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Effects of Bilateral and Unilateral Resistance Training on Horizontally-Orientated Movement Performance: A Systematic Review and Meta-Analysis

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ABSTRACT

Background: Both bilateral (BLE) and unilateral resistance exercise (ULE) methods can confer benefit to an athlete but it remains to be established which has a greater effect on movement speed.

Objectives: To evaluate the effects of BLE and ULE on horizontal movement performance.

Data sources: Google Scholar, CrossRef and PubMed.

Study eligibility criteria: To qualify for inclusion in the meta-analysis, studies must have included a resistance training intervention that compared the effects of BLE and ULE on a measure of movement speed such as sprinting, in healthy study participants.

Study appraisal and synthesis methods: We used the inverse-variance random effects model for meta-analyses. Effect sizes (standardised mean difference), calculated from measures of horizontally-orientated performance, were represented by the standardised mean difference and presented alongside 95% confidence intervals (CI).

Results: Though both modalities were effective (BLE = 0.60 [95% CI: 0.34, 0.87], Z = 4.44 [$p < 0.01$]; ULE = 0.57 [95% CI: 0.24, 0.89], Z = 3.44 [$p = 0.0006$]), there was no difference between the effect of BLE and ULE on movement speed (0.17 [95% CI: -0.15, 0.50], Z = 1.03 [$p = 0.30$]). For BLE, combined strength and plyometric training had the largest effect size (0.88 [95% CI: 0.40, 1.36]]) followed by plyometric training (0.55 [95% CI: 0.09, 1.01]), with the lowest effect in strength training (0.42 [95% CI: -0.02, 0.86]). For ULE, the largest effect size for training type was in plyometric training (0.78 [95% CI: 0.33, 1.24]) closely followed by combined (0.63 [95% CI: 0.03, 1.24]) with strength (0.29 [95% CI: -0.42, 1.01]) having a substantially lower effect size.

Conclusions: Both BLE and ULE are effective in enhancing horizontal movement performance. However, contrary to popular opinion, supported by the concept of training specificity, ULE was no more effective at achieving this than BLE.

Key points:

- Unilateral resistance exercise seems no more effective than bilateral resistance exercise at enhancing horizontal movement performance.
- Coaches should use both bilateral and unilateral resistance exercise to enhance horizontal movement performance.
- Combined strength and plyometric resistance exercise types is preferable though maximal adaptations can be achieved if these modalities are carried out both bilaterally and unilaterally.

1. Introduction

In line with the concept of training specificity, an athlete must be exposed to training stimuli that possess similar physical demands to those that would be encountered during sports performance. Previous literature (1,2) has emphasised this principle with muscle action velocity and movement direction considered to be some of the key variables that must be considered by coaches (3). However, recently, there has been some pointed debate about the importance of another variable that must be addressed by coaches, that being the extent to which bilaterally- (BLE) and unilaterally-executed lower body exercises (ULE) can enhance movement speed (4). The differing views on this issue are outlined in recent articles which emphasise the comparative advantages of BLE and ULE, the former facilitating the use of higher training loads (5) and the latter enabling the exploitation of the 'bilateral deficit' to enhance adaptation (4). Accordingly, both training methods can confer benefit to an athlete but it remains to be established which has a greater effect on movement such as sprinting or changing of direction.

This is a key dilemma for coaches to consider. Many field and court sports impose repeated demands on an athlete's ability to traverse short distances at high speed, commonly in a repeated fashion over the course of an individual game (6–9). Accordingly, the enhancement of an individual's capacity to meet this demand should theoretically translate to improved performance on the field of play. Extending from this, the type of training that a coach chooses to prescribe could have implications for how an athlete develops running speed over short distances. On this, a bilateral deficit is observed when the combined force exerted by two limbs, independently and unilaterally, exceeds that which is generated by both limbs combined and bilaterally (10). Accordingly, during ULE, an individual could produce relatively more force through one leg than they could through two. Given this phenomenon, coaches may prefer ULE over BLE, as the former may facilitate better alignment between the applied training stimuli and the imposed demands of a given sport (4).

Several studies offer support to the above described programming philosophy. Though certain discrepancies arise in relation to reported results, close inspection of individual dependent variables reveal some interesting findings. Makaruk et al. (11) exposed physically-active collegiate females to a 12-week plyometric training programme, with one group undertaking ULE, and the other BLE. For the horizontal bounding outcome measure (five alternate leg bounds), the authors found a favourable result for the group undertaking ULE, surmising that greater activation of the vastus medialis and gastrocnemius was accompanied by increased activity of stabiliser muscles and improved postural control. Similarly, McCurdy et al. (12), having exposed male students to two sessions of either ULE or BLE for a period of eight weeks, reported greater jump height and relative power in the ULE group. The authors suggested that the better results for ULE were related to the specificity of the utilised tests, thus reinforcing the use of such exercises to enhance sporting performance.

The results of the above studies are robust and widely-applied by coaches and sports scientists. However, up to now, no researcher has undertaken a cumulative analysis of study results meaning only isolated findings have tended to inform the approach of coaches to programming BLE and ULE. This has resulted in controversy in relation to what can be considered the more effective training type for enhancing performance. Accordingly, the aim of this systematic review and meta-analysis was to evaluate the effects of BLE and ULE on movement speed such as short sprinting, or change of direction type movements. Our objective was to help to determine the relative effectiveness of these training types to better inform coaches' programming choices with regard to clarifying the specificity of the training stimulus.

2. Methods

This meta-analysis was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement (13).

2.1 Literature search

The Google Scholar, PubMed and CrossRef databases were searched. With no date restrictions, a systematic search was first undertaken. Following this, manual searches were also performed. Only articles published in the English language were considered. These searches were performed in March and April, 2020. The following Boolean search syntax was applied: Plyometric OR jump OR resistance AND training OR exercise AND bilateral OR double leg OR unilateral OR single leg. In selecting studies for inclusion, a review of all relevant article titles was conducted before an examination of article abstracts and, then, full published articles. Only peer-reviewed articles were included in the meta-analysis.

2.2 Data extraction

Data were extracted from gathered articles with a form created in Microsoft Excel. Where required data were not clearly or completely reported, article authors were contacted for clarification. In case authors did not respond to our queries, the respective dataset was not considered for further analysis.

