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SYSTEMATIC REVIEW

Effects and Dose–Response Relationships of Motor Imagery Practice on Strength Development in Healthy Adult Populations: a Systematic Review and Meta-analysis

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Abstract

Background Motor imagery (MI), a mental simulation of a movement without overt muscle contraction, has been largely used to improve general motor tasks. However, the effects of MI practice on maximal voluntary strength (MVS) remain equivocal.

Objectives The aims of this meta-analysis were to (1) estimate whether MI practice intervention can meaningfully improve MVS in healthy adults; (2) compare the effects of MI practice on MVS with its combination with physical practice (MI-C), and with physical practice (PP) training alone; and (3) investigate the dose–response relationships of MI practice.

Data Sources and Study Eligibility Seven electronic databases were searched up to April 2017. Initially 717 studies were identified; however, after evaluation of the study characteristics, data from 13 articles involving 370 participants were extracted. The meta-analysis was completed on MVS as the primary parameter. In addition, parameters associated with training volume, training intensity, and time spent training were used to investigate dose–response relationships.

Results MI practice moderately improved MVS. When compared to conventional PP, effects were of small benefit in favour of PP. MI-C when compared to PP showed unclear effects. MI practice produced moderate effects in both upper and lower extremities on MVS. The cortical representation area of the involved muscles did not modify the effects. Meta-regression analysis revealed that (a) a training period of 4 weeks, (b) a frequency of three times per week, (c) two to three sets per single session, (d) 25 repetitions per single set, and (e) single session duration of 15 min were associated with enhanced improvements in muscle strength following MI practice. Similar dose–response relationships were observed following MI and PP.

Conclusions The present meta-analysis demonstrates that compared to a no-exercise control group of healthy adults, MI practice increases MVS, but less than PP. These findings suggest that MI practice could be considered as a substitute or additional training tool to preserve muscle function when athletes are not exposed to maximal training intensities.

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Key Points

Motor imagery practice is an effective method for maximal strength development in healthy adults, while there is no convincing evidence that the combination of motor imagery and physical practice is more effective than conventional strength training alone.

The following motor imagery variables were associated with enhanced strength: a training period of 4 weeks, a training frequency of three sessions per week, a training volume of two to three sets, 25 repetitions per set, and single session duration of 15 minutes.

Cortical representation of the involved muscle has minor modulating power, suggesting that both large and small cortically represented muscles can almost equally benefit from motor imagery practice.

1 Introduction

To improve motor performance in athletes, sport psychologists are using several techniques designed to increase physical and mental activation without execution of overt movement [1, 2]. These "psyching-up" techniques have been proven as beneficial tools for strength improvement among athletes [3] and non-athletes [1, 2, 4, 5]. Currently, motor imagery (MI) represents one of the most widely used cognitive strategies designed to enhance physical performance for both sports-based [6] and therapeutic interventions [7, 8]. For example, it contributes to rehabilitation of Parkinson's disease patients [8–10] and following immobilization [11], stroke [7, 12, 13], and orthopaedic surgeries [14–16]. Imagery is the process which refers to all those quasi-sensory or quasi-perceptual experiences of which we are self-consciously aware, and which exist even in the absence of the stimulus conditions known to produce their genuine sensory and perceptual counterparts [17]. Imagery has different modalities, like the visual (with internal or external perspectives), kinesthetic (based on somatosensory information normally generated during actual movement), auditory, olfactory, gustatory, and tactile senses [6, 18]. MI practitioners may use these modalities independently or combine them in order to enhance performance and/or achieve different types of outcomes [19–22]. However, this review will only focus on MI, which we defined as explicit mental simulation of a specific action without any corresponding motor output (e.g. overt motor execution) [23], hence, requiring a representation of the body as the generator of acting forces, regardless of the modality used.

The efficiency of MI practice relies on the fact that MI and motor execution share common neural substrates [23, 24], supporting the theory of functional equivalence [23, 25, 26]. Accordingly, functional equivalence relies on three factors: (1) that executed and imagined tasks are the same in duration [27]; (2) both processes follow Fitts' law, that more difficult movements take more time to produce physically than do easier ones [28]; and (3) subjective rating of the mental effort during the mentally simulated task correlates with the amount of force which is needed for the task execution [29].

Accordingly, an early review published in 1983 dealing with the effects of MI practice included 60 studies and yielded 146 effect sizes (ESs) in total. The authors concluded that MI could enhance performance for motor, strength, cognitive, self-paced, and reactive tasks (ES = 0.48) [30]. However, the effects of MI practice on strength tasks were trivial (ES = 0.20) [30]. More promising results were reported in a recent literature review [1] in which the effects of various cognitive strategies (i.e. imagery, goal setting, self-talk, preparatory arousal, and free choice) on strength performance were investigated. The authors concluded that imagery is reliably associated with increased strength performance (results ranged from 63 to 74%) [1], which agree with the results of Scholefield and colleagues [31]. However, although the authors reported positive alterations after MI practice, none of the six included studies reported a minimal clinically important difference in strength gains [31]. Another recent review [32], which aimed to investigate the effects of MI on muscular strength in healthy and patient populations, concluded that MI in combination with physical practice (PP) is more efficient than PP training only on strength. Further, Slimani and colleagues [32] reported the advantageous effects for muscular strength development of internal imagery (range 2.6–136.3%) compared to external imagery (range 4.8–23.2%). Nonetheless, a recent meta-analysis [33], based on only four studies that yielded six ESs, reported that MI practice alone does not enhance strength gains in healthy adults [ES = − 0.10; 95% confidence interval (CI) − 1.46 to 1.24; $p < 0.001$]. However, Manochio and colleagues' [33] meta-analysis needs to be replicated, given the variability across the small number of the studies included, because it is possible the meta-analysis was underpowered [34]. Also, a number of relevant studies were not included, but have been included in this review. One recent review aimed to identify the specific characteristics of successful MI training sessions (MITS) within five disciplines: education, medicine, music, psychology, and sports [35]. On average, the study intervention lasted 34 days, with participants practising MI a mean three times per week for 17 min, with 34 MI trials. The average total MI time was 178 min, including 13 MITS. However, the authors reported that only seven of the total 141 interventions involved strength-focussed activities [35]. In addition, strength-focused MI interventions were investigated in healthy participants aged between 20 to 39 years only.

Several methodological issues limit all the aforementioned reviews. For example, the majority of the reviews in this area included studies that evaluated the effects of various interventions on general motor tasks [1, 30, 36], or included small numbers of studies [31, 33]. Also, since the first review on this topic [30], a number of experimental studies investigating MI effectiveness have been published, but despite these new additions, many questions still remain unclear and unanswered. For example, data are scarce on the magnitude of the effects following MI practice and/or MI combined with PP training (MI-C), compared with PP only. Nonetheless, although it is known that the imagery perspective used [32, 37] and the participant skill level [38, 39] might moderate the effects, less thoroughly analysed are the dose–response relationships of quantitative training variables (i.e. training volume, duration, frequency, and numbers of sets and repetitions) [30, 35, 36], and especially qualitative ones (i.e. trained muscle and type and intensity of contraction).

Based on the functional equivalence theory [40], we hypothesized that both MI practice and PP training effectiveness will be modified by common variables used in conventional strength training (CST) (i.e. training volume, type and intensity of the contraction, time spent in training, and trained muscles) [41–43]. Therefore, the current meta-analysis aims to provide an evidence-based synthesis of the currently published research and addresses the following questions: (1) In healthy adult populations, does MI practice enhance strength performance compared to no-exercise controls? (2) Is MI or MI-C practice superior to PP training? (3) How is the MI-performance relationship modified by training volume, training type, intensity of the contraction, time spent in training, and muscles trained? Accordingly, the answers to these questions will enable evidence-based optimization of MI practice and consequently lead to proper programme prescription designed to achieve the best results.

2 Methods

2.1 Search Strategy

This systematic review and meta-analysis was undertaken in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement guidelines [44]. Thus, a systematic search of the research literature published in peer-reviewed journals was conducted for randomized controlled trials (RCTs) studying the effects of MI practice on strength performance in populations of healthy adults. To carry out this review, English and German language literature searches of the PubMed, ERIC, DOAJ, Web of Science, SPORTDiscus, Google Scholar, and ScienceDirect databases were conducted from January 2016 up to April 2017. Electronic databases were searched using the following keywords: “motor imagery training”, “movement imagery”, “mental practice”, “mental simulation”, “cognitive training”, “strength”, “force”, “performance”, “effects”, “improvement”, and “healthy adults”. The reference lists of each included article were also scanned to identify additional relevant studies.

2.2 Inclusion and Exclusion Criteria

In accordance with the PICOS (patient population/problem, intervention, comparison, outcome, study design) approach [45], inclusion criteria were selected in the following manner. (1) *Population*: studies recruiting as participants male and female healthy adults in any age category. (2) *Intervention*: MI practice interventions were required to be a minimum of 1 week in duration (more than three training sessions) and include at least one control group and/or another experimental PP group. For preliminary analysis, the control groups included were those without any treatment. (3) *Comparison*: maximal voluntary strength (MVS) was compared across (a) the intervention type (i.e. MI practice vs no-exercise controls, PP vs no-exercise controls, PP vs MI practice, and MI-C vs PP alone), (b) the body regions trained (upper vs lower limbs), (c) the type of contraction (isometric vs dynamic), (d) the muscle groups trained [larger vs smaller cortical representation area (CRA)], (e) the degree of control of muscle activity during MI sessions (controlled or not controlled), and (f) the presence or absence of encouragement during MVS testing. (4) *Outcome*: MVS. (5) *Study design*: RCTs published in peer-reviewed journals.

Studies were excluded according to the following criteria: (1) studies written in languages other than English and German; (2) non-randomized, uncontrolled studies; (3) studies that sampled unhealthy populations; (4) studies where data about dose–response relationship variables were not reported; and (5) studies from which we could not extract enough information to calculate ESs or include them in the analysis.

2.3 Screening Strategy

Two independent reviewers (AP and UM) performed the literature search, along with study identification, screening, quality assessment, and data extraction. First, the titles were initially screened by the reviewers, during the electronic searches, to assess the papers' suitability, and all papers beyond the scope of this meta-analysis were excluded. Second, the abstracts were assessed using predetermined inclusion and exclusion criteria. Third, the full texts of the remaining papers that met the inclusion criteria were retrieved and included in the ongoing procedure and reviewed by the two reviewers to reach a final decision on inclusion in the meta-analysis. Finally, the reference lists from the retrieved manuscripts were also examined for any other potentially eligible papers. Any disagreements between the reviewers were resolved by consensus or arbitration through a third reviewer (RP). If the full text of any paper was not available, the corresponding author was contacted by mail or ResearchGate. The study selection process as described above is illustrated in Fig. 1.

2.4 Data Extraction

The Cochrane Consumers and Communication Review Group's data extraction protocol was used to extract the participant information, including sex, age, sample size, and training status; description of the intervention; study design; and study outcomes [46]. This extraction was undertaken by one author (AP), while a second author (UM) checked the extracted data for accuracy and completeness. Disagreements were resolved by consensus or by a third reviewer (RP). Reviewers were not blinded to authors, institutions, or manuscript journals. In those studies where the data were shown in figures or graphs, either the corresponding author was contacted to get the numerical data to enable analysis or the Web Plot Digitizer software (version 3.10; Ankit Rohatgi; Austin, TX, USA) was used to extract the necessary data.

