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Effects of mental imagery on muscular strength in healthy and patient participants: A systematic review

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Running head: Mental imagery and strength gain/loss.

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Abstract

The aims of the present review were to (i) provide a critical overview of the current literature on the effects of mental imagery on muscular strength in healthy participants and patients with immobilization of the upper extremity (i.e., hand) and anterior cruciate ligament (ACL), (ii) identify potential moderators and mediators of the “mental imagery-strength performance” relationship and (iii) determine the relative contribution of electromyography (EMG) and brain activities, neural and physiological adaptations in the mental imagery-strength performance relationship. This paper also discusses the theoretical and practical implications of the contemporary literature and suggests possible directions for future research. Overall, the results reveal that the combination of mental imagery and physical practice is more efficient than, or at least comparable to, physical execution with respect to strength performance. Imagery prevention intervention was also effective in reducing of strength loss after short-term muscle immobilization and ACL. The present review also indicates advantageous effects of internal imagery (range from 2.6 to 136.3%) for strength performance compared with external imagery (range from 4.8 to 23.2%). Typically, mental imagery with muscular activity was higher in active than passive muscles, and imagining “lifting a heavy object” resulted in more EMG activity compared with imagining “lifting a lighter object”. Thus, in samples of students, novices, or youth male and female athletes, internal mental imagery has a greater effect on muscle strength than external mental imagery does. Imagery ability, controllability, past experiences, and self-efficacy have been shown to be the variables mediating the effect of mental imagery on strength performance. Finally, the greater effects of internal imagery than those of external imagery could be explained in terms of neural adaptations, stronger brain activation, higher muscle excitation, greater somatic and sensorimotor activation and physiological responses such as blood pressure, heart rate, and respiration rate.

Key words: Imagery, strength gains, strength loss, rehabilitation.

Key Points:

- Coupling mental imagery with physical training is the best suited intervention for improving strength performance.
- An examination of potential moderator variables revealed that the effectiveness of mental imagery on strength performance may vary depending on the appropriate matching of muscular groups, the characteristics of mental imagery interventions, training duration, and type of skills.
- Self-efficacy, motivation, and imagery ability were the mediator variables in the mental imagery-strength performance relationship.
- Greater effects of internal imagery perspective on strength performance than those of external imagery could be explained in terms of neural adaptations, stronger brain activation, higher muscles excitation, greater somatic and sensorimotor activation, and higher physiological responses such as blood pressure, heart rate, and respiration rate.
- Mental imagery prevention interventions may provide a valuable tool to improve the functional recovery after short-term muscle immobilization and anterior cruciate ligament in patients.

Introduction

Several sports coaches around the world have discovered that optimal performance is contingent upon "psyching-up" just as much as it is on physical preparation and technical skill (Tod et al., 2003, 2015). However, sport and exercise psychologists have reported that strength athletes need to undertake some form of psyching-up prior to performance, both in training and competition (McCormick et al., 2015; Tod et al., 2015). Cognitive strategies or psyching-up strategies are reliably associated with increased strength performance (results range from 61 to 65%) (Tod et al., 2015). Typical strategies include mental imagery. This psyching-up technique has been applied to (a) reduce muscle fatigue, (b) improve strength performance in sports without sensorial input, using mental training with perceptual experiences, which includes simulations of movements and specific task perceptions and (c) enhance motor recovery in patients after injuries (Reiser et al., 2011; Rozand et al., 2014; Tod et al., 2015). Mental imagery is defined as "using all the senses to recreate or create an experience in the mind" (Cumming and Williams, 2014). This technique has become one of the most widely used simulation tools and performance enhancement strategies in sports psychological interventions (Cumming and Williams, 2014; Slimani et al., 2016). Recent research has shown that mental imagery improves motor tasks (muscular power: Slimani and Chéour, 2016; sprinting: Hammoudi-Nassib et al., 2014; and endurance: McCormick et al., 2015). The improvements associated with this technique have been related to several mechanisms, including psychological skills such as motivation (Martin and Hall, 1995; Slimani and Chéour, 2016), self-efficacy (Beauchamp et al., 2002; Slimani et al., 2016), self-confidence (Weinberg, 2008; Slimani et al., 2016), and managing competitive anxiety (Vadoaab et al., 1997). As will be discussed, a few early researches suggest that mental imagery training may improve functional recovery after short-term muscle immobilization and anterior cruciate ligament (ACL) by the reduction of strength loss (Clark et al., 2014; Frenkel et al., 2014; Newsom et al., 2003).

Mental imagery can be carried out in various forms, including the auditory, olfactory, tactile, gustatory, kinesthetic, and visual modes (Cumming and Williams, 2014). Furthermore, mental imagery can be performed using one of two basic perspectives, namely internal or external (Cumming and Williams, 2014). The internal perspective involves imaging from within the body and experiencing the motor act without overt movement, i.e., the subject imagines that he or she is really performing the motor act, that his or her muscles are contracting, and that he or she feels kinesthetic sensations (Jeannerod, 1994). The external perspective, on the other hand, involves imagining the action as if it is outside the body, i.e., the motor task is generated in the mind of subjects (Wang and Morgan, 1992). Despite the general consensus among experts that mental imagery could offer promising opportunities for the enhancement of physical strength performance (Tod et al., 2003; Feltz and Landers, 1983), there is no conclusive result regarding which modality is most effective. In fact, research on this cognitive simulation technique has evolved over the past three decades, and researchers have spent considerable efforts investigating the mental imagery perspectives and their relationship with strength performance. Despite a voluminous literature on this subject, there is no definitive understanding of the effects of mental imagery perspectives on muscle strength (Sidaway and Trzaska, 2005). In fact, the literature presents different and sometimes opposing views, and it is only recently that researchers have realized the need for a timely literature review that critically analyzes and updates current knowledge on mental imagery.

Ranganathan et al. (2002) showed stronger effects on strength for high compared with low mental effort (20.5% vs. 2%, respectively). They also showed that internal imagery induces a greater improvement in strength performance compared with that induced by external imagery techniques (10% vs. 5.3%, respectively). Furthermore, several studies have demonstrated the presence of muscular activity (electromyography: EMG) during mental imagery directed towards the production of force (Guillot and Collet, 2005; Yao et al., 2013). Accordingly, and based on the imagery perspectives and the relationship with EMG activity, internal imagery results in significantly higher muscle excitation than external imagery of the same movement (Bakker et al., 1996; Hale, 1982; Harris and Robinson, 1986). Thus, several studies have demonstrated that alternation of mental imagery and voluntary contractions could increase the volume of training and limit the development of muscle fatigue in healthy adults (Ranganathan et al., 2004). Research in this area could provide both theoretical and practical contributions to the field. For example, it could provide athletes and coaches with principled insight on how to optimize their use of mental imagery, help understand the underlying mediators and moderators influencing the effect of mental imagery on strength performance, and stimulate future research on the multiple factors involved in the development of mental imagery theory and practice.

Although many practical imagery interventions have been shown to improve strength performance, little is known about the mechanisms underlying these improvements. According to the literature, such mechanisms are marked largely by references to the role of neurophysiological variables. There is also little question that neural factors play an important role in muscle strength gains and motor recovery after injuries. One of the historical reasons for the lack of evidence is that mental imagery has not been subject to extensive empirical examination. The situation has evolved somewhat over the past two decades, and researchers have expended considerable effort investigating the mental imagery and the mechanisms underlying strength increases.