2.3 Inclusion and exclusion criteria

To qualify for inclusion in the meta-analysis, studies must have compared interventions of lower-body resistance training (including plyometrics) executed in a bilateral manner, and resistance training (including plyometrics) executed in a unilateral manner. Accordingly, each study must have included at least two experimental groups, each allocated to a different type of training meaning a control condition was not necessary. Only studies with healthy participants were considered. There was no restriction on population type. We defined resistance training as “a specialised method of physical conditioning that involves the progressive use of a wide range of resistive loads, different movement velocities and a variety of training modalities including weight machines, free weights (barbells and dumbbells), elastic bands, medicine balls and plyometrics” (14). Each study must have included a measure of horizontally-orientated locomotion, such as sprinting over a short distance (0 to 40 m), change of direction type movements or clinical measures such as stair-climbing or horizontally-orientated jumping. Studies which included assistive exercise apparatus, aquatic-based training, nutritional or drug supplementation or techniques such as blood flow restriction or electrostimulation were not considered. In addition, studies were excluded if they did not assess a measure of horizontally-orientated movement performance. The characteristics of the study participants are displayed in Table 1.

Table 1 Characteristics of study participants

2.4 Analysis and interpretation of results

Meta-analytical comparisons were carried out in RevMan version 5.3 (24). Means and standard deviations for a measure of horizontal movement performance, most commonly a short sprint (<15 m), were used to calculate an effect size (standardised mean difference). In the absence of sprint data, we were satisfied to include studies that assessed movement speed by means of other correlated measures, basing this on logically defensible rationale and the specific nature of our research question (25–27). This is an accepted method of study inclusion justification in a meta-analysis (25) and, in this case, we pooled strongly related outcome measures of performance in horizontally-orientated movement, based on the underpinnings of previous research (28–30). Also, the inverse-variance random effects model for meta-analyses was used because it allocates a proportionate weight to trials based on the size of their individual standard errors (31) and facilitates analysis whilst accounting for heterogeneity across studies (32). Effect sizes are presented alongside 95% confidence intervals (CI). The calculated effect sizes were interpreted using the conventions outlined for standardised mean difference by Hopkins et al (33) (<0.2 = trivial; 0.2-0.6 = small, 0.6-1.2 = moderate, 1.2-2.0 = large, 2.0-4.0 = very large, >4.0 = extremely large).

To gauge the degree of heterogeneity amongst the included studies, the I^2 statistic was calculated. This represents the percentage of variation across studies that is due to heterogeneity as opposed to chance (13). Low, moderate and high levels of heterogeneity correspond to I^2 values of 25%, 50% and 75% respectively; however, these thresholds are considered tentative (34). The X^2 (chi square) assesses if any observed differences in results are compatible with chance alone. A low P value, or a large chi-squared statistic relative to its degree of freedom, provides evidence of heterogeneity of intervention effects beyond those attributed to chance (31).

2.5 Sensitivity analysis

A secondary sensitivity analysis (35) was performed for trials that included measures of horizontally-orientated movement that were not considered to be short sprints. For this, we present a main effect analysis with all such studies removed from the analysis and, also, with each singularly included alongside those studies that incorporated a short sprint outcome measure into the study design.

2.6 Assessment of risk of bias

The Physiotherapy Evidence Database (PEDro) scale was used to assess the risk of bias and methodological quality of eligible studies included in the meta-analysis. This scale evaluates internal study validity on a scale from 0 (high risk of bias) to 10 (low risk of bias). A median score of ≥6 represents the threshold for studies with low risk of bias (36).

2.7 Analysis of moderator variables

To assess the potential effects of moderator variables, subgroup analyses were performed based on an *a priori* identification of factors which could affect the main effect. Using a random effects model, we selected potential moderators likely to influence the effects of training. This included the number of weeks in the applied programme, the total number of training sessions in the programme (37), the training status (38) of the study participants, their age, and the type of resistance training undertaken. For number of weeks and total sessions, median split was used to form the subgroups. For training status, we formed ‘more experienced’ and ‘less experienced’ subgroups. The ‘more experienced’ subgroup comprised of those study participants with no less than one year of training experience (39). For age, a simple division was possible with ‘adults’ classified as those older 18 years and ‘youth’ as those younger than 18 years. For resistance training type, the classifications were plyometric training, strength training or combined plyometric and strength training.

3. Results

3.1. Study selection

In total, eleven studies met the inclusion criteria and were included in the meta-analysis. The PRISMA flow diagram, illustrating the number of studies excluded at each stage of the systematic review and meta-analysis, is shown in Figure 1. Together, the studies achieved the required standard to be considered to be at a low risk of bias (median quality score = 6.0). These data are presented in Table 2.

Figure 1 Flow chart for inclusion and exclusion of studies

Table 2 Results of PEDro scale to inform risk of bias in meta-analysed studies

3.2 Primary analyses

Displayed in Figure 2, the primary analysis compared BLE to ULE. There was no difference between the effect of BLE and ULE on movement speed (0.17 [95% CI: -0.15, 0.50], Z = 1.03 [p = 0.30]). Between-study heterogeneity was moderate and significant (I^2 = 44% [p = 0.05]).

Figure 2 Forest plot of comparison of bilateral vs. unilateral training on movement speed

3.3 Sensitivity analysis

Table 3 details the sensitivity analyses for those studies (11,12,21,22) which included outcome measures of horizontally-orientated movement, that were not short sprints. The withdrawal from the analysis of all of these studies had no impact on the main effect with the primary effect size remaining trivial for all analyses. Similarly, the singular addition of studies to the main analysis resulted in no deviations from the originally observed trivial effect size seen in the primary meta-analysis as all effect sizes remained trivial.

Table 3 Sensitivity analyses for studies which included outcomes of non-sprint horizontal locomotion

3.4 Within-group effects of intervention

We also explored the within-group intervention effects of BLE and ULE conditions. In this analysis, the independent baseline to follow-up effects of BLE and ULE on movement speed were calculated (Figure 3). Both BLE ((BLE = 0.60 [95% CI: 0.34, 0.87], Z = 4.44 [p < 0.01] and ULE (0.57 [95% CI: 0.24, 0.89], Z = 3.44 [p = 0.0006]) demonstrated statistically significant increases in performance, with a slightly larger effect for BLE. Heterogeneity was low to moderate (0% to 32%).

