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Effect of unilateral and bilateral resistance exercise on maximal voluntary strength, total volume of load lifted, and perceptual and metabolic responses

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ABSTRACT: The present study investigated the effect of unilateral and bilateral resistance exercise (RE) on maximal voluntary strength, total volume of load lifted (TVLL), rating of perceived exertion (RPE) and blood lactate concentration of resistance-trained males. Twelve healthy men were assessed for the leg extension one-repetition maximum (1RM) strength using bilateral and unilateral contractions. Following this assessment, an RE session (3 sets of repetitions to failure) was conducted with bilateral and unilateral (both limbs) contractions using a load of 50% 1RM. The TVLL was calculated by the product of the number of repetitions and the load lifted per repetition. RPE and blood lactate were measured before, during and after each set. Session RPE was measured 30 minutes after RE sessions. There was a significant difference in the bilateral (120.0±11.9) and unilateral (135.0±20.2 kg) 1RM strength ($p<0.05$). The TVLL was similar between both RE sessions. Although the repetitions decreased with each successive set, the total number of repetitions completed in the bilateral protocol (48) was superior to the unilateral (40) protocol ($p<0.05$). In both bouts, RPE increased with each subsequent set whilst blood lactate increased after set 1 and thereafter remained stable ($p<0.05$). The RPE and lactate responses were not significantly different between both sessions. In conclusion, a bilateral deficit in leg extension strength was confirmed, but the TVLL was similar between both RE sessions when exercising to voluntary fatigue. This outcome could be attributed to the number of repetitions completed in the unilateral RE bout. The equal TVLL would also explain the similar perceptual and metabolic responses across each RE session.

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INTRODUCTION

The bilateral deficit (BD) is a recognized phenomenon that occurs when the maximal voluntary strength of a simultaneous bilateral contraction is less than the sum of the strength of the right and left limbs when contracting alone [1]. Since the early 1960s when the BD was initially described [2,3], it has since been verified in different populations such as athletes, non-athletes, elderly and adolescents [2-7]. This phenomenon has also been observed in situations involving the lower and upper limbs, small and large muscle groups, and during exercise of maximal and submaximal intensities [1,4,5,8,9]. The exact mechanism underpinning this phenomenon is unclear, but neural inhibition when attempting to contract 2 homologous limbs simultaneously has been proposed [2,4,9,10].

Most studies investigating the BD have demonstrated that the unilateral performance of exercise increases one's ability to generate maximal strength in relation to the bilateral performance [1,4,5, 7,9, 10]. However, there are no data concerning the impact of unilateral and bilateral execution on the total volume of load lifted (TVLL) (sets x repetitions x load) during a resistance exercise (RE) session. This is an important consideration because the TVLL can modulate the physiological responses and, over time, the adaptive outcome [11-13]. Indeed, the TVLL has been shown to influence the neural [14], hypertrophic [15], metabolic [16,17], and hormonal [18] responses to RE.

A previous study [19] examined the acute endocrine response to unilateral and bilateral RE sessions in trained men (18-25 years). Participants completed 2 sessions of 5 different upper-body exercises at 80% of one-repetition maximum (1RM). The main finding was a greater blood lactate level and immune reactive growth hormone (iGH) concentration in the bilateral session and this was attributed to difference in the TVLL between the 2 protocols, being 48% higher in the bilateral exercise bout. However, only the dominant arm performed the unilateral RE bout, which would explain the observed differences in load volume and subsequent response patterns. Although the *American College of Sports Medicine* (ACSM) position stand [20] recommends the inclusion of unilateral and bilateral exercises in resistance training to promote load progression and the variation of stimuli, no previous research has examined the effect of bilateral and unilateral RE bouts (with the execution of 2 limbs) on the TVLL.

To better understand the effects of unilateral and bilateral RE, as adaptive stimuli, it would also be informative to monitor the internal load responses. The rating of perceived exertion (RPE) offers a simple method for monitoring RE intensity [21-24], which is one possible determinant of training improvements of physical fitness and performance [25]. The lactate response to RE is another marker of internal load [12]. For instance, Crewther et al. [12] mentioned that a greater change in blood lactate was observed following a high-volume RE bout, when compared to a bout of a lower volume. Migiano et al. [19] also reported a greater lactate response to a bout of bilateral RE (vs. unilateral RE), but again the 48% difference in the TVLL makes interpretation difficult. Until now, no previous studies have specifically addressed the perceptual and metabolic responses to unilateral and bilateral RE.

