Comparison Between Unilateral and Bilateral Plyometric Training on Single- and Double-Leg Jumping Performance and Strength

Gregory C. Bogdanis,[1] Athanasios Tsoukos,[1] Olga Kaloheri,[1] Gerasimos Terzis,[1] Panagiotis Veligekas,[1] and Lee E. Brown[2]

[1]*School of P. E. and Sport Science, National and Kapodistrian University of Athens, Athens, Greece; and* [2]*Human Performance Laboratory, California State University, Fullerton, California*

Abstract

Bogdanis, GC, Tsoukos, A, Kaloheri, O, Terzis, G, Veligekas, P, and Brown, LE. Comparison between unilateral and bilateral plyometric training on single- and double-leg jumping performance and strength. *J Strength Cond Res* 33(3): 633–640, 2019—This study compared the effects of unilateral and bilateral plyometric training on single- and double-leg jumping performance, maximal strength, and rate of force development (RFD). Fifteen moderately trained subjects were randomly assigned to either a unilateral (U, $n = 7$) or bilateral group (B, $n = 8$). Both groups performed maximal effort plyometric leg exercises 2 times per week for 6 weeks. The B group performed all exercises with both legs, whereas the U group performed half the repetitions with each leg, so that total exercise volume was the same. Jumping performance was assessed by countermovement jumps (CMJs) and drop jumps (DJs), whereas maximal isometric leg press strength and RFD were measured before and after training for each leg separately and both legs together. Countermovement jump improvement with both legs was not significantly different between U (12.1 ± 7.2%) and B (11.0 ± 5.5%) groups. However, the sum of right- and left-leg CMJ only improved in the U group (19.0 ± 7.1%, $p < 0.001$) and was unchanged in the B group (3.4 ± 8.4%, $p = 0.80$). Maximal isometric leg press force with both legs was increased similarly between groups (B: 20.1 ± 6.5%, U: 19.9 ± 6.2%). However, the sum of right- and left-leg maximal force increased more in U compared with B group (23.8 ± 9.1% vs. 11.9 ± 6.2%, $p = 0.009$, respectively). Similarly, the sum of right- and left-leg $RFD_{0\text{-}50}$ and $RFD_{0\text{-}100}$ were improved only in the U group (34–36%, $p < 0.01$). Unilateral plyometric training was more effective at increasing both single- and double-leg jumping performance, isometric leg press maximal force, and RFD when compared with bilateral training.

Key Words eccentric training, training specificity, countermovement jump, reactive strength index, rate of force development

Introduction

During single- and double-leg muscle actions, the sum of force or power generated by each limb acting separately may be greater than the force or power produced when the muscles of both legs act simultaneously (3,6,13). This is termed the bilateral deficit and has been attributed to reduced neural drive and a failure to maximally activate the muscles of the 2 limbs when they contract simultaneously (30). Previous studies have shown that the maximal force bilateral deficit may be reduced significantly or even eliminated, after bilateral strength training, because of the greater magnitude of improvement in bilateral compared with unilateral strength (12,14). By contrast, there is evidence from a cross-sectional (13) and a recent training study (5), suggesting that unilateral training may increase bilateral deficit, supporting the principle of training specificity.

Based on the phenomenon of bilateral deficit, that also occurs in jumping (3), it is tempting to hypothesize that strength and power training performed with each leg separately (unilateral) may allow greater loads and thus greater adaptations compared with bilateral training. Earlier resistance training studies using middle-aged and elderly men and women (12), students (24), or postmenopausal women (14) have presented conflicting results regarding the effectiveness of unilateral and bilateral lower-limb training. For example, Taniguchi (24) reported that only bilateral leg extension training resulted in an increase in maximal force, whereas Häkkinen et al. (12) and Janzen et al. (14) reported strength gains that were specific to the training mode used (bilateral or unilateral). One recent study (5) using unilateral and bilateral knee extension strength training found that isometric strength gains were almost 2-fold greater after unilateral compared with bilateral training. The possibility that

Address correspondence to Gregory C. Bogdanis, gbogdanis@phed.uoa.gr.

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unilateral may be more effective than bilateral training may be exploited by coaches and athletes who wish to maximize the benefits of strength training. However, in sports requiring power, explosive force production may be more important than maximal strength. In explosive movements, such as jumping, sprinting, and plyometrics, the time to develop force is limited to less than 250 ms, and thus the ability to exert force rapidly, i.e., rate of force development (RFD) is an important determinant of performance (16,25). In that respect, plyometric training may be more effective than resistance training in improving explosive force, but some studies have reported conflicting results (17,20,21). Exploring the effects of unilateral and bilateral plyometric training has important implications for practitioners who use this type of training (jumping, hopping, bounding) to improve explosive performance. Thus, the purpose of this study was to evaluate the effects of 6 weeks of unilateral (U) vs. bilateral (B) lower-limb plyometric training on maximal strength, RFD, and jumping performance.