Figure 3 Within-group forest plot of the effect of bilateral training on movement speed

Figure 4 Within-group forest plot of the effect of unilateral training on movement speed

3.5 Effect of moderator variables

The results of the moderator analysis are displayed in Tables 3 (BLE) and 4 (ULE). Differences between subgroups were not significant and had low to moderate heterogeneity for both BLE and ULE moderators. For BLE, the effect size for programme duration (number of weeks) was larger for programmes longer than six weeks (0.78 [95% CI: 0.35, 1.21] vs. 0.49 [95% CI: 0.15, 0.83]) and with more than twelve training sessions (0.78 [95% CI: 0.35, 1.21] vs. 0.49 [95% CI: 0.15, 0.83]). The effect size was also larger in ‘more experienced’ than in ‘less experienced’ study participants (0.68 [95% CI: 0.34, 1.01] vs. 0.47 [95% CI: -0.04, 0.97]), though it was of a similar magnitude for those older (0.57 [95% CI: 0.22, 0.92]) and younger (0.64 [95% CI: 0.24, 1.04]) than 18 years. Also for BLE, combined strength and plyometric training had the largest effect size (0.88 [95% CI: 0.40, 1.36]) followed by plyometric training (0.55 [95% CI: 0.09, 1.01], with the lowest effect in strength training (0.42 [95% CI: -0.02, 0.86]).

For ULE, the effect size for programme duration (number of weeks) was larger for programmes longer than six weeks (0.70 [95% CI: 0.27, 1.13] vs. 0.51 [95% CI: 0.04, 0.97]) and with more than twelve training sessions (0.70 [95% CI: 0.27, 1.13] vs. 0.51 [95% CI: 0.04, 0.97]). The effect size was larger in 'more experienced' than in 'less experienced' study participants (0.65 [95% CI: 0.32, 0.99] vs. 0.39 [95% CI: -0.41, 1.20]). Youth participants (<18 years) displayed a larger effect (0.76 [95% CI: 0.36, 1.16]) than adults (0.39 [95% CI: -0.15, 0.92]). Also for ULE, the largest effect size for training type was in plyometric training (0.78 [95% CI: 0.33, 1.24]) closely followed by combined (0.63 [95% CI: 0.03, 1.24]) with strength (0.29 [95% CI: -0.42, 1.01]) having a substantially lower effect size.

Table 4 Influence of moderator variables on the effect of bilateral training on horizontal movement performance

Table 5 Influence of moderator variables on effect of unilateral training on horizontal movement performance

4. Discussion

4.1 Primary findings

Both the between-group and within-group findings of this systematic review and meta-analysis show that BLE and ULE are similarly effective in enhancing horizontally-orientated movement performance such as sprinting. This is an important result for coaches as previous debate about the relative merits of each modality as a means of performance enhancement has driven disagreement between two distinct schools of thought (40,41). The bilateral deficit is a phenomenon that occurs when the combined force exerted by two limbs, independently and unilaterally, exceeds that which can be generated by both limbs combined and bilaterally (10). This has been observed across a variety of movement patterns and populations (10) and the apparently greater specificity afforded by ULE seems to have encouraged some coaches' to favour it over BLE (4,40,41). Though this approach has ostensible advantages, it is neither supported by extant evidence (40), nor the findings of the current meta-analysis with bilateral facilitation a potential confounding factor (42).

Despite the findings that no differences exist in the performance-enhancing quality of BLE and ULE, each training type could well confer independent benefits to the athlete, with these benefits deriving from their respective unique kinetic and kinematic characteristics. Outlining the advantages of each, Appleby et al. (5) indicate the greater loads that can be used when undertaking bilateral squatting exercise whilst acknowledging the enhanced antagonist recruitment and cocontraction of involved musculature for unilateral squatting. This is important for coaches to consider given that balance and maximal strength are apparently unrelated in both males and females (43), a finding which suggests that they represent independent physical abilities that must be separately addressed with appropriate training methods, such as BLE and ULE. In relation to this, the relative benefits of either one of these types of training represents the relative weaknesses of the other with ULE requiring the use of lower loads to ensure sound execution and BLE lacking an appreciable stability challenge. Though free weight BLE might lack this challenge (44,45), it does still provide enough instability to augment core and limb muscle activation, whilst still enabling maximal force output (46). On the other hand, the programming of ULE enables a coach to leverage the apparent benefits of the bilateral deficit (4) with relatively larger impulses and longer muscle action times generated due to this phenomenon (47). Moreover, ULE has previously been shown to result in greater electromyographic activity in the vastus medialis and gastrocnemius muscles during countermovement jumps (48), though this may be exercise-specific as higher quadriceps activation was also previously reported in bilateral knee extensions (49). Unilateral resistance exercise can also induce higher trunk (core) and stabiliser muscle activation (50) and this can be of particular benefit to those trainees whose movement patterns have yet to fully develop.

Based on the above, the apparent ULE advantages of greater training specificity, trunk and stabiliser muscle activation and the exploitation of the bilateral deficit, have contributed to ULE proponents' assertion that that form of training is superior in enhancing sports-specific performance (4,40,41). Furthermore, the unilateral nature of sprinting could be sensibly argued to be more suited to the biomechanical characteristics of ULE, with sprinting being ostensibly less similar to BLE, at least from a kinematic perspective (22). Still more, because of the aforementioned lower loads used during ULE, particularly those exerted through the spine, they could be a preferable mode of exercise for athletes with back pain or those engaged in rehabilitation programmes (51), as lower loads are conducive to reduced shear and compressive forces on the spine (52). Indeed, combined axial and torsional compressive forces, applied whilst in a ventrally-flexed position, can result in a substantial reduction in vertebral stability, potentially leading to a greater risk for spinal disk herniation (53). Accordingly, a prescribed combination of BLE for strength development and ULE for technique refinement represents a prudent approach to programming. Coaches should nonetheless be aware that as unilateral strength increases, the greater fatigability associated with using progressively higher loads on a narrow base of support, as in ULE, could result in changes to technique such as increased trunk flexion and rotation, increased pelvic tilt and greater hip flexion and adduction range (51,54,55). Accordingly, ULE should be prescribed cautiously and performed with technical proficiency.

