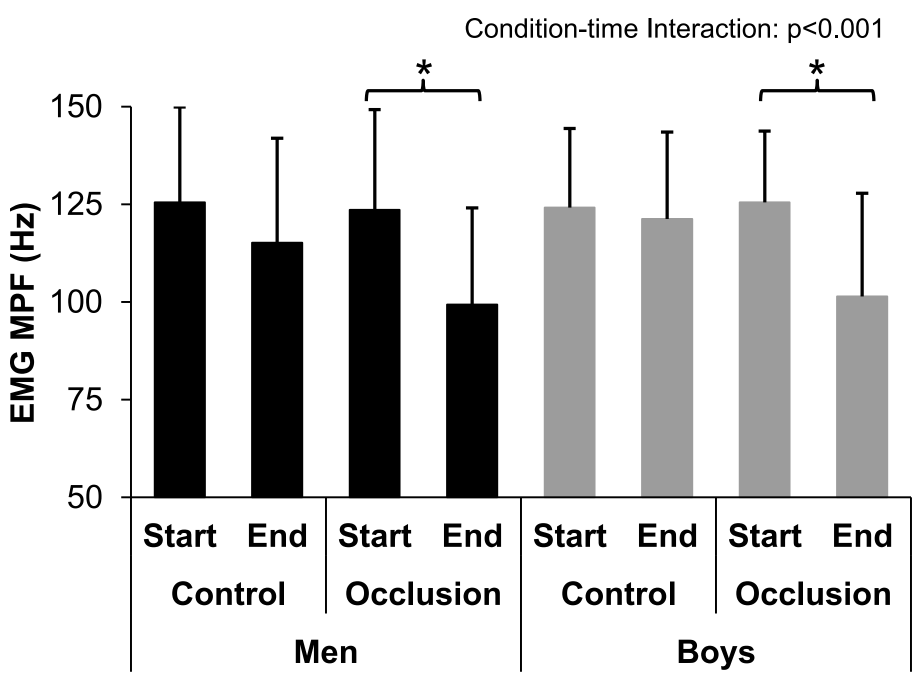

Fig. 5 The mean ± 1 SD MPF from the beginning to the end of both experimental conditions across both groups. The asterisk (*) indicates a significant difference from the start to the end of the trial

experimental trials, both groups were instructed to exercise at 35% MVC and thus, relative to their maximal force, there were no differences in force between men and boys ($F_{1,28} = 0.506$; $p = 0.483$). Both the men's and boys' force did not change from the start to the end of each condition ($F_{1,28} = 1.714$; $p = 0.201$) and did not differ between conditions ($F_{1,28} = 1.437$; $p = 0.241$).

For both age groups MVC, force following the occlusion condition was impacted by the main effect of time point ($F_{1,27} = 3.95$; $p = 0.050$). Pairwise comparisons revealed that maximal force decreased from 2.9 ± 0.8 N/kg at the start (i.e., MVC_{pre}) to 2.4 ± 0.6 N/kg immediately after the 25th contraction (i.e., MVC_{post1}). This represented a mean decrease of 0.6 ± 0.4 N/kg (95% CI [0.4, 0.6]; $p < 0.001$) or a relative decrease of 18.6 ± 12.5%. Two minutes following BFO exercise cessation (i.e., at MVC_{post2}), maximal force had increased to 2.8 ± 0.8 N/kg, which represented a 0.4 ± 0.3 N/kg (95% CI [0.3, 0.6], $p < 0.001$) or 18.5 ± 11.2% increase compared to MVC_{post1}. In fact, the maximal force had returned back to the pre-exercise level since the 6.2 ± 15.0% (or 0.1 ± 0.4 N/kg; 95% CI [−0.4, 0.3]) decrease in MVC force compared to pre-exercise was not statistically different ($p = 0.171$). Similarly, the control condition did not result in any force decrements following exercise as across both age groups there were no differences between MVC values at any time points ($F_{1,27} = 1.20$; $p = 0.283$) (Fig. 6).