2.5 Quality Assessment

The Physiotherapy Evidence Database (PEDro) scale was used to assess the methodological quality of the included studies [47]. The quality assessment score was interpreted

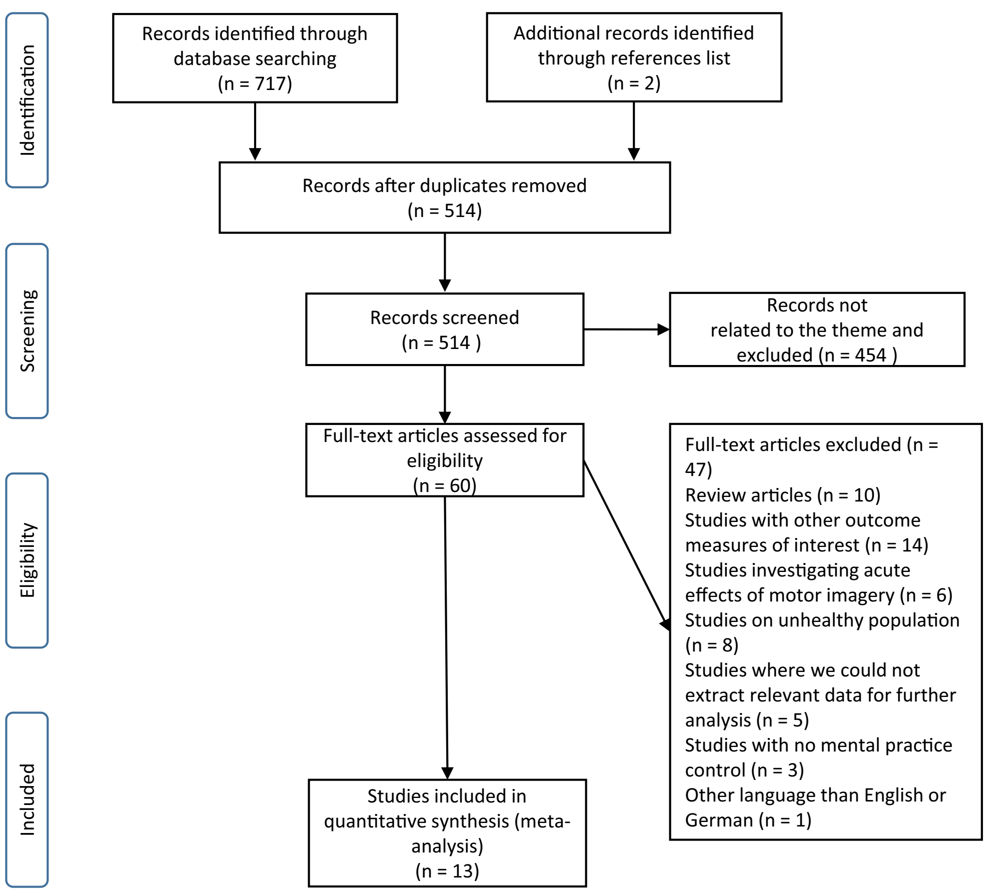

Fig. 1 Flow diagram of the study selection process

using the following 10-point scale: ≤ 3 points was considered as poor quality, 4–5 points as moderate quality, and 6–10 points as high quality. The PEDro scale consists of 11 items designed for rating the methodological quality. Each satisfied item contributes 1 point to the overall PEDro score (range 0–10 points). Item 1 was not included as part of the study quality rating for this review, because it pertains to external validity, which was beyond the scope of the current review questions. The quality assessment was conducted by one author (AP).

2.6 Statistical Analyses

The meta-analyses were performed using Comprehensive Meta-analysis software (version 3.0; Biostat Inc., Englewood, NJ, USA). The mean differences and 95% CIs were calculated for the included studies. The I^2 measure was used to examine between-study variability; values of 25, 50, and 75% represent low, moderate, and high statistical heterogeneity, respectively [48]. Although the heterogeneity of the effects in the present meta-analysis ranged from 0 to 48% (see Sect. 3), it was decided to apply a random-effects model of the meta-analysis in all comparisons, to determine the pooled effect of MI practice on measures of MVS. To test the robustness of these analyses, a fixed-effects model for major comparisons was calculated and reported. The ESs were calculated using the following formula (Eq. 1):

$$\mathrm{ES} = \frac{\text{Raw Mean Change}_1 - \text{Raw Mean Change}_2}{\mathrm{SD}_{\text{post-pooled}}}. \quad (1)$$

Standard deviation $(\mathrm{SD})_{\text{post-pooled}}$ was calculated using the following formula (Eq. 2):

$$\mathrm{SD}_{\text{post-pooled}} = \sqrt{\frac{(N_1 - 1) \times \mathrm{SD}_1^2 + (N_2 - 1) \times \mathrm{SD}_2^2}{N_1 + N_2 - 2}}. \quad (2)$$

If two or more studies reported the same training variable (e.g. training volume, intensity, time spent in training), random-effects meta-analysis was performed over the studies and presented as filled squares in the dose–response relationship figures of the Sect. 3. Each unfilled symbol illustrates the ES per single study, while circles and triangles represent the isometric [i.e. maximal voluntary isometric contraction (MViC)] and the dynamic (submaximal intensity) types of contraction used in the training settings.

Furthermore, a random-effects meta-regression was performed to examine whether the effects of MI on MVS were moderated by different training variables. Training variables were grouped according to the following: training volume (i.e. period, frequency, number of sets per exercise, number of repetitions per set, number of repetitions per single session, and number of repetitions per study); training intensity [i.e. maximal or submaximal, and duration of imagined contraction, in other words time under tension (TUT)]; and time spent in training (total training duration per study, total training duration per week, and duration of single training session). If exercise progression was realized over the course of the intervention or if training variables were reported, the average of these variables was calculated. For sub-group analysis, only protocols with the same value for the variable of interest were selected and averaged.

To improve the generalizability and the external validity of the present findings, we combined the results from all the included studies that examined muscle strength based on 1 repetition maximum (RM) dynamic contractions and/or MViC tests. In addition to the meta-regression, dose–response relationships were calculated independently using the ESs of characteristics of each training variable.

The chance of the true effect being trivial, beneficial, or harmful was interpreted using the following scale, according to a previous approach developed by Hopkins [49]: 25–75% (possibly), 75–95% (likely), 95–99.5% (very likely), and 99.5% (most likely). The publication bias was assessed by examining the asymmetry of the funnel plots using Egger's test, and a significant publication bias was considered if the p value was < 0.10. The magnitude of the MI practice effects on strength performance were interpreted as changes using the following criteria: trivial (< 0.20), small (0.21–0.60), moderate (0.61–1.20), large (1.21–2.00), very large (2.01–4.00), and extremely large (> 4.00) [49].

3 Results

The Egger's test was performed to provide statistical evidence of funnel plot asymmetry (Fig. 2), and the results indicated publication bias for all analyses ($p < 0.10$).

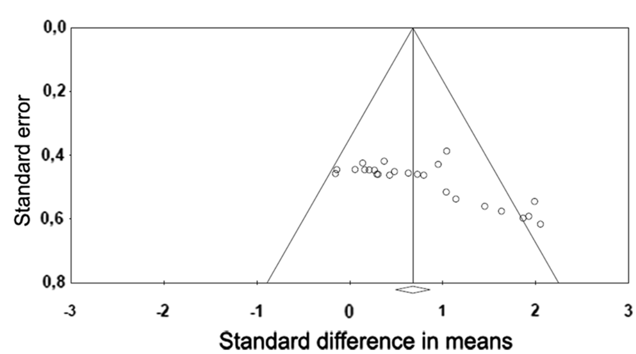

Fig. 2 Funnel plot of the standard differences in means vs standard errors. The aggregated standard difference in means is the random effects mean effect size weighted by the degrees of freedom

3.1 Study Selection

A total of 717 articles were identified by the literature search (Fig. 1). Following the removal of duplicates and the elimination of articles based on title and abstract screening, 60 studies remained. An evaluation of the remaining 60 studies was conducted independently by two researchers. Following the final screening process, 13 studies were included in the systematic review and meta-analysis.

3.2 Study Characteristics

After the computerized literature search, 13 eligible articles were found (Table 1). Table 1 presents details of each included study regarding sample, measures, results, and additional comments. The pooled sample size of the 13 studies yielded 370 participants, where the typical sample size of the individual studies ranged from eight to 15 subjects per group (mean = ten subjects). All of the selected studies except one [50] included a non-exercise, non-imagery control group. Nine studies included an additional PP group, involving maximum isometric contractions [51–55], submaximal isometric contractions [56], moderate- to high-intensity dynamic contractions [57, 58], or low-intensity (as fast as possible) dynamic contractions [59]. Three further studies included a combination of MI and PP practice [50, 56, 58], thus enabling its comparison with PP only. Regarding the MI practice itself, almost all the included studies investigated the effects of traditional MI practice, while one [58] additionally studied the effects of another modified type of MI practice, called the Physical, Environment, Task, Timing, Learning, Emotion and Perspective (PETTLEP) intervention, that relies on the functional equivalence approach to imagery. The PETTLEP intervention was designed according to the important dimensions involved in imagery [60].

The 13 eligible studies varied in sense of duration, trained muscle, training frequency, volume, intensity (Table 2), and other methodological items (e.g. control for muscle activity during MI sessions, method of outcome measurement assessment, and the researchers' approach regarding the MVS protocol itself). The most common duration of intervention was 4 weeks and was applied in eight studies [50–54, 59, 61, 62], while the remaining five studies were 1 [63], 2 [57], 3 [55], 6 [58], and 12 [56] weeks in durations. Additionally, the 13 eligible studies varied regarding the trained muscle group; more specifically, extensor muscles of the knee joint [50, 59, 63], dorsal [54] and plantar flexors of ankle joint [62], flexors of the hip joint [57], pectoral and arm extensor muscles (e.g. bench press exercise) [50, 53], flexors of the elbow joint [56, 58, 61], hand flexors [55], and abductors of the little finger of the hand [51, 52]. The most common training frequencies were three to five sessions per week (mean ± SD 4.08 ± 1.24). The number of sets per one training session ranged from one to four (mean ± SD 2.42 ± 1.00), while the repetitions per set ranged from two to 25 (mean ± SD 13.64 ± 7.89). The overall training volume, presented as total number of repetitions per individual study (total repetitions per set × number of sets × training session per study) [64], ranged from 120 to 3000 (mean ± SD 646.36 ± 839.77). However, four studies [55, 56, 61, 62] had considerably higher volumes than others, with 450 [55], 1000 [61, 62], and 3000 [56]. In nine studies, the intensity of the MI practice in regard to the imagined movement was set to 100% of maximal voluntary contraction (MVC) [51–56, 61–63], since the tasks were to imagine an MViC. In the remaining studies [50, 57, 58], the intensity was submaximal and varied from 70 to 95%. In these submaximal studies, participants imagined dynamic contractions. Finally, in one study, the participants imagined maximal explosive isometric contractions [59]. Across all studies, MVS was measured by either the 1RM test [50, 57, 58] or the MViC strength test.

Previously, it was shown that the MVS protocol assessment could influence the MVS results moderating participants' motivation levels [65]. To control the measurement of MVS, several criteria were previously proposed [65], including visual or verbal feedback, standardized verbal encouragement, rewards with repeated testing, and elimination of subject-perceived submaximal efforts. All of these aim to promote true maximal voluntary efforts. At best, only two of the recommended criteria were fulfilled [59, 61], or at least one was [51, 55], while nine studies did not report any effort to control motivation [50, 52–54, 56–58, 62, 63]. Moreover, of all the initially included studies, seven controlled the muscle activity during the MI sessions: three studies used electromyography (EMG) [51, 52, 63]; one used dynamometry in combination with visual inspection [54]; and three studies used visual control only [53, 59, 61]. The remaining six studies did not report any control of muscle activity [50, 55–58, 62].

3.3 Participants' Characteristics

The pooled sample size of the 13 studies was 370, with a mean age of 28.5 years (age range 18–83 years), where two studies examined the effects of MI practice on a population of older adults (mean age of 72.9 years) [55, 56]. One study included females only [63], four studies included males [55, 57, 61, 62], and four studies used both males and females [53, 54, 56, 59], while four studies did not report a gender [50–52, 58]. Thus, none of the included studies reported sex-specific effects. Regarding the training status of the participants, it can be noticed that all studies

Table 1 Systematic overview of the included studies in the meta-analysis with their characteristics and relevant outcomes

Study	Population			Trained movement; measurement equipment/trained muscle	Outcome measures	Results	Additional comments
	Sex; age (years) [mean ± SD]	Training status	Sample size				
Cornwall et al. [63]	F; 21–25	Untrained	MI (n = 12) CON (n = 12)	Knee extension; isokinetic dynamometer	MVC; isometric	MI: 12.6% ↑* CON: 0.89% ↓	No MI ability assessment No specific instructions concerning how to practice EMG was used to monitor MI practice
Yue and Cole [51]	ND; 21–29	Untrained	MI (n = 10) PP (n = 8) CON (n = 9)	Abduction of little finger of the hand	MVC; isometric	MI: 22.03% ↑** PP: 29.75% ↑** CON: 3.7% ↑	No MI ability assessment Imagery modality is not defined 80% of training session monitored by EMG Left hand
Smith et al. [52]	ND; 29.33 ± 8.72	Untrained	MI (n = 8) PP (n = 8) CON (n = 8)	Right hand (fifth digit); isometric dynamometer	MVC: isometric	MI: 23.2% ↑* PP: 53.3% ↑** CON: 5.3% ↓	MI ability assessed by MIQ-R Kinesthetic MI approach was used EMG was used to monitor MI practice
Reiser [53]	M and F; 23.9 ± 1.8	Untrained	MI (n = 11) PP (n = 12) CON (n = 11)	Pectoral and arm extensor muscles; isometric bench press	MVC; isometric	MI: 5% ↑** PP: 13.9% ↑** CON: 1.7% ↑	MI ability was assessed by MIQ Internal MI was used in MI group Muscle activation was visually monitored
Sidaway and Trzaska [54]	M and F; 19–26	Untrained	MI (n = 10) PP (n = 10) CON (n = 10)	Ankle dorsiflexion; isokinetic dynamometer	MVC; isometric	MI: 17.13% ↑* PP: 23.28% ↑* CON: 1.77% ↓	No MI ability assessment Kinesthetic MI approach was used Muscle activation was monitored by dynamometer and visually
Shackell and Standing [57]	M; 18–24	Trained	MI (n = 10) PP (n = 10) CON (n = 10)	Hip flexors; hip flexor machine—dynamic movement	MVC; dynamic	MI: 23.7% ↑** PP: 28.2% ↑** CON: 3.5% ↑	No MI ability assessment Kinesthetic MI approach was used No control of muscle activity during MI practice
Wright and Smith [58]	ND; 20.74 ± 3.71	Untrained	MIp (n = 10) MI (n = 10) PP (n = 10) MI-C (n = 10) CON (n = 10)	Upper limb, not defined which, or maybe both were trained; bicep curl machine	MVC; dynamic	MIp: 23.2% ↑* MI: 13.7% ↑ PP: 26.5% ↑* MI-C: 28% ↑* CON: 5.1% ↑	MI ability assessed by MIQ-R Kinesthetic MI approach was used in MI group, while MIp used PETTLEP model The CON completed a placebo task (reading some literature related to body building)