When making programming decisions, coaches must consider the training history of the individual with whom they are working. The bilateral deficit is more apparent in less experienced trainees than it is in those with an appreciable training history (40). This would seem to imply that once an individual has reached their upper threshold of adaptation to exercise, when no further improvements are likely, the relative amount of force that can be produced by one leg is similar to that which can be produced by two. The exploitation of the bilateral deficit is one of the primary attractors for coaches to choose ULE over BLE and whilst this may be a prudent approach in the inexperienced athlete, it may not be as advantageous in advanced athletes who may benefit more from the greater loads that can be used for BLE. Wahl et al. (56) reported that, in individuals with an average of eight year's resistance training experience, unstable conditions did not stimulate enhanced soleus, biceps femoris, rectus femoris, lower abdominal, or lumbosacral erector spinae activity. These authors concluded that more experienced individuals may already possess enhanced stabilisation capability from the use of dynamic free weights and, thus, the prescription of less stable ULE, at the expense of more stable BLE, may not be necessary. To this end, coaches should place an increased emphasis on using BLE in advanced athletes whose technique is already well-developed and whose potential to leverage the bilateral deficit is diminished through having accumulated a larger body of training experience over time.

When programming plyometric ULE, coaches must also exercise caution with inexperienced athletes, potentially showing favouritism towards the use of BLE to preserve stable performance. Unilateral jump landings are characterised by less knee flexion than bilateral and a greater degree of knee valgus at ground contact (57). The latter occurs as a compensatory pattern to maintain the resting length of the quadriceps muscles which can more readily decelerate the landing body and minimise impact forces. Less flexion keeps the knee in a near-extended position which, whilst beneficial for maintaining balance, can predispose an individual to injury of the anterior cruciate ligament (57). Moreover, an extended knee landing position can result in larger ground reaction forces absorbed by the joint, resulting in bone to bone contact and damage to meniscus (58). If novice athletes lack the neuromuscular control to coordinate these compensations, bilateral plyometrics could serve as a more suitable training option in the earlier stages of an individual's training life. This is also a factor to consider when programming for female athletes who can land with even greater knee valgus and ground reaction forces than their male counterparts (57).

Another important issue relates to the amount of muscle damage that could be caused by ULE and BLE. Though studies on hormonal responses to BLE and ULE are scarce, Migiano et al. (59) examined the effects of upper body BLE and ULE on acute post-exercise growth hormone levels. The researchers reported significantly larger increases in the group which undertook BLE and this was accompanied by increased plasma lactate concentrations. This could represent a potentially synergistic response to BLE with the greater metabolic demands of exercise associated with larger secretions of growth hormone (59). For programmes that are aimed at specifically increasing muscle hypertrophy, this evidence seems to favour BLE, though not all of the limited evidence corroborates this point (60).

4.2 Moderating variables

Moderator analysis was undertaken for both BLE and ULE. Aside from highlighting potentially important moderators of the main effects seen in this meta-analysis, the evaluation of these moderators could also have implications for the prescription of both BLE and ULE in athletic populations. Unsurprisingly, the moderator analysis supported the use of longer programme (>6 weeks) and more training sessions per programme (>12) for the enhancement of movement speed for both BLE and ULE. This reinforces the widely accepted principle that longer resistance and plyometric programmes result in larger adaptations to training (37,61,62). Accordingly, regardless of whether BLE or ULE is used to increase variables such as sprinting speed, coaches should aim to maintain a constant stimulus of this type within athletes' programmes of physical preparation for sport.

Another notable result from the moderator analysis, for BLE, was the finding that a combination of strength and plyometric training was more effective than either of those two modalities carried out in isolation. Several studies (63–65) have demonstrated similar results with combined training stimuli seemingly providing a more comprehensive adaptation than singular methods. The inclusion of varying training stressors may be especially valuable in youth athletes. A study involving younger participants demonstrated that the combination of Olympic style lifts with plyometric training was more effective than resistance training alone (66), whilst the integration of balance either before (67), or in conjunction with, plyometric training (68) was more effective than plyometric training alone. In this way, training that facilitates access to multiple independent pathways of adaptation is probably most effective with, for example, increases in muscle size through strength training and enhanced elastic energy utilisation through plyometric training both contributing to increased running speed (69). Contrary to this finding, for ULE, plyometric training was the most effective training type, though only marginally so with combined strength and plyometric training showing a slightly smaller effect size. This result does seem to counteract conventional recommendations for multidimensional training programmes but could be due to the specificity of the training stimulus relative to the type of motor skill being tested. The shorter ground contact times of unilateral plyometric training are more specific to the locomotive demands of sprinting, than to resistance training which is usually performed with the foot in constant contact with the ground. In this way, the addition of load can increase the ground contact time of an exercise, thus making it less specific to the objective of increasing movement speed (70). Indeed, over the 15 m distance, ground contact time is approximately 200 ms in both relatively faster and relatively slower athletes, indicating that this characteristic must be incorporated into specific training practices regardless of athletic ability. In the case of our ULE moderator analysis, it seems that the devotion of a greater proportion of training time (i.e. plyometric [100%] vs. strength [50%] and plyometric [50%]) to the most sprint-specific type of training observed in this meta-analysis resulted in enhanced gains. That singular strength training was, by some way, the least effective modality in both subgroup analyses seems to lend further weight to this argument, thus coaches must align training stimuli to the particular demands of the movements being trained for. Coaches are encouraged to include both ULE and BLE, for both strength and plyometric modalities, in the physical preparation programmes of athletes.

4.3 Future research

Just two studies in this meta-analysis included female participants meaning the applicability of the results to that population are somewhat limited. This is reflective of recent observations that female participants have been underrepresented in sports science research and this has given rise to the suboptimal trend of extrapolating findings in males to female populations (71). This is not a trivial issue in sports that require a high investment in resistance training to improve performance with sex-related differences affecting the pattern of aspects such as delayed onset muscle soreness (71). Moreover, females' biomechanical characteristics are different to those of males with the former's jump landings exhibiting increased knee valgus and higher vertical ground reaction forces (57). These considerations must be appreciated by researchers whose study results can help coaches to construct more precise programmes of physical preparation for female athletes. Further to this, additional research in experienced athletes is warranted due to the possibility that the bilateral deficit often observed between bilateral and unilateral movements may, indeed, be influenced by training experience with a phenomenon of bilateral facilitation apparent in more experienced trainees (42).

4.4 Limitations

There are some limitations to the current study so our results should be interpreted with at leat some caution. For subgroup analyses, the dichotomisation of continuous data with median split could result in residual confounding and reduced statistical power (72,73). Furthermore, moderator analyses were calculated independently, and not interdependently. Such univariate analysis must be interpreted with caution because the programming parameters were calculated as single factors, irrespective of between-parameter interactions.