Methods

Experimental Approach to the Problem

A repeated measures design was used to investigate the short-term effects of unilateral vs. bilateral plyometric training on maximal force and explosive performance. Subjects were randomly assigned to 1 of 2 groups of either unilateral or bilateral training. They were required to take part in 2 familiarization and 3 preliminary measurement sessions, including countermovement jumps (CMJs), drop jumps (DJs), maximum peak force, and RFD in the leg press exercise. On the first 2 visits, they were familiarized with DJs, CMJs, and isometric leg press to maximize reliability (16). On the first preliminary visit, CMJ and DJ performances were measured and served as baseline values. On the second preliminary visit, maximum isometric force and RFD were measured. In the third preliminary visit, 1 repetition maximum (1RM) leg extension and leg curl were measured. All measurements were performed on both legs simultaneously and each leg separately. After baseline testing, subjects performed training with either unilateral (U) or bilateral (B) plyometric exercises for 6 weeks. All measurements were repeated at the end of training.

Subjects

This study was approved by the review board at the School of PE and Sport Science of the National & Kapodistrian University of Athens, Greece and all procedures were in accordance with the Code of Ethics of the World Medical Association (Helsinki declaration of 1964, as revised in 2013). Fifteen physical education students (mean ± *SD*: age range: 18.2 to 25.8; 8 men [age: 19.8 ± 2.9 years, height: 1.78 ± 0.06 m, body mass: 72.3 ± 10.2 kg] and 7 women [mean ± *SD*: age: 19.4 ± 0.5 years, height: 1.64 ± 0.07 m, body mass: 58.0 ± 4.1 kg]) took part in this study after being informed of the aims and possible risks involved and after signing an informed consent form. Participants were physically active and took part in recreational activities 2–3 times per week, without performing any resistance training. They were randomly assigned to either a unilateral (U, $n = 7$) or bilateral (B, $n = 8$) training group and were matched for baseline CMJ performance and maximal isometric force.

Procedures

Measurement of Countermovement Jump Performance. Countermovement jump performance was defined as the displacement of the center of mass from take-off to the vertex of the flight trajectory, calculated by flight time obtained from a force plate (Applied Measurements Ltd, Reading, United Kingdom) with a sampling frequency of 1 kHz (26). Displacement of center of mass was calculated by the following equation:

$$\text{Displacement of the center of mass} = \frac{1}{2}g\cdot\left(\frac{t}{2}\right)^2$$

where $g = 9.81\ \text{m}\cdot\text{s}^{-2}$, $t =$ flight time.

Participants were asked to jump as high as possible with their hands akimbo throughout the jump and to maintain the same body position at the instants of take-off and landing. This method has been shown to be simple and highly reliable (7) and the results are directly comparable with those obtained by inexpensive devices such as contact mats and optoelectric cells used widely by researchers and practitioners (10). For each measurement, participants performed 3 CMJ with 45 seconds of rest between jumps. Countermovement jump intraclass correlation coefficient (ICC) was 0.99 ($p < 0.01$).

Measurement of Drop Jump Performance. Drop jump height was calculated by flight time measured on the same force plate as CMJ. Participants were asked to step off a wooden box at a set height of 30 cm without lifting their center of gravity (2,27) and land on the force plate with both legs or 1 leg depending on the measurement (bilateral or unilateral). After contact, they rebounded and immediately jumped as high as possible trying to minimize ground contact time (31). As in the CMJ, hands were kept akimbo throughout the entire jump and a straight body position was maintained at the instants of take-off and landing. Subjects performed 3 DJ with 45 seconds of rest between jumps (2). Reactive strength index (RSI) was calculated by the following formula:

$$\text{RSI}\left(\text{m}\cdot\text{s}^{-1}\right) = \text{maximal DJ height} \times \text{ground contact time}^{-1}$$

Intraclass correlation coefficients for the DJ parameters were the following: height: ICC = 0.95 ($p < 0.01$), contact time: ICC = 0.96 ($p < 0.01$), RSI: ICC = 0.99 ($p < 0.01$).

Measurement of Maximum Isometric Force and Rate of Force Development. Maximum isometric force and RFD were measured with the same force plate mounted firmly on a concrete wall in front of a custom-made, rigid steel leg press chair, with the seat back set at a 106° angle with the horizontal being level (27). Subjects wore Olympic weightlifting shoes and their torso angle relative to the ground was 110 ± 2°, hip angle (between the thigh and the torso) was 62 ± 4°, and knee angle was 101 ± 5° (180° = full knee extension). Participants were instructed to push with both legs "as fast and hard as possible" (16,27) for 4 seconds and avoid any counter movement. A sampling frequency of 1,000 Hz was used (11) with a low-pass, fourth order, zero lag Butterworth digital filter with a cutoff frequency of 25 Hz for smoothing the raw data (27). Two maximum trials were performed with 2 minutes of recovery. Maximum isometric force was calculated as the highest 100 ms average of the force-time curve. Rate of force development was calculated at specific time windows of 0–50, 0–100, 0–200, and 0–300 ms ($RFD_{0\text{-}50}$, $RFD_{0\text{-}100}$, $RFD_{0\text{-}200}$, and $RFD_{0\text{-}300}$) as the slope of the force-time curve over each time window (1). Intraclass correlation coefficients for maximum isometric force for unilateral and bilateral measurements were 0.979 and 0.992 ($p < 0.01$), respectively. Intraclass correlation coefficient for RFD for unilateral measurements ranged from 0.873 ($p < 0.01$ for $RFD_{0\text{-}50}$) to 0.980 ($p < 0.01$ for $RFD_{0\text{-}300}$). Intraclass correlation coefficient for RFD for bilateral measurements ranged from 0.951 ($p < 0.01$ for $RFD_{0\text{-}50}$) to 0.990 ($p < 0.01$ for $RFD_{0\text{-}300}$).

