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

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12
13 **Running head:** Mental imagery and strength gain/loss.

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1 **Abstract**

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

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

2 **Key Points:**

3 • Coupling mental imagery with physical training is the best suited intervention for
4 improving strength performance.

5 • An examination of potential moderator variables revealed that the effectiveness of
6 mental imagery on strength performance may vary depending on the appropriate
7 matching of muscular groups, the characteristics of mental imagery interventions,
8 training duration, and type of skills.

9 • Self-efficacy, motivation, and imagery ability were the mediator variables in the
10 mental imagery-strength performance relationship.

11 • Greater effects of internal imagery perspective on strength performance than those of
12 external imagery could be explained in terms of neural adaptations, stronger brain
13 activation, higher muscles excitation, greater somatic and sensorimotor activation, and
14 higher physiological responses such as blood pressure, heart rate, and respiration rate.

15 • Mental imagery prevention interventions may provide a valuable tool to improve the
16 functional recovery after short-term muscle immobilization and anterior cruciate
17 ligament in patients.

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1 **Introduction**

2 Several sports coaches around the world have discovered that optimal performance is
3 contingent upon “psyching-up” just as much as it is on physical preparation and technical skill
4 (Tod et al., 2003, 2015). However, sport and exercise psychologists have reported that
5 strength athletes need to undertake some form of psyching-up prior to performance, both in
6 training and competition (McCormick et al., 2015; Tod et al., 2015). Cognitive strategies or
7 psyching-up strategies are reliably associated with increased strength performance (results
8 range from 61 to 65%) (Tod et al., 2015). Typical strategies include mental imagery. This
9 psyching-up technique has been applied to (a) reduce muscle fatigue, (b) improve strength
10 performance in sports without sensorial input, using mental training with perceptual
11 experiences, which includes simulations of movements and specific task perceptions and (c)
12 enhance motor recovery in patients after injuries (Reiser et al., 2011; Rozand et al., 2014; Tod
13 et al., 2015). Mental imagery is defined as “using all the senses to recreate or create an
14 experience in the mind” (Cumming and Williams, 2014). This technique has become one of
15 the most widely used simulation tools and performance enhancement strategies in sports
16 psychological interventions (Cumming and Williams, 2014; Slimani et al., 2016). Recent
17 research has shown that mental imagery improves motor tasks (muscular power: Slimani and
18 Chéour, 2016; sprinting: Hammoudi-Nassib et al., 2014; and endurance: McCormick et al.,
19 2015). The improvements associated with this technique have been related to several
20 mechanisms, including psychological skills such as motivation (Martin and Hall, 1995;
21 Slimani and Chéour, 2016), self-efficacy (Beauchamp et al., 2002; Slimani et al., 2016), self-
22 confidence (Weinberg, 2008; Slimani et al., 2016), and managing competitive anxiety
23 (Vadoaab et al., 1997). As will be discussed, a few early researches suggest that mental
24 imagery training may improve functional recovery after short-term muscle immobilization

1 and anterior cruciate ligament (ACL) by the reduction of strength loss (Clark et al., 2014;
2 Frenkel et al., 2014; Newsom et al., 2003).

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

22 Ranganathan et al. (2002) showed stronger effects on strength for high compared with
23 low mental effort (20.5% vs. 2%, respectively). They also showed that internal imagery
24 induces a greater improvement in strength performance compared with that induced by
25 external imagery techniques (10% vs. 5.3%, respectively). Furthermore, several studies have

1 demonstrated the presence of muscular activity (electromyography: EMG) during mental
2 imagery directed towards the production of force (Guillot and Collet, 2005; Yao et al., 2013).
3 Accordingly, and based on the imagery perspectives and the relationship with EMG activity,
4 internal imagery results in significantly higher muscle excitation than external imagery of the
5 same movement (Bakker et al., 1996; Hale, 1982; Harris and Robinson, 1986). Thus, several
6 studies have demonstrated that alternation of mental imagery and voluntary contractions could
7 increase the volume of training and limit the development of muscle fatigue in healthy adults
8 (Ranganathan et al., 2004). Research in this area could provide both theoretical and practical
9 contributions to the field. For example, it could provide athletes and coaches with principled
10 insight on how to optimize their use of mental imagery, help understand the underlying
11 mediators and moderators influencing the effect of mental imagery on strength performance,
12 and stimulate future research on the multiple factors involved in the development of mental
13 imagery theory and practice.

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

23 As it is now well known, common neural substrates underlie motor performance and
24 mental imagery (Guillot et al., 2008; Guillot and Collet, 2008; Zijdwind et al., 2003), and
25 understanding the neural correlates of goal-directed action, whether executed or imagined, has

1 been an important aim of cognitive brain research since the advent of functional imaging
2 studies (Gabriel et al., 2006). In addition, despite the consensus between sports psychologists
3 regarding the increase in strength conditions with internal mental imagery and the correlations
4 between neural adaptations and strength performance improvement, there is no conclusive
5 result concerning which modality (perspective) is most effective in neurophysiological
6 adaptations. To date, each type of mental imagery has been considered to have different
7 properties with respect to both psychophysical (Jeannerod, 1995) and physiological (Stinear et
8 al., 2006) perspectives and to the nature of the neural networks that they activate (Guillot et
9 al., 2009; Solodkin et al., 2004). Accordingly, many studies have shown that external imagery
10 perspective produces a little physiological response (Lang et al., 1980; Ranganathan et al.,
11 2004; Wang, 1992) and is not as effective in enhancing muscle force as internal imagery
12 training did (Ranganathan et al., 2002).