The present study assessed the effect of unilateral and bilateral RE on maximal voluntary strength, TVLL, perceptual (RPE) and metabolic (blood lactate) responses of resistance-trained males. It was hypothesized that a BD would occur during the strength testing of a leg extension exercise when using both limbs simultaneously. It was also hypothesized that the unilateral performance of this exercise would increase the TVLL across an RE session when multiple sets are performed compared to the bilateral execution of exercise. This, in turn, would elevate the perceptual and metabolic responses of the study population. However, since no study has examined both perceptual and metabolic responses to unilateral and bilateral RE sessions, these hypotheses are more exploratory in nature.

MATERIALS AND METHODS

Subjects. A total of 12 healthy men (24 ± 3.7 years; body mass index 25.12 ± 1.73 kg·m^{-2}; 12.1 ± 5.3% body fat) with resistance training experience (at least 6 months) volunteered for the present study. Participants completed a health questionnaire and were considered to be healthy, active and injury-free at the time of this study. This study was approved by the Institutional Ethics Committee, and all volunteers gave written informed consent before the study commenced.

Experimental design

A randomized, crossover and counterbalanced design was used to examine the effect of unilateral and bilateral RE sessions on maximal voluntary strength, TVLL, RPE score and blood lactate concentration. Over a 2-week period, the study volunteers visited the laboratory on 4 separate occasions to be assessed for: 1) physical evaluation and 1RM testing of leg extension with bilateral execution; 2) 1RM testing of leg extension with unilateral execution; 3) bilateral RE session; 4) unilateral RE session. The TVLL of each RE bout was calculated by the product of the number of repetitions and the load lifted per repetition. RPE was assessed after each set and session RPE was determined 30 minutes after the end of each session. Blood lactate was measured before and after each set in both RE bouts.

Physical evaluation and 1RM testing

In the first week of this study, participants visited the laboratory to complete the bilateral and unilateral 1RM tests, respectively, with a rest interval of 48 hours. In the first visit, a simple physical evaluation was carried out (i.e. assessment of body weight, height, and body fat percentage) followed by 1RM testing of leg extension strength. Body weight and height were respectively assessed using electronic scales and a stadiometer. Body fat percentage (%) was determined from skinfold measurements taken by a qualified researcher using a pair of skinfold calipers (Lange®, Cambridge, USA). The generalized equation of Jackson & Pollock [26] for men (sum of chest, abdomen, and thigh skinfolds) was used to estimate body fat percentage.

The 1RM testing of leg extension strength was performed in a pin-loaded leg extension machine (Physicus®, São Paulo, Brazil). Before testing, a 10 minute warm-up was performed on a cycle ergometer (60-70 rpm, 100 watt load) followed by a lower-body active stretching routine. A single repetition to failure protocol was used, in which the load resistance was increased during successive attempts (each separated by a 3-minute rest) until a 1RM load was achieved using a proper technique through a full range of motion. For each participant, the back rest was moved to ensure that the knee joint was aligned to the pivot point of leg extension machine. Trained spotters were always present to assist with the 1RM testing of participants [27,28].

Bilateral and unilateral RE sessions

In the second week of this study, participants completed the bilateral and unilateral RE sessions in the laboratory (using the same exercise and technique described above) with 48 hours rest provided between each session. Participants were randomly allocated to each RE session using a computational program (http://graphpad.com/quickcalcs/randomize2.cfm). Both protocols were performed at the same time of day (± 1 hour) to account for circadian variation. Prior to each session, a brief warm-up for the lower body was performed (as per the 1RM leg extension tests). In both protocols, 3 sets of leg extensions were completed until voluntary fatigue (concentric failure) using a load of 50% 1RM. The rest interval between each set was fixed at 2 minutes. The velocity of movements was standardized, being 1 second for the concentric phase (i.e. lifting the load) and 2 seconds for the eccentric phase (i.e. lowering the load). In the unilateral RE session, participants began exercising with the dominant limb and immediately after voluntary fatigue, and without any rest; they continued to exercise using the non-dominant limb until fatigue. During the entire experimental period, participants did not perform any other physical training involving the lower limbs.