Calculation of Bilateral Index. Bilateral index was calculated with the following formula (13):

$$\text{Bilateral index}(\%) = \left(100\times\frac{\text{bilateral[2-leg]measurement}}{\text{right} + \text{left unilateralmeasurement}}\right)-100$$

Negative bilateral index values indicate bilateral deficit, i.e., that the sum of right + left leg measurements was greater than the 2-leg measurement, whereas a positive bilateral index indicates bilateral facilitation, i.e., that the 2-leg measurement was greater than the sum or the right + left leg measurements.

Table 1. Training program for the bilateral and unilateral training group.*†

	Week 1–3 sets	Week 4–6 sets	Repetitions
Bilateral training group			
1. Two-leg jumps for distance	2	3	10
2. Countermovement jumps	2	3	10
3. Lateral jumps	2	3	10
4. Box jumps	2	3	10
5. Jumps over hurdles	2	3	10
6. Drop jumps	2	3	10
7. Leg extensions	3	4	6 at 60% or 3 at 90% 1RM‡
8. Leg curls	3	4	8 at 60% 1RM
Unilateral training group			
1. Hops	2	3	5 per leg
2. Single-leg countermovement jumps	2	3	5 per leg
3. Single-leg lateral jumps	2	3	5 per leg
4. Single-leg box jumps	2	3	5 per leg
5. Single-leg jumps over hurdles	2	3	5 per leg
6. Single-leg drop jumps	2	3	5 per leg
7. Single-leg leg extensions	3	4	6 at 60% or 3 at 90% 1RM‡
8. Single-leg leg curls	3	4	8 at 60% 1RM

*1RM = 1 repetition maximum.
†The program was performed twice per week for 6 wk.
‡Performed on the first or the second session of each training week (see text for details).

Plyometric Training Program. Training took place across 6 weeks. Participants trained 2 days per week, 72 hours apart (total sessions = 12) on nonconsecutive days. Each training session lasted 60–75 minutes. Subjects performed a standardized warm-up which included 5 minutes of light jogging on a treadmill (≈60% of predicted maximal heart rate) and 5 minutes of dynamic stretching (4,26,28). Subsequently, they performed running warm-up drills for 10 minutes which consisted of 2 sets of 20 m of butt kickers, a-skips, b-skips, a-runs, and 2 × 40-m running progressions. Table 1 shows the exercises included in the training program. All plyometric exercises were performed with maximal effort. Leg extensions and leg curls were included in both unilateral and bilateral training programs as supplementary exercises. On the first training day of the week, the load for leg extension was 60% 1RM and 6 explosive repetitions were performed per set. On the second day of the week, the load for leg extension was 90% 1RM and 3 repetitions were performed per set. Load was readjusted at the end of week 3. Resting intervals were 1 minute between sets and 3 minutes between exercises. A 10 minute-cooldown, including light jogging and static stretching, was performed after each session.

Statistical Analyses

Data are presented as mean ± standard deviation. To examine the effect of unilateral and bilateral training, performances of the right and left legs were summed and compared with 2-leg performance. Multiple 3-way mixed factor analyses of variance (ANOVAs) (2 training groups × 2 time points × 2 measurements [2-legs or sum of right and left legs]) were conducted to examine differences in CMJ performance, RSI, maximal isometric peak force, and RFD. When a significant 3-way interaction was observed, 2-way repeated measures ANOVAs were performed. Changes in Bilateral index were examined using 2-way mixed factor ANOVA (2 training groups × 2 time points). When significant main effects or interactions were found ($p < 0.05$), Tukey's test was used for post hoc analyses. Partial eta squared (η^2) values were used to estimate effect sizes (small: 0.01 to 0.059, moderate: 0.06 to 0.137, and large >0.138). For pairwise comparisons, the magnitude of effect sizes were determined by Cohen's d (small: >0.2, medium: >0.5, and large: >0.8). Test-retest reliability for all dependent variables was assessed by the ICC using a 2-way random effect model. Statistical significance was set at $p \leq 0.05$. All statistical analyses were performed using SPSS (IBM SPSS Statistics Version 23).