Table 1 continued

Study	Population			Trained movement; measurement equipment/trained muscle	Outcome measures	Results	Additional comments
	Sex; age (years) [mean ± SD]	Training status	Sample size				
Lebon et al. [50]	ND; 19.75 ± 1.72	Untrained	MI-C ($n = 9$) PP ($n = 10$)	Bench press; leg press	MVC; dynamic	MI-C: BP 9% ↑**; LP 26.2% ↑** PP: BP 12.2% ↓**; LP 21.2% ↑**	MI ability assessed by MIQ-R Kinaesthetic MI approach from internal perspective was used
Bahari et al. [61]	M; 22.5 ± 1.36	Untrained	MI ($n = 8$) CON ($n = 8$)	Right hand; elbow flexion; isometric dynamometer	MVC; isometric	MI: 30% ↑* CON: 5.5% ↑	MI ability was assessed by MIQ Internal MI approach was used Muscle activity was visually monitored during MI practice
de Ruiter et al. [59]	M and F; 18–24	Untrained	MI ($n = 10$) PP ($n = 9$) CON ($n = 10$)	Leg extensors; isometric torque	MVC; isometric	MI: 9.3% ↑* PP: 6.6% ↑* CON: 5.4% ↓	MI ability was assessed by SIAM; internal perspective was used MI sessions were guided by script reading EMG was used to monitor MI practice
Darvishi et al. [55]	M; 70.93	Untrained	MI ($n = 10$) PP ($n = 10$) CON ($n = 10$)	Hand flexors; isometric dynamometer	MVC; isometric	MI: 11.2% ↑* PP: 25% ↑** CON: 2.82% ↑	MI ability was assessed by VVIQ and VMIQ No specific instructions concerning how to practice
Niazi et al. [62]	M; 22.4 ± 1.25	Untrained	MI ($n = 15$) CON ($n = 15$)	Plantar flexors; isometric dynamometer	MVC; isometric	MI: 13.4% ↑* CON: 0.5% ↓	MI ability was not assessed Internal MI perspective was used
Jiang et al. [56]	M and F; 75 ± 7.9	NR	MET ($n = 10$) PP ($n = 10$) CON ($n = 7$)	Elbow flexion; isometric dynamometer	MVC; isometric	MET: 13.83% ↑** PP: 17.58% ↑** CON: 3.28% ↓	MI ability was not assessed Internal MI perspective was used

BP bench press, *CON* controls, *EMG* electromyography, *F* females, *LP* leg press exercise, *M* males, *MI* motor imagery, *MIp* motor imagery based on PETTLEP method, *MI-C* MI combined with physical practice, *MVC* maximal voluntary contraction, *MIQ* Motor Imagery Questionnaire, *MIQ-R* Motor Imagery Questionnaire-Revised, *ND* not defined, *NR* not reported, *PETTLEP* Physical, Environment, Task, Timing, Emotion, Perspective, *PP* physical practice, *SD* standard deviation, *SIAM* Sport Imagery Ability Measure, *VMIQ* Vividness of Movement Imagery Questionnaire, *VVIQ* Vividness of Visual Imagery Questionnaire

↑ indicates increase, ↑* indicates significant increase ($p < 0.05$), ↑** indicates significant increase ($p < 0.01$), ↓ indicates decrease

involved untrained individuals, except one study, which included active individuals from various sports, both individual and team sports [57]. The participants had not previously been engaged before in any kind of structured MI or cognitive practice interventions.

3.4 Methodological Quality

Overall, the included studies were of high quality, with PEDro scores of 6.00 (Table 3). All the checked studies failed to satisfy the following items: allocation was

Table 2 Training variables

Study	Study duration (weeks)	Weekly frequency	Duration of 1 TS (min)	NSTS	NRS	Type of contraction	TNRS	TTST (min)	CRA (L/S)	ES
Cornwall et al. [63]	1	4	20	3	NR	Isometric	NR	80	S	0.96
Yue and Cole [51]	4	5	7	1	15	Isometric	300	140	L	0.44
Smith et al. [52]	4	2	12	2	10	Isometric	160	96	L	1.15
Reiser [53]	4	5	8	4	8	Isometric	160	190	S	0.15
Sidaway and Trzaska [54]	4	3	15	3	10	Isometric	360	180	S	2.06
Shackell and Standing [57]	2	5	15	4	10	Dynamic	320	150	S	0.64
Wright and Smith [58]	6	2	10	2	25	Dynamic	240	120	S	0.14[a]
Bahari et al. [61]	4	5	15	2	10	Isometric	1000	300	S	1.46
de Ruiter et al. [59]	4	3	15	1	10	Dynamic	120	180	S	0.33
Darvishi et al. [55]	3	5	20	3	25	Isometric	450	300	L	0.8
Niazi et al. [62]	4	5	15	2	2	Isometric	1000	240	S	1.05
Jiang et al. [56]	12	5	15	2	25	Isometric	3000	900	S	1.93

CRA cortical representation area of the muscle, *ES* effect size, *L* large, *NRS* number of repetitions per set, *NSTS* number of sets per training session, *S* small, *TNRS* total number of repetitions per study, *TS* training session, *TTST* total time spent in training

[a]Averaged effects of two ESs from same study

concealed, blinding for all subjects, and blinding of therapist and/or assessors. Also, all of the included studies received points for the following items: randomized allocation to groups, baseline indicators, measures of at least one key outcome was obtained from more than 85% of the subjects, all subjects received the treatment or control condition, and statistical comparison between groups and point measures.

3.5 Overall Findings

3.5.1 *Effects of Motor Imagery (MI) Practice on Maximal Voluntary Strength*

Eleven studies reported a favourable effect of MI on the upper and lower extremity muscles (Fig. 3a). Compared to no-exercise controls, the effect of MI was most likely moderately beneficial for MVS (ES = 0.72; 95% CI 0.42–1.02). An almost identical effect was observed when a fixed-effect model was used (ES = 0.71; 95% CI 0.45–0.97). The statistical heterogeneity of the effects was small ($I^2 = 21.34\%$). For the upper and lower extremities, we determined a likely moderate beneficial effect (ES = 0.54; 95% CI 0.16–0.91; $I^2 = 11.95\%$), and a likely moderate beneficial effect (ES = 0.95; 95% CI 0.51–1.39; $I^2 = 16.45\%$), respectively. With respect to the type of contraction, a moderate ES was seen after applying isometric contraction (ES = 0.92, 95% CI 0.55–1.30, most likely moderately beneficial), compared to a small ES in dynamic (ES = 0.35; 95% CI −0.10 to 0.79, likely beneficial). A moderate ES was observed when muscles with larger CRA were trained (ES = 0.76; 95% CI 0.21–1.31, very likely beneficial), and those with smaller areas (ES = 0.69; 95% CI 0.39–0.99, very likely beneficial). When the muscle activity during MI sessions was controlled, the effect was likely moderately beneficial (ES = 0.87; 95% CI 0.41–1.32; $I^2 = 36.79\%$), compared to a small, very likely beneficial effect of non-controlled conditions (ES = 0.58; 95% CI 0.2–0.97; $I^2 = 0.00\%$). In addition, for both encouragement (ES = 0.74; 95% CI 0.26–1.20; $I^2 = 0.00\%$) and non-encouragement (ES = 0.72; 95% CI 0.31–1.13; $I^2 = 39.52\%$), the conditional results were similar, that is the effect was found to be very likely moderate. Moreover, MI effects were also observed in contralateral (i.e. non-trained limb), as well as in non-trained movements during strength tasks. Following MI practice, one study observed contralateral effects of up to a 10.45% strength increase on average ($p < 0.005$) [51], while in the PP group an increase of 14.43% was observed ($p < 0.02$), without a significant difference between the groups [51]. Furthermore, positive alterations ($p < 0.05$) were also observed for the non-trained strength task (i.e. the increase in fifth-digit flexion force after abduction was imagined [51], or when the knee flexion strength after extension was imagined [59]).

Eight studies examined the effects of both PP and MI practice models on the measure of muscle strength (Fig. 3b). The observed I^2 value of 0% ($Q = 7.21$, $df = 8$, $p = 0.51$) is indicative of non-existent heterogeneity, which was not further sub-analysed. The pooled effect for

Table 3 Quality assessment of the included studies

Study	Criterion 1	Criterion 2	Criterion 3	Criterion 4	Criterion 5	Criterion 6	Criterion 7	Criterion 8	Criterion 9	Criterion 10	Criterion 11	Total
Cornwall et al. [63]	/	1	0	1	0	0	0	1	1	1	1	6
Yue and Cole [51]	/	1	0	1	0	0	0	1	1	1	1	6
Smith et al. [52]	/	1	0	1	0	0	0	1	1	1	1	6
Reiser [53]	/	1	0	1	0	0	0	1	1	1	1	6
Sidaway and Trzaska [54]	/	1	0	1	0	0	0	1	1	1	1	6
Shackell and Standing [57]	/	1	0	1	0	0	0	1	1	1	1	6
Wright and Smith [58]	/	1	0	1	0	0	0	1	1	1	1	6
Lebon et al. [50]	/	1	0	1	0	0	0	1	1	1	1	6
Bahari et al. [61]	/	1	0	1	0	0	0	1	1	1	1	6
de Ruiter et al. [59]	/	1	0	1	0	0	0	1	1	1	1	6
Darvishi et al. [55]	/	1	0	1	0	0	0	1	1	1	1	6
Niazi et al. [62]	/	1	0	1	0	0	0	1	1	1	1	6
Jiang et al. [56]	/	1	0	1	0	0	0	1	1	1	1	6

Criterion 1 eligibility criteria were specified, *Criterion 2* subjects were randomly allocated to groups, *Criterion 3* allocation was concealed, *Criterion 4* the groups were similar at baseline regarding the most important prognostic indicators, *Criterion 5* there was blinding of all subjects, *Criterion 6* there was blinding of all therapists who administered the therapy, *Criterion 7* there was blinding of all assessors who measured at least one key outcome, *Criterion 8* measures of at least one key outcome were obtained from more than 85% of the subjects initially allocated to groups, *Criterion 9* all subjects for whom outcome measures were available received the treatment or control condition as allocated, *Criterion 10* the results of between-group statistical comparisons are reported for at least one key outcome, *Criterion 11* the study provides both point measures and measures of variability for at least one key outcome

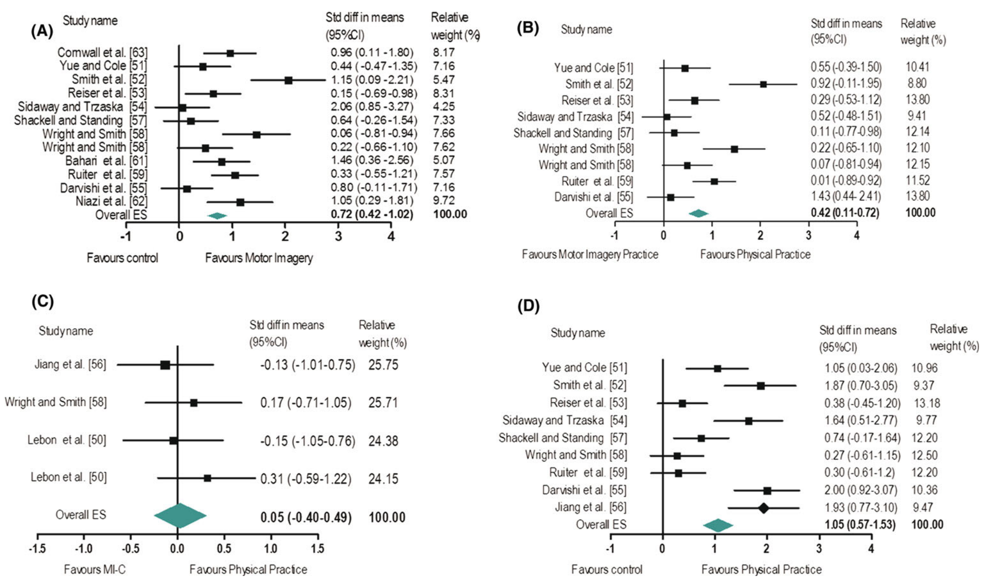

Fig. 3 Effects on maximal muscle strength: **a** motor imagery (MI) practice vs no-exercise control; **b** MI vs physical practice (PP); **c** MI combined with PP (MI-C) vs PP only; and **d** PP vs no-exercise control. *CI* confidence interval, *ES* effect size, *Std diff* standardized difference

eight studies showed a likely small beneficial effect (ES = 0.42; 95% CI 0.11–0.72) on MVS, favouring PP. An identical effect was observed when the fixed-effect model was applied (ES = 0.42; 95% CI 0.11–0.72).

