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Original Article

Effects of Bilateral or Unilateral Plyometric Training of Lower Limbs on the Bilateral Deficit During Explosive Efforts

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Abstract

Objectives: Bilateral Deficit (BLD) occurs when the force generated by both limbs together is smaller than the sum of the forces developed separately by the two limbs. BLD may be modulated by physical training. Here, were investigated the effects of unilateral or bilateral plyometric training on BLD and neuromuscular activation during lower limb explosive extensions. **Methods**: Fourteen young males were randomized into the unilateral (UL_) or bilateral (BL_) training group. Plyometric training (20 sessions, 2 days/week) was performed on a sled ergometer, and consisted of UL or BL consecutive, plyometric lower limb extensions (3-to-5 sets; 8-to-10 repetitions). Before and after training, maximal explosive efforts with both lower limbs or with each limb separately were assessed. Electromyography of representative lower limb muscles was measured. **Results**: BL_training significantly and largely decreased BLD (p=0.003, effect size=1.63). This was accompanied by the reversion from deficit to facilitation of the electromyography amplitude of knee extensors during bilateral efforts (p=0.007). Conversely, UL_training had negligible effects on BLD (p=0.781). Also, both groups showed similar improvements in their maximal explosive power generated after training. **Conclusions**: Bilateral plyometric training can mitigate BLD, and should be considered for training protocols focused on improving bilateral lower limb motor performance.

Keywords: Bilateral Deficit, EMG, Lower Limbs, Maximal Explosive Power, Training

Introduction

A bilateral deficit (BLD) occurs when the force (or power) generated by both limbs together is smaller than the sum of the forces (or powers) developed separately by the two limbs under the same experimental condition. This phenomenon, which was initially described by Henry and Smith in 1961[1,2], has been observed in different populations (males and females; athletic and non-athletic individuals) and different muscle groups[3–5]. BLD was consistently observed during dynamic movements such as isokinetic knee flexion and extension[4] as well as lower limb extension while performing jumps and squats, on a leg press and on an explosive ergometer[6–10]. BLD values were reported to range between 6% and 37%, thus resulting in an important limiting factor[11] for athletes performing bilateral tasks, such as rowing and weightlifting, as well as for deconditioned individuals attempting, for example, to perform a sit to stand transition.

The reduction of the descending neural drive between cortical level and lower motor neurons is generally identified as a key mechanism underlying BLD. This perspective is supported by several studies pointing out the parallel decline of force exertion and electromyography (EMG) amplitude during BL contractions[3,7,11,12]. Motor unit recruitment pattern was also different between unilateral and bilateral explosive efforts, with a more rapid and synchronized muscle activation throughout the push phase

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during unilateral extensions[9]. During dynamic tasks, muscle mechanics, and in particular the characteristics of the force-velocity relationship, are the other important determinant of BLD[2,8,13].

BLD can be considered a plastic neuromuscular phenomenon. BLD magnitude may be modulated by the repetitive practice of motor activities. However, to the best of our knowledge, the studies on this topic are rather scant and the related findings not consistent. For example, bilateral isokinetic strength training was reported to mitigate BLD in knee extensors but not in knee flexors[14]. Beurskens and colleagues[15] explored the effect of bilateral strength training and unilateral balance training, finding a BLD reduction in both groups when assessing knee extensors. On the other hand, unilateral resistance training did not result in a significant increase of BLD in some studies[16,17] while it promoted BLD in others[18]. Also, the majority of these interventional studies did not assess the neural adaptations associated with training-induced changes in BLD. Furthermore, we did not find any reference that specifically addressed the effects of a training protocol involving explosive efforts of the lower limbs (rather than resistance training performed with slower, controlled movements) on BLD assessed during multi-articular, lower limb explosive extensions.

Hence, the aim of this study was to investigate the effects of a 10-week unilateral or bilateral training protocol involving explosive, plyometric efforts of the lower limbs on BLD and neuromuscular activation during explosive extensions performed on a sled ergometer. We expected that bilateral training would decrease BLD, and that this adaptation would be associated with higher EMG amplitude generated by knee extensors during bilateral efforts when compared to the unilateral ones. Conversely, we hypothesized that unilateral training would not modulate BLD.