As it is now well known, common neural substrates underlie motor performance and mental imagery (Guillot et al., 2008; Guillot and Collet, 2008; Zijdewind et al., 2003), and understanding the neural correlates of goal-directed action, whether executed or imagined, has been an important aim of cognitive brain research since the advent of functional imaging studies (Gabriel et al., 2006). In addition, despite the consensus between sports psychologists regarding the increase in strength conditions with internal mental imagery and the correlations between neural adaptations and strength performance improvement, there is no conclusive result concerning which modality (perspective) is most effective in neurophysiological adaptations. To date, each type of mental imagery has been considered to have different properties with respect to both psychophysical (Jeannerod, 1995) and physiological (Stinear et al., 2006) perspectives and to the nature of the neural networks that they activate (Guillot et al., 2009; Solodkin et al., 2004). Accordingly, many studies have shown that external imagery perspective produces a little physiological response (Lang et al., 1980; Ranganathan et al., 2004; Wang, 1992) and is not as effective in enhancing muscle force as internal imagery training did (Ranganathan et al., 2002).

Previous reviews examined the effects of mental imagery on various outcomes (i.e., motor learning and performance, motivation, self-confidence and anxiety, strategies and problem-solving, and injury rehabilitation) (Bowering et al., 2013; Khaled, 2004; Kossert and Munroe-Chandler, 2007; Zimmermann-Schlatter et al., 2008) and neurophysiological adaptations (Guillot and Collet, 2005). Thus, six imagery models and frameworks were reviewed by Guillot and Collet (2008). Although some psychophysiological models related to endurance performance are currently available in the literature (Smirmaul et al., 2013), similar models related to strength performance are still lacking. The purpose of the present systematic review is to examine the influence of mental imagery on the outcome of muscular strength. There are three reasons why such a systematic review will advance current understanding. First, previous reviews have not examined the effects of mental imagery on strength performance in healthy participants as well as strength loss for persons with immobilization and ACL (Braun et al., 2013; Tod et al., 2003, 2015). Second, much research is currently interested in the relationship between mental imagery and muscular strength to provide guidelines for coaches, sports psychologists, and therapists to create effective imagery intervention for use with their athletes or patients. Third, unlike narrative review, systematic review involves a detailed and comprehensive plan and search strategy derived a priori, with the goal of reducing the risk of bias by identifying, appraising, and synthesizing all relevant studies on the present topic. Thus, a systemic review about effects of mental imagery on muscular strength in healthy and patients subjects is a well planned way to answer this specific research question using a systematic and explicit methodology to identify, select, and critically evaluate results of the studies included in the literature review (Khan et al., 2000). While narrative review works have an important role in continuing education because they provide readers with up-to-date knowledge about a specific topic or theme (Khan et al., 2000). Furthermore, this review aims to (a) identify the effects of mental imagery on strength performance and EMG activity in healthy participants and patients with immobilization and ACL, (b) evaluate the moderator and mediator variables related to the mental imagery-strength performance relationship and (c) determine the neurophysiological mechanisms implicated in the imagery-muscle strength relationship with the goal of laying the foundation for practical applications in sports medicine.

Methods

Search strategy

This systematic review was conducted in accordance with Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) Statement guidelines (Moher et al., 2009). Actually, Moher et al. (2009) claimed that the PRISMA is the best way to improve the transparency, accuracy, completeness, and frequency of documented systematic review and meta-analysis protocols. Some papers claiming to be systematic reviews are actually narrative reviews, because they do not apply transparent, objective, and replicable methods to all aspects including the literature search, data extraction, and data analysis. Many times these papers also report results from individual studies without making objective and rigorous attempts to integrate findings and advance knowledge. Adherence to PRISMA guidelines in this review helped ensure these standards of rigor and objectivity were applied to all aspects of the study. The PRISMA guidelines include the four-step systematic approach of identification, screening, eligibility, and inclusion (Figure 1). A systematic search of the research literature was conducted for randomized controlled trials (RCTs) studying the effects of mental imagery on strength performance and strength loss. Studies were obtained through manual and electronic journal searches (up to March 2016). The present review used the following databases: PubMed, SCOPUS, SportDiscus, PsycINFO, PsycARTICLES, Google Scholar, and ScienceDirect. Electronic databases were searched using keywords and/or MeSH terms, such as "mental", "mental imagery", or "mental imagery perspectives", in combination with the terms "sport", "strength", "performance", "strength loss", "immobilization", "anterior cruciate ligament", "muscular activity", "neural", and "physiology". The search was restricted to studies written in the English language published in a peer-reviewed journal. Reference lists of included studies were selected.

*** Figure 1 here***

Inclusion and exclusion criteria

The present review examined internal validity and included studies: (a) involving a control group, (b) measuring maximal strength, (c) RCTs studies, (d) using instruments with high reliability, (e) with minimal experimental mortality, and (f) choosing healthy subjects and patients with immobilization of the upper extremity (i.e., hand) and ACL as participants. Moreover, studies using the moderator and mediator variables of mental imagery for the enhancement of strength performance were also reviewed. In addition, studies examined neural mechanisms underlie mental imagery-muscle strength gain/loss relationship were included. Investigations studied the effects of mental imagery on physiological changes were also included. Furthermore, studies not mentioning mental imagery perspectives (i.e., external or internal) were excluded. Reviews, comments, interviews, letters, posters, book chapters, and books were also excluded.

Evaluation of study quality

The quality of the included studies was assessed formally using the Physiotherapy Evidence Database (PEDro) scale (Maher et al., 2003). This rates validity on a scale of 1-11 according to the following criteria: (a) eligibility criteria specified, (b) random allocation of subjects, (c) concealed allocation of subjects, (d) groups similar at baseline, (e) subject blinding, (f) therapist blinding, (g) assessor blinding, (h) less than 15% dropouts, (i) intention-to-treat analysis, (j) between-group statistical comparisons, and (k) point measures and variability of the data. Item 1 is not used in the scoring because it is related to external validity.

Additional evaluation criteria were also applied. Moderating variables whose strength performance changed were recorded when applicable. Consistent with other systematic reviews (Tod et al., 2011; Tod et al., 2015), the direction of each effect was subsequently coded as positive (+), negative (–), no effect (0), or indeterminant/inconsistent (?) if the effect was ambiguous. In addition, researchers had often used different measures of the same potential mediator concurrently, which may have exaggerated the study's influence on the results (e.g., they may have used two or more imagery questionnaires).

Moderator and mediator variables

Overall, the current literature on mental imagery provides ample evidence that internal mental imagery is an effective strategy for enhancing strength performance. Nevertheless, interesting questions have been raised concerning the factors that might govern mental imagery effectiveness. These factors can be classified into four broad categories: (a) intervention characteristics, (b) training duration, (c) type of skills, and (d) participant characteristics. Furthermore, self-confidence, imagery ability, controllability, and past experiences represent key mediator variables involved in the effects of mental imagery on muscular strength.

Results

Descriptive characteristics of included studies

The search strategies yielded a preliminary pool of 2787 possible papers. After a reading of abstracts and full-text review, only 27 articles met the inclusion criteria. Nineteen papers examined the effects of mental imagery on strength performance in healthy participants. Particularly, fourteen of them studied the effects of imagery perspectives on muscular strength. Thus, eight investigations examined the effects of imagery on strength loss and functional recovery in patients with immobilization of the upper extremity (i.e., hand) and ACL (Table 1AB). Each research work was analyzed in terms of a wide range of characteristics, including participants' age, gender, level, health status and intervention (Table 1AB, 2AB). Each study is listed according to training duration (from 2 to 12 weeks).

Furthermore, the number of participants per study ranged between 17 and 54, and the studies included males and females (Table 1AB and 2AB). The total population size included in this review was 811 (595 healthy and 216 injured participants). Others elements differed between the mental imagery interventions: the number of weeks (range from 2 to 12), the number of mental imagery sessions per week (range from 1 to 5) and the number of imagined trials per mental imagery session (range from 10 to 60) in healthy participants. While in injured participants, the number of weeks ranged from 10 days to 6 months.