13 Previous reviews examined the effects of mental imagery on various outcomes (i.e.,
14 motor learning and performance, motivation, self-confidence and anxiety, strategies and
15 problem-solving, and injury rehabilitation) (Bowering et al., 2013; Khaled, 2004; Kossert and
16 Munroe-Chandler, 2007; Zimmermann-Schlatter et al., 2008) and neurophysiological
17 adaptations (Guillot and Collet, 2005). Thus, six imagery models and frameworks were
18 reviewed by Guillot and Collet (2008). Although some psychophysiological models related to
19 endurance performance are currently available in the literature (Smirmaul et al., 2013), similar
20 models related to strength performance are still lacking. The purpose of the present systematic
21 review is to examine the influence of mental imagery on the outcome of muscular strength.
22 There are three reasons why such a systematic review will advance current understanding.
23 First, previous reviews have not examined the effects of mental imagery on strength
24 performance in healthy participants as well as strength loss for persons with immobilization
25 and ACL (Braun et al., 2013; Tod et al., 2003, 2015). Second, much research is currently

1 interested in the relationship between mental imagery and muscular strength to provide
2 guidelines for coaches, sports psychologists, and therapists to create effective imagery
3 intervention for use with their athletes or patients. Third, unlike narrative review, systematic
4 review involves a detailed and comprehensive plan and search strategy derived a priori, with
5 the goal of reducing the risk of bias by identifying, appraising, and synthesizing all relevant
6 studies on the present topic. Thus, a systemic review about effects of mental imagery on
7 muscular strength in healthy and patients subjects is a well planned way to answer this
8 specific research question using a systematic and explicit methodology to identify, select, and
9 critically evaluate results of the studies included in the literature review (Khan et al., 2000).
10 While narrative review works have an important role in continuing education because they
11 provide readers with up-to-date knowledge about a specific topic or theme (Khan et al., 2000).
12 Furthermore, this review aims to (a) identify the effects of mental imagery on strength
13 performance and EMG activity in healthy participants and patients with immobilization and
14 ACL, (b) evaluate the moderator and mediator variables related to the mental imagery-
15 strength performance relationship and (c) determine the neurophysiological mechanisms
16 implicated in the imagery-muscle strength relationship with the goal of laying the foundation
17 for practical applications in sports medicine.

18

19 **Methods**

20 **Search strategy**

21 This systematic review was conducted in accordance with Preferred Reporting Items for
22 Systematic Reviews and Meta-analyses (PRISMA) Statement guidelines (Moher et al., 2009).
23 Actually, Moher et al. (2009) claimed that the PRISMA is the best way to improve the
24 transparency, accuracy, completeness, and frequency of documented systematic review and

1 meta-analysis protocols. Some papers claiming to be systematic reviews are actually narrative
2 reviews, because they do not apply transparent, objective, and replicable methods to all
3 aspects including the literature search, data extraction, and data analysis. Many times these
4 papers also report results from individual studies without making objective and rigorous
5 attempts to integrate findings and advance knowledge. Adherence to PRISMA guidelines in
6 this review helped ensure these standards of rigor and objectivity were applied to all aspects
7 of the study. The PRISMA guidelines include the four-step systematic approach of
8 identification, screening, eligibility, and inclusion (Figure 1). A systematic search of the
9 research literature was conducted for randomized controlled trials (RCTs) studying the effects
10 of mental imagery on strength performance and strength loss. Studies were obtained through
11 manual and electronic journal searches (up to March 2016). The present review used the
12 following databases: PubMed, SCOPUS, SportDiscus, PsycINFO, PsycARTICLES, Google
13 Scholar, and ScienceDirect. Electronic databases were searched using keywords and/or MeSH
14 terms, such as “mental”, “mental imagery”, or “mental imagery perspectives”, in combination
15 with the terms “sport”, “strength”, “performance”, “strength loss”, “immobilization”,
16 “anterior cruciate ligament”, “muscular activity”, “neural”, and “physiology”. The search was
17 restricted to studies written in the English language published in a peer-reviewed journal.
18 Reference lists of included studies were selected.

19 *** Figure 1 here***

20 **Inclusion and exclusion criteria**

21 The present review examined internal validity and included studies: (a) involving a control
22 group, (b) measuring maximal strength, (c) RCTs studies, (d) using instruments with high
23 reliability, (e) with minimal experimental mortality, and (f) choosing healthy subjects and
24 patients with immobilization of the upper extremity (i.e., hand) and ACL as participants.
25 Moreover, studies using the moderator and mediator variables of mental imagery for the

1 enhancement of strength performance were also reviewed. In addition, studies examined
2 neural mechanisms underlie mental imagery-muscle strength gain/loss relationship were
3 included. Investigations studied the effects of mental imagery on physiological changes were
4 also included. Furthermore, studies not mentioning mental imagery perspectives (i.e., external
5 or internal) were excluded. Reviews, comments, interviews, letters, posters, book chapters,
6 and books were also excluded.

7 **Evaluation of study quality**

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

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

22 **Moderator and mediator variables**

23 Overall, the current literature on mental imagery provides ample evidence that internal mental
24 imagery is an effective strategy for enhancing strength performance. Nevertheless, interesting

1 questions have been raised concerning the factors that might govern mental imagery
2 effectiveness. These factors can be classified into four broad categories: (a) intervention
3 characteristics, (b) training duration, (c) type of skills, and (d) participant characteristics.
4 Furthermore, self-confidence, imagery ability, controllability, and past experiences represent
5 key mediator variables involved in the effects of mental imagery on muscular strength.

6

7 **Results**

8 **Descriptive characteristics of included studies**

9 The search strategies yielded a preliminary pool of 2787 possible papers. After a reading of
10 abstracts and full-text review, only 27 articles met the inclusion criteria. Nineteen papers
11 examined the effects of mental imagery on strength performance in healthy participants.
12 Particularly, fourteen of them studied the effects of imagery perspectives on muscular
13 strength. Thus, eight investigations examined the effects of imagery on strength loss and
14 functional recovery in patients with immobilization of the upper extremity (i.e., hand) and
15 ACL (Table 1AB). Each research work was analyzed in terms of a wide range of
16 characteristics, including participants' age, gender, level, health status and intervention (Table
17 1AB, 2AB). Each study is listed according to training duration (from 2 to 12 weeks).

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

25

*** Table 1A here***

1 *** Table 1B here***

2 *** Table 2A here***

3 *** Table 2B here***

4 **Quality of included studies**

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

13 **Potential moderator and mediator variables**

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

23 Mental imagery was classified as consisting of internal and external imagery
24 perspectives and their effect on strength performance. Nevertheless, the empirical research
25 findings (60%) indicated that internal imagery was more beneficial for closed skills than

1 external imagery, whereas performance involving open skills might benefit most from
2 external imagery (Table 3).