Materials and methods

Research participants

Fourteen healthy and physically active male individuals (mean ± standard deviation age: 22.9 ± 3.5 years; stature: 1.81 ± 0.08 m; body mass: 80.3 ± 13.7 kg) were recruited to participate in this study. Research participants were recreational athletes practicing team sports (soccer, rugby, basketball), individual sports (roller-skating, cross-country skiing) and/or related conditional training activities three to four times per week. Before the study began, the purpose and risks were carefully explained to the subjects and written informed consent was obtained from all of them. Research participants were randomly assigned to the bilateral or unilateral lower limb training group (N = 7 in each group). Experimental sessions, which were performed one week before the beginning of training and one week after the completion of training, consisted of the assessment of anthropometric characteristics, lower limb power output and EMG amplitude of four representative lower limb muscles during explosive extensions. Maximal voluntary isometric contractions (MVC) were also performed to normalize EMG signals.

Anthropometric characteristics

Body mass was measured to the nearest 0.1 kg with a manual weighing scale (Seca 709, Hamburg, Germany) with the subject dressed only in light underwear and no shoes. Stature was measured to the nearest 0.5 cm on a standardized wall-mounted height board.

Explosive efforts of lower limbs

The Explosive Ergometer (EXER), described in detail by previous work from our group[19] was used to assess the biomechanical parameters of the lower limb explosive extensions. Briefly, the EXER consists of a metal frame supporting one rail, which was positioned horizontally. An electric motor was positioned in front of the carriage seat, imposing predetermined braking forces that were acting along the direction of motion. The motor, controlled by a custom built Labview program (National Instruments, Texas, USA), was linked to the seat by a chain, and initiated the braking action at the onset of each push. A seat, fixed on a carriage was free to move on the rail, its velocity along the direction of motion being continuously recorded by a wire tachometer (LIKA SGI, Vicenza, Italy). The total moving mass of the EXER (seat and carriage together) was equal to 31.6 kg. The subject was seated on the carriage seat, secured by a safety belt tightened around the shoulders and abdomen, with the arms on the handlebars. Two mechanical blocks were used to set the distance between the seat and the force platforms (LAUMAS PA 300, Parma, Italy), so that the knee angle at rest was 110 degrees. The blocks also prevented any countermovement during the pushing phase. During explosive efforts with both lower limbs, the soles of the feet were placed against the force platforms in a flat standardized position, whereas during unilateral efforts the foot of the non-pushing limb was placed on an appropriate support. When the subject performed an explosive effort, he and the seat moved backward, and the force, velocity and EMG (see below) signals were sampled at a frequency of 1 kHz using a data acquisition system (MP100, BIOPAC Systems, Inc., USA).

After a brief familiarization session, the participants performed six bilateral maximal explosive efforts, six with the right lower limb only, and six with the left one. After each push, the subjects rested for 2 minutes with their feet placed on a dedicated support. The maximal efforts were performed against different braking forces selected within the range 25-200% of the subject's body weight, the unilateral braking forces being half the bilateral ones. The absolute braking forces ranged approximately from 130 to 1900 N. The subjects performed the same kind of effort twice, and the one with the higher peak power was considered for analysis.

This manuscript is focused on the investigation of the maximal expression of muscle power under different experimental conditions (bilateral and unilateral efforts performed before and after training). Thus, for each subject, only the attempt with the highest peak power (maximal explosive power) within each experimental condition was taken into consideration for further analysis.

Surface EMG recordings

Surface EMG was recorded from vastus lateralis (VL), rectus femoris (RF), biceps femoris (BF) and medial gastrocnemius (MG) of the right lower limb during both explosive efforts on the sled ergometer and isometric contractions. Pre-gelled surface EMG electrodes (circular contact area of 1 cm diameter, BIOPAC Systems, Inc., USA) were placed (inter electrode distance equal to 20 mm) at the following locations[20]: a) for VL at two-third on the line from the anterior spina iliaca superior to the lateral side of the patella; b) for RF midway between the anterior spina iliaca superior and the superior part of the patella; c) for BF midway between the ischial tuberosity and the lateral epicondyle of the tibia; d) for MG, on the most prominent bulge of the muscle. To ensure a good electrode-skin interface, prior to the application of the electrodes, the subject's skin was shaved, rubbed with an abrasive paste, cleaned with an alcohol solution, and dry-cleaned with a gauze. EMG data were sampled at a frequency of 1 kHz, and recorded by an EMG system (EMG100C, BIOPAC Systems, Inc., USA; Band-pass Filter: 10-500 Hz; RMS Noise Voltage: 0.2 μV; Input impedance: 2 MΩ; Common Mode Rejection Ratio: 110 dB).