5. Conclusion

Based on the overall findings of this systematic review and meta-analyses, both BLE and ULE are effective in enhancing movement speed. However, contrary to popular belief, supported by the concept of training specificity, ULE was no more effective at achieving this than BLE. This is an interesting result for coaches as it accommodates differing preferences in the manner in which training programmes are formulated for athletes. For example, if an athlete struggles with maintaining their stability during exercise execution, the use of a BLE-only protocol could be justified. Similarly, whereas BLE allows the coach to impose a larger absolute load on the athlete, ULE could be more suitable for those who are suffering from injuries, such as those to the low back, necessitating programme modifications. For healthy advanced athletes it seems prudent to use heavily-loaded BLE for strength development as it appears that the magnitude of the bilateral deficit decreases over time. Despite this, the variable influence of moderators, such as the additive benefit of combination training, must be considered and coaches should therefore remain cognisant that a multidimensional resistance training programme, which includes both BLE and ULE, is likely to be preferable to the utilisation of singular modalities.

Compliance with Ethical Standards

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Conflicts of Interest

Jason Moran, Rodrigo Ramirez-Campillo, Bernard Liew, Helmi Chaabene, David Behm, Antonio García-Hermoso, Mikel Izquierdo and Urs Granacher declare that they have no conflicts of interest relevant to the content of this review.

Authorship Contributions

JM collected the data, analysed the data and wrote the manuscript, RRC collected the data and wrote the manuscript, BL analysed the data and wrote the manuscript, HC analysed the data and wrote the manuscript, DB wrote the manuscript, AGH analysed the data and wrote the manuscript, MI wrote the manuscript, UG analysed the data and wrote the manuscript.

Data sharing statement

There are no underlying data.

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Table 1.

Study	Group	Sex	Age (yrs; mean ± SD)	Height (cm; mean ± SD)	Weight (kg; mean ± SD)	Study duration (weeks)	Mean frequency (per week)	Total sessions	Training experience	Training type	Exercises	Sets	Repetitions	Test used
Fisher and Wallin (15)	Bilateral training	Male	20.14 (1.77)	180 (6)	85.7 (7.06)	6	2	12	>2 years	Bilateral strength and plyometric exercises	Back squat, forward jumps, lateral jump, hexagon jump, max speed jumps, box jumps	1-3	6-10, 30s	10 m sprint
	Unilateral training	Male	19.8 (1.49)	182 (8.0)	82.6 (6.52)	6	2	12	>2 years	Unilateral strength and plyometric exercises	Single leg squat, forward hop, lateral hop, hexagon hop, max speed hops	1-3	6-10, 30s	10 m sprint
Gonzalo-Skok (16)	Bilateral training	Male	16.9 (2.1)	189.7 (6.9)	77.6 (9.3)	6	2	12	2-5 years	Bilateral strength and plyometric exercises	Eccentric strength, balance and coordination exercises, bilateral 90 deg. squat, bilateral 0.25m drop jump, bilateral countermovement jump,	2-3	5, >90% max power	15 m sprint
	Unilateral training	Male	16.9 (2.1)	189.7 (6.9)	77.6 (9.3)	6	2	12	2-5 years	Unilateral strength and plyometric exercises	Eccentric strength, balance and coordination exercises, unilateral 90 deg. squat, unilateral 0.25m drop jump, unilateral countermovement jump,	2-3	5, >90% max power	15 m sprint
Gonzalo-Skok (17)	Bilateral training	Male	20.5 (2.0)	180.1 (6.3)	73.2 (9.3)	8	2	16	1-3 years	Bilateral strength exercises	Parallel squats	6	6-10	10 m sprint
	Unilateral training	Male	20.5 (2.0)	180.1 (6.3)	73.2 (9.3)	8	2	16	1-3 years	Unilateral strength and cutting exercises	Backward lunges, defensive-like shuffling steps, side-step, crossover cutting, lateral crossover cutting, and lateral squat	1	6-10	10 m sprint
Gonzalo-Skok (18)	Bilateral training	Male	13.3 (0.6)	172.8 (7.9)	59.1 (12.8)	6	2	12	Trained	Bilateral plyometric exercises	20 cm drop jump, squat jump with arms swing, countermovement jump with arms swing, tuck jump, hurdle jumps	2-5	2.5	10 m sprint
	Unilateral training	Male	13.2 (0.5)	171.7 (7.2)	59.6 (11.7)	6	2	12	Trained	Unilateral plyometric exercises	10 cm drop jump, standing long jump, standing long jump without	2-5	2-5	10 m sprint

											countermovement, unilateral jumps, triple jumps			
Makaruk et al. (11)	Bilateral training	Female	20.9 (1.7)	166 (5)	57.3 (4.2)	11	2	22	Physically active but inexperienced	Bilateral plyometric exercises	Multiple jumps, hops and bounds in horizontal, vertical and multidirectional patterns	2-12	4-15	Five alternate leg bounds (m)
	Unilateral training	Female	20.6 (1.3)	167 (4.0)	59.2 (4.9)	11	2	22	Physically active but inexperienced	Unilateral plyometric exercises	Multiple jumps, hops and bounds in horizontal, vertical and multidirectional patterns	2-12	4-15	Five alternate leg bounds (m)
McCurdy et al. (12) (Men) [a]	Bilateral training	Male	20.74 (2.6)		78.3 (21.47)	8	2	16	Inexperienced	Bilateral supported strength and plyometric exercises	Bilateral squats, front squats	3-6	5-15	Stair climb
	Unilateral training	Male	20.74 (2.6)		78.3 (21.47)	8	2	16	Inexperienced	Unilateral supported strength and plyometric exercises	Unilateral squats, lunges, step-ups	3-6	5-15	Stair climb
McCurdy et al. (12) (Women)[a]	Bilateral training	Female	20.74 (2.6)		78.3 (21.47)	8	2	16	Inexperienced	Bilateral supported strength and plyometric exercises	Bilateral squats, front squats, countermovement jumps, pogo jumps	3-6	5-15	Stair climb
	Unilateral training	Female	20.74 (2.6)		78.3 (21.47)	8	2	16	Inexperienced	Unilateral supported strength and plyometric exercises	Unilateral squats, lunges, step-ups, countermovement jumps, pogo jumps	3-6	5-15	Stair climb
Nunez et al. (19)	Bilateral training	Male	22.6 (2.7)	164.2 (7)	79.5 (12.8)	6	2	12	Physically active but inexperienced	Bilateral flywheel squat resistance training	Flywheel squats	4	7	10 m sprint
	Unilateral training	Male	22.8 (2.9)	177.3 (3.7)	75.3 (8.8)	6	2	12	Physically active but inexperienced	Unilateral flywheel lunge resistance training	Flywheel lunges	4	7	10 m sprint
Ramirez-Campillo et al. (20)	Bilateral training	Male	11 (2.0)	146 (13.7)	43.5 (14.9)	6	2	12	Inexperienced	Bilateral plyometric exercises	Countermovement jumps	6	5-10	15 m sprint
	Unilateral training	Male	11.6 (1.7)	147 (11.1)	45 (9.3)	6	2	12	Inexperienced	Unilateral plyometric exercises	Countermovement jumps	2-3	5-10	15 m sprint