3 *** Table 3 here***

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

11 *** Table 4 here***

12 **Discussion**

13 **Mental imagery-muscle strength relationship in healthy and patient participants**

14 Mental imagery has been reported to induce a performance improvement in skilled
15 movements in a comparable way to physical training, which could be explained in terms of
16 adaptation in motor cortex neurons (Guillot and Collet, 2005). This effect is linked to an
17 elevation of time-locked cortical potentials and has been explained in terms of stronger
18 cortical signals to muscles, generated by repetitive mental attempts at maximal muscle
19 activation (Ranganathan et al., 2004). Moreover, the effect is not limited to an improvement
20 of motor execution but also involved muscle strength. Mental imagery training has been
21 reported to increase the performance of strength-based tasks (e.g., voluntary muscular
22 contraction: VMC) for both distal and proximal muscles of the human upper and lower
23 extremities (Fontan et al., 2007; Ranganathan et al., 2004; Reiser et al., 2011; Zijdwind et al.,
24 2003). Recently, Tod et al. (2015) showed a significant effect of mental imagery on muscular
25 strength (63%) similar to that reported in the studies detailed previously in the present review.

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

5 According to previous research, external imagery training is not as effective in
6 enhancing muscle force (Ranganathan et al., 2002) as internal imagery training (Herbert et al.,
7 1998; Ranganathan et al., 2004). Yao et al. (2013) showed that although training involving the
8 internal mental imagery of strong muscle contractions significantly improved voluntary
9 muscle strength, the external mental imagery of the same motor task did not yield the same
10 result.

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

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

1 Accordingly, Newsom et al. (2003) showed that imagery prevention intervention was
2 effective in reducing strength loss of wrist flexion/extension after short-term muscle
3 immobilization. More recently, Clark et al. (2014) found the effectiveness of integrating
4 mental imagery in a rehabilitation process on the reduction of strength loss and voluntary
5 activation. Likewise, other study reported greater knee strength and less reinjury anxiety and
6 pain after mental imagery during the rehabilitation period after ACL (Cupal and Brewer,
7 2001). Mental imagery may thus be considered as a therapeutic strategy to help injured
8 patients to recover motor functions after reconstructive surgery of ACL (Lebon et al., 2011).
9 Moreover, other studies have used imagery as part of a psychological prevention intervention
10 program in the sports rehabilitation process. Ievleva and Orlick (1991) found that goal setting,
11 positive self-talk, healing imagery, and focus of concentration as most highly related to faster
12 healing rates of injured athletes with sports injuries. Further study reported that motor
13 imagery coupled with proprioceptive neuromuscular facilitation was better than physical
14 practice alone in enhancing and maintaining range of motion at the hip joint (Williams et al.,
15 2004). Further RCTs and non-RCTs studies have shown the benefits of short- and long-term
16 mental imagery programs on relearning and performance (e.g., gait) of daily arm function in
17 post-stroke patients (Dickstein et al., 2004; Liu et al., 2004; Page et al., 2007).

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

21 **Mental imagery and electromyography (EMG) activity**

22 Mental imagery centrally organizes a motor program and activates neurons within various
23 areas of the brain responsible for priming the execution of the motor command in what is
24 thought to lead to increased performance and learning through repeated imagery use. Several
25 authors have demonstrated the presence of electrical muscle activity during subliminal mental

1 simulation of a movement directed towards the production of force (Guillot and Collet,
2 2005b; Harris and Robinson, 1986). Psycho-neuromuscular theory postulates that feedback
3 generated during mental imagery helps strengthen the motor program corresponding to a
4 motor task (Jacobson, 1932). Otherwise, several data have suggested that mental imagery is
5 accompanied by EMG activity and even by specific selective muscle activation (Guillot and
6 Collet, 2005).

7 Furthermore, significant increases in maximal and isometric strength were observed
8 after the mental imagery training of previously healthy and patient participants and were
9 largely attributed to increased motor unit activation (Brody et al., 2000; Guillot and Collet,
10 2005). The increases in the magnitude of EMG caused by mental imagery could be the result
11 of an increased number of active motor units and/or their firing frequencies (Jeannerod,
12 1994). Some researchers have, however, required the absence of EMG activity as a
13 precondition to perform a specific mental imagery task (Brody et al., 2000; Herbert et al.,
14 1998; Naito et al., 2002; Yue and Cole, 1992). They consider the absence of a significant
15 increase in EMG activity as proof that the pattern of cerebral activation observed during
16 mental imagery is not due to any movement. These differences, which could be attributed to
17 methodological problems, have been explained by Bakker et al. (1996), who reported that
18 during the mental imagery of a movement involving one arm, muscular activity was higher in
19 the active than in the passive arm and that imagining lifting a heavy object resulted in higher
20 EMG activity than that induced by imagining lifting a lighter object (9 kg vs. 4.5 kg,
21 respectively). Consequently, a low or high EMG activity was observed during mental
22 imagery, which was modulated by the lateralization (Jeannerod, 1994), intensity, activity, and
23 lifted the weight of the imagined movement. Another interpretation attributes the decrease in
24 EMG amplitude to a decrease in the central drive to the muscle. Moreover, Guillot et al.
25 (2007) showed that a pattern was recorded for EMG activity during mental imagery in all the