Isometric contractions

Maximal voluntary isometric contractions (MVC) were performed after the explosive efforts with the right (dominant) lower limb only, in order to obtain the maximal EMG response and normalize the signal collected during the explosive extensions. EMG electrodes were fixed at the beginning of the experimental session and were not removed between explosive and isometric contractions. The subjects were seated on either (a) the EXER or (b) a special chair.

(a) The subject was seated on EXER, with the right lower limb fully extended. The forward part of the foot sole was placed against the force platform in a flat standardized position, to obtain an ankle angle of 90 degrees. The carriage was then blocked, and the subject performed a maximal isometric plantar flexion.

(b) Subjects were seated with their legs hanging vertically down. A strap was tightened around the right ankle and was then linked by a steel chain to a fixed frame. The chain length was set to obtain a knee angle of 110 degrees. The fixed frame behind the ankle was used to perform the isometric knee extensions, whereas the one in front of it was used for the isometric knee flexions. A force sensor (TSD121C, BIOPAC Systems, Inc. ,USA) was connected in series to the chain. Force analog outputs were sampled at a frequency of 1 kHz using a data acquisition system (MP100, BIOPAC Systems, Inc. , USA) connected with a personal computer.

The subjects were asked to perform MVC of 4 - 5 seconds under each isometric effort. To prevent fatigue, after each contraction the subject rested for 2 minutes.

Signal analysis

Data were processed using the software LabChart Reader (ADInstruments, Inc., New Zealand). The mechanical power developed by the right and left lower limb was obtained from the instantaneous product of the two forces multiplied by the backward velocity. Peak values of force, velocity and power were considered for analysis.

EMG signal was band pass-filtered (10-500 Hz). The EMG activity defined in a 500-ms window centered on maximal force exerted during MVC was analyzed: EMG raw signal was processed using a 5-ms running-window root mean square, and its mean value was considered as 100%MVC. To investigate the EMG amplitude during the explosive efforts, EMG raw signal recorded during the push phase (i.e. throughout the period of force development) was processed using a 5-ms running-window root mean square to obtain its mean value throughout each push. This value was then expressed as percentage of the EMG amplitude obtained during MVC. EMG amplitude of VL and RF were averaged to assess the overall behavior of knee extensors (KE) across training groups and time points[21]. The bilateral deficit was calculated as the difference between the sum of the two unilateral (UL) peak forces (F) and the bilateral (BL) one, divided by the sum of the two UL peak forces:

$$BLD\_F = \frac{ULR+ULL-BL}{ULR+ULL} = 1 - \frac{BL}{ULR+ULL} \qquad (1)$$

where $_R$ and $_L$ indicate right and left limb, respectively.

The power BLD (BLD_w) was also calculated by using peak power values (instead of force values) as input to Eq.1.

In order to investigate the effect of bilateral and unilateral training on the BL vs UL relationship of other neuromuscular parameters, the following indexes based on BLD calculation were computed. A bilateral deficit index for peak velocity (BLD_v) was defined as the difference between the average of the two UL peak velocities (i.e., those generated during the best UL left and UL right efforts considered for analysis) and the BL one, divided by the average of the two UL peak velocities. Hence, lower BLD_v values indicate greater velocity in BL compared to UL efforts. Similarly, in terms of EMG amplitude (which was collected from the right lower limb) the difference between UL and BL amplitudes was divided by the UL one. Hence, lower values of this BLD_EMG index indicate greater amplitudes generated during BL as compared to UL efforts.