Total volume of load lifted

The TVLL was calculated in each RE session by the product of the total number of leg extension repetitions performed, either bilaterally or unilaterally (both limbs combined), and the amount of load lifted (in kg) per repetition [29].

RPE measures

RPE was assessed immediately after each set using the CR-10 scale answering the question "How was your set?" Session RPE was determined within 30 minutes following the completion of RE in order to provide a more accurate assessment of the entire exercise session [21]. Each participant was asked to rate their session RPE by answering the question "How was your workout?" [32]. Standard assessment and anchoring procedures were employed to determine session RPE [30-33]. The ratings scale was determined by associating a resting state (i.e. with no effort and no exercise) with the rating of 0 and maximal effort during exercise with the rating of 10.

Blood lactate assessment

A commercial lactate monitor (Accutrend®, Roche Diagnostics, Indianapolis, USA) was used to measure blood lactate concentration. This lactate analyzer has been recognized as having good accuracy and high reliability and linearity for research across a wide range of physical exercise [34]. Briefly, a small incision was made at the ear lobe using a commercial lancet (Accutrend®, Indianapolis, USA) and a drop of blood was transferred to the lactate monitor for reading. This variable was measured before, during (immediately after the first, second and third set) and 5 minutes after the RE sessions.

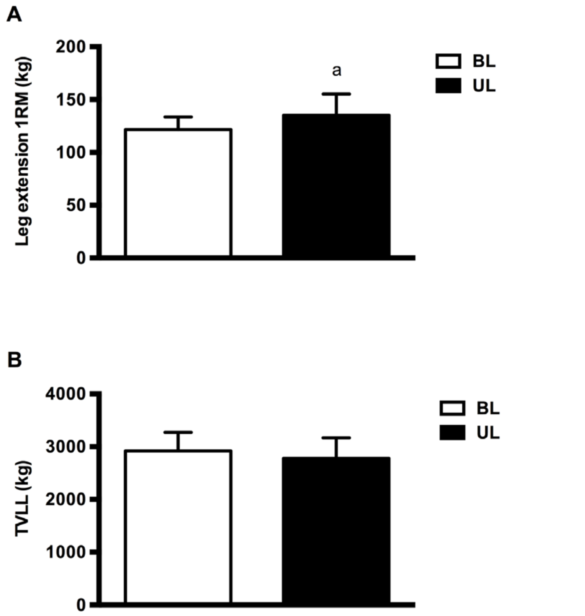

FIG. 1. Maximum strength during the bilateral and unilateral leg extension testing (A) and total volume of load lifted (TVLL) during the bilateral and unilateral RE sessions (B).
Note: BL = bilateral execution; UL = unilateral execution; RE = resistance exercise; a = significantly different from BL ($p < 0.05$).

Statistical analyses

A paired sample t-test was used to compare the outcomes of the leg extension 1RM test, the TVLL and the session RPE between the bilateral and unilateral protocols. A two-way analysis of variance with repeated measures was used to compare any changes or differences in the RPE and blood lactate measures between the bilateral and unilateral protocols. When a significant interaction (condition × time) was identified, a Tukey post-hoc test for multiple comparisons was performed. The significance level was set at $p<0.05$. All data are expressed by mean ± SD.

RESULTS

As seen in Figure 1A, there was a significant difference between the respective bilateral and the unilateral testing of leg extension 1RM strength (120.0 ± 11.9 vs. 135.0 ± 20.2 kg; $p<0.05$). A BD of ~11% in favour of unilateral movements was observed. A post hoc statistical power analysis (two-tailed) for the difference in 1RM strength between the bilateral and unilateral RE bouts was conducted to determine the achieved power of the paired t-test, based on the investigated sample size (n=12). With an alpha of 0.05, and an effect size of d = 0.85, the achieved power was 0.77 (critical t (11) = 2.20). For the RE sessions, 50% 1RM loads of 60.0 ± 6.0 kg and 67.5 ± 10.1 kg were used in the bilateral and unilateral protocols, respectively ($p<0.05$). Regarding the TVLL (Figure 1B), no difference between the bilateral and unilateral RE bouts was observed (2918 ± 353 kg vs. 2780 ± 387 kg, p>0.05).