1 muscles involved in the movement, which was considered a function of the weight to be lifted
2 and muscle contraction type, i.e., the highest amplitude being recorded during concentric
3 contraction, the lowest amplitude during eccentric contraction, and the “intermediate”
4 amplitude during isometric contraction. They reported that mental imagery of a heavy
5 concentric contraction (80% of one-repetition maximum [1RM]) resulted in a greater pattern
6 of EMG activity than during mental imagery of a light concentric condition (50% of 1RM).
7 Furthermore, the physiological responses to imagery are specific within one response system
8 and reflect the spatial differentiation and quantitative characteristics of an image (Guillot et
9 al., 2007). These responses have been reported to occur following the performance of a
10 cognitive self-control task (Bray et al., 2008) and to support the postulation that imagining an
11 effortful task causes central fatigue alongside self-control strength depletion (Graham et al.,
12 2014). In fact, taking the imagery perspectives-EMG activity relationship into account,
13 significantly higher muscle excitation can be induced by the internal than external imagery of
14 the same movement (Bakker et al., 1996; Hale, 1982; Harris and Robinson, 1986). Hale
15 (1982) showed that whereas the internal perspective resulted in muscle activity during the
16 imagery of an arm movement, the external perspective did not. The experiment of Harris and
17 Robinson (1986), although less well controlled than the experiment of Hale, have provided
18 further evidence supporting the hypothesis that internal imagery produces higher EMG
19 activity than external imagery. Accordingly, when comparing mental imagery perspectives,
20 Lang (1979) demonstrated that subjects trained in "response propositions" (similar to internal
21 imagery) experienced greater physiological arousal during images than subjects instructed to
22 respond perceptually (external imagery). Moreover, subjects who engaged in kinesthetic
23 imagery showed greater somatic arousal (less sensorimotor alpha) and less visual activity
24 (greater occipital alpha) than subjects who employed visual attention and imagery (external)
25 (Davidson and Schwartz, 1977). Thus, internal imagery is more effective in performance

1 because of the greater muscular, somatic and sensorimotor activities (Fourkas et al., 2006;
2 Hale, 1982; Harris and Robinson, 1986) than those associated with external imagery.

3 **Moderator-related factors affecting mental imagery-strength performance relationship**

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

8 *Characteristics of imagery interventions*

9 The present review showed that the most important factor influencing mental imagery
10 efficiency relates to the type of intervention. In fact, whereas some studies incorporated
11 shorter (e.g., 3-5 days) or longer (e.g., 3-12 weeks) interventions on imagery, including
12 training on the use of the mental imagery strategy (Ranganathan et al., 2004; Yue and Cole,
13 1992), other studies did not include any training on mental imagery (Shackell and Standing,
14 2007). As with any mental imagery strategy, the effects of studies involving training are
15 greater than those not involving training. Furthermore, the level of mental effort during
16 training plays a crucial role in determining strength gains. Ranganathan et al. (2002) showed
17 that high mental effort yielded more strength than low mental effort did (20.5% vs. 2%,
18 respectively) and that internal imagery induced more strength than external imagery did (10%
19 vs. 5.3%, respectively). Several studies have tested the effectiveness of mental skill packages-
20 interventions implementing a variety of mental techniques, such as self-talk, goal setting,
21 relaxation, and performance routines in combination with mental imagery (Patrick and
22 Hrycaiko, 1998; Slimani and Chéour, 2016; Thelwell and Maynard, 2003). For instance,
23 mental imagery has been described to be effective for performance enhancement when
24 combined with other cognitive techniques, such as relaxation, goal setting, hypnosis, and self-
25 talk (Hatzigeorgiadis et al., 2011). The effects of mental training packages on strength

1 performance are also demonstrated (Slimani and Chéour, 2016). In fact, currently available
2 research generally indicates that most athletic interventions are multimodal and include
3 mental imagery along with physical training (Driskell et al., 1994; Wright and Smith, 2009).
4 Researchers have also noted that the addition of mental imagery to a physical training
5 regimen does not induce additional muscle fatigue and that the practice of mental imagery
6 before or during a physical activity activates the corticospinal pathways and improve the
7 intrinsic motivation and stimulation of athletes without causing negative effects on their
8 future performances (Rozand et al., 2014).

9 The present review indicates advantageous effects of internal imagery (range from 2.6
10 to 136.3%) for strength performance compared with external imagery (range from 4.8 to
11 23.2%)

12 ***Training duration***

13 To date, imagery studies have used a variety of strength tasks as well as differing volumes and
14 frequencies of imagery training. The data presented in table 1AB and 2AB corroborate the
15 hypothesis that some sort of training increase isometric and maximal strength by inducing
16 adaptations of the central nervous system in student athletes. Thus, a comparison of previous
17 studies involving have similar muscle groups and experimental designs showed that shorter
18 mental imagery training (3-6 weeks) induced greater effects on strength performance in
19 student athletes. In other words, the findings of the present review reveal that mental imagery
20 training performed in shorter durations has greater effects on muscle strength than mental
21 imagery training performed over longer durations (7-12 weeks) (Table 1AB and 2AB). This
22 can be due to the increases of motor-evoked potentials (MEP) amplitudes during short-term
23 motor imagery strength training (3 weeks). Wakefield and Smith (2011) also indicate that
24 training programs delivered in three sessions per week are more effective than those
25 conducted once or twice per week. Although more research is required to explore the effects

1 of differing volumes and frequencies of imagery training on the strength performance of
2 different muscle groups, the current review suggests that three sessions/week training
3 programs might be a good starting point for athletes wishing to benefit from these effects.
4 Furthermore, Feltz and Landers (1983) and Driskell and Moran (1994) have previously
5 proposed that a range of 100 to 200 hundred sessions, lasting from a few seconds to 3 hours,
6 can produce beneficial effects. It is worth noting, however, that athletes could encounter
7 difficulties in maintaining focus and experience mental fatigue over several imagery sessions
8 (Guillot and Collet, 2008). Accordingly, further research on the specific outcomes of mental
9 imagery is needed to better clarify the duration and frequency required for imagery
10 interventions to produce beneficial effects, and why an imagery intervention three sessions
11 per week are more effective than once or twice per week.