*** Table 1A here***

*** Table 1B here***

*** Table 2A here***

*** Table 2B here***

Quality of included studies

The methodological quality of all eligible studies was assessed through the PEDro scale. Procedural objectivity is presumed to optimize the validity of review outcomes, or to yield a closer approximation to 'reality' via the control and/or minimization of bias (Maher et al., 2003). Procedural objectivity, however, does not remove the subjectivity of the process, nor does it even guarantee the transparency or replicability of articles reviewed (Maher et al., 2003). The quality of the included studies is presented in Table 1AB and 2AB. The mean PEDro score was 5.92/10 (range: 3 to 8). In addition, all eligible investigations were randomized controlled trials with an acceptable sample size.

Potential moderator and mediator variables

Overall, the information gathered in the present review indicated that mental imagery can make a valuable contribution to strength performance enhancement in sports. However, an examination of potential moderator variables revealed that the effectiveness of mental imagery on strength performance may vary depending on the appropriate matching of the characteristics of imagery interventions, training duration, and type of skills. Moreover, the present review showed that the following factors affected the effectiveness of mental imagery on muscular activity: low or high EMG activity during mental imagery modulated by imagery perspectives, the intensity of mental effort, weight to be lifted, and activity of the imagined movement.

Mental imagery was classified as consisting of internal and external imagery perspectives and their effect on strength performance. Nevertheless, the empirical research findings (60%) indicated that internal imagery was more beneficial for closed skills than external imagery, whereas performance involving open skills might benefit most from external imagery (Table 3).

*** Table 3 here***

Concerning EMG activity, the results obtained in the present review showed that internal imagery produces higher EMG activity than external imagery does. The high mental effort resulted in more muscular activity compared to that induced by low mental effort. Furthermore, mental imagery with muscular activity was higher in active than passive muscles, and imagining “lifting a heavy object” resulted in higher EMG activity than imagining “lifting a lighter object”. Finally, self-efficacy, motivation and imagery ability were the mediator variables in the mental imagery-strength performance relationship (Table 4).

*** Table 4 here***

Discussion

Mental imagery-muscle strength relationship in healthy and patient participants

Mental imagery has been reported to induce a performance improvement in skilled movements in a comparable way to physical training, which could be explained in terms of adaptation in motor cortex neurons (Guillot and Collet, 2005). This effect is linked to an elevation of time-locked cortical potentials and has been explained in terms of stronger cortical signals to muscles, generated by repetitive mental attempts at maximal muscle activation (Ranganathan et al., 2004). Moreover, the effect is not limited to an improvement of motor execution but also involved muscle strength. Mental imagery training has been reported to increase the performance of strength-based tasks (e.g., voluntary muscular contraction: VMC) for both distal and proximal muscles of the human upper and lower extremities (Fontan et al., 2007; Ranganathan et al., 2004; Reiser et al., 2011; Zijdewind et al., 2003). Recently, Tod et al. (2015) showed a significant effect of mental imagery on muscular strength (63%) similar to that reported in the studies detailed previously in the present review.

In contrast, other studies showed no significant effect of mental imagery on strength performance (Herbert et al., 1998). This difference can be attributed to the variations in moderators' factors, such as mental imagery perspectives, training duration, and muscle groups.

According to previous research, external imagery training is not as effective in enhancing muscle force (Ranganathan et al., 2002) as internal imagery training (Herbert et al., 1998; Ranganathan et al., 2004). Yao et al. (2013) showed that although training involving the internal mental imagery of strong muscle contractions significantly improved voluntary muscle strength, the external mental imagery of the same motor task did not yield the same result.

Muscle groups, whether distal and proximal muscles, differ in the size of cortical representation, the extent of monosynaptic corticospinal projection (Pyndt et al., 2003), and the relative contribution of motor unit recruitment and modulation of discharge rate to the gradation of muscle force (Kukulka and Clamann, 1981). However, some studies reported that maximal strength gain was significantly greater for the distal than the proximal muscle group after mental imagery (Ranganathan et al., 2004). This difference could presumably be attributed to the more frequent use of proximal muscles, which are considered "highly trained", during daily activities (Ranganathan et al., 2004). Lebon et al. (2010) showed that motor imagery effect increase lower-limb muscular force (leg press) but not in the upper-limb movements (bench press) without increase of morphological adaptations. The participants reported that leg press training was here more physically painful and uncomfortable than bench press exercise (this being probably due to the difference in the weight the participants lifted in each of the 2 movements).

Also, the present review indicates that imagery injury prevention interventions have a large effect on reducing strength loss during ACL or when injured athletes remain inactive.

Accordingly, Newsom et al. (2003) showed that imagery prevention intervention was effective in reducing strength loss of wrist flexion/extension after short-term muscle immobilization. More recently, Clark et al. (2014) found the effectiveness of integrating mental imagery in a rehabilitation process on the reduction of strength loss and voluntary activation. Likewise, other study reported greater knee strength and less reinjury anxiety and pain after mental imagery during the rehabilitation period after ACL (Cupal and Brewer, 2001). Mental imagery may thus be considered as a therapeutic strategy to help injured patients to recover motor functions after reconstructive surgery of ACL (Lebon et al., 2011). Moreover, other studies have used imagery as part of a psychological prevention intervention program in the sports rehabilitation process. Ievleva and Orlick (1991) found that goal setting, positive self-talk, healing imagery, and focus of concentration as most highly related to faster healing rates of injured athletes with sports injuries. Further study reported that motor imagery coupled with proprioceptive neuromuscular facilitation was better than physical practice alone in enhancing and maintaining range of motion at the hip joint (Williams et al., 2004). Further RCTs and non-RCTs studies have shown the benefits of short- and long-term mental imagery programs on relearning and performance (e.g., gait) of daily arm function in post-stroke patients (Dickstein et al., 2004; Liu et al., 2004; Page et al., 2007).

In summary, mental imagery training is a promising intervention to improve strength performance and to minimize strength loss in healthy participants and patients with muscle immobilization and ACL, respectively.

Mental imagery and electromyography (EMG) activity

Mental imagery centrally organizes a motor program and activates neurons within various areas of the brain responsible for priming the execution of the motor command in what is thought to lead to increased performance and learning through repeated imagery use. Several authors have demonstrated the presence of electrical muscle activity during subliminal mental simulation of a movement directed towards the production of force (Guillot and Collet, 2005b; Harris and Robinson, 1986). Psycho-neuromuscular theory postulates that feedback generated during mental imagery helps strengthen the motor program corresponding to a motor task (Jacobson, 1932). Otherwise, several data have suggested that mental imagery is accompanied by EMG activity and even by specific selective muscle activation (Guillot and Collet, 2005).