Ramirez-Campillo et al. (21)	Bilateral training	Male	17.6 (0.5)	174.9 (5.3)	68.3 (3.6)	8	2	16	>2 years	Bilateral strength and plyometric exercises	Bilateral knee extensions, knee flexions, 20-cm horizontal drop jumps, horizontal jumps	1-3	3-10	T-Test
	Unilateral training	Male	17.3 (1.1)	177.1 (5.9)	64.9 (5.5)	8	2	16	>2 years	Unilateral strength and plyometric exercises	Unilateral knee extensions, knee flexions, 20-cm horizontal drop jumps, horizontal jumps	1-3	3-10	T-Test
Speirs et al. (22)	Bilateral training	Male	18.1 (0.5)	185 (8.9)	98.1 (13.4)	5	2	10	1.62 years	Bilateral strength training	Bilateral back squat	4	3-6	Pro agility
	Unilateral training	Male	18.1 (0.5)	96.7 (9.3)	183 (3.4)	5	2	10	1.65 years	Unilateral strength training	Rear-foot elevated split squat	4	3-6	Pro agility
Stern et al. (23)	Bilateral training	Male	17.6 (1.2)	179.6 (7.27)	77.3 (7.91)	6	2	12	>2 years	Bilateral strength and plyometric exercises	Back squat, drop jump, countermovement jump, broad jump	4	3-6	10 m sprint
	Unilateral training	Male	17.6 (1.2)	179.6 (7.27)	77.3 (7.91)	6	2	12	>2 years	Unilateral strength and plyometric exercises	Rear-foot elevated split squat, Single-leg drop jump, Single-leg countermovement jump, Single-leg broad jump	4	3-6	10 m sprint

Table 2.

Study	1[a]	2	3	4	5	6	7	8	9	10	11	Total
Fisher and Wallin (15)	1	1	0	1	0	0	0	1	1	1	1	6
Gonzalo-Skok (16)	0	1	0	1	0	0	0	1	1	1	1	6
Gonzalo-Skok (17)	1	1	0	1	0	0	0	1	1	1	1	6
Gonzalo-Skok (18)	0	1	0	1	0	0	0	1	1	1	1	6
Makaruk et al. (11)	1	1	0	1	0	0	0	1	1	1	1	6
McCurdy et al. (12)	0	1	0	0	0	0	0	1	1	1	1	5
Nunez et al. (19)	0	0	0	1	0	0	0	1	1	1	1	5
Ramirez-Campillo et al. (20)	1	1	0	1	0	0	0	1	1	1	1	6
Ramirez-Campillo et al. (21)	1	1	0	0	0	0	0	1	1	1	1	5
Speirs et al. (22)	1	1	0	0	0	0	0	1	1	1	1	5
Stern et al. (23)	1	1	0	1	0	0	0	1	1	1	1	6

[a] Item #1 is not used to calculate final rating

Table 3.

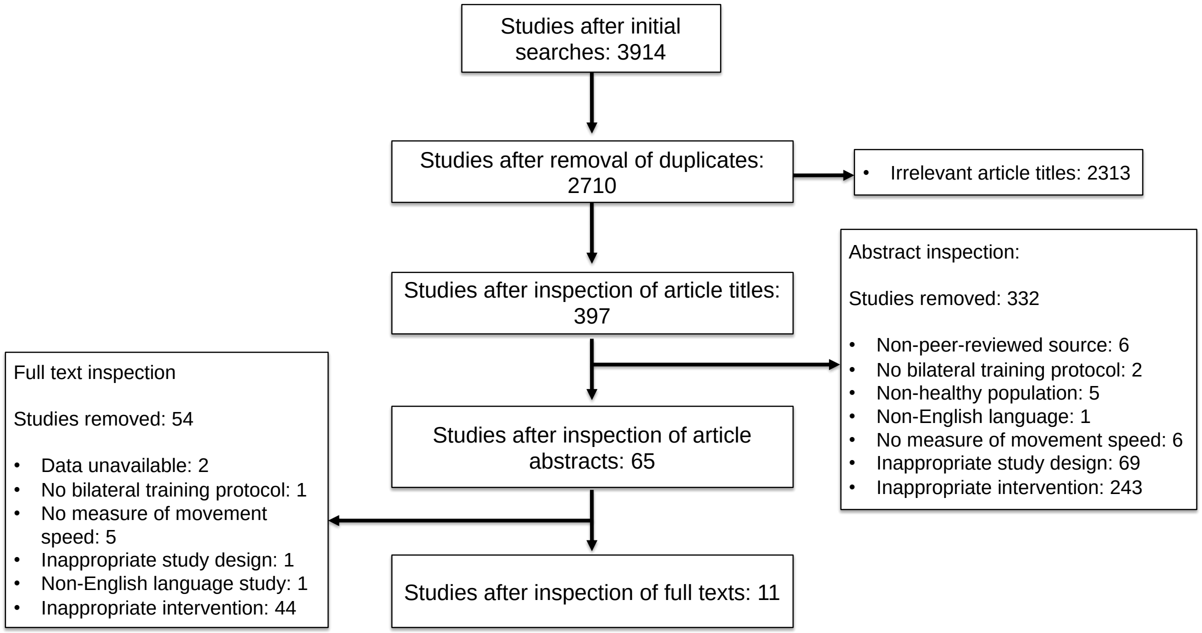
Study groups	Effect size [95% CI]
All studies (primary main effect)	0.17 [-0.15, 0.50]
Studies which included a sprint outcome measure	0.06 [-0.25, 0.36]
Sprint studies and Makaruk et al. (11)	0.14 [-0.14, 0.42]
Sprint studies and McCurdy et al. (12) (Men)	0.19 [-0.15, 0.53]
Sprint studies and McCurdy et al. (12) (Women)	0.04 [-0.25, 0.33]
Sprint studies and Ramirez-Campillo et al. (21)	-0.05 [-0.36, 0.27]
Sprint studies and Speirs et al. (22)	0.13 [-0.16, 0.43]

Table 4.