12 *Types of skills*

13 If imagery perspective affects the effective use of imagery, then investigating the use of
14 imagery perspectives is imperative to understanding how to use imagery effectively (Morris et
15 al., 2005). In fact, the type of task and preference for imagery perspective could influence the
16 effectiveness of the imagery perspective used by participants. To the best of authors'
17 knowledge, however, to date no literature review has focused on the type of skills-mental
18 imagery relationship implemented and its effects on the achievement of best performance. In
19 fact, several studies have shown that the type of mental imagery used is important in terms of
20 strength performance outcomes (Ranganathan et al., 2002). In this respect, Mahoney and
21 Avenier (1977) defined perspective in terms of whether an image is internal or external. Based
22 on this theoretical proposition that conceptualizes mental imagery as either internal or
23 external in nature, studies have often hypothesized that whereas external mental imagery
24 predominantly supports performance on only one task, internal imagery serves multi-task
25 performance. Some studies have also reported that the performance of different types of tasks

1 is affected differently by different perspectives, with external imagery producing greater gains
2 in one task and internal imagery in another (Glisky et al., 1996; Hardy and Callow, 1999;
3 White and Hardy, 1995); these studies have not, however, investigated perspective use.

4 Morris et al. (2005) have classified skills as open or closed. Open skills are those that
5 require athletes to coordinate their movements to a changing environment during the
6 performance of a task, whereas closed skills are those performed in a relatively constant or
7 predictable environment in which activity is often self-paced, e.g., gymnastics, darts, diving,
8 or shooting. Some psychologists (Harris and Robinson, 1986) have suggested that
9 performance involving closed skills might benefit more from internal imagery whereas
10 performance involving open skills might benefit more from external imagery. Spittle and
11 Morris (2007) reported no significant difference between imagery perspectives in open and
12 closed sports skills, although the use of external imagery during imagery of closed skills
13 tended to be higher than that during imagery of open skills. In contrast, Spittle and Morris
14 (2011) showed no significant difference between the use of external and internal imagery for
15 imagery of open and closed skills. This difference can be attributed to the number of imagery
16 perspective training sessions. Perhaps with more than four sessions, the changes in scores
17 would have been larger.

18 Other psychologists have suggested that different elements of task performance, such as
19 form (Lanning and Hisanga, 1983) or spatial elements (Paivio, 1985), might influence which
20 perspective is more effective for imagery practice. Furthermore, from a functional
21 equivalence perspective, internal imagery would appear preferable because it more closely
22 approximates the athlete's view when performing (Jeannerod, 1994; 1995). Some studies,
23 however, support the use of an external orientation when imaging certain form-based skills
24 (Hardy and Callow, 1999; White and Hardy, 1995). It may be more beneficial for athletes to
25 use a combination of perspectives, and more advanced performers will be able to switch from

1 one perspective to another (Smith, 1998). Whereas internal imagery may be more inherent for
2 some mental imagery rehearsal programs in sports, external imagery might add something
3 new and different to the experience.

4 *Athlete skill levels*

5 Tables 1AB and 2AB present the results obtained with regard to the effect of mental imagery
6 on performance across different athlete skill levels. In fact, no studies that directly address
7 this issue have been performed to date. Imagery perspectives were selected as a moderator
8 because descriptive evidence suggests that these perspectives may influence the effectiveness
9 of mental imagery interventions as far as performance is concerned. The results of the present
10 review indicate that the sample consisted of students (Reiser et al., 2011; Shackell and
11 Standing, 2007; Sidaway and Trzaska, 2005; Smith and Collins, 2004; Tenenbaum et al.,
12 1995) and national athletes (Fontani et al., 2007). Furthermore, even though many studies
13 have employed athletes, the range in terms of experience and level varies from beginners (de
14 Ruiten et al., 2012; Ranganathan et al., 2004) to more experienced and elite athletes (Fontani
15 et al., 2007). Typically, the results reported in the literature indicate that elite or more
16 successful performers use more internal imagery than less elite/successful athletes do
17 (Carpinter and Cratty, 1983; Mahoney and Avenier, 1977). Some studies recorded no
18 differences between these categories of performer (Hall et al., 1990; Highlen and Bennet,
19 1983), and other studies reported that elite athletes used more external imagery (Ungerleider
20 and Golding, 1991). The results obtained in the present review indicate a greater effect of
21 internal than external mental imagery on muscular strength for student samples, novices, and
22 youth athletes; for elite athletes, the results are not yet definitive, particularly because of the
23 scarcity of studies in this area.

24 **Mediator-related factors influencing the effectiveness of mental imagery**

1 The present review shows that imagery ability is a variable mediating the effectiveness of
2 mental imagery with regard to strength performance. Athletes and healthy participants who
3 have imagery ability are supposed to have greater control of their images and to create more
4 vivid images than participants with poor imagery ability (Nordin and Cumming, 2005;
5 Slimani et al., 2016). Imagery ability was, for example, found to be an important variable in
6 studies examining the effect of mental imagery on performance (Cumming and Williams,
7 2014; Slimani et al., 2016). Other studies indicate that successful athletes report having better
8 control of their imagery (Slimani et al., 2016) and experiencing more vivid images (Cumming
9 and Williams, 2012) than less successful ones. Therefore, it appears desirable to determine
10 imagery ability to avoid assessment confusions caused by a difference in imagery ability
11 between participants. Furthermore, it may be hypothesized that better imagers will produce
12 muscular activity patterns during imagery that will correspond more closely to the patterns
13 observed with real movements than subjects who have less vivid images and greater difficulty
14 in controlling them. Future research that includes mediating variables (e.g., potential
15 motivation and mental imagery ability) could clarify the psychological and cognitive
16 mechanisms through which psychological manipulations affect strength performance. Finally,
17 researchers are encouraged to include additional psychological mediating variables, such as
18 self-efficacy, sport confidence and motivation (Levy et al., 2015; Slimani and Chéour, 2016),
19 which could shed light on the psychological mechanisms underlying changes in strength
20 performance.

21 **The mechanisms of imagery-muscle strength relationship**

22 *Neural adaptations*

23 Neurological mechanisms, most likely at the cortical level and physiological factors are key
24 determinants of muscle strength/weakness (loss). Physiology research into strength training
25 has found that the increase in strength gains is mostly caused by neural adaptations. In fact,

1 Ranganathan et al. (2004) and Yao et al. (2013) have suggested that neural factors, rather than
2 changes at the muscular level, largely account for imagery training-induced strength gains.
3 However, imagery training-induced neural adaptations may also include improvements in
4 muscle coordination, such as reductions in the activity of the antagonist muscles when
5 exerting the agonist muscle (maximal voluntary contraction: MVC) (Ranganathan et al.,
6 2004).