Furthermore, significant increases in maximal and isometric strength were observed after the mental imagery training of previously healthy and patient participants and were largely attributed to increased motor unit activation (Brody et al., 2000; Guillot and Collet, 2005). The increases in the magnitude of EMG caused by mental imagery could be the result of an increased number of active motor units and/or their firing frequencies (Jeannerod, 1994). Some researchers have, however, required the absence of EMG activity as a precondition to perform a specific mental imagery task (Brody et al., 2000; Herbert et al., 1998; Naito et al., 2002; Yue and Cole, 1992). They consider the absence of a significant increase in EMG activity as proof that the pattern of cerebral activation observed during mental imagery is not due to any movement. These differences, which could be attributed to methodological problems, have been explained by Bakker et al. (1996), who reported that during the mental imagery of a movement involving one arm, muscular activity was higher in the active than in the passive arm and that imagining lifting a heavy object resulted in higher EMG activity than that induced by imagining lifting a lighter object (9 kg vs. 4.5 kg, respectively). Consequently, a low or high EMG activity was observed during mental imagery, which was modulated by the lateralization (Jeannerod, 1994), intensity, activity, and lifted the weight of the imagined movement. Another interpretation attributes the decrease in EMG amplitude to a decrease in the central drive to the muscle. Moreover, Guillot et al. (2007) showed that a pattern was recorded for EMG activity during mental imagery in all the muscles involved in the movement, which was considered a function of the weight to be lifted and muscle contraction type, i.e., the highest amplitude being recorded during concentric contraction, the lowest amplitude during eccentric contraction, and the “intermediate” amplitude during isometric contraction. They reported that mental imagery of a heavy concentric contraction (80% of one-repetition maximum [1RM]) resulted in a greater pattern of EMG activity than during mental imagery of a light concentric condition (50% of 1RM). Furthermore, the physiological responses to imagery are specific within one response system and reflect the spatial differentiation and quantitative characteristics of an image (Guillot et al., 2007). These responses have been reported to occur following the performance of a cognitive self-control task (Bray et al., 2008) and to support the postulation that imagining an effortful task causes central fatigue alongside self-control strength depletion (Graham et al., 2014). In fact, taking the imagery perspectives-EMG activity relationship into account, significantly higher muscle excitation can be induced by the internal than external imagery of the same movement (Bakker et al., 1996; Hale, 1982; Harris and Robinson, 1986). Hale (1982) showed that whereas the internal perspective resulted in muscle activity during the imagery of an arm movement, the external perspective did not. The experiment of Harris and Robinson (1986), although less well controlled than the experiment of Hale, have provided further evidence supporting the hypothesis that internal imagery produces higher EMG activity than external imagery. Accordingly, when comparing mental imagery perspectives, Lang (1979) demonstrated that subjects trained in "response propositions" (similar to internal imagery) experienced greater physiological arousal during images than subjects instructed to respond perceptually (external imagery). Moreover, subjects who engaged in kinesthetic imagery showed greater somatic arousal (less sensorimotor alpha) and less visual activity (greater occipital alpha) than subjects who employed visual attention and imagery (external) (Davidson and Schwartz, 1977). Thus, internal imagery is more effective in performance because of the greater muscular, somatic and sensorimotor activities (Fourkas et al., 2006; Hale, 1982; Harris and Robinson, 1986) than those associated with external imagery.

Moderator-related factors affecting mental imagery-strength performance relationship

The present review examined the literature to identify the influential variables that have the potential to moderate the mental imagery–strength performance relationship. The results revealed the prevalence of three major variables, namely (1) characteristics of the imagery intervention, (2) training duration, and (3) type of skills.

Characteristics of imagery interventions

The present review showed that the most important factor influencing mental imagery efficiency relates to the type of intervention. In fact, whereas some studies incorporated shorter (e.g., 3-5 days) or longer (e.g., 3-12 weeks) interventions on imagery, including training on the use of the mental imagery strategy (Ranganathan et al., 2004; Yue and Cole, 1992), other studies did not include any training on mental imagery (Shackell and Standing, 2007). As with any mental imagery strategy, the effects of studies involving training are greater than those not involving training. Furthermore, the level of mental effort during training plays a crucial role in determining strength gains. Ranganathan et al. (2002) showed that high mental effort yielded more strength than low mental effort did (20.5% vs. 2%, respectively) and that internal imagery induced more strength than external imagery did (10% vs. 5.3%, respectively). Several studies have tested the effectiveness of mental skill packages-interventions implementing a variety of mental techniques, such as self-talk, goal setting, relaxation, and performance routines in combination with mental imagery (Patrick and Hrycaiko, 1998; Slimani and Chéour, 2016; Thelwell and Maynard, 2003). For instance, mental imagery has been described to be effective for performance enhancement when combined with other cognitive techniques, such as relaxation, goal setting, hypnosis, and self-talk (Hatzigeorgiadis et al., 2011). The effects of mental training packages on strength performance are also demonstrated (Slimani and Chéour, 2016). In fact, currently available research generally indicates that most athletic interventions are multimodal and include mental imagery along with physical training (Driskell et al., 1994; Wright and Smith, 2009). Researchers have also noted that the addition of mental imagery to a physical training regimen does not induce additional muscle fatigue and that the practice of mental imagery before or during a physical activity activates the corticospinal pathways and improve the intrinsic motivation and stimulation of athletes without causing negative effects on their future performances (Rozand et al., 2014).

The present review indicates advantageous effects of internal imagery (range from 2.6 to 136.3%) for strength performance compared with external imagery (range from 4.8 to 23.2%)

Training duration

To date, imagery studies have used a variety of strength tasks as well as differing volumes and frequencies of imagery training. The data presented in table 1AB and 2AB corroborate the hypothesis that some sort of training increase isometric and maximal strength by inducing adaptations of the central nervous system in student athletes. Thus, a comparison of previous studies involving have similar muscle groups and experimental designs showed that shorter mental imagery training (3-6 weeks) induced greater effects on strength performance in student athletes. In other words, the findings of the present review reveal that mental imagery training performed in shorter durations has greater effects on muscle strength than mental imagery training performed over longer durations (7-12 weeks) (Table 1AB and 2AB). This can be due to the increases of motor-evoked potentials (MEP) amplitudes during short-term motor imagery strength training (3 weeks). Wakefield and Smith (2011) also indicate that training programs delivered in three sessions per week are more effective than those conducted once or twice per week. Although more research is required to explore the effects of differing volumes and frequencies of imagery training on the strength performance of different muscle groups, the current review suggests that three sessions/week training programs might be a good starting point for athletes wishing to benefit from these effects. Furthermore, Feltz and Landers (1983) and Driskell and Moran (1994) have previously proposed that a range of 100 to 200 hundred sessions, lasting from a few seconds to 3 hours, can produce beneficial effects. It is worth noting, however, that athletes could encounter difficulties in maintaining focus and experience mental fatigue over several imagery sessions (Guillot and Collet, 2008). Accordingly, further research on the specific outcomes of mental imagery is needed to better clarify the duration and frequency required for imagery interventions to produce beneficial effects, and why an imagery intervention three sessions per week are more effective than once or twice per week.

Types of skills

If imagery perspective affects the effective use of imagery, then investigating the use of imagery perspectives is imperative to understanding how to use imagery effectively (Morris et al., 2005). In fact, the type of task and preference for imagery perspective could influence the effectiveness of the imagery perspective used by participants. To the best of authors' knowledge, however, to date no literature review has focused on the type of skills-mental imagery relationship implemented and its effects on the achievement of best performance. In fact, several studies have shown that the type of mental imagery used is important in terms of strength performance outcomes (Ranganathan et al., 2002). In this respect, Mahoney and Avener (1977) defined perspective in terms of whether an image is internal or external. Based on this theoretical proposition that conceptualizes mental imagery as either internal or external in nature, studies have often hypothesized that whereas external mental imagery predominantly supports performance on only one task, internal imagery serves multi-task performance. Some studies have also reported that the performance of different types of tasks is affected differently by different perspectives, with external imagery producing greater gains in one task and internal imagery in another (Glisky et al., 1996; Hardy and Callow, 1999; White and Hardy, 1995); these studies have not, however, investigated perspective use.

Morris et al. (2005) have classified skills as open or closed. Open skills are those that require athletes to coordinate their movements to a changing environment during the performance of a task, whereas closed skills are those performed in a relatively constant or predictable environment in which activity is often self-paced, e.g., gymnastics, darts, diving, or shooting. Some psychologists (Harris and Robinson, 1986) have suggested that performance involving closed skills might benefit more from internal imagery whereas performance involving open skills might benefit more from external imagery. Spittle and Morris (2007) reported no significant difference between imagery perspectives in open and closed sports skills, although the use of external imagery during imagery of closed skills tended to be higher than that during imagery of open skills. In contrast, Spittle and Morris (2011) showed no significant difference between the use of external and internal imagery for imagery of open and closed skills. This difference can be attributed to the number of imagery perspective training sessions. Perhaps with more than four sessions, the changes in scores would have been larger.