Training protocol

Training of lower limbs was performed twice a week for ten weeks, resulting in a total of 20 sessions for each participant. Each training session consisted of a 5- to 10-minute warm-up followed by 3 to 5 sets of 8 to 10 consecutive plyometric efforts; rest was 2 minutes in between sets. Participants were instructed to generate the maximum power during every lower limb extension.

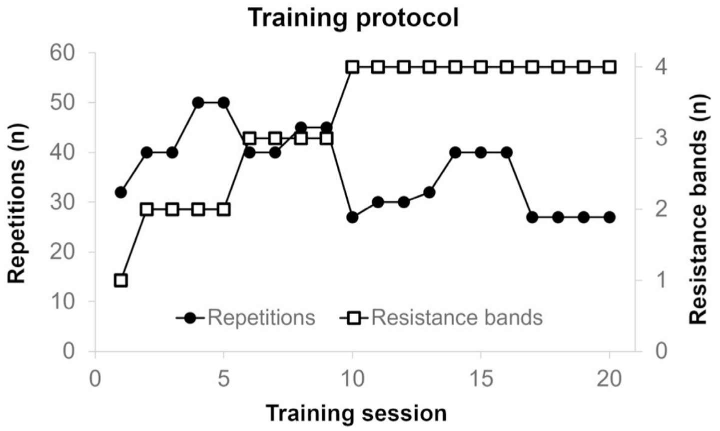

Figure 1. Time course of volume (i.e., number repetitions per lower limb, filled circles) and intensity (i.e., number of resistance bands, empty squares) indexes throughout the 20 plyometric training sessions performed on the sled ergometer.

Table 1. Baseline characteristics of research participants enrolled in the unilateral (UL_) or bilateral (BL_) training group.

	UL_training group (n=7)	BL_training group (n=7)	Difference (%)	*p* value
Age (years)	23.0 ± 5.0	22.1 ± 1.9	0.9	0.744
Stature (m)	1.81 ± 0.09	1.79 ± 0.08	4.8	0.560
BM (kg)	77.0 ± 10.8	80.9 ± 13.7	4.9	0.565
MEP$_{BL}$ (W)	3165 ± 721	3009 ± 512	3.9	0.648
MEP$_{UL}$ (W)	1904 ± 336	1829 ± 189	8.9	0.617
BLD_F (%)	32.9 ± 5.2	31.7 ± 3.0	0.9	0.836
BLD_w (%)	18.1 ± 7.6	17.2 ± 8.8	1.2	0.615

BM: body mass; MEP: maximal explosive power, assessed during bilateral ($_{BL}$) or unilateral ($_{UL}$) efforts (i.e., average value between left and right efforts); BLD: bilateral deficit; F: force; w: power; n: number of participants. Statistical differences between groups were assessed by unpaired t test or Mann-Whitney test depending on data distribution.

Each training session lasted approximately 20 minutes for the BL_training group, and approximately 35 minutes for the UL_training group as the lower limbs were trained separately. The consecutive plyometric efforts were performed on the EXER, which was inclined by 20 degrees. Furthermore, one to four resistance bands (Exercise Tubing silver, Thera-Band®, Ohio, USA) were connected between the carriage seat and the fixed front frame of the EXER. Hence, these resistance bands were stretched when the carriage seat moved backward following the lower limb extensions. In particular, the bands length was set in order not to exert any braking force throughout the push phase (i.e., until the lower limbs were fully extended). However, the eccentric part of the exercise (i.e., landing) was potentiated by the elastic energy accumulated by the bands from the take-off to the farthest point reached by the carriage seat while moving backward. This training protocol presents a modulation of training volume (total number of repetitions per leg *per session*) and number of resistance bands (i.e., intensity) (Figure 1) that is consistent with the undulating periodized approach[22], and was successfully implemented in a previous pilot study involving professional rugby players[23].