Three studies examined the effects of both MI-C and PP models separately on the measures of muscle strength. An I^2 value of 0% ($Q = 0.74$, $df = 3$, $p = 0.83$) is indicative of non-existent heterogeneity, which was not further subanalysed (Fig. 3c). The pooled effect across the three ESs was trivial and clinically unclear (ES = 0.05; 95% CI −0.40–0.49), slightly, but not significantly favouring MI-C. An identical effect was observed when the fixed-effect model was applied (ES = 0.05; 95% CI −0.40–0.49).

3.5.2 Effects of Physical Practice on Maximal Voluntary Strength

All nine studies that included an analysis of PP on upper and lower extremity muscles reported favourable effects. The current analysis, as displayed in Fig. 3d, shows that the pooled effect of PP, when compared with controls, was most likely moderately beneficial on MVS (ES = 1.05; 95% CI 0.57–1.53). A somewhat lower effect was observed when the fixed-effect model was applied (ES = 0.97; 95% CI 0.64–1.30). The statistical heterogeneity of the effects was moderate ($I^2 = 51.62\%$). We determined a most likely moderately beneficial effect (ES = 1.18; 95% CI 0.52–1.83; $I^2 = 60.39\%$) and a very likely moderately beneficial effect (ES = 0.83; 95% CI 0.10–1.55; $I^2 = 39.54\%$) for the upper and lower extremities, respectively. With respect to the type of contraction, large ES was seen after applying the isometric contraction (ES = 1.40; 95% CI 0.83–1.98, most likely beneficial), compared to the small ES in the dynamic model (ES = 0.43; 95% CI − 0.09 to 0.95, likely beneficial). A noticeably large ES was observed when muscles with larger CRA (ES = 1.6; 95% CI 0.98–2.23, most likely beneficial) were trained compared to moderate ES in smaller areas (ES = 0.79; 95% CI 0.26–1.32, very likely beneficial). Furthermore, for both the encouragement (ES = 1.08; 95% CI 0.12–2.04; $I^2 = 64.41\%$) and non-encouragement conditions (ES = 0.89; 95% CI 0.28–1.49; $I^2 = 48.15\%$), the conditional results were almost similar, that is, very likely moderate effects were observed, slightly favouring the encouragement condition.

3.6 Dose–Response Relationship of MI Effects on Maximal Voluntary Strength

3.6.1 Meta-Regression Analysis for Training Variables of Maximal Voluntary Strength Following MI Practice

Table 4 shows the results of the meta-regression for the three subcategories of variables: training intensity, training volume, and training duration. In the subcategory of training intensity, only the type of contraction predicted the effect of MI practice ($p = 0.05$). Concerning the training volume, both the number of repetitions per one training session ($p = 0.01$) and per study ($p = 0.05$) predicted the effects of MI on MVS. On the other hand, the number of repetitions per set showed a trend that was nearly significant ($p = 0.08$). In the subcategory of training duration, the only predictor for the explanation of effects of MI on MVS was the duration of the single training session ($p = 0.04$).

Table 4 Meta-regression for the training variables of different subscales to predict the MI effects on maximal voluntary strength

	Coefficient	Standard error	95% lower CI	95% upper CI	*Z* value	*p* value
Training intensity						
Maximal (MViC)[a]	0.5595	0.2812	0.0083	1.1106	1.99	**0.05**
Time under tension (s)[b]	− 0.0543	0.0474	− 0.1473	0.0387	− 1.14	0.25
Training volume						
Training period (weeks)	− 0.1366	0.105	− 0.3424	0.0692	− 1.3	0.19
Training frequency (per week)	0.0618	0.1232	− 0.1797	0.3033	0.5	0.61
Number of sets (per training)	0.0101	0.1748	− 0.3325	0.3526	0.06	0.95
Number of repetitions (per set)	0.038	0.0219	− 0.0049	0.0808	1.74	0.08
Number of repetitions per single session	0.0237	0.01	0.004	0.0433	2.36	**0.01**
Number of repetitions (per study)	0.0009	0.0005	0	0.0019	1.95	**0.05**
Time spent in training						
Total training duration per study (min)	0.0023	0.0022	− 0.0021	0.0066	1.02	0.31
Total training duration per week (min)	0.00859	0.00571	− 0.0026	0.01978	1.50	0.13
Duration of single training session (min)	0.06686	0.03222	0.00371	0.1300	2.07	**0.04**

Bolded values refers to statistical significance of the observed result

CI confidence interval, *MI* motor imagery, *MVC* maximal voluntary contraction, *MViC* maximal voluntary isometric contraction, *RM* repetition maximum

[a]Dichotomous variable (dynamic contraction, i.e. less than 100% 1RM or MVC was used as reference group)

[b]Time under tension was calculated only for MViC contraction (100% intensity)

3.6.2 Different Training Variables Effects on Maximal Voluntary Strength Following MI Practice

In addition to the meta-regression, dose–response relationships were calculated independently using the ES of the characteristics of each training variable (Table 5). On average, the training intensity of the imagined contraction was classified as maximal (100% of MViC) and submaximal (less than 100% MViC or 1RM). Moderate ES was seen after a maximal contraction was used (ES = 0.92; 95% CI 0.55–1.30, most likely beneficial), while submaximal contraction showed small ES (ES = 0.30; 95% CI − 0.09 to 0.79, likely beneficial). Furthermore, on average, the TUT for isometric contraction only was 6.8 s (range 5–15 s). The mean ES for TUT was most likely moderately beneficial 0.92 (95% CI 0.55–1.30; $df = 7$; $I^2 = 22.55\%$). The largest improvements were associated with a 5-s contraction duration (mean ES = 1.05; 95% CI 0.57–1.52;

Table 5 Training variables with the largest mean effect on maximal voluntary strength

Training variables	Motor imagery vs no-exercise controls	
	Highest value	Effect size (CI)
Training period (weeks)	4	0.88 (0.43–1.34)
Training frequency (per week)	3	1.22 (− 0.32 to 2.75)
Number of sets (per training)	2–3	0.90 (0.49–1.31)
Number of repetitions (per set)	25	1.18 (0.56–1.81)
Number of repetitions (per single session)	50	1.18 (0.56–1.81)
Number of repetitions (per study)	1000	1.18 (0.56–1.81)
Training intensity (% of 1RM or MViC)	100	0.92 (0.55–1.30)
Time under tension (s)[a]	5	1.05 (0.57–1.52)
Total training duration per study (min)	300	1.07 (0.37–1.77)
Total training duration per week (min)	60–80	0.99 (0.55–1.43)
Duration of one training session (min)	15	1.04 (0.54–1.54)

The content of this table is based on the individual training variables with no respect for interaction between training variables

CI confidence interval, *MViC* maximal voluntary isometric contraction, *RM* repetition maximum

[a]Time under tension was calculated only for MViC contraction (100% intensity)

$df = 5$), and similar gains were observed for longer than 5 s of sustained contractions (ES = 0.80; 95% CI −0.11 to 1.71; $df = 0$).

On average, the training period in 11 studies lasted 3.8 weeks. The pooled effect was most likely moderately beneficial 0.72 (95% CI 0.42–1.02; $I^2 = 21.34\%$). The largest mean effect (ES = 0.88; 95% CI 0.43–1.34) was associated with a period of 4 weeks training; the most frequent period assessed (seven studies, Table 5).

The training frequency averaged 3.8 sessions per week and yielded a mean effect of 0.72 (95% CI 0.42–1.02; $df = 11$; $I^2 = 21.34\%$), which was most likely moderately beneficial. Based on two studies, the largest improvements in MVS were observed after three training sessions per week (ES = 1.22, Table 5).

Regarding the number of sets per one training session, 2.4 sets were performed on average, which gave a most likely moderately beneficial effect of 0.72 (95% CI 0.42–1.02; $df = 11$; $I^2 = 21.34\%$). Two to three sets per one session resulted in the largest improvements in MVS (mean ES = 0.90; 95% CI 0.49–1.31; $df = 7$).

Overall, in ten studies, the number of repetitions averaged 12.2 per one set (with a range of two to 25 repetitions), 25.9 per single session (with a range of eight to 50 repetitions), and 395.4 repetitions per study (range of 120 to 1000 repetitions). The mean ES for the average number of repetitions was most likely moderately beneficial (ES = 0.70; 95% CI 0.37–1.02; $df = 11$; $I^2 = 26.54\%$). More specifically, 25 repetitions per single set (ES = 1.18; 95% CI 0.56–1.81; $df = 1$) resulted in the largest improvements in MVS (Table 5). The dose–response relationship for the number of repetitions per single set is shown in Fig. 4a. Fifty repetitions per single training session (ES = 1.18; 95% CI 0.56–1.81; $df = 1$) resulted in the largest improvements in MVS. The dose–response relationship for the number of repetitions per single training session is presented in Fig. 4b, and when between 30 and 32 repetitions per single sessions were used, the effect was 1.07, thus only slightly lower compared to when the highest number of repetitions was applied. In addition, 1000 repetitions per study (ES = 1.18; 95% CI 0.56–1.81; $df = 1$) resulted in the largest improvements in MVS. The dose–response relationship for the number of repetitions per study is displayed in Fig. 4c.

Regarding all duration variables, the mean ES was most likely moderately beneficial on MVS (ES = 0.72; 95% CI 0.42–1.02; $I^2 = 21.34\%$; $df = 11$, $p = 0.23$). The longest time spent in training per study was 300 min and thus revealed the largest improvements (ES = 1.07; 95% CI 0.37–1.77; $df = 1$), which was slightly larger in comparison with 80–100 min spent in training (ES = 1.03; 95% CI 0.37–1.69; $df = 1$). Regarding the duration of training per week, the largest effect was found between 60 and 80 min of training per week (ES = 0.99; 95% CI 0.55–1.43; $df = 3$). On average, for the studies examined, the most frequent duration of a single session was 15 min (ES = 1.04; 95% CI 0.54–1.54; $df = 4$), and the dose response for duration of a single training session is presented in Fig. 4d. It shows that prolonging the duration to 20 min did show comparable results as with a 15-min session duration.

4 Discussion

This study presents a quantitative evaluation of MI practice for MVS improvements in healthy adult populations. The present results showed that MI practice elicits moderate improvements in muscle strength (Fig. 3a). However, when directly compared with PP, the results favour PP (Fig. 3b). When MI-C, that is MI in combination with PP, was compared with PP only, the effect was trivial and probably only due to three clinically unclear studies. There was very low to moderate heterogeneity of the effects within each meta-analysis, suggesting that all trials likely examined the same population effect [34]. Moreover, the sensitivity analysis using both random- and fixed-effects models did not yield considerably different mean effects or CIs, suggesting that the results of the meta-analysis were robust. Further, a meta-regression analysis showed that the number of repetitions per single session, the repetitions for the whole study, along with the duration of the single training session, and maximal isometric versus submaximal dynamic contraction, significantly predicted the effects of MI on MVS.