Other psychologists have suggested that different elements of task performance, such as form (Lanning and Hisanga, 1983) or spatial elements (Paivio, 1985), might influence which perspective is more effective for imagery practice. Furthermore, from a functional equivalence perspective, internal imagery would appear preferable because it more closely approximates the athlete’s view when performing (Jeannerod, 1994; 1995). Some studies, however, support the use of an external orientation when imaging certain form-based skills (Hardy and Callow, 1999; White and Hardy, 1995). It may be more beneficial for athletes to use a combination of perspectives, and more advanced performers will be able to switch from one perspective to another (Smith, 1998). Whereas internal imagery may be more inherent for some mental imagery rehearsal programs in sports, external imagery might add something new and different to the experience.

Athlete skill levels

Tables 1AB and 2AB present the results obtained with regard to the effect of mental imagery on performance across different athlete skill levels. In fact, no studies that directly address this issue have been performed to date. Imagery perspectives were selected as a moderator because descriptive evidence suggests that these perspectives may influence the effectiveness of mental imagery interventions as far as performance is concerned. The results of the present review indicate that the sample consisted of students (Reiser et al., 2011; Shackell and Standing, 2007; Sidaway and Trzaska, 2005; Smith and Collins, 2004; Tenenbaum et al., 1995) and national athletes (Fontani et al., 2007). Furthermore, even though many studies have employed athletes, the range in terms of experience and level varies from beginners (de Ruiter et al., 2012; Ranganathan et al., 2004) to more experienced and elite athletes (Fontani et al., 2007). Typically, the results reported in the literature indicate that elite or more successful performers use more internal imagery than less elite/successful athletes do (Carpinter and Cratty, 1983; Mahoney and Avener, 1977). Some studies recorded no differences between these categories of performer (Hall et al., 1990; Highlen and Bennet, 1983), and other studies reported that elite athletes used more external imagery (Ungerleider and Golding, 1991). The results obtained in the present review indicate a greater effect of internal than external mental imagery on muscular strength for student samples, novices, and youth athletes; for elite athletes, the results are not yet definitive, particularly because of the scarcity of studies in this area.

Mediator-related factors influencing the effectiveness of mental imagery

The present review shows that imagery ability is a variable mediating the effectiveness of mental imagery with regard to strength performance. Athletes and healthy participants who have imagery ability are supposed to have greater control of their images and to create more vivid images than participants with poor imagery ability (Nordin and Cumming, 2005; Slimani et al., 2016). Imagery ability was, for example, found to be an important variable in studies examining the effect of mental imagery on performance (Cumming and Williams, 2014; Slimani et al., 2016). Other studies indicate that successful athletes report having better control of their imagery (Slimani et al., 2016) and experiencing more vivid images (Cumming and Williams, 2012) than less successful ones. Therefore, it appears desirable to determine imagery ability to avoid assessment confusions caused by a difference in imagery ability between participants. Furthermore, it may be hypothesized that better imagers will produce muscular activity patterns during imagery that will correspond more closely to the patterns observed with real movements than subjects who have less vivid images and greater difficulty in controlling them. Future research that includes mediating variables (e.g., potential motivation and mental imagery ability) could clarify the psychological and cognitive mechanisms through which psychological manipulations affect strength performance. Finally, researchers are encouraged to include additional psychological mediating variables, such as self-efficacy, sport confidence and motivation (Levy et al., 2015; Slimani and Chéour, 2016), which could shed light on the psychological mechanisms underlying changes in strength performance.

The mechanisms of imagery-muscle strength relationship

Neural adaptations

Neurological mechanisms, most likely at the cortical level and physiological factors are key determinants of muscle strength/weakness (loss). Physiology research into strength training has found that the increase in strength gains is mostly caused by neural adaptations. In fact, Ranganathan et al. (2004) and Yao et al. (2013) have suggested that neural factors, rather than changes at the muscular level, largely account for imagery training-induced strength gains. However, imagery training-induced neural adaptations may also include improvements in muscle coordination, such as reductions in the activity of the antagonist muscles when exerting the agonist muscle (maximal voluntary contraction: MVC) (Ranganathan et al., 2004).

Research that focuses on internal biological factors during and after imagery could assist in understanding why these negative performance after-effects occur. Although several theories have been proposed to account for the effects of mental imagery on physical performance, two distinct perspectives are evident in the literature: central and peripheral (Mulder, 2007). The central perspective of imagery suggests that engaging in the imagery of physical tasks leads to the activation of neurons in the various structures of the central nervous system (CNS) (e.g., primary motor cortex, pre-motor cortex, basal ganglia, cerebellum, parietal cortex, and the prefrontal cortex) that are responsible for the execution of the movement (Hetu et al., 2013; Mulder, 2007). In other words, imagery centrally organizes a motor program and activates neurons within various areas of the brain responsible for priming the execution of the motor command, which is what is thought to lead to increased performance and learning through repeated imagery use. Yue and Cole (1992) have proven that changes in the cortico-cortical network are the source of strength gain after mental imagery. Furthermore, changes in the neural control of muscles might underlie the effect of imagery training on muscle force production, e.g., a change in muscle coordination or an increase in the activation levels of the target muscles (Zijdewind et al., 2003).

Few neuroimaging studies concerning the distinction between internal and external imagery have been reported. Jeannerod (1994) suggested that not only are internal and external imagery encoded in the brain using different neural networks but these neural pathways are also activated by imagery in the same way that they are activated when actually performing the imagined act. For instance, previous study has suggested that the overlapping of neural networks in motor and pre-motor cortices, including supplementary motor area (SMA), is activated during internal imagery and motor performance (Porro et al., 2000), although the primary motor cortex (M1) has not always been found to be activated (Guillot and Collet, 2005). Neuroimaging data have also provided evidence that cerebral plasticity occurring during the incremental acquisition of a motor task is reflected in the same brain regions during mental imagery and that specific cerebral structures are activated when distinguishing mental imagery through a first-person (internal imagery) process from the mental imagery of another person (external imagery) engaging with an object (Ruby and Decety, 2001). Thus, the combination of both imagery methods is expected to be maximally effective for enhancing performance because it activates both neural pathways (Hardy and Callow, 1999).

Traditional neurorehabilitation approaches and mental imagery have an impact on such reorganization and associated motor, functional and neurological recovery (Arya et al., 2011). Thus, neural reorganization after injuries is thought to be an important mechanism to facilitate motor recovery. Thus, the capability of the cerebral cortex and related network can be exploited for patients with ACL. Mental imagery can be performed during the phase of recovery when volitional movements are either impossible or being performed synergistically. In terms of the relative contribution of neural and muscular factors regulating strength loss in patients, previous studies have postulated that much of the disuse-induced loss of strength is related to neural factors (Deschenes et al., 2002; Kawakami et al., 2001). Clark et al. (2006b) reported that neural factors (primarily deficits in central activation) explained 48% of the variability in strength loss, whereas muscular factors (primarily sarcolemma function) explained 39% of the variability. They did not found any effect of mental imagery on the Hreflex or nerve conduction responses. Although the influence of mental imagery training was observed on supraspinal neural functional, as the primary mechanism underlying the strength increase following mental training-induced enhancement (in the absence of disuse) is the supraspinal command to muscle, probably mostly localized to the cerebral cortex (Ranganathan et al., 2004).

Physiological responses

If mental imagery shares neural mechanisms with those responsible for motor programming, then brain activation during imagined action should be reflected, in some way, at the peripheral effectors level (Roth et al., 1996). Autonomic nervous system (ANS) peripheral effectors are activated by mental imagery (Lang, 1979). The imagination and observation of exercise (i.e., anaerobic exercise) has also been shown to cause changes in the cardiovascular system, with significant changes in blood pressure, heart rate, and respiration, which occur in the absence of muscle contraction or movement (Fusi et al., 2005; Paccalin and Jeannerod, 2000; Wang and Morgan, 1992; Williamson et al., 2002) (Table 5). Previous studies have shown that heart rate increases during mental imagery (Beyer et al., 1990; Jones and Johnson, 1980). Furthermore, Williamson et al. (2002) observed increases in both heart rate and blood pressure during imagined handgrip. Accordingly, other studies have demonstrated that similar autonomic responses in an attentionally engaging task (shooting events) occur during real and imagined attempts (Deschaumes-Molinaro et al., 1992; Guillot et al., 2004).