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

23 Few neuroimaging studies concerning the distinction between internal and external
24 imagery have been reported. Jeannerod (1994) suggested that not only are internal and
25 external imagery encoded in the brain using different neural networks but these neural

1 pathways are also activated by imagery in the same way that they are activated when actually
2 performing the imagined act. For instance, previous study has suggested that the overlapping
3 of neural networks in motor and pre-motor cortices, including supplementary motor area
4 (SMA), is activated during internal imagery and motor performance (Porro et al., 2000),
5 although the primary motor cortex (M1) has not always been found to be activated (Guillot
6 and Collet, 2005). Neuroimaging data have also provided evidence that cerebral plasticity
7 occurring during the incremental acquisition of a motor task is reflected in the same brain
8 regions during mental imagery and that specific cerebral structures are activated when
9 distinguishing mental imagery through a first-person (internal imagery) process from the
10 mental imagery of another person (external imagery) engaging with an object (Ruby and
11 Decety, 2001). Thus, the combination of both imagery methods is expected to be maximally
12 effective for enhancing performance because it activates both neural pathways (Hardy and
13 Callow, 1999).

14 Traditional neurorehabilitation approaches and mental imagery have an impact on such
15 reorganization and associated motor, functional and neurological recovery (Arya et al., 2011).
16 Thus, neural reorganization after injuries is thought to be an important mechanism to facilitate
17 motor recovery. Thus, the capability of the cerebral cortex and related network can be
18 exploited for patients with ACL. Mental imagery can be performed during the phase of
19 recovery when volitional movements are either impossible or being performed synergistically.
20 In terms of the relative contribution of neural and muscular factors regulating strength loss in
21 patients, previous studies have postulated that much of the disuse-induced loss of strength is
22 related to neural factors (Deschenes et al., 2002; Kawakami et al., 2001). Clark et al. (2006b)
23 reported that neural factors (primarily deficits in central activation) explained 48% of the
24 variability in strength loss, whereas muscular factors (primarily sarcolemma function)
25 explained 39% of the variability. They did not find any effect of mental imagery on the H-

1 reflex or nerve conduction responses. Although the influence of mental imagery training was
2 observed on supraspinal neural functional, as the primary mechanism underlying the strength
3 increase following mental training-induced enhancement (in the absence of disuse) is the
4 supraspinal command to muscle, probably mostly localized to the cerebral cortex
5 (Ranganathan et al., 2004).

6

7 *Physiological responses*

8 If mental imagery shares neural mechanisms with those responsible for motor programming,
9 then brain activation during imagined action should be reflected, in some way, at the
10 peripheral effectors level (Roth et al., 1996). Autonomic nervous system (ANS) peripheral
11 effectors are activated by mental imagery (Lang, 1979). The imagination and observation of
12 exercise (i.e., anaerobic exercise) has also been shown to cause changes in the cardiovascular
13 system, with significant changes in blood pressure, heart rate, and respiration, which occur in
14 the absence of muscle contraction or movement (Fusi et al., 2005; Paccalin and Jeannerod,
15 2000; Wang and Morgan, 1992; Williamson et al., 2002) (Table 5). Previous studies have
16 shown that heart rate increases during mental imagery (Beyer et al., 1990; Jones and Johnson,
17 1980). Furthermore, Williamson et al. (2002) observed increases in both heart rate and blood
18 pressure during imagined handgrip. Accordingly, other studies have demonstrated that similar
19 autonomic responses in an attentionally engaging task (shooting events) occur during real and
20 imagined attempts (Deschaumes-Molinario et al., 1992; Guillot et al., 2004).

21

*** Table 5 here***

22

23 Measuring cardiac and respiratory activity during the mental simulation of locomotion
24 at increasing levels revealed a co-variation of heart rate and pulmonary ventilation with the
25 degree of imagined effort (Decety et al., 1991; 1993). The possibility that cardiac and

1 respiratory effects recorded during such mental imagery could have been caused by peripheral
2 factors (such as co-contraction of antagonist muscle groups) was eliminated because muscular
3 metabolism measured using nuclear magnetic resonance spectroscopy remained unchanged
4 (no change in phosphocreatine concentration and intracellular pH levels). In contrast, Wang
5 and Morgan (1992) proved that heart rate, subjective rating of perceived exertion (RPE) and
6 metabolic responses to imagined exercise were significantly lower than in actual exercise,
7 whereas blood pressure was found to be similar between the two conditions. This difference
8 can be attributed to the degree of imagined effort and mental imagery perspectives. The
9 mechanisms underlying the cardiovascular effect of imagined exercise is not known, but it is
10 possible that the CNS and the activation of the cortex cause an increase in sympathetic
11 outflow and reciprocal inhibition of parasympathetic activity.

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

19 **Theoretical implications**

20 The results presented in this review may provide important theoretical and practical
21 contributions to mental imagery researchers and practitioners. The latter can, for instance,
22 provide athletes and coaches with principled advice on optimizing their use of mental
23 imagery. Moreover, the critical summary of the available literature on the mental imagery-
24 strength performance relationship and the moderator and mediator-related factors involved in
25 mental imagery practice should stimulate future investigations with strong theoretical and

1 applied implications. In a sporting situation, the use of mental imagery is observed during
2 training preceding competitive events and during rehabilitation. However, although some
3 psychophysiological models related to sport performance and endurance performance are
4 currently available in the literature (Smirmaul et al., 2013), similar models related to strength
5 performance are still lacking. The information gathered in the present review and the evidence
6 provided by other research studies in support for the mental imagery-muscle strength
7 relationship and motivational intensity theory (Brehm and Self, 1989) show that the increase
8 in maximal voluntary activation (MVA) and potential motivation are the ultimate
9 determinants of enhanced strength performance. Consequently, the psychobiological model
10 predicts that any psychological or physiological factor that increases potential motivation or
11 increases MVA will improve strength performance and that any psychological or
12 physiological factors that reduce the potential motivation or MVA will undermine strength
13 performance. It may thus be noted that the effect of mental imagery on the individual's ability
14 to enhance motivation and self-confidence to improve strength is greater than its effect on the
15 technical key components of the movement per se.