Results

For CMJ performance, there was a significant 3-way interaction ($p = 0.002$, $\eta^2 = 0.52$). The follow-up 2-way ANOVA (time × measurement) showed that after training, the U and B groups improved 2-leg CMJ performance similarly by 12.1 ± 7.2% ($p < 0.001$, $d = 1.01$) and 11.0 ± 5.5% ($p < 0.001$, $d = 0.59$), respectively (Figure 1). However, unilateral CMJ performance only improved in the U group (19.0 ± 7.1%, $p < 0.001$, $d = 1.17$) and was unchanged in the B group (3.4 ± 8.4%, $p = 0.80$, $d = 0.08$, Figure 1).

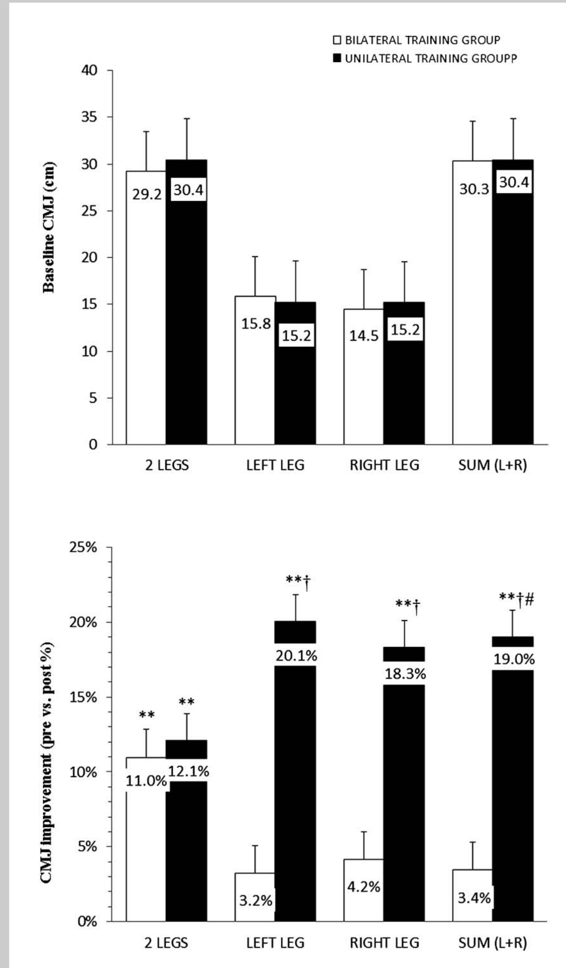

Figure 1. Baseline values of countermovement jump (CMJ) performance (upper panel) and percent improvement of CMJ performance after 6 weeks of training for the unilateral and bilateral training groups. Two LEGS: 2-leg CMJ; LEFT LEG and RIGHT LEG: single-leg CMJ; SUM (L + R): sum of left and right CMJ performance. **: $p < 0.01$ from pre-training (baseline) values; †: $p < 0.01$ between bilateral and unilateral training groups; #: $p < 0.01$ between CMJ improvement for 2 LEGS and SUM (L + R).

For CMJ bilateral index, there was a significant time × group interaction ($p = 0.002$, $\eta^2 = 0.52$). At baseline, it was not different from zero, indicating neither facilitation nor deficit in both groups (B: −0.4 ± 12.7%, U: 0.9 ± 7.2%). However, after training, post hoc test showed an increase to bilateral facilitation in the B group to 6.8 ± 11.5% ($p = 0.045$, $d = 0.64$), whereas the U group showed a nonsignificant increased deficit to −5.0 ± 6.5% ($p = 0.14$, $d = 0.92$).

For DJ, there were no 3-way ($p = 0.17$, $\eta^2 = 0.14$) or 2-way interactions ($p > 0.26$), but there was a main effect for time

TABLE 2. Maximal force and rate of force development (RFD) at different time windows during double-leg and single-leg (sum of right and left legs) isometric leg press measurements, pretraining and posttraining in the bilateral and unilateral training groups.*

	Bilateral training group			Unilateral training group			
	Pretraining	Posttraining	% Pre vs. post	Pretraining	Posttraining	% Pre vs. post	Bilateral vs. unilateral group improvement
Double-leg measurements							
Maximal force (N)	1,766 ± 583	2,093 ± 611	18.5†	1,724 ± 329	2,070 ± 415	20.0†	n.s.
RFD 0–50 ($N \cdot s^{-1}$)	6,265 ± 3,392	7,142 ± 3,369	14.0	8,555 ± 3,032	9,918 ± 2,379	15.9	n.s.
RFD 0–100 ($N \cdot s^{-1}$)	6,310 ± 2,514	8,002 ± 3,010	26.8‡	7,591 ± 2,308	9,674 ± 1,905	27.4†	n.s.
RFD 0–200 ($N \cdot s^{-1}$)	5,195 ± 1,944	6,280 ± 2,078	20.9	5,452 ± 1,406	6,821 ± 1,222	25.1	n.s.
RFD 0–300 ($N \cdot s^{-1}$)	3,948 ± 1,509	4,765 ± 1,528	20.7	3,894 ± 974	4,964 ± 804	27.5	n.s.
Sum of right- and left-leg measurements							
Maximal force (N)	2,003 ± 593	2,241 ± 573	11.9†	2,019 ± 375	2,499 ± 470	23.8†	<0.01
RFD 0–50 ($N \cdot s^{-1}$)	7,327 ± 3,593	7,233 ± 2,577	−1.3	7,971 ± 4,098	10,677 ± 3,303	33.9†	<0.05
RFD 0–100 ($N \cdot s^{-1}$)	7,343 ± 2,873	8,330 ± 2,863	13.4	7,794 ± 3,160	10,620 ± 2,890	36.3†	<0.05
RFD 0–200 ($N \cdot s^{-1}$)	5,896 ± 2,028	6,755 ± 2,076	14.6	6,097 ± 1,783	7,710 ± 1,642	26.5	n.s.
RFD 0–300 ($N \cdot s^{-1}$)	4,327 ± 1,386	5,045 ± 1,485	16.6	4,549 ± 1,235	5,607 ± 1,113	23.2	n.s.