4.1 Effects of MI Practice on Maximal Voluntary Strength

Taken together, previous reviews yielded equivocal conclusions regarding the effects of MI practice on the measures of MVS [30–33, 36]. However, using meta-analytic procedures and conforming to the standards required of a systematic review, we found improvements of MVS in healthy adult populations following MI practice that on average ranged from 5 to 30% for the 13 included studies. Hence, by examining the potential moderators and knowing that these studies varied regarding the training variables (Table 2), our results suggest that diverse forms of MI practice have the potential to improve the maximal muscle strength. These findings are consistent with the results of a previous review [31], where the relative increase in strength varied from 12.6 to 35%. More interestingly, the MI effects were also observed in the contralateral or the non-trained limb, as well as in non-trained movements during a strength task. It was shown that following MI

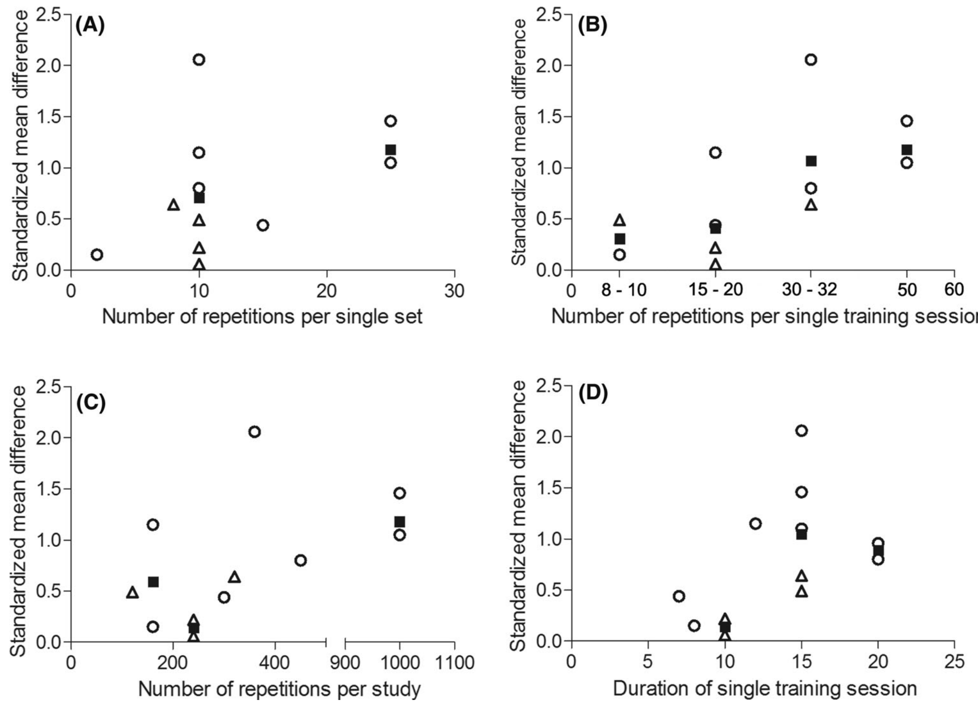

Fig. 4 Dose–response relationship and effect on the maximal strength measure following motor imagery practice for **a** the number of repetitions per single set; **b** the number of repetitions per single training session; **c** the number of repetitions per study; and **d** the duration of single training session. Each *unfilled symbol* illustrates the standardized mean difference (SMD) per single study. The *filled black squares* represent the mean SMD of all studies for the assigned value. *Circles* and *triangles* symbolize imagined maximal isometric contractions and the dynamic contractions during practice, respectively

practice, the contralateral effects were on average up to 10.45% of strength increase, while in the PP group the increase was 14.43% without a significant difference between the groups [51]. Similar contralateral limb effects following CST were shown elsewhere [66–68]. Furthermore, significant positive alterations were observed upon a non-trained strength task (i.e. when imagining the increase in the fifth digit flexion force after abduction, or the knee flexion strength after extension) [51, 59]. The underlying mechanisms of the observed strength gains might be explained in alteration on both central and peripheral levels, which will be discussed in the next paragraphs.

The short-term positive effects of MI (that ranged from 1 to 6 weeks) not associated with morphological changes (e.g. muscle hypertrophy) can likely be attributed to psychological and neurophysiological factors [39, 50, 51, 69]. In the early years of research in this field, Richardson [70] suggested that motivation may be partially responsible for the observed gains. Thus, in order to control or eliminate the influence of motivation, Feltz and Landers [30] proposed the use of a no-exercise group. Accordingly, some studies reported a non-significant increase in MVS (ranging from 1.7 to 5.5%) for the control groups [51, 53, 55, 57, 58, 61], suggesting that motivation was constant. Moreover, the observed non-significant gains in controls may be ascribed to the learning effect of the trained tasks [71, 72]. However, the learning effect is difficult to argue because of the ease and simplicity of the strength tasks, which took only a few trials of practice to be performed correctly [69, 73]. After three pre-training test sessions were performed, instead of the usual one, Ranganathan and colleagues [69] showed that both motivational and learning factors were not likely the significant determinants of the strength gains. In addition, the control group, whose individuals maintained their strength level throughout the course of the whole study, showed that a learning effect was likely trivial [69]. Further, previously it was shown that the MVS protocol assessment could influence test results by mitigating the participants' motivation level [65]. We noticed similar strength gains after both encouragement and non-encouragement protocols in the included studies, and therefore, the underlying mechanisms of MI practice might be predominantly influenced by neurophysiological factors, rather than psychological aspects. Consequently, given that duration of interventions ranged from 1 to 6 weeks, MI might encourage strength to be enhanced in the absence of structural muscle changes (e.g. muscle hypertrophy) [51]. The muscle hypertrophy following CST is a well-known phenomenon [74], where increase in muscle size is shown to occur just after 8–10 weeks of training [74–76]. Another aspect to take into account is that the appearance of the contralateral limb effect following MI practice might reflect neural components of adaptations in the absence of real movement and muscle hypertrophy [51]. Due to the advent of certain technologies, including neuroimaging and other brain activity measuring techniques, particularly functional magnetic resonance imaging and electroencephalography, the last two decades have been populated with studies investigating neurological mechanisms of MI practice. The findings from such studies lend support to MI's effectiveness related to motor performance improvement [24, 40, 77–81].

Currently, the underlying mechanisms of MI practice might be explained by both central and peripheral factors [18, 82]. First, the central explanation relies on the fact that MI can stimulate several brain regions which are known to play a role during actual movements [83, 84], including the primary motor cortex [24, 85–87]. Accordingly, prolonged MI practice leads to brain reorganization; that is brain plasticity [88, 89], which represents the intrinsic property of the human brain and its primary mechanism of learning and development [88], including motor-skill learning and cognitive motor actions [90]. Second, the peripheral mechanism supposes that MI may result in excitability of the spinal motor neurons [91–93], further contributing to greater neural impulse output to agonist muscles [56], and thus increasing muscular activity [14, 51, 61, 69]. Consequently, this might lead to better synchronization of the fibres and inhibition at the level of antagonist muscle activation [61], thus improving MVS [61, 81, 94]. A recent comprehensive review of Ruffino et al. [18] presented a potential model of neural adaptations in the learning process following MI practice, confirming aforementioned spinal and supraspinal factors as underlying mechanisms. However, of importance is to note that methodological considerations (e.g. experimental set-up, measurement equipment and the technique used, the task imagined, the imagery modality used, and the imagery ability and the skill level of the studied subjects) might influence the strength or even the existence of both central and peripheral responses (for review, see [18, 83, 84, 95, 96]).

Generally, the functional equivalence principle [23, 25] is based on the theory that imagery enhances performance, because of the similar neurophysiological processes that underlie both imagery and actual movement [26, 97], and has found its support elsewhere [24, 80, 98–100]. More precisely, during both motor execution and MI tasks, acute differences were shown in the supplementary motor area (SMA), the premotor cortex (PMC), and the primary motor cortex (M1one) movement, when compared to resting conditions. This suggested that imagining the motor task and its actual execution do share similar neural patterns [80]. Further, longitudinal studies involving the learning of a novel task [81] showed that MI practice can improve muscular abilities such as strength and power. Besides, these performance improvements by MI practice could modify movement-related cortical potentials (MRCP) comparable to those observed following PP [81]. Thus, this suggests a central role of MI practice similar to that shown during execution of motor tasks [39, 69, 89, 101, 102].

However, despite the fact that similar neural patterns have been found previously, and identical dose–response relationships were confirmed in the present review (Table 5), a difference was observed; namely smaller effects in performance following mental simulation tasks (e.g. MI practice) when compared to motor executed tasks [51–54, 59, 62]. Therefore, in absence of such structural changes, the central mechanism (i.e. neural circuits controlling the motor action) also can be used to argue favouring effects in strength gains following PP, when compared to the MI practice group. Accordingly, the lack of somatosensory feedback [98, 103] during MI due to restriction of overt movement execution contributes to inhibition of the posterior cerebellum and the SMA [80, 103, 104]. As such, these inhibitions play key roles in motor output suppression and consequently lead to less activation of M1one [24, 104, 105] and thus lower both electromechanical muscle output and performance enhancement [69]. A study by Ranganathan and colleagues [69] may extend our understanding of the central mechanism's role following MI practice, where the gains of MVS were followed by a significant increase of MRCP. This was previously shown to correlate highly with muscular activity and the level of the expressed force [102]. Furthermore, the authors observed that the MRCP amplitudes were always higher for the MVC tasks than for the mental MVC tasks, thus providing evidence of crucial central mechanisms following the imagined task.

Despite the preceding evidence on the similarities between imagined and actual movement, there are several important facts that should be pointed out. First, when comparing training outcomes between MI and PP regimes, one must consider the fact that the PP training could almost always maximally activate—assuming training involves MVC—not only the muscle, but also the neural circuits controlling the motor action. Therefore, PP optimally trains both the central and the peripheral systems [106, 107]. Second, although similar neural networks underlie both the imagined and the actual movement execution, they are not strictly identical, which might be influenced by the nature of the MI practice that requires inhibition of the efferent sensorimotor output [26, 104]. Third, for MI training, difficulties of optimally performing the task (people have different abilities to accurately perform the MI task) could lead to suboptimal activation (and training) of the control network [19, 95, 108, 109]. The extent to which a given subject can optimally activate the motor control network during MI training may determine both the training outcome and the variability between participants and studies.

In contrary to both practice models alone (MI and PP), its combination (MI-C) was found to elicit greater cerebral activity in motor-related brain regions [76, 100]. Hence, both symptomatic [14, 94, 110, 111] and asymptomatic (i.e. healthy population) [47, 58] experienced greater benefits compared to PP alone. However, the present results indicate that those improvements are trivial (ES = 0.05) compared to PP alone. These trivial results are likely due to the initially higher performance level of the included subjects (i.e. a generally healthy population) from the three analysed studies. Furthermore, Jiang et al. [112] compared the level of mental effort, i.e. high mental effort (HME) versus low mental effort (LME), with a no-training control group (CON), during a low-intensity (30% MVC) muscle exercise training programme (6 weeks, 15 min/day, 5 days/week). They reported that HME for elbow flexion contractions, combined with a low (30% maximal) level of physical elbow flexion exercise, can significantly increase elbow flexion strength. But those trained with an LME combined with the same low level of physical elbow flexion exercise and those in the CON group did not increase elbow flexion in healthy young individuals. Thus, Jiang et al. [56] reported that at the end of the 12-week training in healthy elderly subjects, CST (high-intensity physical exercise) and HME significantly increased the elbow flexion strength, compared to the CON group (− 6%), with no significant difference between CST and HME groups. The amount of increase in MRCP in the HME group was significantly greater than that in CST and CON groups [56]. These results suggest that HME training combined with low-intensity physical exercise is an effective method for voluntary muscle strengthening in healthy populations and might be useful for those individuals who have difficulties in participating in high-intensity exercise training. Therefore, when maximal intensity of PP is limited, incorporating MI practice may help trainees to optimally train their system, and may yield better training effects.

Two studies [50, 58] different in design concerning the trained muscles reported slightly greater effects (ES = 0.17; 0.15 and 0.31; for biceps brachi, pectoralis major and quadriceps, respectively) favouring the combination of the two models (MI and PP) over PP only. Accordingly, Lebon et al. [50] used imagery practice in addition to CST during the rest periods in between the individual sets. Thus, one might assume that the overall active time spent in training might have influenced the effects of the combined mode, compared to PP only. Wright and Smith [58], however, mitigated this assumption by using consecutive sets of both models (one PP set followed by one MI set), compared to two sets of PP training. This resulted in equal time spent in training and similar effects in strength gains (ES = 0.17), parallel to the study of Lebon et al. (ES = 0.15 and 0.31) [50]. The authors suggest that the greater results following a combination of the two models were influenced by enhancing the technical execution of the movement, the individual intrinsic motivation [70], and maybe the cerebral reorganization [89]. Thus, of importance seems to be driving the motor units to a higher intensity [101] and/or leading to the recruitment of motor units that remain otherwise inactive, rather than the overall time spent in training [50]. In summary, compared with CST, MI has less beneficial effects, which suggests that PP will remain the most efficient method for strength increase, while MI can be used as additional, or sometimes even as a substitutional tool, in the same manner. Regarding the combined effect of MI and PP, more research is necessary to draw strong evidence about its likely beneficial effect compared to CST.