Statistical analysis

Statistical analysis was performed using GraphPad Prism (version 10.0.2 for Windows, GraphPad Software, San Diego California USA). A P value less than 0.05 was considered statistically significant. Results were expressed as mean and standard deviation. The Shapiro-Wilk test was used to verify the normality of distributions. Baseline characteristics of the two groups were compared by unpaired t test or Mann-

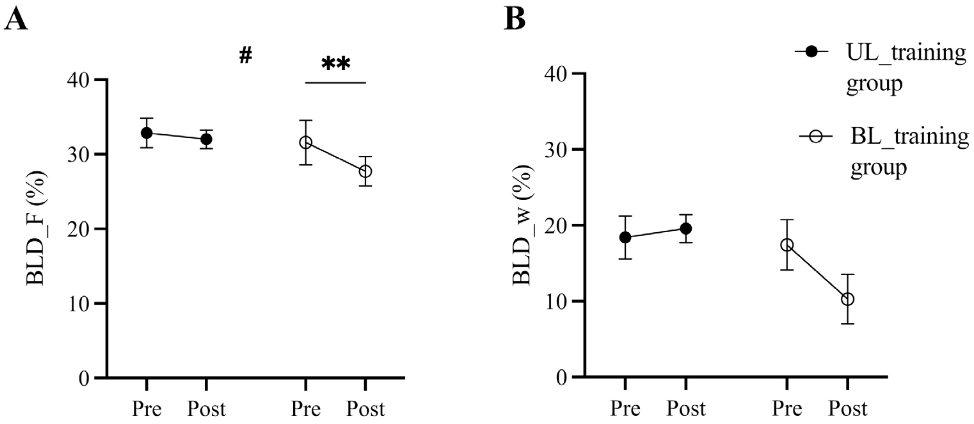

Figure 2. Bilateral deficit considering force (BLD_F, Panel A) or power (BLD_w, Panel B) values are shown for the study groups that underwent unilateral training (UL_training group; filled circles) or bilateral training (BL_training group; empty circles), before (Pre) and after (Post) the intervention. Differences in BLD_F and BLD_w among the two groups (BL_ and UL_training group) and time points (Pre and Post training) were tested using ANOVA analysis. # significant Time x Group interaction, $p \leq 0.05$; ** significant Pre vs Post training difference by Bonferroni post hoc test, $p \leq 0.01$.

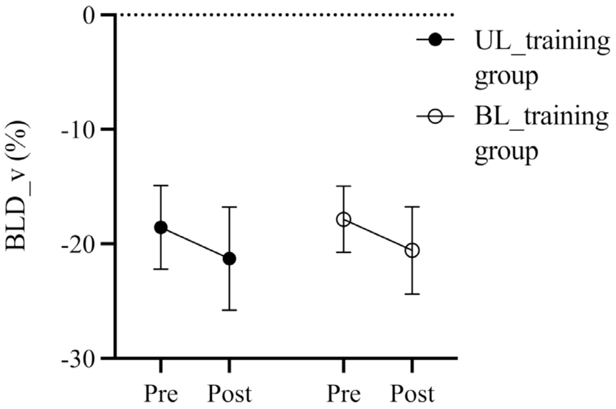

Figure 3. BLD index for peak velocity (BLD_v) is reported for the unilateral training group (UL_training group, filled circles) and bilateral training group (BL_training group, empty circles) before (Pre) and after (Post) training. Negative values indicate higher velocity during bilateral as compared to unilateral efforts. Differences in BLD_v among the two groups (BL_ and UL_training group) and time points (Pre and Post training) were tested using ANOVA analysis.

Whitney test depending on data distribution.

After checking homogeneity of variances, BLD indexes and maximal explosive power values were analyzed with a repeated measures analysis of variance (ANOVA). When significant differences were found, a Bonferroni post hoc test was used to determine the exact location of the difference. Finally, effect sizes (ES) comparing pre vs post changes within each group were calculated. ES values lower than 0.20 were considered negligible, between 0.20 and 0.49 small, between 0.50 and 0.79 medium, and equal or greater than 0.80 large[24].