*Data are mean ± *SD*.
†$p < 0.01$.
‡$p < 0.05$.

(prepost training, $p = 0.024$, $\eta^2 = 0.33$), showing a similar improvement for both groups ($\approx 5\%$, $d = 0.14$ for B and $\approx 9\%$, $d = 0.46$ for U). There was also a main effect for time (prepost training, $p = 0.03$, $\eta^2 = 0.31$) for contact time, showing a similar decrease in both groups (from 0.243 ± 0.043 to 0.219 ± 0.035 seconds, $d = 0.68$ for B and from 0.260 ± 0.034 to 0.228 ± 0.026 seconds, $d = 1.07$, for U).

For RSI, there was no 3-way interaction, but there was a time × group interaction ($p = 0.013$, $\eta^2 = 0.38$) where the post hoc test showed an improvement in the U group (from 1.01 ± 0.22 to 1.25 ± 0.25 $m \cdot s^{-1}$, $p = 0.001$, $d = 1.03$) but not in the B group (from 0.93 ± 0.34 to 0.97 ± 0.28 $m \cdot s^{-1}$, $p = 0.92$, $d = 0.14$).

For maximum isometric force, there was a significant 3-way interaction ($p = 0.021$, $\eta^2 = 0.34$). The follow-up 2-way ANOVA showed that after training, the double-leg measurements were increased significantly and similarly in both groups (Table 2). However, for each leg separately, the sum of maximal force of the 2 legs increased 2-fold more in the U compared with the B group ($d = 1.22$).

For $RFD_{0\text{-}50}$ and $RFD_{0\text{-}100}$, there were significant 3-way interactions ($p = 0.037$, $\eta^2 = 0.29$) ($p = 0.03$, $\eta^2 = 0.31$). The follow-up 2-way ANOVAs showed that after training, $RFD_{0\text{-}50}$ for the double-leg measurements remained unchanged, but $RFD_{0\text{-}100}$ was increased similarly in both groups ($d = 0.66$ for B and $d = 1.05$ for U, Table 2). However, the sum of left and right legs for $RFD_{0\text{-}50}$ and $RFD_{0\text{-}100}$ was improved only in the U group ($d = 0.77$ and $d = 1.0$, respectively, Table 2), while RFD remained unchanged at all time windows in the B group. There were no 2-way or 3-way interactions for $RFD_{0\text{-}200}$ or $RFD_{0\text{-}300}$ ($p = 0.17$–0.65), but there was a main effect for time for both $RFD_{0\text{-}200}$ and $RFD_{0\text{-}300}$ ($p = 0.001$, $\eta^2 = 0.75$–0.80, Table 2) which were increased.

For maximal force bilateral index, there was a significant time × group interaction ($p = 0.015$, $\eta^2 = 0.37$). At baseline, bilateral index was negative and similar in both groups, indicating a bilateral deficit (B: −12.6 ± 6.8%, U: −14.6 ± 3.9%). After training, the bilateral index was not changed in either group (B: −7.3% ± 6.2%, U: −17.0 ± 7.5%; $p = 0.065$, and $p = 0.63$, respectively).

For leg extension and leg curl 1RM, there were no significant 3-way ($p = 0.47$–0.68) or 2-way interactions ($p = 0.15$–0.72), but there were significant main effects for time for both ($p < 0.001$, $\eta^2 = 0.91$ and $p < 0.001$, $\eta^2 = 0.88$, respectively), demonstrating that both groups increased similarly in double-leg and the sum of both legs. The average increase for leg extension 1RM was 30.8 ± 14.7% ($p < 0.001$, $d = 0.92$) and for leg curl 1RM was 22.2 ± 14.1% ($p = 0.001$, $d = 0.51$).