Despite the substantial effect of MI on muscle strength, the present results indicate there was still considerable variation among the studies in the magnitude of adaptations. This may be ascribed to various methodological issues. Accordingly, the magnitude of the response varies between the body regions (upper vs lower limbs), the muscle groups, the type and/or intensity of the contractions, and the existence of the muscle activity control during the MI practice session. Previous adaptations to MI practice were shown to be specific, as training induced changes in MVS that differ between the exercise practised [50], and/or distal and proximal muscles [69]. Furthermore, the variation could be modified by the type and the intensity of the imagined contraction [113]. Different musculature was investigated among the analysed studies. We assumed, based on the observed discrepancies and the outcomes among them, as well as on previous findings [31, 69], that this can have a possible influence on the results of the MI practice. It is known that distal and proximal muscles differ in many aspects [114]. For example, the size of the CRA [115], the firing rate scheme (both recruitment and decruitment), and the modulation of the discharge rate to the gradation of muscle force can be different [116]. For example, distal muscles [e.g. musculus (m.) opponens pollicis] have a significantly greater excitability of cortical area compared to the proximal muscles (m. biceps brachii) [117]. To what extent those features might modulate the outcomes following MI practice with respect to MVS, however, has been poorly investigated. To our knowledge, only one study [69] was performed with that aim. It showed that distal muscles (m. abductor digiti minimi) experience larger improvement in MVS strength compared to proximal muscles (m. biceps brachii), 35 vs 13.5%, respectively, following 12 weeks of training (15 min/day, 5 days per week). Furthermore, the study showed greater potential for an increase of the descending command to the target muscle favouring large versus small CRA muscles [69], which might alter muscular activity and thus the level of expressed force [102]. However, the authors [69] ascribed these favouring effects of distal muscles simply to the training status of the involved muscles [118], rather than to the neurophysiological features. It is well-known that untrained individuals have a greater starting potential to increase their strength compared to trained ones [118], due to lower levels of initial strength [119], as well as to maximal voluntary activation (MVA) level [120]. An individual probably seldom intentionally contracts the intrinsic muscles of the hand like the little finger abductor [69] or thumb adductor muscles [121]. These muscles have a lower MVA level compared to the proximal muscles (e.g. biceps brachii) [121]. Consequently, there may have been more potential for increasing the voluntary activation in the intrinsic finger muscles, which might lead to greater force exertion following strength training. However, a study by Lebon and colleagues [50] showed that MI practice in addition to CST significantly modulates the effect of only the lower limb muscles (i.e. leg extensors), compared to the upper limb muscles (i.e. pectoral and arm adductors). This is in accordance with our findings, where we observed that the lower body parts experienced greater strength gains compared to the upper ones. Unfortunately, the previously discussed causal link between individual muscle MVA (i.e. its trainability level and the MI practice effect) cannot argue for the observed discrepancies in the results of Lebon et al.'s study, due to the many varieties of sports in which the participants were engaged, and their randomized control and experimental grouping, respectively. To summarize, with respect to the CRA of the involved muscles, this review does not suggest a strong conclusion, and although we showed a minor influence on the training outcomes, we cannot ascribe it only to CRA, but should mention as an important factor the trainability status (i.e. muscular fitness level) of the involved muscles. However, contrary to previous findings on this particular topic [31], we suggest that both large and small CRA muscles might almost equally benefit from MI practice.

Considering the MI practice principle that only mental rehearsal must be performed, without overt movement execution, both brain and muscle activity during MI session should be provided, otherwise it might confound the interpretation of the results [31]. However, probably due to the high costs, time consumption, and the complexity of the recording set-up, there is no research that directly measured the brain activity during MI practice sessions over prolonged periods of time. In those shorter-term studies where muscle activity was monitored, greater strength gains were observed [51, 52, 54, 59, 61, 63], suggesting that the supervised muscle activity might lead to consciously greater focus on mental simulation of the movements.

4.2 Dose–Response Relationship of MI Practice to Increase Muscle Strength

In the previous section, we established a moderate effect of the MI practice on MVS in healthy adults. The present meta-regression identified the training variables that moderated the changes in strength following MI practice. Further, based on the additional analyses, the dose–response relationships were presented for each variable independently (Table 5), i.e. of the six "training volume" variables, the ones that were significant predictors of the effects of MI on MVS: the number of repetitions, both per single training session and for the whole study.

Based on seven studies, the most frequent period of 4 weeks yielded a moderate effect (ES = 0.88). However, when compared to a 1-week period (ES = 0.96) and three weeks (ES = 0.80), the most frequent period led to, respectively, a somewhat lower (compared with 1 week) and larger (compared with 3 weeks) effect. This suggests that MI practice might be a suitable intervention for strength increase in healthy adults after only performing a few sessions [63]. Supporting our findings, a study by Reiser [53] observed the largest improvement in strength after the first week of MI practice. In addition, although the increase in strength was linear throughout the next 5 weeks, it suggests that the nervous system exhibits a rapid modulation to adapt to new mental demands [86, 122, 123].

In contrast to the meta-regression, the dose–response relationship analysis revealed considerably different effects regarding the weekly frequency and the number of sets during a single MI session. This was reflected as an inverted U shape. Thus, three sessions of MI practice per week produced a substantially larger effect on MVS (ES = 1.22) compared to the protocols where two (ES = 0.42) or five sessions (ES = 0.72) per week were performed. One rare study conducted by Wakefield and Smith [124] aimed to investigate the influence of different frequencies of MI, and indicated that although the training programmes delivered at least once per week can be beneficial, practising imagery more frequently can be more effective. Based on the average frequency used across the studies and the additional analysis of the dose–response relationships, the current review suggests an optimal three sessions per week as a starting point for those who want to benefit from MI practice. More frequent practice would not lead to greater strength gains in periods fewer than 6 weeks in duration. Considering "the number of sets", notably greater effects were found with two to three sets (ES = 0.90) compared to the training protocols where one (ES = 0.46) or four sets (ES = 0.37) were performed. A similar trend reflected as an inverted U shape was observed following CST [125, 126]. Hence, the largest effect was observed during protocols that applied three and two sets per session [125, 126]. Since changes on the structural level are lacking for a short period of CST [74–76], our data suggests that similar neural mechanisms might underlie short-term effects [26, 40, 99]. In summary, positive effects of both practice models should be expected regardless of single or multiple sets used. Two to three sets should be recommended when designing an MI practice programme.

Regarding "the number of repetitions per set" variable, its effect on strength gains following the MI practice was nearly significant, whereas both the derived variables (i.e. the total number of repetitions per single session and per whole study) significantly predicted the effect in strength gains. Additional dose–response analysis supports the meta-regression data, where the largest effects were found after the use of the greatest number of repetitions. When planning an MI practice programme, this observation underlines the importance of considering the right training volume, rather than the total number of repetitions per set only. Bearing in mind that only a few studies investigated the MI ability of participants [52, 53, 55, 58, 61] and only two studies used participants' MI ability as inclusion criteria [52, 53], an overall greater number of mentally simulated trials was probably needed to induce positive alterations following MI practice. The need for a greater number of simulated trials was most likely influenced by the initial lower ability of the subjects to visualize and kinaesthetically feel the task. The imagery ability may have had a significant impact upon its effectiveness, because it is likely that someone who cannot clearly imagine performing a motor task will not benefit much from MI practice [19, 108].

Moreover, previous experience [38], as well as an internal versus external perspective of the imagined task [39], elicit greater brain activity of motor-related areas during an MI session [38]. Consequently, those alterations on the cortical level lead to greater descending command of the involved muscles, improving its motor unit recruitment and activation, finally improving the muscle mechanical output following MI practice. Furthermore, our data suggest that both the type and the intensity of the imagined contraction have a large influence on the MI practice outcomes. Considerably larger strength gains were observed when MViC compared to submaximal dynamic contractions was investigated. This was also confirmed by the meta-regression analysis (Table 4). To support our findings, a larger muscular activity (in elbow flexors) during imaging a heavy lift compared to the light lifting task and the isometric type of contraction compared to the light dynamic type of contractions were found [113]. Moreover, the authors observed the mirroring effect when comparing imagined and executed contractions regarding both types and intensities [113]. In overt execution of motor task, the MVA level was found to be moderated by the type of muscle contraction when maximal effort was used [127]. More precisely, for the use of three different MVC types of quadriceps muscle, it was found that the MVA levels during eccentric and concentric contractions were 88.3 and 89.7%, respectively, and were significantly lower with respect to maximal isometric contractions (95.2%) [127]. Consequently, it leads to improvement in MVS by 10.8, 15.3, and 34.1%, following eccentric, concentric, or isometric types of training, respectively [73]. In accordance with our results, another recent meta-analysis [128] showed that high training loads ($\geq$ 65% 1RM) lead to notably greater strength gains compared to low-load training ($\leq$ 60% 1RM). Hence, similar to overt movement execution [73], the type, along with the intensity of the imagined contractions, plays an important role in the magnitude of the MI intervention. This might be linked to the previously discussed greater descending command to the muscle, when maximal mental and/or physical effort is produced [102, 112].

Along with the mechanical stress induced by the training intensity (percentage of 1RM), metabolic stress results in increased muscle size and strength [129, 130]. Accordingly, TUT is a variable which should be controlled during the training [131], because its manipulation induces different responses of the neuromuscular system [132]. How the neuromuscular system operates and to what extent TUT might affect the strength gains following MI practice was until now not investigated. Expressed as the time of sustained contraction during imagined or executed MViC, the TUT showed an insignificant effect on the strength gains. Comparable large effect was observed following MI practice using both 5 and 10 s of sustained contraction. These observations probably reflect that subjects were mainly untrained individuals. Thus, 5–10 s of sustained contraction in less than 6 weeks of resistance training were adequate to induce the optimal neuromuscular adaptation and the greatest strength gains. One study, which aimed to investigate the differences between short intermittent contractions (3 s with 2 s rest) versus long continuous isometric contraction (30 s with 1 min rest in between sets), found that both groups increased their MVC after 6 weeks of training [133], although not significantly compared to baseline. However, following 14 weeks of training, both groups significantly increased strength compared to baseline. Regarding strength gains, the longer contractions were shown to be more beneficial compared to the short isometric contractions. Thus, due to the greater metabolic changes elicited following long isometric contraction training, sustained contraction longer than 5 s might be the most beneficial when training longer than 6 weeks is planned. Only hypothetically, increasing the time of contraction following the first few weeks of training might be applicable for either mental or CST, knowing that training periodization leads to optimal and continuous adaptations of both the neural and structural components [43, 134, 135].

Regarding the "time spent in training" variable, only the duration of the single training session was shown to be a significant predictor of strength gains following the MI practice. The regression curve showed a slightly inverse U shape. Hence, our results suggest that moderate time spent in training, of around 15 min, is an optimal framework to induce the most benefits from MI. This finding is similar to those of the previous reviews that suggested that the optimal duration of mental practice was 20 min on average [35, 36]. In addition, it was mentioned that longer duration may decrease the motivation and thus can trigger negative effects like focus reduction and advent of boredom [36]. To support the shorter periods of MI practice, another study aimed to investigate the effectiveness of a single practice session when 100 imagined movements were performed, and found that the participants experienced subjective feelings of mental fatigue following the protocol [136]. This was accompanied by an increased duration of both the actual and the imagined movements. Thus, the observed decline in performance suggests that a session of prolonged duration should not be performed, to help avoid mental fatigue, which could worsen the performance of the motor task. However, an integration of one actual movement on every ten imagined might delay an advent of mental fatigue [136], and this should be considered carefully when designing an MI practice programme, especially since it is easily implemented.

4.3 Limitations of the Present Review

Some limitations of this systematic review must be outlined. One limitation might be the overall variability of the included studies with the training design, making it difficult to reach firm conclusions on some issues. There were limitations in the external validity as well: almost all the participants included were untrained and healthy. Therefore, no comparison could be made between trained and untrained, as well as between healthy and symptomatic individuals. In addition, it was not feasible to use chronological age as a moderator variable, as only two studies included older adults. Given the number of studies resulting from the search, we were not able to assess interaction effects among the moderating variables. Finally, the publication bias results indicated the presence of bias. It is possible that some studies may have not been published, due to null or negative results, reducing the general positive effect of MI practice on strength.

5 Conclusion

The present meta-analysis demonstrates that MI practice has most likely moderate beneficial effects on MVS development, compared to a no-exercise control group. However, when compared to a PP group, we found likely small beneficial effects, favouring PP. There is no strong evidence that the combination of both practices has a greater effect than PP only. The dose–response relationship analysis showed that the number of repetitions per single session (50 repetitions) and during the whole study (1000 repetitions), the intensity and/or the type of the imagined contractions (MViC), along with a single training session duration (15 min) can all significantly modify the effects of MI practice on muscle strength in healthy adults.

To summarize, our finding suggest that CST will remain the most efficient method of strength development. However, MI practice should be considered as a substitute or additional training tool to preserve muscle function when athletes are not exposed to maximal training intensities. Hypothetically, MI might also apply in patients' rehabilitation planning as well, when motor execution is constrained or impaired. Moreover, we propose a thorough and proper MI practice design, regarding a multitude of training variables. Our results provide guidance for strength and conditioning coaches, as well as physiotherapists, to get the most out of the mental simulation practice for their clients.