Rating of perceived exertion

There was a main effect of condition on the participant's RPE ($F_{1,28} = 138.418$; $p < 0.001$). Regardless of age, participants reported feeling higher exertion levels immediately following the occlusion (6.6 ± 2.0 out of 10) compared to the control condition (3.4 ± 1.6 out of 10), with no difference between groups.

Discussion

The purpose of this study was to determine how children's muscle activation, as reflected by the EMG signal, and force production is affected by low-intensity (35% MVC) resistance exercise performed with BFO, and whether their response is different than adults'. Our results indicate that men's motor unit activation, as reflected by the EMG RMS amplitude, increased with the application of BFO during low-intensity exercise. In contrast, boys' EMG RMS amplitude did not change from the beginning to the end of the occlusion condition. Blood flow occlusion resulted in a reduced MVC force, compared to pre-exercise values, immediately following the exercise in both men and boys, but the relative magnitude of change was not different between groups. These results suggest that, while resistance exercise with BFO results in similar muscle performance decrement in children and adults, the mechanism may be different. The greater increase in EMG RMS in the men, suggests a greater increase in recruitment of higher-threshold motor units during resistance exercise with BFO in adults compared with children.

Similar to previous studies, the men displayed an increase in EMG amplitude during low-intensity resistance exercise with BFO (Moritani et al. 1992; Takarada et al. 2000; Yasuda et al. 2009). Interestingly, the increase in EMG RMS in this study (16%) was lower than what has been previously reported, where increases in EMG amplitude resulting from BFO have ranged from 86 to 285% when performed at

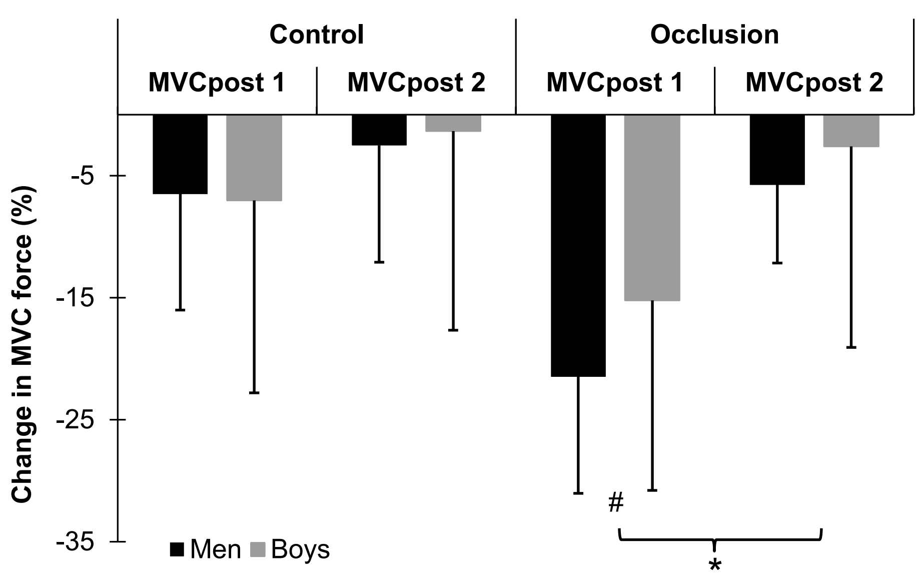

Fig. 6 The mean ± 1 SD decrease in MVC force relative to MVC_{pre} at MVC_{post1} (i.e., immediately following the 25 contraction trials) and at MVC_{post2} (i.e., two minutes following the completion of the 25 contraction trials). The hashtag (#) indicates a significant difference from MVC_{pre} to MVC_{post1} for both men and boys and the asterisk (*) indicates a significant difference between MVC_{post1} and MVC_{post2} for both men and boys