Discussion

The main finding of this study was that unilateral lower-limb plyometric training was effective at improving both single- and double-leg explosive performance, whereas an equal volume of bilateral training only improved bilateral performance. This is the first study that examined explosive force (RFD), as well as dynamic muscle performance during a multijoint movement involving hip, knee, and ankle extension, as opposed to single-joint movements (e.g., knee extension) used in most previous studies (e.g., 6, 14, 28). A novel and important finding of this study was the large increase in maximal isometric force and RFD in the first 50 and 100 ms of single-leg muscle actions, only after U training, which may partially explain the 2-fold greater improvement in single-leg CMJ and the increase in RSI during DJs. These improvements only after unilateral plyometric training show that the principle of training specificity was valid only for unilateral training, whereas bilateral performance was improved equally in the U and B training groups. Thus, this study highlights the effectiveness of unilateral training for increasing not only isometric strength (5) but more functional parameters of explosive muscle performance.

The large improvements in explosive lower-limb performance in this study may be due to the fact that multijoint plyometric exercises were used during training, as opposed to single-joint exercises used in other unilateral studies, e.g., (5,12,24). Very few studies of bilateral and unilateral training have used plyometric exercises. McCurdy et al. (20) examined the effects of 8 weeks of strength and plyometric training and reported that unilateral vertical jump height improved more after unilateral than bilateral training. However, they concluded that after adjusting for pretest differences, the posttest scores in all measured parameters were similar between groups. In another study that used a 6-week plyometric program with adolescent soccer players (21), it was concluded that a combination of bilateral and unilateral training induced superior performance improvements than each training mode alone. However, careful examination of the 21 performance measurements in that study showed that the unilateral training groups improved marginally more than the other groups in 5 of 8 jump measurements, equally with the combination group in the 5 soccer-specific explosive performance tests, whereas surprisingly, the unilateral group improved less than the bilateral and the combination groups in the 8 balance tests (21). Therefore, based on these observations, it may be argued that unilateral training may be more effective than bilateral training both in adults and in adolescents. Interestingly, the total number of jumps performed in that study (21) (2,160 jumps in 6 weeks with 2 sessions per week) was similar to the total of jumps performed in this study (1,800 in total).

Another finding of this study was that similar improvements were seen in unilateral and bilateral plyometric training in bilateral measurements of neuromuscular performance. Countermovement jump performance with both legs significantly improved equally in the U and B groups. Furthermore, $RFD_{0\text{-}100}$ and maximum isometric force increased to similar levels after U and B training, when measured with both legs simultaneously. In agreement with our results, Makaruk et al. (17) showed that after 12 weeks of unilateral vs. bilateral plyometric training, there was a similar increase in bilateral peak power and jumping ability in both groups. This is in contrast with the principle of specificity supported by findings of other studies, which showed that unilateral training primarily enhances unilateral performance, whereas bilateral training primarily enhances bilateral performance (12,21,24). These discrepancies may be attributed to factors such as study population, type of measurement, subjects level of physical activity, sex, contraction type, or movement velocity (5,9,12,14,15,20,21,23). A noteworthy finding of this study was that the larger gains in unilateral explosive strength and power after U were not transferred to bilateral performance. This may be due to reduced neural drive and failure to maximally activate muscles of the 2 limbs when contracting together (30), or that leg muscles operate at a different part of the force- and power-velocity relationships during faster 2-leg jumps (3). The former applies to isometric force, whereas both arguments may apply to jumping performance.

Our results are in accordance with other studies regarding maximum strength, which was increased in both groups after training. Botton et al. (5) found a similar improvement in dynamic knee extension in both U and B groups in recreationally active women, whereas Janzen et al. (14) concluded that monoarticular exercises such as leg extensions improved maximum strength to the same degree regardless of U or B training intervention. Thus, it seems that the unilateral and bilateral plyometric training, which constituted the largest part of training in this study, did not affect the test results of nonspecific, monoarticular dynamic tests, such as the leg extension and curl.

A possible explanation for the superiority of unilateral plyometric training in this study may be related to neural factors. Van Soest et al. (29) reported that unilateral vertical jumps significantly increased electromyography (EMG) activity of the vastus medialis and gastrocnemius muscles by 10–25% compared with bilateral vertical jumps. Thus, although EMG was not measured in this study, unilateral plyometric training may have resulted in greater neural activation of the leg muscles, resulting in a greater training load. However, Bobbert et al. (3) reported that the higher force generated during single-leg jumps is not accompanied by greater EMG activity, but is related to slower movement speed when jumping off 1 compared with 2 legs. Thus, during unilateral plyometric training, muscles contract at slower velocities, which are closer to their optimum, resulting in greater impulse (3,29). By contrast, during bilateral vertical jumps, muscles contract at greater speeds and because of the force-velocity relationship, produce less force (3). Moreover, plyometric training with additional weight (8,18) is more effective than training with no external load (34). Taken collectively, the previous findings suggest that during unilateral training, muscles operate at higher intensities and thus greater adaptation is achieved (19). The higher force generating capacity of single-leg muscle actions in this study is inferred by the bilateral index which was large and negative. Interestingly, both bilateral indices (for maximal force and CMJ) became more negative at the end of training, suggesting that training load was progressively higher during the 6 weeks of training, because of the ability of single-leg actions to produce higher force and power.