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Compliance with Ethical Standards

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References

1. Tod D, Edwards C, McGuigan M, Lovell G. A systematic review of the effect of cognitive strategies on strength performance. Sports Med. 2015;45(11):1589–602.
2. Tod D, Iredale F, Gill N. "Psyching-up" and muscular force production. Sports Med. 2003;33(1):47–58.
3. Shelton TO, Mahoney MJ. The content and effect of "psyching-up" strategies in weight lifters. Cogn Ther Res. 1978;2(3):275–84.
4. Whelan JP, Epkins CC, Meyers AW. Arousal interventions for athletic performance: influence of mental preparation and competitive experience. Anxiety Res. 1990;2(4):293–307.
5. Gould D, Weinberg R, Jackson A. Mental preparation strategies, cognitions, and strength performance. J Sport Psychol. 1980;2(4):329–39.
6. Cumming J, Williams SE. The role of imagery in performance. In: Murphy SM, editor. The Oxford Handbook of sport performance and psychology. New York: Oxford University Press; 2012. pp. 213–32.
7. Braun S, Kleynen M, van Heel T, Kruithof N, Wade D, Beurskens A. The effects of mental practice in neurological rehabilitation; a systematic review and meta-analysis. Front Hum Neurosci. 2013;7(August):390.
8. Caligiore D, Mustile M, Spalletta G, Baldassarre G. Action observation and motor imagery for rehabilitation in Parkinson's disease: a systematic review and an integrative hypothesis. Neurosci Biobehav Rev. 2017;72:210–22.

9. Tamir R, Dickstein R, Huberman M. Integration of motor imagery and physical practice in group treatment applied to subjects with Parkinson's disease. Neurorehabil Neural Repair. 2007;21(1):68–75.
10. Braun S, Beurskens A, Kleynen M, Schols J, Wade D. Rehabilitation with mental practice has similar effects on mobility as rehabilitation with relaxation in people with Parkinson's disease: a multicentre randomised trial. J Physiother. 2011;57(1):27–34.
11. Newsome J, Knight P, Balnave R. Use of mental imagery to limit strength loss after immobilization. J Sport Rehabil. 2003;12(3):249–58.
12. Lee H, Kim H, Ahn M, You Y. Effects of proprioception training with exercise imagery on balance ability of stroke patients. J Phys Ther Sci. 2015;27:1–4.
13. Dunsky A, Dickstein R, Marcovitz E, Levy S, Deutsch J. Home-based motor imagery training for gait rehabilitation of people with chronic poststroke hemiparesis. Arch Phys Med Rehabil. 2008;89(8):1580–8.
14. Lebon F, Guillot A, Collet C. Increased muscle activation following motor imagery during the rehabilitation of the anterior cruciate ligament. Appl Psychophysiol Biofeedback. 2012;37(1):45–51.
15. Cupal DD, Brewer BW. Effects of relaxation and guided imagery on knee strength, reinjury anxiety, and pain following anterior cruciate ligament reconstruction. Rehabil Psychol. 2001;46(1):28–43.
16. Marusic U, Grosprêtre S, Paravlic A, Kovač S, Pišot R, Taube W. Motor Imagery during Action Observation of Locomotor Tasks Improves Rehabilitation Outcome in Older Adults after Total Hip Arthroplasty. Neural Plast. 2018. https://doi.org/10.1155/2018/5651391.
17. Richardson A. Mental imagery. Berlin: Springer; 1969.
18. Ruffino C, Papaxanthis C, Lebon F. Neural plasticity during motor learning with motor imagery practice: review and perspectives. Neuroscience. 2017;341:61–78.
19. Martin KA, Moritz SE, Hall CR. Imagery use in sport: a literature review and applied model. Sport Psychol. 1999;13:245–68.
20. Murphy SM. Imagery interventions in sport. Med Sci Sports Exerc. 1993;26:486–94.
21. Orlick T, Partington J. Mental links to excellence. Sport Psychol. 1988;2:105–30.
22. Lotze M. Kinesthetic imagery of musical performance. Front Hum Neurosci. 2013;7:1–9.
23. Jeannerod M. The representing brain: neural correlates of motor intention and imagery. Behav Brain Sci. 1994;17(2):187–245.
24. Porro CA, Francescato MP, Cettolo V, Diamond ME, Baraldi P, Zuiani C, et al. Primary motor and sensory cortex activation during motor performance and motor imagery: a functional magnetic resonance imaging study. J Neurosci. 1996;16(23):7688–98.
25. Finke RA. The functional equivalence of mental images and errors of movement. Cogn Psychol. 1979;11(2):235–64.
26. Grezes J, Decety J. Functional anatomy of execution, mental simulation, observation, and verb generation of actions: a meta-analysis. Hum Brain Mapp. 2000;2001(12):1–19.
27. Decety J. Comparative analysis of actual and mental movement times in two graphic tasks. Brain Cogn. 1989;11(1):87–97.
28. Fitts PM. The information capacity of the human motor system in controlling the amplitude of movement. J Exp Psychol. 1954;47(6):381–91.
29. Decety J, Lindgren M. Sensation of effort and duration of mentally executed actions. Scand J Psychol. 1991;32(2):97–104.
30. Feltz D, Landers D. The effects of mental practice on motor skill learning and performance: a meta-analysis. J Sport Psychol. 1983;5(1):25–57.
31. Scholefield SC, Cooke CP, Van Vliet PM, Heneghan NR. The effectiveness of mental imagery for improving strength in an asymptomatic population. Phys Ther Rev. 2015;20(2):86–97.
32. Slimani M, Tod D, Chaabene H, Miarka B, Chamari K. Effects of mental imagery on muscular strength in healthy and patient participants: a systematic review. J Sport Sci Med. 2016;15(3):434–50.
33. Manochio JP, Lattari E, Mello Portugal EM, Monteiro-Junior RS, Paes F, Budde H, et al. From mind to body: is mental practice effective on strength gains? A meta-analysis. CNS Neurol Disord Targets. 2015;14(9):1145–51.
34. Borenstein M, Hedges LV, Higgins JPT, Rothstein HR. Introduction to meta-analysis. Chichester, UK: Wiley; 2009. pp. 249–95.
35. Schuster C, Hilfiker R, Amft O, Scheidhauer A, Andrews B, Butler J, et al. Best practice for motor imagery: a systematic literature review on motor imagery training elements in five different disciplines. BMC Med. 2011;9(1):75.
36. Driskell JE, Copper C, Moran A. Does mental practice enhance performance? J Appl Psychol. 1994;79(4):481–92.
37. Yu Q-H, Fu ASN, Kho A, Li J, Sun X-H, Chan CCH. Imagery perspective among young athletes: differentiation between external and internal visual imagery. J Sport Heal Sci. 2016;5(2):211–8.
38. Olsson C-J, Jonsson B, Larsson A, Nyberg L. Motor representations and practice affect brain systems underlying imagery: an FMRI study of internal imagery in novices and active high jumpers. Open Neuroimaging J. 2008;2:5–13.
39. Yao WX, Ranganathan VK, Allexandre D, Siemionow V, Yue GH. Kinesthetic imagery training of forceful muscle contractions increases brain signal and muscle strength. Front Hum Neurosci. 2013;7(September):561.
40. Decety Grèzes. Neural mechanisms subserving the perception of human actions. Trends Cogn Sci. 1999;3(5):172–8.
41. Wernbom M, Augustsson J, Thomeé R. The influence of frequency, intensity, volume and mode of strength training on whole muscle cross-sectional area in humans. Sports Med. 2007;37(3):225–64.
42. Peterson MD, Rhea MR, Alvar BA. Maximizing strength development in athletes: a meta-analysis to determine the dose–response relationship. J Strength Cond Res. 2004;18(2):377.
43. American College of Sports Medicine. Progression models in resistance training for healthy adults. Med Sci Sports Exerc. 2002;41(3):687–708.
44. Moher D, Liberati A, Tetzlaff J, Altman DG, Grp P. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement (reprinted from annals of internal medicine). Phys Ther. 2009;89(9):873–80.
45. Liberati A, Altman DG, Tetzlaff J, Mulrow C, Gøtzsche PC, Ioannidis JPA, et al. The PRISMA statement for reporting systematic reviews and meta-analyses of studies that evaluate health care interventions: explanation and elaboration. J Clin Epidemiol. 2009;62(10):e1–34.
46. Cochrane. Consumers and Communication Group resources for authors (Internet). 2016 (cited 15 Feb 2017). p. 1. http://cccrg.cochrane.org/author-resources.
47. Maher CG, Sherrington C, Herbert RD, Moseley AM, Elkins M. Reliability of the PEDro scale for rating quality of randomized controlled trials. Phys Ther. 2003;83(8):713–21.
48. Higgins JPT, Thompson SG, Deeks JJ, Altman DG. Measuring inconsistency in meta-analyses. BMJ Br Med J. 2003;327(7414):557–60.
49. Hopkins WG, Marshall SW, Batterham AM, Hanin J. Progressive statistics for studies in sports medicine and exercise science. Med Sci Sports Exerc. 2009;41(1):3–12.