16 **Limitations and recommendations for future research**

17 Although this review provides clear evidence of the positive effects of mental imagery on
18 strength performance, most of the included studies presented some limitations with respect to
19 the adopted methodology (an average PEDro score < 6). It is well known that bias may
20 complicate efforts to establish a cause-effect relationship between procedures of mental
21 imagery and strength outcomes. Thus, because some degree of bias is almost always present
22 in the study of mental imagery, researchers must consider how bias might influence strength
23 effects. Research on the impact of mental imagery perspectives on neurophysiological and
24 hormonal adaptations are scarce or unavailable and future studies, thereafter, are
25 recommended. Most of the studies conducted on this topic to date have also used samples

1 drawn from student and/or untrained populations. It is not clear whether the results observed
2 in these groups can be generalized to well-trained or elite populations. For that reason,
3 researchers are encouraged to compare different mental imagery intervention perspectives and
4 to examine the effects of these interventions for athletes in competitive situations.
5 Furthermore, future investigations should detail why and how a short duration imagery
6 interventions would increase athletes' muscular strength. Additionally, the present review
7 recommends the improvement of the internal validity, which refers to the reliability and/or
8 accuracy of the protocol used in mental imagery studies. Internal validity ensures that the
9 study design, implementation, and data analysis confidently minimize bias and that the
10 findings are representative of the true association between mental imagery and increase in
11 strength performance.

12

13 **Conclusion and practical implication**

14 This systematic review provided a critical overview of the major peer-reviewed studies
15 published to date in the literature seeking evidence in support of or opposition to the effect of
16 mental imagery perspectives on strength performance. The review also searched for the
17 potential moderator and mediator variables that might affect the mental imagery-strength
18 performance relationship. The neurophysiologic mechanisms of the mental imagery-strength
19 performance relationship were also discussed. The results reveal that the combination of
20 mental and physical training is more efficient than, or at least comparable to, physical
21 execution when there is no decrease in the total physical performance time. The findings also
22 indicate that maximal strength gain is significantly greater for the distal than proximal muscle
23 group after mental imagery training. Thus, the results demonstrate that the internal imagery
24 perspective has greater effects on strength performance than on external imagery. In addition,
25 this review suggests that mental imagery might be of benefit in preventing the strength losses

1 that occur during immobilization and ACL. The data available on the direct effects of mental
2 imagery on strength performance and EMG activity are very limited. This limitation could be
3 attributed to (1) the fact that internal imagery involves higher degrees of muscle excitation
4 than external imagery, (2) that mental imagery with muscular activity is higher in the active
5 than in the passive organ, and (3) that imagining “lifting a heavy object” results in higher
6 EMG activity than imagining “lifting a light one”. It was also noted that high mental effort
7 induced higher EMG activity than low mental effort. The present review reported on the
8 factors that may moderate the effectiveness of mental imagery, namely mental imagery
9 perspectives, characteristics of the intervention, training duration, and types of skills.
10 Furthermore, internal mental was reported to have greater effects on strength among healthy
11 participants than external imagery. Thus, external imagery perspective predominantly
12 supports performance on only one task, although internal imagery serves multi-task
13 performance. Furthermore, short-duration (3-6 weeks) mental imagery training has greater
14 effects on strength performance than long-duration mental training (7-12 weeks). However,
15 the effects of mental imagery interventions on strength performance after three or more
16 months are unknown.

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

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

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

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16 **References**

17 Arya, K.N., Pandian, S., Verma, R. and Garg, R.K. (2011) Movement therapy induced neural
18 reorganization and motor recovery in stroke: a review. *Journal of Bodywork and Movement*
19 *Therapies* **15**(4), 528-37.

20 Bakker, F.C., Boschker, M.S.J. and Chung, T. (1996) Changes in muscular activity while
21 imagining weight lifting using stimulus or response propositions. *Journal of Sport and*
22 *Exercise Psychology* **18**, 313-324.

23 Beauchamp, M.R., Bray, S.R. and Albinson, J.G. (2002) Pre competition imagery, self-
24 efficacy and performance in collegiate golfers. *Journal of Sports Sciences* **20**, 697-705.

- 1 Beyer, L., Weiss, T., Hansen, E., Wolf, A. and Seidel, A. (1990) Dynamics of central nervous
2 activation during motor imagination. *International Journal of Psychophysiology* **9**, 75-80.
- 3 Bray, S.R., Martin, Ginis, K.A., Hicks, A.L. and Woodgate, J. (2008) Effects of self-
4 regulatory strength depletion on muscular performance and EMG activation.
5 *Psychophysiology* **44**, 337-343.
- 6 Brehm, J.W. and Self, E.A. (1989) The intensity of motivation. *Annual Review of Psychology*
7 **40**, 109-31.
- 8 Bowering, K.J., O'Connell, N.E., Tabor, A., Catley, M.J., Leake, H.B., Moseley, G.L. and
9 Stanton, T.R. (2013) The effects of graded motor imagery and its components on chronic
10 pain: a systematic review and meta-analysis. *Journal of Pain* **14(1)**, 3-13.
- 11 Braun, S., Kleynen, M., Heel, T.V., Kruithof, N., Wade, D. and Beurskens, A. (2013) The
12 effects of mental practice in neurological rehabilitation; a systematic review and meta-
13 analysis. *Frontiers in Human Neuroscience* **7**, 390.
- 14 Brody, E.B., Hartfield, B.D., Spalding, T.W., Frazer, M.B. and Caherty, F.J. (2000) The effect
15 of a psyching strategy on neuromuscular activation and force production in strength-
16 trained men. *Research Quarterly for Exercise and Sport* **71**, 162-170.
- 17 Clark, B.C., Fernhall, B. and Ploutz-Snyder, L.L. (2006) Adaptations in human neuromuscular
18 function following prolonged unweighting: I. Skeletal muscle contractile properties and
19 applied ischemia efficacy. *Journal of Applied Physiology* **101**, 256-263.
- 20 Clark, B.C., Mahato, N.K., Nakazawa, M., Law, T.D. and Thomas, J.S. (2014) The power of
21 the mind: the cortex as a critical determinant of muscle strength/weakness. *Journal of*
22 *Neurophysiology* **15**, 3219-26.
- 23 Carpinter, P.J. and Cratty, B.J. (1983) Mental activity, dreams and performance in team sport
24 athletes. *International Journal of Sports Psychology* **14**, 186-197.