In both the bilateral and unilateral RE sessions, the number of repetitions completed decreased significantly from set 1 to set 2 and from set 2 to set 3 ($p<0.05$, Figure 2). Comparison between the exercise bouts revealed a lower number of repetitions performed in each set during the unilateral RE session ($p<0.05$). Thus, during the unilateral RE session the individuals performed a lower number of repetitions compared to the bilateral RE session (41.6 ± 5.5 vs. 48.6 ± 5.9; $p<0.05$). The post hoc statistical power analysis (two-tailed) for the difference in total number of repetitions performed in both RE bouts to determine the achieved power of the paired t-test, with an alpha of 0.05, and an effect size of d = 1.22 (investigated sample; n = 12), revealed an achieved power of 0.97 (critical t (11) = 2.20).

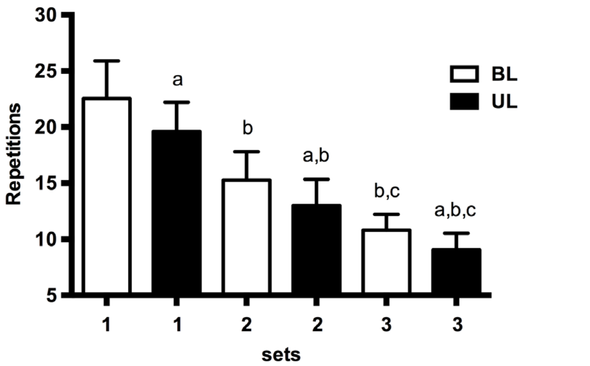

FIG. 2. Number of repetitions completed during the unilateral and bilateral RE sessions.
Note: BL = bilateral execution; UL = unilateral execution; RE = resistance exercise; 1, 2 and 3 = sets; a = significantly different from BL (p< 0.05); b = significantly different from set 1 (p< 0.05); c = significantly different from set 2 ($p< 0.05$).

The RPE response was similar in both protocols and there was no significant difference between the bilateral and unilateral RE bouts at any time (Figure 3A). In both protocols, there was a significant ($p<0.05$) increase in RPE across each subsequent set (set 1 < set 2 < set 3, Figure 3 A). No difference was detected for session RPE between the bilateral and unilateral RE bouts. There was no difference between the RPE score taken after the third set and the overall score of session RPE.

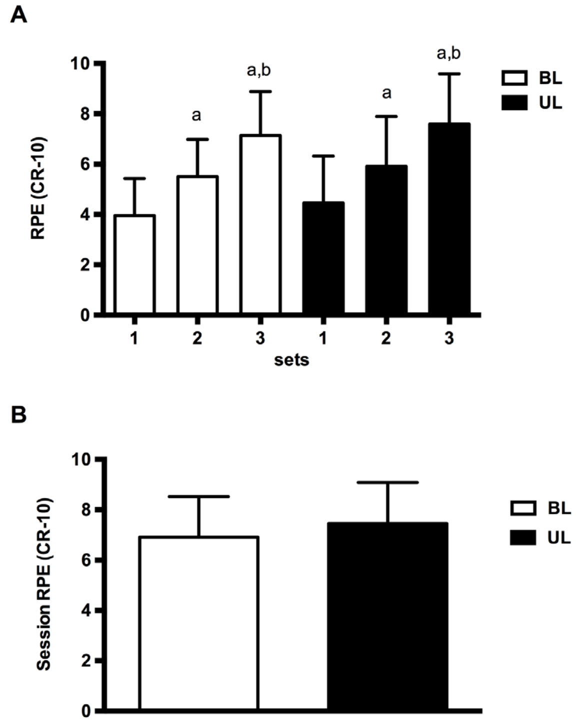

FIG. 3. RPE (A) and session RPE (B) during the bilateral and unilateral RE sessions.
Note: BL = bilateral execution; UL = unilateral execution; 1, 2 and 3 = sets; S = session RPE; RE = resistance exercise; a = different from 1 set (p< 0.05); b = different from 2 set ($p<0.05$).