loads ranging from 20 to 60% MVC (Wernbom and Aagaard 2019). These differing results may be due to the short duration and low-intensity nature of the protocol in the present study, which may not have induced sufficient fatigue to result in the previously observed EMG parameter changes. In contrast to the men, boys exhibited no changes in EMG amplitude throughout the exercise regardless of whether BFO was or was not applied. This suggests that there was little, if any, additional recruitment of higher-threshold motor units during the repetitive, sub-maximal contractions (Murphy et al. 2014). Moreover, children have been found to recruit a smaller percentage of their available motor unit pool (O'Brien et al. 2010) and thus, the boys may have been relying more on their lower-threshold, typically fatigue-resistant motor units than the men. Due to the boys' lower motor unit activation, it is possible that while both groups were exercising at 35% of their MVC, the boys may have exercised at an intensity which was lower than 35% of their true maximal force and thus, at a lower relative intensity compared with the men. This may explain the observation that EMG RMS did not change in the boys during BFO. Future investigations examining the effect of BFO on neuromotor response in children and adults should utilize a given intensity, relative to true maximal force, as assessed using the interpolated twitch technique.

The decrease in MPF of the EMG signal during the resistance exercise, in conjunction with the decrement in MVC force and increase in RPE at the end of the exercise, suggests the development of some fatigue and that the amount of fatigue was greater during the occlusion compared to control condition. Despite these measures changing by a similar amount between men and boys, there was a divergent pattern in how the EMG RMS amplitude and MPF changed over time between the two groups. Specifically, it is unclear why in the men, the RMS amplitude increased but MPF decreased during the occlusion condition, while in the boys, there was no change in EMG RMS but an apparent decrease in MPF. Previous research has noted discrepancies between children and adults in EMG MPF changes as a result of fatigue-inducing protocols (Armatas et al. 2010; Halin et al. 2003; Paraschos et al. 2007). On the other hand, in line with our findings, other researchers have found that changes in MPF during fatiguing protocols are similar in children and adults (Armatas et al. 2010; Bouchant et al. 2012; Hatzikotoulas et al. 2009, 2014). Armatas et al. (2010) reported that the EMG MPF of boys and men were the same until 60% of the repetitions to fatigue were completed. Similarly, Hatzikotoulas et al. (2009) found no differences in EMG MPF between age groups and noted that if the submaximal protocol had not been of a discrete duration but rather lasted until fatigue, differences in MPF may have been observed between age groups. This may also be the case for this study, as a fixed number of contractions were used rather than continuing until task failure. However, this does not eliminate the discrepancy between RMS and MPF. It should be noted that changes in RMS and MPF can reflect changes within the muscle, other than simply motor unit recruitment or discharge rate (Farina et al. 2014) and indeed, over time, the changes in the two outcomes may not occur in parallel.

The results of this study suggest that low-load resistance exercise with BFO modifies physiological responses to exercise in both boys and men, although the modifications were not always similar. That is, decreases in EMG MPF, increases in RPE, and decreases in maximal force generating capacity following BFO were similar in boys and men, suggesting that boys may be able to use low-load BFO for strength training in the same way that men do. However, contrary to the men's response, the boys did not display an increase in EMG RMS amplitude as a result of low-load exercise with BFO. This is potentially a result of boys' greater reliance on lower-threshold motor units during exercise. Since BFO training in adults is largely based on the use of higher-threshold (typically type II) motor units (Karabulut et al. 2010; Manimmanakorn et al. 2013; Takarada et al. 2000; Wernbom and Aagaard 2019), it is possible that BFO training may not induce as large an effect for boys. Future low-load BFO resistance training research using larger muscle groups, trials to fatigue, and higher exercise intensities (40–70% MVC) are recommended to determine the effectiveness of such training on long-term muscle adaptations in children as compared to adults.

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Author contributions AB, BF, DG and CT participated in the study's design. AB and CA performed the testing. AB, BF and CT analyzed the data. AB, BF, DG, and CT interpreted the results. AB, BF, and CT drafted the manuscript. All authors edited and revised the manuscript. All authors read and approved the final version of manuscript.

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Declarations

Conflict of interest The authors declare that they have no competing interests.

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