50. Lebon F, Collet C, Guillot A. Benefits of motor imagery training on muscle strength. J Strength Cond Res. 2010;24(6):1680–7.
51. Yue G, Cole KJ. Strength increases from the motor program: comparison of training with maximal voluntary and imagined muscle contractions. J Neurophysiol. 1992;67(5):1114–23.
52. Smith D, Collins D, Holmes P. Impact and mechanism of mental practice effects on strength. Int J Sport Exerc Psychol. 2003;1(3):293–306.
53. Reiser M. Kraftgewinne durch Vorstellung maximaler Muskelkontraktionen. Zeitschrift für Sport. 2005;12(1):11–21.
54. Sidaway B, Trzaska AR. Can mental practice increase ankle dorsiflexor torque? Phys Ther. 2005;85(10):1053–60.
55. Darvishi M, Ahmadi S, Hierani A, Jabari N. Effects of motor imagery and maximal isometric action on grip strength of elderly men. World Appl Sci J. 2013;24(4):556–60.
56. Jiang C, Ranganathan VK, Zhang J, Siemionow V, Yue GH. Motor effort training with low exercise intensity improves muscle strength and descending command in aging. Medicine (Baltimore). 2016;24(August 2015):1–7.
57. Shackell EM, Standing LG. Mind over matter: mental training increases physical strength. N Am J Psychol. 2007;9(1):189–200.
58. Wright CJ, Smith D. The effect of PETTLEP imagery on strength performance. Int J Sport Exerc Psychol. 2009;7(1):18–31.
59. de Ruiter CJ, Hutter V, Icke C, Groen B, Gemmink A, Smilde H, et al. The effects of imagery training on fast isometric knee extensor torque development. J Sports Sci. 2012;30(2):166–74.
60. Holmes PS, Collins DJ. The PETTLEP approach to motor imagery: a functional equivalence model for sport psychologists. J Appl Sport Psychol. 2001;13(1):60–83.
61. Bahari SM, Damirchi A, Rahmaninia F, Salehian MH. The effects of mental practice on strength gain and electromyographic changes in elbow flexor muscles. Ann Biol Res. 2011;2(6):198–207.
62. Niazi SM, Bai N, Shahamat MD, Branch J, Branch A. Investigation of effects of imagery training on changes in the electrical activity of motor units of muscles and their strength in the lower extremities. Eur J Exp Biol. 2014;4(1):595–9.
63. Cornwall M, Bruscato M, Barry S. Effect of mental practice on isometric muscular strength. J Orthop Sport Phys Ther. 1991;13(5):231–4.
64. Feigenbaum MS, Pollock ML. Prescription of resistance training for health and disease. Med Sci Sport Exerc. 1998;31(March):38–45.
65. Gandevia SC. Spinal and supraspinal factors in human muscle fatigue. Physiol Rev. 2001;81(81):1725–89.
66. Abazović E, Kovačević E, Kovač S, Bradić J. The effect of training of the non-dominant knee muscles on ipsi- and contralateral strength gains. Isokinet Exerc Sci. 2015;23(3):177–82.
67. Munn J, Herbert RD, Gandevia SC. Contralateral effects of unilateral resistance training: a meta-analysis. J Appl Physiol. 2004;96(5):1861–6.
68. Adamson M, MacQuaide N, Helgerud J, Hoff J, Kemi OJ. Unilateral arm strength training improves contralateral peak force and rate of force development. Eur J Appl Physiol. 2008;103(5):553–9.
69. Ranganathan VK, Siemionow V, Liu JZ, Sahgal V, Yue GH. From mental power to muscle power—gaining strength by using the mind. Neuropsychologia. 2004;42(7):944–56.
70. Richardson A. Mental practice: a review and discussion part II. Res Q Am Assoc Health Phys Educ Recreat. 2015;1967(38):263–73.
71. Zijdewind I, Toering ST, Bessem B, Van der Laan O, Diercks RL. Effects of imagery motor training on torque production of ankle plantar flexor muscles. Muscle Nerve. 2003;28(2):168–73.
72. Herbert RD, Dean C, Gandevia SC. Effects of real and imagined training on voluntary muscle activation during maximal isometric contractions. Acta Physiol Scand. 1998;163(4):361–8.
73. Jones DA, Rutherford OM. Human muscle strength training: the effects of three different regimens and the nature of the resultant changes. J Physiol. 1987;391:1–11.
74. Akima H, Takahashi H, Kuno SY, Masuda K, Masuda T, Shimojo H, et al. Early phase adaptations of muscle use and strength to isokinetic training. Med Sci Sports Exerc. 1999;31(4):588–94.
75. Hakkinen K, Newton RU, Gordon SE, McCormick M, Volek JS, Nindl BC, et al. Changes in muscle morphology, electromyographic activity, and force production characteristics during progressive strength training in young and older men. J Gerontol A Biol Sci Med Sci. 1998;53(6):B415–23.
76. Higbie EJ, Cureton KJ, Iii GLW, Prior BM, Warren GL III. Effects of concentric and eccentric training on muscle strength, cross-sectional area, and neural activation. J Appl Physiol. 1996;81(3):2173–81.
77. Formaggio E, Storti SF, Cerini R, Fiaschi A, Manganotti P. Brain oscillatory activity during motor imagery in EEG-fMRI coregistration. Magn Reson Imaging. 2010;28(10):1403–12.
78. Olsson C, Jonsson B, Nyberg L. Learning by doing versus learning by thinking: an fMRI study of motor and mental training. Front Hum Neurosci. 2008;2(5):1–7.
79. Lacourse MG, Orr ELR, Cramer SC, Cohen MJ. Brain activation during execution and motor imagery of novel and skilled sequential hand movements. Neuroimage. 2005;27(3):505–19.
80. Lotze M, Montoya P, Erb M, Hülsmann E, Flor H, Klose U, et al. Activation of cortical and cerebellar motor areas during executed and imagined hand movements: an fMRI study. J Cogn Neurosci. 1999;11(5):491–501.
81. Fontani G, Migliorini S, Benocci R, Facchini A, Casini M, Corradeschi F. Effect of mental imagery on the development of skilled motor actions. Percept Mot Skills. 2007;105:803–26.
82. Grosprêtre S, Lebon F, Papaxanthis C, Martin A. New evidence of corticospinal network modulation induced by motor imagery. J Neurophysiol. 2016;115:1279–88.
83. Munzert J, Lorey B, Zentgraf K. Cognitive motor processes: the role of motor imagery in the study of motor representations. Brain Res Rev. 2009;60(2):306–26.
84. Hétu S, Grégoire M, Saimpont A, Coll MP, Eugène F, Michon PE, et al. The neural network of motor imagery: an ALE meta-analysis. Neurosci Biobehav Rev. 2013;37(5):930–49.
85. Dechent P, Merboldt K-D, Frahm J. Is the human primary motor cortex involved in motor imagery? Brain Res Cogn Brain Res. 2004;19(2):138–44.
86. Debarnot U, Clerget E, Olivier E. Role of the primary motor cortex in the early boost in performance following mental imagery training. PLoS One. 2011;6(10):e26717.
87. Li S, Latash ML, Zatsiorsky VM. Effects of motor imagery on finger force responses to transcranial magnetic stimulation. Cogn Brain Res. 2004;20(2):273–80.
88. Pascual-Leone A, Amedi A, Fregni F, Merabet LB. The plastic human brain cortex. Annu Rev Neurosci. 2005;28(1):377–401.
89. Baeck JS, Kim YT, Seo JH, Ryeom HK, Lee J, Choi SM, et al. Brain activation patterns of motor imagery reflect plastic changes associated with intensive shooting training. Behav Brain Res. 2012;234(1):26–32.
90. Sanes JN, Donoghue JP. Plasticity and primary motor cortex. Annu Rev Neurosci. 2000;23:393–415.
91. Bunno Y, Onigata C, Suzuki T. Excitability of spinal motor neurons during motor imagery of thenar muscle activity under maximal voluntary contractions of 50% and 100%. J Phys Ther Sci. 2015;27:2775–8.

92. Bunno Y, Yurugi Y, Onigata C, Suzuki T, Iwatsuki H. Influence of motor imagery of isometric opponens pollicis activity on the excitability of spinal motor neurons: a comparison using different muscle contraction strengths. J Phys Ther Sci. 2014;26(7):1069–73.
93. Bunno Y, Suzuki T, Iwatsuki H. Motor imagery muscle contraction strength influences spinal motor neuron excitability and cardiac sympathetic nerve activity. J Phys Ther Sci. 2015;27(12):3793–8.
94. Park J. Influence of mental practice on upper limb muscle activity and activities of daily living in chronic stroke patients. J Phys Ther Sci. 2016;28:1061–3.
95. Milton J, Small SL, Solodkin A. Imaging motor imagery: methodological issues related to expertise. Methods. 2008;45(4):336–41.
96. Di Rienzo F, Debarnot U, Daligault S, Saruco E, Delpuech C, Doyon J, et al. Online and offline performance gains following motor imagery practice: a comprehensive review of behavioral and neuroimaging studies. Front Aging Neurosci. 2016;10(June):1–15.
97. Decety J. Neural representations for action. Rev Neurosci. 1996;7(4):285–97.
98. Lotze M, Zentgraf K. Contribution of the primary motor cortex to motor imagery. In: Guillot A, Collet C, editors. Neurophysiological foundations of mental and motor imagery. New York: Oxford University Press; 2010. pp. 31–45.
99. Jeannerod M. Neural simulation of action: a unifying mechanism for motor cognition. Neuroimage. 2001;14(1):S103–9.
100. Hanakawa T, Dimyan MA, Hallett M. Motor planning, imagery, and execution in the distributed motor network: a time-course study with functional MRI. Cereb Cortex. 2008;18(12):2775–88.
101. Ranganathan VK, Kuykendall T, Siemionow V, Yue GH. Level of mental effort determines training induced strength increases. Abstr Soc Neurosci. 2002;32:768.
102. Siemionow V, Yue GH, Ranganathan VK, Liu JZ, Sahgal V. Relationship between motor activity-related cortical potential and voluntary muscle activation. Exp Brain Res. 2000;133(3):303–11.
103. Kasess CH, Windischberger C, Cunnington R, Lanzenberger R, Pezawas L, Moser E. The suppressive influence of SMA on M1 in motor imagery revealed by fMRI and dynamic causal modeling. Neuroimage. 2008;40(2):828–37.
104. Guillot A, Di Rienzo F, MacIntyre T, Moran A, Collet C. Imagining is not doing but involves specific motor commands: a review of experimental data related to motor inhibition. Front Hum Neurosci. 2012;6(September):1–22.
105. Solodkin A, Hlustik P, Chen EE, Small SL. Fine modulation in network activation during motor execution and motor imagery. Cereb Cortex. 2004;14(11):1246–55.
106. Jeannerod M. Mental imagery in the motor context. Neuropsychologia. 1995;33(11):1419–32.
107. Gandevia SC. Mind, muscles and motoneurones. J Sci Med Sport. 1999;2(3):167–80.
108. Moran A. Conceptual and methodological issues in the measurement of mental imagery skills in athletes. J Sport Behav. 1993;16:156–70.
109. Guillot A, Collet C, Nguyen VA, Malouin F, Richards C, Doyon J. Functional neuroanatomical networks associated with expertise in motor imagery. Neuroimage. 2008;41(4):1471–83.
110. García Carrasco D, Aboitiz Cantalapiedra J. Effectiveness of motor imagery or mental practice in functional recovery after stroke: a systematic review. Neurology (English Ed.). 2016;31(1):43–52.
111. Mahmoud N. The efficacy of motor imagery training on range of motion, pain and function of patients after total knee replacement. 2016. CUNY Academic Works. http://academicworks.cuny.edu/gc_etds/1235. Accessed 11 Jan 2017.
112. Jiang C-H, Ranganathan VK, Siemionow V, Yue GH. The level of effort, rather than muscle exercise intensity determines strength gain following a six-week training. Life Sci. 2017;178:30–4.
113. Guillot A, Lebon F, Rouffet D, Champely S, Doyon J, Collet C. Muscular responses during motor imagery as a function of muscle contraction types. Int J Psychophysiol. 2007;66(1):18–27.
114. Penfield W, Rasmussen T. The cerebral cortex of man: a clinical study of localization of function. J Am Med Assoc. 1950;144(16):1412.
115. Bernhard C, Bohm E. Cortical representation and functional significance of the corticomotoneuronal system. AMA Arch Neurol Psychiatry. 1954;72(4):473–502.
116. de Luca CJ, LeFever RS, McCue MP, Xenakis AP. Behaviour of human motor units in different muscles during linearly varying contractions. J Physiol. 1982;329:113–28.
117. Abbruzzese G, Assini A, Buccolieri A, Schieppati M, Trompetto C. Comparison of intracortical inhibition and facilitation in distal and proximal arm muscles in humans. J Physiol. 1999;514(3):895–903.
118. Ahtiainen JP, Pakarinen A, Alen M, Kraemer WJ, Häkkinen K. Muscle hypertrophy, hormonal adaptations and strength development during strength training in strength-trained and untrained men. Eur J Appl Physiol. 2003;89(6):555–63.
119. Yamada H, Kaneko K, Masuda T. Effects of voluntary activation on neuromuscular endurance analyzed by surface electromyography. Percept Mot Skills. 2002;95:613–9.
120. Amiridis IG, Martin A, Morlon B, Martin L, Cometti G, Pousson M, et al. Co-activation and tension regulating phenomena during isokinetic knee extension in sedentary and highly skilled humans. Eur J Appl Physiol Occup Physiol. 1996;73(1–2):149–56.
121. Herbert RD, Gandevia SC. Muscle activation in unilateral and bilateral efforts assessed by motor nerve and cortical stimulation. J Appl Physiol. 1996;80(4):1351–6.
122. Bergmann J, Kumpulainen S, Avela J, Gruber M. Acute effects of motor imagery on performance and neuromuscular control in maximal drop jumps. J Imag Res Sport Phys Act. 2013;8(1):45–53.
123. Avila BJ, Brown LE, Coburn JW, Statler TA. Effects of imagery on force production and jump performance. J Exerc Physiol. 2015;18(4):42–8.
124. Wakefield C, Smith D. From strength to strength: a single-case design study of PETTLEP imagery frequency. Sport Psychol. 2011;25(3):305–20.
125. Krieger JW. Single versus multiple sets of resistance exercise: a meta-regression. J Strength Cond Res. 2009;23(6):1890–901.
126. Granacher U, Borde R, Hortoba T. Dose–response relationships of resistance training in healthy old adults: a systematic review and meta-analysis. Sports Med. 2015;45:1693–720.
127. Babault N, Pousson M, Ballay Y, Van Hoecke J. Activation of human quadriceps femoris during isometric, concentric, and eccentric contractions. J Appl Physiol. 2001;91(6):2628–34.
128. Schoenfeld BJ, Wilson JM, Lowery RP, Krieger JW. Muscular adaptations in low- versus high-load resistance training: a meta-analysis. Eur J Sport Sci. 2014;16(1):1–10.
129. Suga T, Okita K, Morita N, Yokota T, Hirabayashi K, Horiuchi M, et al. Intramuscular metabolism during low-intensity resistance exercise with blood flow restriction. J Appl Physiol. 2009;106(4):1119–24.
130. Loenneke JP, Wilson JM, Pujol TJ, Bemben MG. Acute and chronic testosterone response to blood flow restricted exercise. Horm Metab Res. 2011;43(10):669–73.
131. Tran QT, Docherty D, Behm D. The effects of varying time under tension and volume load on acute neuromuscular responses. Eur J Appl Physiol. 2006;98(4):402–10.

132. Burd NA, Andrews RJ, West DWD, Little JP, Cochran AJR, Hector AJ, et al. Muscle time under tension during resistance exercise stimulates differential muscle protein sub-fractional synthetic responses in men. J Physiol. 2012;590(Pt 2):351–62.
133. Schott J, McCully K, Rutherford OM. The role of metabolites in strength training. Eur J Appl Physiol Occup Physiol. 1995;71(4):337–41.
134. Taylor NF, Dodd KJ, Damiano DL. Progressive resistance exercise in physical therapy: a summary of systematic reviews. Phys Ther. 2005;85(11):1208–23.
135. Kreamer WJ, Kent A, Enzo C, Dudley GA, Dooly C, Feigenbaum MS. Progression models in resistance training for healthy adults. Med Sci Sport Exerc. 2009;41(3):687–708.
136. Rozand V, Lebon F, Stapley PJ, Papaxanthis C, Lepers R. A prolonged motor imagery session alter imagined and actual movement durations: potential implications for neurorehabilitation. Behav Brain Res. 2016;297:67–75.