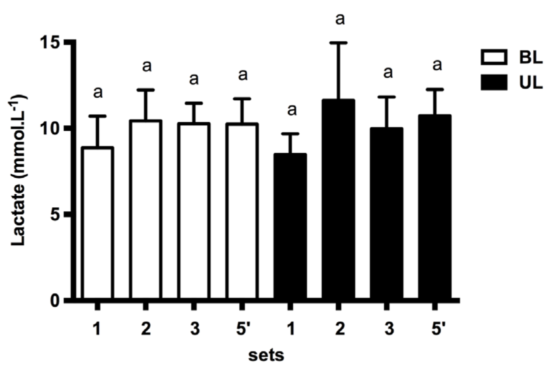

FIG. 4. B Blood lactate response during the bilateral and unilateral RE sessions. BL = bilateral execution; UL = unilateral execution; 1, 2 and 3 = sets; 5' = lactate concentration 5 minutes after the end of each RE session; RE = resistance exercise; a = different from pre-exercise ($p<0.05$).

In both sessions, blood lactate concentration increased when compared to pre-exercise ($p<0.05$) and thereafter remained stable across each subsequent set (first, second and third) and 5 minutes after exercise. The blood lactate response to the bilateral and unilateral RE protocols was not significantly different at any time (Figure 4).

DISCUSSION

This is the first investigation that assessed the effect of unilateral and bilateral RE on maximal voluntary strength, TVLL, RPE score and blood lactate concentration of resistance-trained males. The present study was designed to examine the BD and whether the expected difference during strength testing (unilateral > bilateral) would increase the TVLL and the subsequent perceptual and metabolic responses across a training session. The current results confirmed the existence of a BD in leg extension 1RM strength. However, no difference in the TVLL between the unilateral and bilateral RE sessions was detected. The perceptual and metabolic measures also exhibited similar response patterns.

It was observed that a BD in 1RM strength does exist during the performance of a standard leg extension movement. This finding is supported by other studies reporting that the unilateral execution of exercise increases one's ability to generate maximal strength in relation to the bilateral execution of the same exercise [1,4,5,7,9,10]. This study was not designed to determine the exact mechanism(s) underpinning this phenomenon, but previous studies have proposed that the BD is the result of neural inhibition when attempting to contract 2 homologous limbs simultaneously, relative to the individual contraction of these limbs [3,4,9,10].

It was also hypothesized that, with the occurrence of BD during the leg extension exercise, the study population would exercise with a greater absolute load in the unilateral RE session and this would result in a greater TVLL when compared with the bilateral RE session. Indeed, after strength testing, a greater absolute load was employed during the unilateral session, as compared with the bilateral session (67.5 ± 10.1 kg and 60.0 ± 6.0 kg, respectively), even when each repetition was performed using an equal relative intensity of 50% 1 RM. However, no difference was found in the TVLL between these 2 RE protocols after the completion of 3 sets of leg extensions. This result can be explained by the total number of repetitions performed during the respective bilateral and the unilateral protocols (~14% lower in unilateral RE bout). Thus, although the BD can influence the maximal expression of strength during a single repetition movement, this effect may not be readily apparent during a training session when a large number of repetitions and sets are performed.

Interestingly, Janzen et al. [3] hypothesized that the unilateral training would be more beneficial for increasing strength and muscle mass than the bilateral training. This assumption was tested in 2 groups of post-menopausal women (unilateral training, bilateral training) who each trained 3 times a week for a period of 26 weeks. The unilateral and bilateral training groups both showed improvement in whole-body lean mass and upper- and lower-body strength, in comparison to a control group, but there was no difference between the 2 training groups. McCurdy et al. [35] also examined the short-term effect of unilateral and bilateral training on measures of strength and power in young untrained men and women. The TVLL and intensity of training were equated for both groups. After 8 weeks of training, they found that the unilateral and bilateral training were both equally effective for inducing early phase improvement in unilateral and bilateral leg strength and power.