*** Table 5 here***

Measuring cardiac and respiratory activity during the mental simulation of locomotion at increasing levels revealed a co-variation of heart rate and pulmonary ventilation with the degree of imagined effort (Decety et al., 1991; 1993). The possibility that cardiac and respiratory effects recorded during such mental imagery could have been caused by peripheral factors (such as co-contraction of antagonist muscle groups) was eliminated because muscular metabolism measured using nuclear magnetic resonance spectroscopy remained unchanged (no change in phosphocreatine concentration and intracellular pH levels). In contrast, Wang and Morgan (1992) proved that heart rate, subjective rating of perceived exertion (RPE) and metabolic responses to imagined exercise were significantly lower than in actual exercise, whereas blood pressure was found to be similar between the two conditions. This difference can be attributed to the degree of imagined effort and mental imagery perspectives. The mechanisms underlying the cardiovascular effect of imagined exercise is not known, but it is possible that the CNS and the activation of the cortex cause an increase in sympathetic outflow and reciprocal inhibition of parasympathetic activity.

Concerning the mental imagery perspectives, internal imagery generates significantly greater physiological responses, such as in blood pressure, heart rate, and respiration rate than external imagery, in which only an image of the motor task is generated in one’s mind, as if the person was viewing him- or herself exercising on a television screen (Lang, 1979; Lang et al., 1980; Wang and Morgan, 1992). Ranganathan et al. (2004) observed significant increases in heart rate and blood pressure during the internal mental training of little finger abduction contractions.

Theoretical implications

The results presented in this review may provide important theoretical and practical contributions to mental imagery researchers and practitioners. The latter can, for instance, provide athletes and coaches with principled advice on optimizing their use of mental imagery. Moreover, the critical summary of the available literature on the mental imagery-strength performance relationship and the moderator and mediator-related factors involved in mental imagery practice should stimulate future investigations with strong theoretical and applied implications. In a sporting situation, the use of mental imagery is observed during training preceding competitive events and during rehabilitation. However, although some psychophysiological models related to sport performance and endurance performance are currently available in the literature (Smirmaul et al., 2013), similar models related to strength performance are still lacking. The information gathered in the present review and the evidence provided by other research studies in support for the mental imagery-muscle strength relationship and motivational intensity theory (Brehm and Self, 1989) show that the increase in maximal voluntary activation (MVA) and potential motivation are the ultimate determinants of enhanced strength performance. Consequently, the psychobiological model predicts that any psychological or physiological factor that increases potential motivation or increases MVA will improve strength performance and that any psychological or physiological factors that reduce the potential motivation or MVA will undermine strength performance. It may thus be noted that the effect of mental imagery on the individual's ability to enhance motivation and self-confidence to improve strength is greater than its effect on the technical key components of the movement per se.

Limitations and recommendations for future research

Although this review provides clear evidence of the positive effects of mental imagery on strength performance, most of the included studies presented some limitations with respect to the adopted methodology (an average PEDro score < 6). It is well known that bias may complicate efforts to establish a cause-effect relationship between procedures of mental imagery and strength outcomes. Thus, because some degree of bias is almost always present in the study of mental imagery, researchers must consider how bias might influence strength effects. Research on the impact of mental imagery perspectives on neurophysiological and hormonal adaptations are scarce or unavailable and future studies, thereafter, are recommended. Most of the studies conducted on this topic to date have also used samples drawn from student and/or untrained populations. It is not clear whether the results observed in these groups can be generalized to well-trained or elite populations. For that reason, researchers are encouraged to compare different mental imagery intervention perspectives and to examine the effects of these interventions for athletes in competitive situations. Furthermore, future investigations should detail why and how a short duration imagery interventions would increase athletes' muscular strength. Additionally, the present review recommends the improvement of the internal validity, which refers to the reliability and/or accuracy of the protocol used in mental imagery studies. Internal validity ensures that the study design, implementation, and data analysis confidently minimize bias and that the findings are representative of the true association between mental imagery and increase in strength performance.

Conclusion and practical implication

This systematic review provided a critical overview of the major peer-reviewed studies published to date in the literature seeking evidence in support of or opposition to the effect of mental imagery perspectives on strength performance. The review also searched for the potential moderator and mediator variables that might affect the mental imagery-strength performance relationship. The neurophysiologic mechanisms of the mental imagery-strength performance relationship were also discussed. The results reveal that the combination of mental and physical training is more efficient than, or at least comparable to, physical execution when there is no decrease in the total physical performance time. The findings also indicate that maximal strength gain is significantly greater for the distal than proximal muscle group after mental imagery training. Thus, the results demonstrate that the internal imagery perspective has greater effects on strength performance than on external imagery. In addition, this review suggests that mental imagery might be of benefit in preventing the strength losses that occur during immobilization and ACL. The data available on the direct effects of mental imagery on strength performance and EMG activity are very limited. This limitation could be attributed to (1) the fact that internal imagery involves higher degrees of muscle excitation than external imagery, (2) that mental imagery with muscular activity is higher in the active than in the passive organ, and (3) that imagining "lifting a heavy object" results in higher EMG activity than imagining "lifting a light one". It was also noted that high mental effort induced higher EMG activity than low mental effort. The present review reported on the factors that may moderate the effectiveness of mental imagery, namely mental imagery perspectives, characteristics of the intervention, training duration, and types of skills. Furthermore, internal mental was reported to have greater effects on strength among healthy participants than external imagery. Thus, external imagery perspective predominantly supports performance on only one task, although internal imagery serves multi-task performance. Furthermore, short-duration (3-6 weeks) mental imagery training has greater effects on strength performance than long-duration mental training (7-12 weeks). However, the effects of mental imagery interventions on strength performance after three or more months are unknown.

Strength gain in healthy participants and strength loss in patients are related to neural factors. Strength gains would also be more directly related to the physiological adaptations and psychological effects (e.g., improve self-confidence and motivation) of mental imagery in healthy participants. For instance, the actual movement has been shown to elicit higher amplitudes of brain activation than mental imagery. Taken together, the reported results provide evidence that mental imagery and motor performance share similar behavioral, physiological, neural mechanisms and anatomical characteristics. However, each type of mental imagery has different properties with respect to both psychophysical and physiological perspectives and with respect to the nature of the neural networks that are activated by them.

Likewise, the present review supports hypotheses indicating a selective effect of internal mental imagery at the level of muscular strength by the higher neurophysiological adaptations of internal imagery than external imagery. In fact, the internal imagery perspective has stronger effects in producing strong brain activation, higher muscle excitation and corticomotor excitability modulation, greater somatic and sensorimotor activation and physiological responses such as blood pressure, heart rate, and respiration rate than the external imagery perspective. In addition, the combination of both imagery methods would be more effective in neural pathways. We suggest also that internal imagery can better improve strength performance than external imagery by enhancing psychological variables such as attentional focus, self-confidence, effort regulation, cognitive and emotional reactions control, and automatic execution triggering. Indeed, this review suggests that the relationship between imagery and strength performance be considered as a starting point to build a psychophysiological model of strength performance. Experimental paradigms that involve brain-mapping techniques and autonomic system measurements in combination with the assessment of performance improvement are necessary in order to gain more insight into the mechanisms underlying mental imagery or mental practice. Future research is encouraged to monitor both brain, physiological responses, and muscle activity during, and following, imagery to gain a better in-depth understanding of the mechanisms involved in the imagery-strength performance relationship. Moreover, the challenge for future researchers is to identify the precise nature of the neuromuscular and hormonal adaptations that accompany mental imagery and to determine patterns of interaction among these adaptations for various classes of movement (e.g., dynamic tasks, muscular power) in healthy and patient participants. The psychological, cognitive and physiological mechanisms underlie mental imagery-strength loss relationship in injured athletes are needed to support the present date.