A parameter that may have caused greater neuromuscular enhancement in the unilateral training group in this study is the contribution of cross-education (22,32,33,35), defined as the phenomenon where chronic unilateral motor activity can affect performance of the homologous muscles in the contralateral limb (35). For example, Weir et al. (32) observed that after 8 weeks of eccentric resistance training with the nondominant limb, isometric strength was increased in both the dominant and nondominant legs. They also reported that this enhancement was seen at specific knee angles, suggesting joint angle specificity. Eccentric training increased the eccentric 1RM of both the trained and untrained limbs as well as bilaterally; however, enhancement of the trained and the untrained limbs was greater than that bilaterally. Based on this, it seems that in this study, the U group might have exhibited cross-education. The physiological mechanisms underlying cross-education of muscular strength may be explained by central neural factors during training (22).

In conclusion, unilateral plyometric training was more effective in increasing both single- and double-leg jumping performance, isometric leg press maximal force, and RFD, when compared with bilateral training. A noteworthy finding of this study that warrants further investigation was that the gains in unilateral explosive strength and power were not transferred to bilateral performance.

Practical Applications

These data show that unilateral plyometric training of the lower limbs is 2–3 fold more effective compared with an equal volume of bilateral training when testing is performed with each limb separately. This advantage is realized within 6 weeks of twice-weekly training, with a total of 1,800 jumps. This large increase in single-leg explosive muscle performance could be useful for many individual and team sports that include high force or power single-leg muscle actions, ranging from track and field jumping and sprinting to basketball and football and soccer. Furthermore, an increase in the ability to develop high forces rapidly may be important for weak and elderly persons who wish to improve balance and prevent falls. Strength and conditioning coaches should incorporate unilateral plyometric lower-limb exercises in their training programs for athletes and special populations.

References

1. Aagaard, P, Simonsen, EB, Andersen, JL, Magnusson, P, and Dyhre-Poulsen, P. Increased rate of force development and neural drive of human skeletal muscle following resistance training. *J Appl Physiol (1985)* 93: 1318–1326, 2002.

2. Barr, MJ and Nolte, VW. Which measure of drop jump performance best predicts sprinting speed? *J Strength Cond Res* 25: 1976–1982, 2011.

3. Bobbert, MF, de Graaf, WW, Jonk, JN, and Casius, LJR. Explanation of the bilateral deficit in human vertical squat jumping. *J Appl Physiol (1985)* 100: 493–499, 2006.

4. Bogdanis, GC, Tsoukos, A, Veligekas, P, Tsolakis, C, and Terzis, G. Effects of muscle action type with equal impulse of conditioning activity on postactivation potentiation. *J Strength Cond Res* 28: 2521–2528, 2014.

5. Botton, CE, Radaelli, R, Wilhelm, EN, Rech, A, Brown, LE, and Pinto, RS. Neuromuscular adaptations to unilateral vs. bilateral strength training in women. *J Strength Cond Res* 30: 1924–1932, 2016.

6. Botton, CE, Radaelli, R, Wilhelm, EN, Silva, BGC, Brown, LE, and Pinto, RS. Bilateral deficit between concentric and isometric muscle actions. *Isokinet Exerc Sci* 21: 161–165, 2013.

7. Cormack, SJ, Newton, RU, McGuigan, MR, and Doyle, TLA. Reliability of measures obtained during single and repeated countermovement jumps. *Int J Sports Physiol Perform* 3: 131–144, 2008.

8. Cormie, P, McGuigan, MR, and Newton, RU. Developing maximal neuromuscular power: Part 2-training considerations for improving maximal power production. *Sports Med* 41: 125–146, 2011.

9. Dickin, CD and Too, D. Effects of movement velocity and maximal concentric and eccentric actions on the bilateral deficit. *Res Q Exerc Sport* 77: 296–303, 2006.

10. Glatthorn, JF, Gouge, S, Nussbaumer, S, Stauffacher, S, Impellizzeri, FM, and Maffiuletti, NA. Validity and reliability of Optojump photoelectric cells for estimating vertical jump height. *J Strength Cond Res* 25: 556–560, 2011.

11. Haff, GG, Ruben, RP, Lider, J, Twine, C, and Cormie, P. A comparison of methods for determining the rate of force development during isometric midthigh clean pulls. *J Strength Cond Res* 29: 386–395, 2015.

12. Häkkinen, K, Kallinen, M, Linnamo, V, Pastinen, UM, Newton, RU, and Kraemer, WJ. Neuromuscular adaptations during bilateral versus unilateral strength training in middle-aged and elderly men and women. *Acta Physiol Scand* 158: 77–88, 1996.

13. Howard, JD and Enoka, RM. Maximum bilateral contractions are modified by neurally mediated interlimb effects. *J Appl Physiol* 70: 306–316, 1991.

14. Janzen, CL, Chilibeck, PD, and Davison, KS. The effect of unilateral and bilateral strength training on the bilateral deficit and lean tissue mass in post-menopausal women. *Eur J Appl Physiol* 97: 253–260, 2006.