No difference in the perceptual and metabolic parameters of internal training load between the bilateral and unilateral RE sessions was detected. These similar responses observed could be explained by the similar TVLL in each bout. Consistent with current results, Charro et al. [36] assessed other hormonal (GH, insulin, cortisol and testosterone) and metabolic (lactate and glucose) parameters after 2 different bouts of RE performed with the same TVLL. In both exercise bouts, participants performed every set to failure and no difference was observed in any of the aforementioned measurements. These data reinforce the idea that TVLL is a key modulator of internal training load, despite the configuration of the various training variables, and that differences in load intensity may be compensated by the performance of more repetitions when exercising to fatigue. Therefore, it is plausible to assume that the production of similar internal training load response may generate similar improvement in variables of physical fitness and performance (e.g. strength, power and muscle mass) over time. The findings of Janzen et al. [3] and McCurdy et al. [35] support this assumption.

Pritchett et al. [37] analyzed RPE between sets and session RPE scores after a low (60% 1RM) and high (90% 1RM) intensity protocol of RE, with both protocols performed until to volitional exhaustion (i.e. concentric failure). This work showed that the RPE and session RPE responses were greater at the low intensity RE, which was achieved by a higher TVLL through the performance of more repetitions, albeit with a lighter relative load. Additionally, a strong relationship was observed between the TVLL and the session RPE in this study ($r = 0.85$). Consistent with the present study, Pritchett et al. [37] suggested that RPE and session RPE are affected by the TVLL more than the intensity when multiple sets are performed until volitional exhaustion.

In contrast to these findings, Day et al. [21] compared the session RPE response to 3 different workouts involving 5 exercises (1 set each) using loads of 50% 1RM (15 repetitions), 70% 1RM (10 repetitions), and 90% 1RM (5 repetitions). They found that the session RPE increased concurrently with the percentage of 1RM lifted. Another study [24] examined the effect of 2 RE protocols performed at the same intensities, but using 2 sets of 6 different exercises. The researchers reported similar results in terms of a linear relationship between the session RPE and the training intensity. Subsequently, Day et al. [21] and Sweet et al. [24] suggested that RPE is influenced primarily by training intensity rather than total work performed (where work = force x distance), which is indicative of the TVLL. However, in both studies, the exercises were not completed until voluntary fatigue so these assertions are more relevant to training situations involving sub-maximal efforts.

The unilateral and bilateral RE sessions also induced a similar lactate response and a likely result of the TVLL across each bout. Early studies by Kraemer et al. [17], Pierce et al. [38], and Brown et al. [39] demonstrated that the peak lactate response to RE is dependent, in part, on the amount of work performed and thus the TVLL. For instance, Brown et al. [39] examined the lactate response of 3 groups of males (weight-trained, endurance-trained and untrained) each performing 1 set of leg press movements to failure at 3 different loads (60%, 70% and 80% 1RM). The amount of work per repetition was higher with the 80% 1RM load in each group, but total work was highest with the 60% 1RM load because of the greater number of repetitions performed, and the lactate response was also related to the external work. These authors also found that stronger weight-trained individuals produced a greater lactate response and performed a greater number of repetitions at any given load (% 1RM) compared to weaker untrained individuals. Thus, the recruitment of a resistance-trained population in this study may explain some of the current observations.

The potential limitations of the present study were the small sample size, and the inclusion of only young trained males. Thus, the generalization of current findings should be done cautiously to other populations, since this is a preliminary exploration on the influence of the unilateral and bilateral RE on maximal voluntary strength, TVLL, and perceptual and metabolic responses.

CONCLUSIONS

In summary, the findings of this study have both theoretical and practical applications. From a theoretical perspective, the testing of leg extension strength confirmed the existence of a BD (unilateral > bilateral). However, the TVLL was similar in both RE sessions when exercising to voluntary fatigue, which could be attributed to the total number of repetitions completed in each RE bout (unilateral < bilateral). From a practical perspective, these findings should be taken into account by fitness professionals during RE prescription, given that the similar TVLL of unilateral and bilateral RE may contribute to balance perceptual and metabolic responses.

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