Results

At baseline, the two study groups showed similar characteristics in terms of age, anthropometric

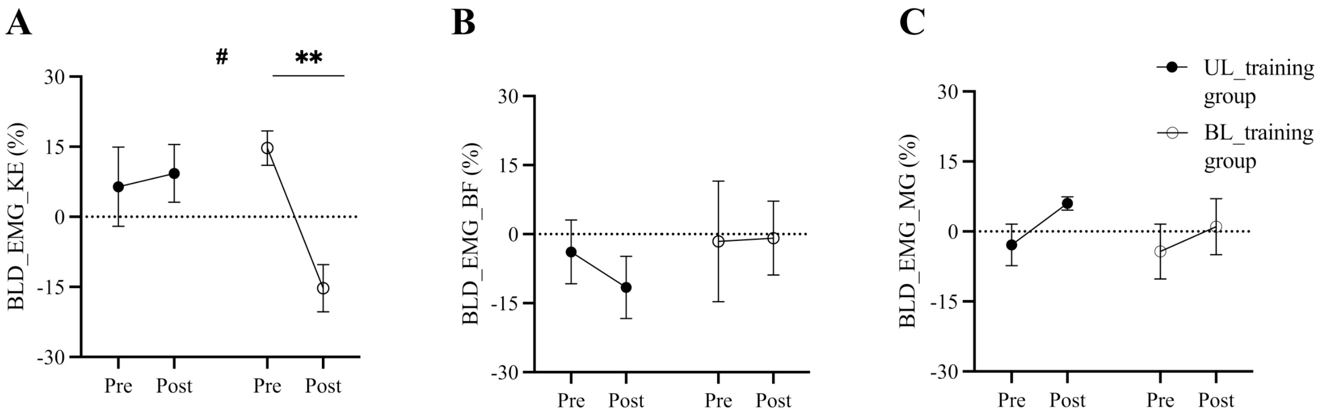

Figure 4. Bilateral deficit index for EMG amplitude (BLD_EMG) of knee extensors (average value between vastus lateralis and rectus femoris, KE, Panel **A**), biceps femoris (BF, Panel **B**), and medial gastrocnemius (MG, Panel **C**) are shown for the unilateral training group (UL_training group, filled circles) and bilateral training group (BL_training group, empty circles) before (Pre) and after (Post) training. Positive values indicate a deficit of activation during bilateral efforts, whereas negative values indicate facilitation during bilateral efforts (i.e., higher EMG amplitude during bilateral than unilateral efforts). Differences in BLD index for EMG amplitude between the two groups (BL_training and UL_training group) and time points (Pre and Post training) were tested using ANOVA analysis. # significant Time x Group interaction, $p \leq 0.05$; ** significant Pre vs Post training difference by Bonferroni post hoc test, $p \leq 0.01$.

measurements, and maximal explosive power of lower limbs (Table 1). Furthermore, both groups presented with very similar and relevant BLD_F and BLD_w values (Table 1).

When considering BLD data collected before and after training from the two groups, we found a significant Time x Group interaction (p = 0.048) for BLD_F, with post hoc analysis revealing a significant decrease in BLD_F for the BL_training group only (p = 0.003, ES: 1.63; Figure 2A). Conversely, BLD_F did not change significantly in the group that underwent UL_training (p = 0.781, ES: 0.18; Figure 2A). A similar trend was observed for BLD_w (Time x Group interaction: p = 0.141), which showed a 7.1% decrease in the BL_training group (ES = 0.77; Figure 2B). On the other hand, a negligible difference (1.4%; ES = 0.15) in BLD_w was found before and after UL_training (Figure 2B).

A BLD index for peak velocity (BLD_v) indicated that higher velocity was achieved during bilateral efforts (i.e., negative BLD_v values) in both study groups. Importantly, neither of the training protocols promoted meaningful trends for BLD_v, with *p* values ranging from >0.999 (Time x group interaction) to p = 0.429 (Time). Post vs Pre difference was equal to -2.8% for the UL_training group (ES = 0.27) and -2.7% for the BL_training group (ES = 0.22; Figure 3).

EMG activity was considered to investigate the training-induced adaptations in the neural component underlying BLD. The changes in BLD_F and BLD_w promoted by the two training protocols were associated with similar trends of the BLD index for EMG amplitude of knee extensors. In particular, a significant (p = 0.017) Time x Group interaction for BLD_EMG-KE was found, with post hoc analysis pointing out that the BL_training group reverted the initial deficit of KE EMG amplitude during bilateral efforts (14.8%) into bilateral facilitation (-15.2%) (p = 0.007, ES = 2.60; Figure 4A). Conversely, the UL_training group did not show any meaningful change between Pre and Post training in terms of BLD index for EMG KE, as indicated by the negligible difference (3.1%, p>0.999, ES = 0.16) in BLD_EMG-KE (Figure 4A). Also, no significant difference or meaningful trends of Time x Group interaction were observed for the other two lower limb muscles considered for analysis (BF: p = 0.650; MG: p = 0.704; Figure 4B and C, respectively).