15. Kuruganti, U, Parker, P, Rickards, J, Tingley, M, and Sexsmith, J. Bilateral isokinetic training reduces the bilateral leg strength deficit for both old and young adults. *Eur J Appl Physiol* 94: 175–179, 2005.

16. Maffiuletti, NA, Aagaard, P, Blazevich, AJ, Folland, J, Tillin, N, and Duchateau, J. Rate of force development: Physiological and methodological considerations. *Eur J Appl Physiol* 116: 1091–1116, 2016.

17. Makaruk, H, Winchester, JB, Sadowski, J, Czaplicki, A, and Sacewicz, T. Effects of unilateral and bilateral plyometric training on power and jumping ability in women. *J Strength Cond Res* 25: 3311–3318, 2011.

18. Maloney, SJ, Turner, AN, and Fletcher, IM. Ballistic exercise as a pre-activation stimulus: A review of the literature and practical applications. *Sport Med* 44: 1347–1359, 2014.

19. McBride, JM, Triplett-McBride, T, Davie, A, and Newton, RU. The effect of heavy- vs. light-load jump squats on the development of strength, power, and speed. *J Strength Cond Res* 16: 75–82, 2002.

20. McCurdy, KW, Langford, GA, Doscher, MW, Wiley, LP, and Mallard, KG. The effects of short-term unilateral and bilateral lower-body resistance training on measures of strength and power. *J Strength Cond Res* 19: 9–15, 2005.

21. Ramírez-Campillo, R, Burgos, CH, Henríquez-Olguín, C, Andrade, DC, Martínez, C, Álvarez, C, Castro-Sepúlveda, M, Marques, MC, and Izquierdo, M. Effect of unilateral, bilateral, and combined plyometric training on explosive and endurance performance of young soccer players. *J Strength Cond Res* 29: 1317–1328, 2015.

22. Shima, N, Ishida, K, Katayama, K, Morotome, Y, Sato, Y, and Miyamura, M. Cross education of muscular strength during unilateral resistance training and detraining. *Eur J Appl Physiol* 86: 287–294, 2002.

23. Speirs, DE, Bennett, MA, Finn, CV, and Turner, AP. Unilateral vs. bilateral squat training for strength, sprints, and agility in academy rugby players. *J Strength Cond Res* 30: 386–392, 2016.

24. Taniguchi, Y. Lateral specificity in resistance training: The effect of bilateral and unilateral training. *Eur J Appl Physiol Occup Physiol* 75: 144–150, 1997.

25. Tillin, NA, Pain, MTG, and Folland, JP. Short-term training for explosive strength causes neural and mechanical adaptations. *Exp Physiol* 97: 630–641, 2012.

26. Tsoukos, A, Bogdanis, GC, Terzis, G, and Veligekas, P. Acute improvement of vertical jump performance after isometric squats depends on knee angle and vertical jumping ability. *J Strength Cond Res* 30: 2250–2257, 2016.

27. Tsoukos, A, Veligekas, P, Brown, LE, Terzis, G, and Bogdanis, GC. Delayed effects of a low volume, power-type resistance exercise session on explosive performance. *J Strength Cond Res*, 2017. Epub ahead of print.

28. Turki, O, Chaouachi, A, Drinkwater, EJ, Chtara, M, Chamari, K, Amri, M, and Behm, DG. Ten minutes of dynamic stretching is sufficient to potentiate vertical jump performance characteristics. *J Strength Cond Res* 25: 2453–2463, 2011.

29. van Soest, AJ, Roebroeck, ME, Bobbert, MF, Huijing, PA, and van Ingen Schenau, GJ. A comparison of one-legged and two-legged countermovement jumps. *Med Sci Sports Exerc* 17: 635–639, 1985.

30. Vandervoort, AA, Sale, DG, and Moroz, J. Comparison of motor unit activation during unilateral and bilateral leg extension. *J Appl Physiol* 56: 46–51, 1984.

31. Viitasalo, JT, Salo, A, and Lahtinen, J. Neuromuscular functioning of athletes and non-athletes in the drop jump. *Eur J Appl Physiol Occup Physiol* 78: 432–440, 1998.

32. Weir, JP, Housh, DJ, Housh, TJ, and Weir, LL. The effect of unilateral eccentric weight training and detraining on joint angle specificity, cross-training, and the bilateral deficit. *J Orthop Sports Phys Ther* 22: 207–215, 1995.

33. Weir, JP, Housh, DJ, Housh, TJ, and Weir, LL. The effect of unilateral concentric weight training and detraining on joint angle specificity, cross-training, and the bilateral deficit. *J Orthop Sports Phys Ther* 25: 264–270, 1997.

34. Wilson, GJ, Newton, RU, Murphy, AJ, and Humphries, BJ. The optimal training load for the development of dynamic athletic performance. *Med Sci Sports Exerc* 25: 1279–1286, 1993.

35. Zhou, S. Chronic neural adaptations to unilateral exercise: Mechanisms of cross education. *Exerc Sport Sci Rev* 28: 177–184, 2000.