Outcome or Subgroup	Studies	Effect Estimate (standardised mean difference [95% CI])
Number of weeks	10	0.60 [0.34, 0.87]
>6	3	0.78 [0.35, 1.21]
≤6	7	0.49 [0.15, 0.83]
Total sessions	10	0.60 [0.34, 0.87]
>12	3	0.78 [0.35, 1.21]
≤12	7	0.49 [0.15, 0.83]
Training status	10	0.60 [0.34, 0.87]
More experienced	7	0.68 [0.34, 1.01]
Less experienced	3	0.47 [-0.04, 0.97]
Age	10	0.60 [0.34, 0.87]
Adult (>18 years)	5	0.57 [0.22, 0.92]
Youth (<18 years)	5	0.64 [0.24, 1.04]
Resistance training type	10	0.60 [0.34, 0.87]
Plyometric	3	0.55 [0.09, 1.01]
Strength	3	0.42 [-0.02, 0.86]
Plyometric and strength	4	0.88 [0.40, 1.36]

Table 5.

Outcome or Subgroup	Studies	Effect Estimate (standardised mean difference [95% CI])
Number of weeks	10	0.57 [0.24, 0.89]
>6	3	0.70 [0.27, 1.13]
≤6	7	0.51 [0.04, 0.97]
Total sessions	10	0.57 [0.24, 0.89]
>12	3	0.70 [0.27, 1.13]
≤12	7	0.51 [0.04, 0.97]
Training status	10	0.57 [0.24, 0.89]
More experienced	7	0.65 [0.32, 0.99]
Less experienced	3	0.39 [-0.41, 1.20]
Age	10	0.57 [0.24, 0.89]
Adult (>18 years)	5	0.39 [-0.15, 0.92]
Youth (<18 years)	5	0.76 [0.36, 1.16]
Resistance training type	10	0.57 [0.24, 0.89]
Plyometric	3	0.78 [0.33, 1.24]
Strength	3	0.29 [-0.42, 1.01]
Plyometric and strength	4	0.63 [0.03, 1.24]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Abstract inspection:
Studies removed: 332
• Non-peer-reviewed source: 6
• No bilateral training protocol: 2
• Non-healthy population: 5
• Non-English language: 1
• No measure of movement speed: 6
• Inappropriate study design: 69
• Inappropriate intervention: 243
Studies after inspection of article abstracts: 65
Full text inspection
Studies removed: 54
• Data unavailable: 2
• No bilateral training protocol: 1
• No measure of movement speed: 5
• Inappropriate study design: 1
• Non-English language study: 1
• Inappropriate intervention: 44
Studies after inspection of full texts: 11

Figure 1.

Study or Subgroup	Bilateral Mean	Bilateral SD	Bilateral Total	Unilateral Mean	Unilateral SD	Unilateral Total	Weight	Std. Mean Difference IV, Random, 95% CI
Fisher and Wallin (15)	2.05	0.09	7	2.05	0.15	8	6.8%	0.00 [-1.01, 1.01]
Gonzalo-Skok (16)	2.46	0.07	9	2.48	0.1	9	7.6%	-0.22 [-1.15, 0.71]
Gonzalo-Skok (17)	1.77	0.07	19	1.76	0.08	19	11.2%	0.13 [-0.51, 0.77]
Gonzalo-Skok (18)	1.9	0.1	9	1.86	0.06	9	7.5%	0.46 [-0.48, 1.40]
Makaruk et al. (11)	-10.76	0.34	18	-10.96	0.39	16	10.5%	0.54 [-0.15, 1.22]
McCurdy et al. (12) (Men)	-121.8	4.7	12	-127.9	4.6	11	7.8%	1.26 [0.35, 2.17]
McCurdy et al. (12) (Women)	-132	6.5	8	-131.1	5.1	8	7.1%	-0.15 [-1.13, 0.84]
Nunez et al. (19)	1.85	0.09	13	1.85	0.08	14	9.6%	0.00 [-0.75, 0.75]
Ramirez-Campillo et al. (20)	3.17	0.23	12	3.31	0.42	16	9.6%	-0.39 [-1.14, 0.37]
Ramirez-Campillo et al. (21)	5.46	0.2	9	5.67	0.16	9	6.8%	-1.10 [-2.11, -0.09]
Speirs et al. (22)	4.64	0.14	9	4.53	0.07	9	7.0%	0.95 [-0.04, 1.93]
Stern et al. (23)	1.64	0.06	12	1.61	0.06	11	8.6%	0.48 [-0.35, 1.31]
Total (95% CI)			**137**			**139**	**100.0%**	**0.17 [-0.15, 0.50]**

Heterogeneity: $Tau^2 = 0.14$; $Chi^2 = 19.49$, df = 11 (P = 0.05); $I^2 = 44\%$

Test for overall effect: Z = 1.03 (P = 0.30)

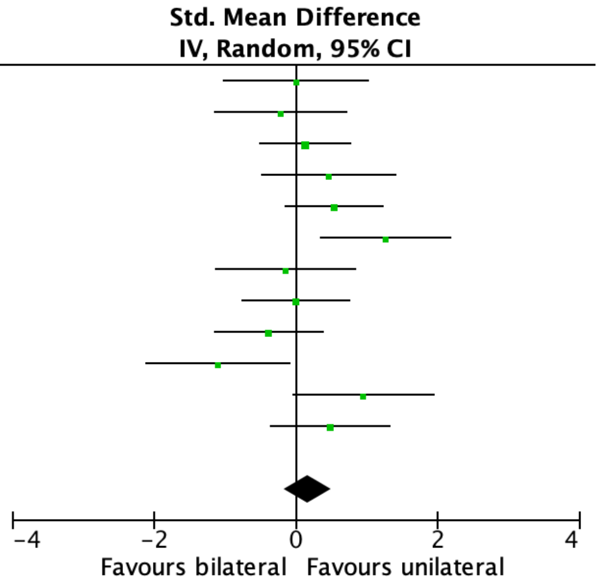

Figure 2.