Finally, it is worth mentioning that a significant Time effect was found for the maximal explosive power generated during both bilateral (p = 0.002) and unilateral efforts (p = 0.001). In particular, training induced large increments in maximal explosive power that ranged between 12.0% (unilateral efforts, BL_training group; ES = 0.73) and 21.8% (bilateral efforts, BL_training group; ES = 1.69). No Time x Group interaction trends were observed for these two variables (p values equal to 0.498 and 0.312 for bilateral and unilateral maximal explosive power, respectively).

Discussion

In the present study, we found relevant BLD of force and power generation during explosive lower limb extensions performed on a sled ergometer in young, physically active individuals. Twenty sessions of bilateral plyometric training performed on the inclined sled ergometer reduced BLD. This was accompanied by the reversion of the initial EMG activation deficit of knee extensors during bilateral efforts into bilateral facilitation. Conversely, no BLD-related adaptations were observed in the study group that underwent unilateral plyometric training. Also, both training groups improved their lower limb neuromuscular performance as assessed by the significantly higher maximal explosive power generated after training.

At the beginning of the study protocol, research participants presented with relevant BLD values, which were equal to approximately 32% and 17% when considering peak force and peak power output, respectively (Table 1). This is consistent with the findings reported in the literature, which found BLD ranging between 6% and 37% when assessing dynamic tasks such as isokinetic knee extension and flexion[4] as well as lower limb extensions during vertical jumps, squats, on a leg press and on a sled ergometer[2,6–10,13]. Reduction of the descending neural drive to the peripheral motor neurons is generally recognized as a primary determinant of BLD. At the cortical level, the activity of one hemisphere of the motor cortex was shown to decrease the maximum motor outflow of homologous parts of the opposite hemisphere, possibly through transcallosal inhibitory connections[25,26]. Spinal cord inhibitory interneurons receiving inputs from the exercising limb and synapsing onto motor neurons of contralateral muscle groups also conceivably contribute to BLD via reciprocal inhibition, reducing the muscle activation generated during bilateral efforts[5,6,27]. We have previously shown that the substantial BLD observed during explosive extensions on a sled ergometer was associated with lower activation of knee extensors during bilateral efforts[9,21], which is consistent with the findings of the present study observed prior to any training (Figure 4A, Pre) for both groups (BLD_EMG-KE Group effect: $p = 0.219$).

A second factor contributing to BLD during dynamic movements is related to muscle mechanical properties. Previous studies suggested that the force–velocity relationship characteristics are responsible for approximately 43%[13] to 75%[8] of the BLD found during explosive extensions of the lower limbs. The greater peak velocity found in the BL efforts compared to the UL ones considered for analysis prior to training (Figure 3, Pre) is consistent with the perspective put forth by Bobbert and colleagues[8], sustaining that the lesser mechanical work performed during bilateral as compared to unilateral vertical jumps was substantially due to the higher shortening velocities in the bilateral efforts.

Twenty sessions of plyometric training performed on an inclined sled ergometer promoted significant and large increments of maximal explosive power of lower limbs, the magnitude of which was similar in the two study groups (see last paragraph of Results). While the present study was not designed to investigate the physiological mechanisms underlying training-induced improvements of maximal explosive power, this finding supports the view that the proposed training protocol had a substantial impact on the neuromuscular system independently of whether the training efforts were generated bilaterally or with one leg at the time. Plyometric training involves rapid stretch-shortening cycles and is effective for improving maximal power output[28]. The plyometric training mechanisms underlying such power output improvements are not entirely elucidated. However, it appears that this training paradigm can elicit relevant neural adaptations (e.g., neural drive, rate of neural activation, intermuscular coordination) while its effects on muscle hypertrophy can be less pronounced, particularly in already-trained individuals[28–30].