Additionally, training programs could be adjusted and adapted to include mental imagery in addition to physical practice, which may reduce the likelihood of overuse injuries, physiological stress and overtraining, while still proving sufficient to stimulate strength increases. Coaches, educators, athletes, sport psychologists, and therapists are strongly advised to practice/perform and persist with their mental imagery plans with physical training routines to maximize gains and minimize the disuse-induced loss in muscle strength.

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Table 1A. Effect of mental imagery in muscular strength/strength loss in healthy and patient participants.

Study	Characteristics (Age; n; Sex; Health status)	Injury	Imagery intervention	Results	PEDro scale
Herbert et al. (1998)	NR; 54; Male and female; Healthy students	No injury		-Maximal isometric contractions (elbow flexor)	7
			Mental imagery	↑6.8	
			PG	↑17.8	
				-Voluntary grip strength	
			Mental imagery	↑8.9	
			PG (8 wks/3 dys)	↑2.1 (NSDG)	
Leung et al. (2013)	18-35; 18; Male and female; Healthy participants	No injury	Motor imagery (3 wks/3 dys)	↑16 Voluntary strength of the right biceps brachii	6
Smith et al. (2007)	*Study 1:* 20.37±3.26; 48; Male and female; Healthy student athletes	No injury		Field hockey penalty flic	6
			PETTLEP-based imagery	↑15.11	
	Study 2: 7-14; 40; Female; Healthy athletes		Traditional imagery (6 wks/1 dys)	↑5.59	
			PETTLEP-based imagery (6 wks/3 dys)	Straight jump on the beam ↑36.36	
Wright and Smith (2009)	20.74±3.71; 50; NR; Healthy students	No injury		1RM: bicep curl machine	6
			PETTLEP imagery	↑23.29	
			PETTLEP + PP	↑28.03	
			Traditional imagery	↑13.75	
			PG (6 wks/2 dys)	↑26.56	
Slimani and Chéour (2016)	23.2 ± 3.1; 45 ; Male; Healthy participants	No injury	Mental imagery	↑13.1 1RM bench press ↑16.9 1RM half-squat	6
			PG (10 wks/3 dys)	↑10.7 1RM bench press ↑8.61RM half-squat	
Cupal and Brewer (2001)	28.2±8.2; 30; Male and female; Patients	Anterior cruciate ligament	Relaxation and guided imagery (10 individual sessions over 6 months; Sessions were spaced approximately 2 wks)	↓35 Knee strength	6
Lebon et al. (2010)	19.75±1.72; 22; NR; Healthy students	Anterior cruciate ligament	Motor imagery (4 wks/3 dys)	↑9 Bench press ↑26 Leg press Creater muscle activation	7

Note: Wks: weeks; dys: days; PG: physical group; PP: physical practice; NSDG: no significant difference between groups; 1RM: one-repetition maximum; ↑: increased; ↓: decreased; NR: not reported.

Table 1B. Effect of mental imagery in muscular strength/strength loss in healthy and patient participants.

Study	Characteristics (Age; n; Sex; Health status)	Injury	Imagery intervention	Results	PEDro scale
Clark et al. (2014)	Adults; 29; Female; Healthy participants	Wrist-hand immobilization	Motor imagery (4 wks/5 dys) (Four blocks of 13 imagined contractions each with 1 min of rest between the blocks; Each imagined contraction was 5 s, followed by 5 s of rest)	Maximal wrist-hand flexion ↓23.8 Loss of strength ↓12.9 Voluntary activation	8
Clark et al. (2006b)	21.00±1.41; 18; Male and female; Healthy participants	Prolonged unweighting (bed rest)	Motor imagery (4 wks/4 dys)	↓8.5 Plantar flexor	8
Frenkel et al (2014)	20-30; 20; Male; Healthy participants	Immobilzation after distal radial fracture	Alternation of kinesthetic imagery of the immobilized hand and physical execution of the non-immobilized hand (3 wks (1 × 60 min/ 3 × 30 min) and (7 × 15 min))	Reduced loss of dorsal extension and ulnar abduction	6
Meugnot et al. (2014)	18-26; 52; Male; Student	Left-hand immobilization	Kinesthetic imagery Visual imagery (24 h (3 × 5 min each))	Slowdown of the left-hand movement simulation Reactivating the sensorimotor processes Recovery of motor function	6
Newsom et al. (2003)	18-30; 17; Male and female; Injured participants	Nondominant forearms immobilized	Immobilization-mental imagery (10 dys; 3 sessions per day; 5 min)	↓1.33 Grip strength ↓1.28 Isometric wrist-extension ↓8.18 Isometric wrist-flexion	7
Stenekes et al. (2009)	18-65; 28; NR; Patients	Immobilzation after flexor tendon injuries	Kinesthetic imagery of finger and wrist extension-flexion (6 wks (8 × 5 min))	Reduced increase of one aspect of hand function (preparation time)	6

Note: Wks: weeks; dys: days; ↓: decreased; NR: not reported.

Table 2A. Effects of mental imagery perspectives on strength performance.

Study	Characteristics (Age; n; Sex; AL)	MI perspective (Weeks/sessions)	Strength task	Results	PEDro scale
Shackell and Standing (2007)	19.8±1.4; 30; Male; Students	Internal MI PG (2 wks/5 dys)	-Hip flexor task	↑23.7 ↑28.3	5
Smith and Collins (2004)	30.44±7.79; 19; Male; Students	Internal MI PG SRPMP (3 wks/2 dys)	-Isometric abduction force (metacarpophalangeal joint of the right fifth digit)	↑53.97 ↑56.28 ↑55.68	5
Tenenbaum et al. (1995)	24.7±3.6; 45; Male; Students	Internal MI Positive statements (4 wks/1 dy)	-Bilateral knee extension	↑9.0 (PF); ↑9.0 (PP) ↑24.6 (PF); ↑9.0 (PP)	6
Smith et al. (2003)	29.33±8.72; 18; Male; Students	Internal MI PG (4 wks/2 dys)	-Isometric abduction force (the right abductor digiti minimi muscle)	↑23.27 ↑53.36	5
Sidaway and Trzaska (2005)	19 to 26 (22.7); 24; Male and female; Students	Internal MI PG (4 wks/3 dys)	-MIC ankle dorsi flexor torque	↑17.13 ↑25.28	6
Reiser et al. (2011)	22.7±2.3; 43; Male and female; Students	Internal MI PG (4 wks/3 dys)	-MIC bench press -Leg press	↑3.0 to 4.2 ↑4.3 ↑2.6 to 4.0 ↑8.3	7
de Ruiter et al. (2012)	18–24; 40; Male and female; Recreationally	Internal MI PG (4 wks/3 dys)	-Isometric torque measurement (knee extensors of the right leg)	↑9.3 ↑6.6	7
Yue and Cole (1992)	21-29; 30; NR; Healthy participants	Internal MI PG (4 wks/5 dys)	-Overage isometric contractions of the abductor muscles of the right fifth digit's metacarpophalangeal joint -MIC of the abductor muscles of the left fifth digit's metacarpophalangeal joint	↑10 ↑14 ↑22 ↑30	5

Note: AL: athlete levels; MI: mental imagery; PG: physical group; PF: peak force; PP: peak power; wks: weeks; dys: days; ↑: increased; MIC: maximal isometric contractions; NSD: no significant difference compared to pre-training; NR: not reported; SRPMP: stimulus and response proposition mental practice.

Table 2B. Effects of mental imagery perspectives on strength performance.