Study or Subgroup	Baseline Mean	Baseline SD	Baseline Total	Follow-up Mean	Follow-up SD	Follow-up Total	Weight	Std. Mean Difference IV, Random, 95% CI
Fisher and Wallin (15)	2.12	0.07	7	2.05	0.09	7	5.7%	0.81 [−0.29, 1.92]
Gonzalo-Skok (16)	2.52	0.09	9	2.46	0.07	9	7.6%	0.71 [−0.25, 1.67]
Gonzalo-Skok (17)	1.82	0.07	19	1.77	0.07	19	16.3%	0.70 [0.04, 1.36]
Gonzalo-Skok (18)	1.91	0.1	9	1.9	0.1	9	8.2%	0.10 [−0.83, 1.02]
Makaruk et al. (11)	−10.42	0.43	18	−10.76	0.34	18	14.9%	0.86 [0.17, 1.54]
Nunez et al. (19)	1.85	0.07	13	1.85	0.09	13	11.9%	0.00 [−0.77, 0.77]
Ramirez-Campillo et al. (20)	3.3	0.3	12	3.17	0.23	12	10.6%	0.47 [−0.34, 1.28]
Ramirez-Campillo et al. (21)	5.67	0.29	9	5.46	0.2	9	7.5%	0.80 [−0.17, 1.77]
Speirs et al. (22)	4.71	0.15	9	4.64	0.14	9	8.0%	0.46 [−0.48, 1.40]
Stern et al. (23)	1.71	0.06	12	1.64	0.06	12	9.2%	1.13 [0.25, 2.00]
Total (95% CI)			**117**			**117**	**100.0%**	**0.60 [0.34, 0.87]**

Heterogeneity: $Tau^2 = 0.00$; $Chi^2 = 6.06$, df = 9 (P = 0.73); $I^2 = 0\%$
Test for overall effect: Z = 4.44 (P < 0.00001)

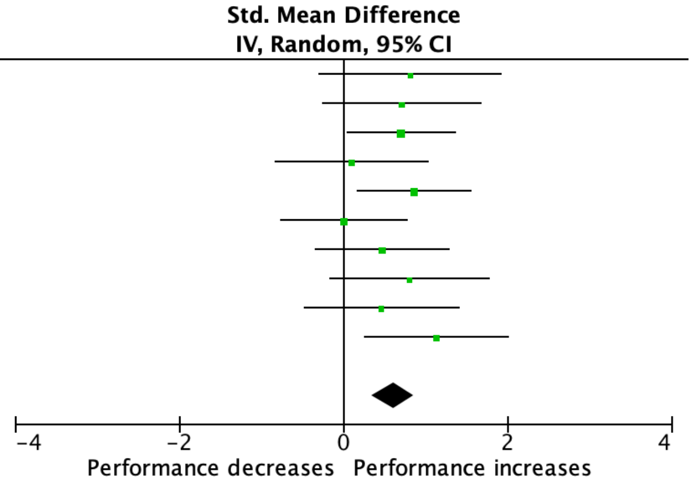

Figure 3.

Study or Subgroup	Baseline Mean	Baseline SD	Baseline Total	Follow-up Mean	Follow-up SD	Follow-up Total	Weight	Std. Mean Difference IV, Random, 95% CI
Fisher and Wallin (15)	2.04	0.07	8	2.05	0.15	8	8.1%	-0.08 [-1.06, 0.90]
Gonzalo-Skok (16)	2.54	0.08	9	2.48	0.1	9	8.4%	0.63 [-0.32, 1.58]
Gonzalo-Skok (17)	1.81	0.1	19	1.76	0.08	19	13.9%	0.54 [-0.11, 1.19]
Gonzalo-Skok (18)	1.92	0.08	9	1.86	0.06	9	8.2%	0.81 [-0.16, 1.78]
Makaruk et al. (11)	-10.55	0.4	16	-10.96	0.39	16	11.9%	1.01 [0.27, 1.75]
Nunez et al. (19)	1.79	0.19	14	1.85	0.08	14	11.7%	-0.40 [-1.15, 0.35]
Ramirez-Campillo et al. (20)	3.5	0.2	16	3.31	0.42	16	12.6%	0.56 [-0.15, 1.27]
Ramirez-Campillo et al. (21)	5.8	0.29	9	5.67	0.16	9	8.6%	0.53 [-0.42, 1.47]
Speirs et al. (22)	4.61	0.11	9	4.53	0.07	9	8.2%	0.83 [-0.15, 1.80]
Stern et al. (23)	1.7	0.06	11	1.61	0.06	11	8.4%	1.44 [0.48, 2.40]
Total (95% CI)			**120**			**120**	**100.0%**	**0.57 [0.24, 0.89]**

Heterogeneity: $Tau^2 = 0.08$; $Chi^2 = 13.19$, df = 9 (P = 0.15); $I^2 = 32\%$
Test for overall effect: Z = 3.44 (P = 0.0006)

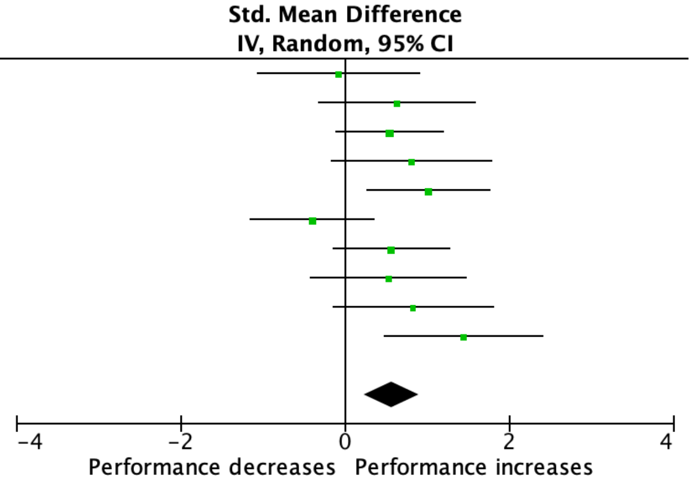

Figure 4.