Notably, in the present study, bilateral plyometric training promoted a large decrease in BLD during explosive lower limb extensions (Figure 2). Furthermore, this adaptation in the BL_training group was associated with a reversion from deficit to facilitation of knee extensors activation during bilateral efforts (Figure 4A). The decrease of BLD showed by the BL_training group is overall in agreement with previous studies assessing the effects of bilateral resistance training protocols on BLD[14–18]. From a practical standpoint, our findings broaden the choice of available training options that are effective to decrease BLD. Utilizing a bilateral plyometric training for this goal can potentially be beneficial for those who aim at decreasing BLD during bilateral neuromuscular activations that are very brief and/or include a stetch-shortening cycle. Furthermore, varying the training stimulus by implementing both bilateral resistance and plyometric training may yield improved outcomes as compared to using consistently a single training modality. From a mechanistic standpoint, it is worth noting that the reversion from deficit to facilitation of knee extensors activation during bilateral efforts was associated with the BLD decrement. This supports the view that BL_training promoted unique neural adaptations that conceivably affected the neural inhibitory connections underlying BLD[5,6,25–27]. Knee extensors are primary force generators for lower limb extension, and we previously showed that their lower activation during bilateral efforts was associated with the BLD observed with the sled ergometer used in this study[9,21]. This may contribute to explain why BL_training affected the activation amplitude of the knee extensors, but not for the biceps femoris or medial gastrocnemius (Figure 4B and C). Additionally, it is important to highlight that BLD was still present after BL_training (Figure 2), supporting the concept that amplitude of muscle activation is not the only determinant of BLD during dynamic movements[8,13]. We have not designed the present work to assess the contribution of muscle mechanical properties to BLD. However, it is worth pointing out that the relationship between peak velocity generated during BL and UL efforts followed a near-identical trend for both study groups between pre and post training (Figure 3). Seen as the higher shortening velocities achieved during bilateral efforts appear to be a contributing factor of BLD[8], further investigation is needed to assess the effects of different training protocols (e.g., resistance and plyometric training) on the muscle mechanical properties contributing to BLD, because different trainings may promote differential adaptations to the neural and mechanical determinants of BLD.

On the other hand, no effect on BLD was brought about by UL_training (Figure 2). The literature suggests that the effects of unilateral training on BLD appear less consistent, with some studies reporting no effects and others reporting an increase in BLD[10,16–18]. The participants of this study were young, physically active individuals that did not practice specifically bilateral lower limb tasks (e.g., Olympic weightlifting or rowing). Hence, their neuromuscular system was not already trained to optimize motor control of bilateral efforts[12]. This UL_training outcome, together with our previous observation that long-term disuse (i.e., 35 days of experimental bedrest) did not affect BLD[21], further suggest that BLD may be considered an intrinsic property of the human neuromuscular system, the mechanisms of which can be modulated (i.e., downregulated) by BL training. Conversely, daily motor activities and unilateral training do not appear to promote an exacerbation of BLD, at least in the investigated population. A limit of the present study is related to the selection of only male research participants. While previous observations pointed out the presence of BLD in females[17,18], training-induced neuromuscular adaptations may differ between sexes[31]. Thus, our results cannot be generalized to female subjects.

In conclusion, bilateral plyometric training performed on a sled ergometer mitigated the relevant BLD observed during explosive lower limb extensions in young, physically active individuals. This adaptation was accompanied by the reversion from deficit to facilitation of knee extensors activation during bilateral efforts. On the other hand, unilateral plyometric training did not lead to any BLD-related adaptations. Bilateral plyometric training can be an effective alternative to resistance training for reducing BLD during lower limbs extension.

Ethics approval

The study was approved by the Institutional Review Board at the University of Udine IRB (9/IRB DAME_17) and adhered to the principles of the Declaration of Helsinki.

Authors' contributions

ER, SL and AB contributed to the conception and design of the study; ER and AB contributed to data analysis; ER, SZ and MD contributed to data analysis and interpretation; ER, SZ and MD drafted the manuscript; all authors provided a critical revision of the manuscript, approved the manuscript, and agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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