Study	**Characteristics (Age; n; Sex; AL)**	**MI perspective (Weeks/sessions)**	**Strength task**	**Results**	**PEDro scale**
Fontani et al. (2007)	35±8.7; 30; Male; National	Internal MI PG (4 wks/5 dys)	-Maximal strength (Karate action: *makiwara*)	↑9.2 ↑8.4	5
Yao et al. (2013)	18–35; 18; NR; Healthy participants	Internal MI External MI (6 wks/5 dys)	-Maximal elbow-flexion contraction (right arm elbow flexion force)	↑10.8 ↑4.8 (NSD)	5
Olsson et al. (2008)	19.3±3.4; 24; Male and female; Elite level	Internal MI PG (6 wks/2 dys)	Jump	↑0.9 ↑1.1	5
Zijdewind et al. (2003)	19-27; 29; Male and female; Healthy participants	Internal MI PG (7 wks/5 dys)	-Plantar-flexors of both legs		5
			After 5 weeks	↑129.6 ↑111.3	
			After 7 weeks	↑136.3 ↑112.9	
			4 weeks after the training period	↑125.3	
Ranganathan et al. (2004)	29.7±4.8; 30; Male and female; Untrained	Internal MI (12 wks/5 dys)	-Fifth finger abductor (distal muscle) -Elbow flexors (proximal muscle)	↑35 ↑13.5	6
Ranganathan et al. (2002)	NR	Internal MI External MI (NR)	NR	↑10 ↑5.3	3

Note: AL: athlete levels; MI: mental imagery; PG: physical group; PP: physical practice; wks: weeks; dys: days; ↑: increased; NR: not reported.

Table 3. Results stratified according to imagery perspectives, training duration and type of skills.

	Numbers of studies	**Sum code**
Imagery perspectives		
Internal imagery	12	+
External imagery	2	?
Training duration		
Short duration	9	+
Long duration	2	?
Open skills		
Internal imagery	5	?
External imagery	5	+
Closed skills		
Internal imagery	5	+
External imagery	5	?

Table 4. Results from mediation variables.

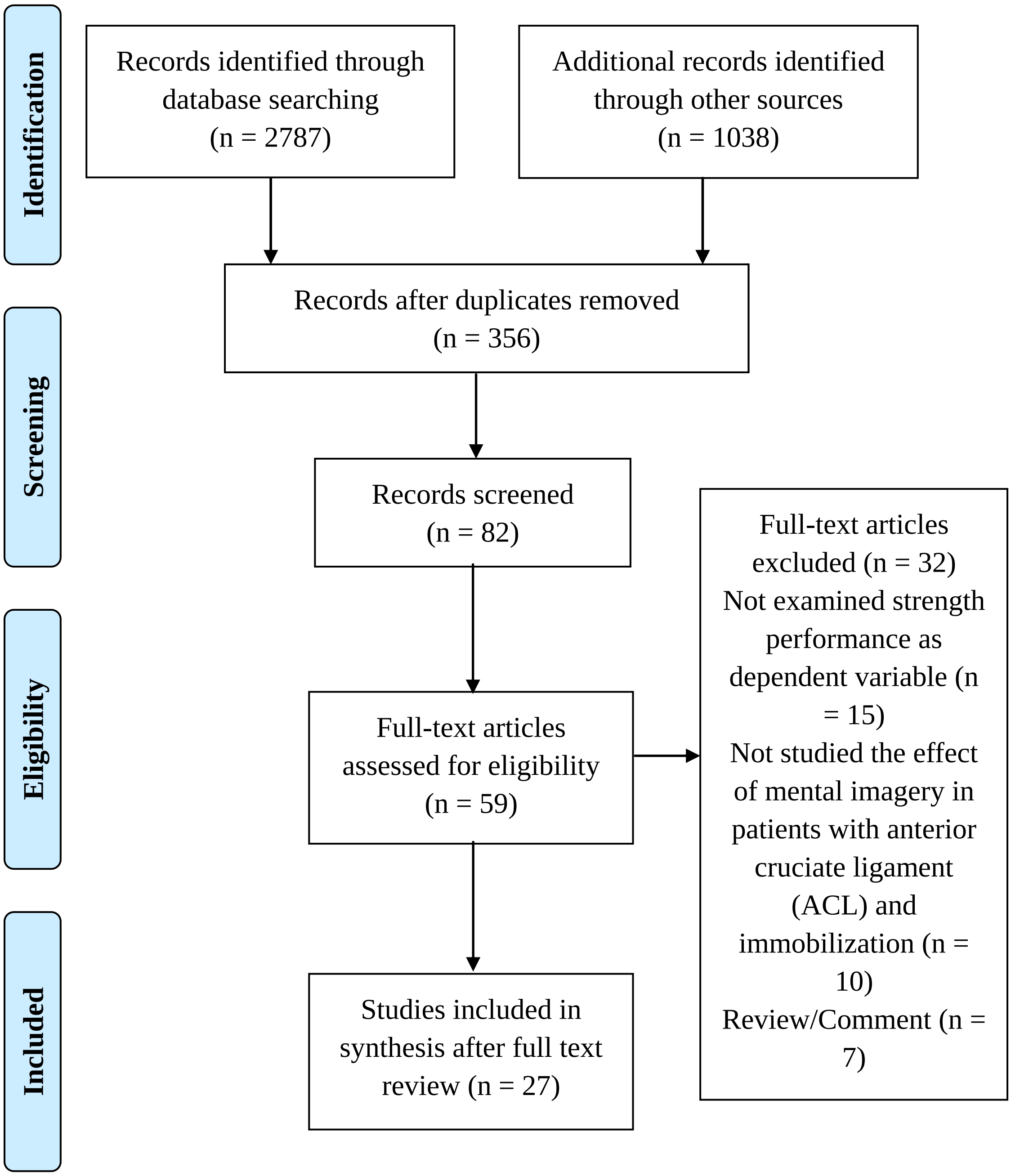
	Number of studies	Sum code
Imagery ability	11	+
Self-efficacy/ self-confidence	2	+
Motivation	1	+

Table 5. Relative changes (%) of physiological variables after imagined exercise.

Study	Characteristics (Age; n; Sex; AL)	Intervention	Physical task	HR (%)	BP (%)	RR (%)
Beyer et al. (1990)	NR; 8; NR; Student	Imagery	Swimming (100 m)	↑71.42	NR	NR
Decety et al. (1993)	21-25; 6; Male; Healthy participants		Leg exercise			
		Imagery	(ergometer)	↑53.57	NR	↑226.92
			15 kg load	↑84.42		↑210.34
		Actual exercise	19 kg load	↑101.59		↑110.93
			15 kg load	↑138.48		↑126.08
			19 kg load			
Decety et al. (1991)	18-26; 11; Male and female; SGPC		Treadmill running (3 min each condition)		NR	NR
		Imagery	5 km/h	↑8.25		
			8 km/h	↑13.20		
			12 km/h	↑19.45		
		Actual exercise	5 km/h	↑44.20		
			8 km/h	↑70.72		
			12 km/h	↑106.08		
Fusi et al. (2005)	22-24; 14; Male and female; Healthy participants		Walking task			
		Imagery	(treadmill)	↑3.75 NSD	NR	NR
			2 km/h	↑5 NSD		
			3.5 km/h	↑5 NSD		
		Actual exercise	5 km/h	↑6.25		
			2 km/h	↑12.5		
			3.5 km/h	↑26.25		
			5 km/h			
Ranganathan et al. (2004)	29.7±4.8; 16; NR; Healthy untrained participants	Imagery	Fifth finger abduction	↑8.33	↑7.76	NR

Note: AL: activity level; HR: heart rate; BP: blood pressure; RR: respiratory rate; SGPC: subjects in good physical condition; NSD: no significant difference compared to pre-training; NR: not reported; ↑: increased.

Figure 1. PRISMA flow diagram detailing the literature search procedure.



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