- 1 Cumming, J. and Williams, S.E. (2014) Imagery. In: *Encyclopedia of sport and exercise*
2 *psychology*. Ed: Eklund R.C., Tenenbaum G. Los Angeles: Sage. 369-373.
- 3 Cumming, J. and Williams, S.E. (2012) The role of imagery in performance. In: *Handbook of*
4 *sport and performance psychology*. Ed: Murphy S. New York, NY: Oxford University
5 Press. 213-232.
- 6 Cupal, D.D. and Brewer, B.W. (2001) Effects of relaxation and guided imagery on knee
7 strength, reinjury anxiety, and pain following anterior cruciate ligament reconstruction.
8 *Rehabilitation Psychology* **46**, 28-43.
- 9 Davidson, R.J. and Schwartz, G.E. (1977) Brain mechanisms subserving self-generated
10 imagery: electrophysiological specificity and patterning. *Psychophysiology* **14**, 598-602.
- 11 Decety, J., Jeannerod, M., Germain, M. and Pastene, J. (1991) Vegetative response during
12 imagined movement is proportional to mental effort. *Behavioural Brain Research* **42**, 1-5.
- 13 Decety, J., Jeannerod, M., Durozard, D. and Baverel, G. (1993) Central activation of
14 autonomic efforts during mental simulation of motor effort. *Journal of Physiology* **461**,
15 549-563.
- 16 Deschaumes-Molinario, C., Dittmar, A. and Vernet-Maury, E. (1992) Autonomic nervous
17 system response patterns correlate with mental imagery. *Physiology and Behavior* **51**,
18 1021-1027.
- 19 de Ruitter, C.J., Hutter, V., Icke, C., Groen, B., Gemmink, A., Smilde, H. and de Haan, A.
20 (2012) The effects of imagery training on fast isometric knee extensor torque development.
21 *Journal of Sports Sciences* **30**, 166-174.
- 22 Deschenes, M.R., Giles, J.A., McCoy, R.W., Volek, J.S., Gomez, A.L. and Kraemer, W.J.
23 (2002) Neural factors account for strength decrements observed after short-term muscle
24 unloading. *American Journal of Physiology. Regulatory, Integrative and Comparative*
25 *Physiology* **282**, R578-R58.

- 1 Dickstein, R., Dunsky, A. and Marcovitz, E. (2004) Motor imagery for gait rehabilitation in
2 post-stroke hemiparesis. *Physical Therapy* **84(12)**, 1167-1177.
- 3 Driskell, J.E., and Copper, C., and Moran A. (1994) Does mental practice enhance
4 performance? *Journal of Applied Psychology* **79**, 481-492.
- 5 Feltz, D.L. and Landers, D.M. (1983) The effects of mental practice on motor skill learning
6 and performance: a meta-analysis. *Journal of Sport Psychology* **5**, 25-27.
- 7 Fontani, G., Migliorini, S, Benocci, R., Facchini, A., Casini, M. and Corradeschi, F. (2007)
8 Effect of mental imagery on the development of skilled motor actions. *Perceptual and*
9 *Motor Skills* **105**, 803-826.
- 10 Fourkas, A.D., Avenanti, A., Urgesi, C. and Aglioti, S.M. (2006) Corticospinal facilitation
11 during first and third person imagery. *Experimental Brain Research*, **168**, 143-51.
- 12 Frenkel, M.O., Herzig, D.S., Gebhard, F., Mayer, J., Becker, C. and Einsiedel, T. (2014)
13 Mental practice maintains range of motion despite forearm immobilization: a pilot study in
14 healthy persons. *Journal of Rehabilitation Medicine* **46**, 225-232.
- 15 Fusi, S., Cutuli, D., Valente, M.R., Bergonzi, P., Porro, C.A. and Di Prampero, P.E. (2005)
16 Cardioventilatory responses during real or imagined walking at low speed. *Archives*
17 *Italiennes de Biologie* **143**, 223-228.
- 18 Gabriel, D.A., Kamen, G. and Frost, G. (2006) Neural adaptations to resistive exercise:
19 mechanisms and recommendations for training practices. *Sports Medicine* **36**, 133-149.
- 20 Glisky, M.L., Williams, J.M., and Kimstrom, JF. (1996) Internal and external mental imagery
21 perspectives and performance on two tasks. *Journal of Sport Behavior* **19**, 3-12.
- 22 Graham, J.D., Sonne, M.W.L. and Bray, S.R. (2014) It wears me out just imagining it! Mental
23 imagery leads to musclefatigue and diminished performance of isometric exercise.
24 *Biological Psychology* **103**, 1-6.

- 1 Guillot, A., Collet, C., Molinaro, C. and Dittmar, A. (2004) Expertise and peripheral
2 autonomic activity during the preparation phase in shooting events. *Perceptual and Motor*
3 *Skills* **98**, 371-381.
- 4 Guillot, A. and Collet, C. (2005) Contribution from neurophysiological and psychological
5 methods to the study of motor imagery. *Brain Research Reviews* **50(2)**, 387-97.
- 6 Guillot, A., Lebon, F., Rouffet, D., Champely, S., Doyon, J. and Collet, C. (2007) Muscular
7 responses during motor imagery as a function of muscle contraction types. *International*
8 *Journal of Psychophysiology* **66**, 18-27.
- 9 Guillot, A., Collet, C., Nguyen, V.A., Malouin, F., Richards, C. and Doyon, J. (2008)
10 Functional neuroanatomical networks associated with expertise in motor imagery ability.
11 *Neuroimage* **41**, 1471-1483.
- 12 Guillot, A. and Collet, C. (2008) Construction of the motor imagery integrative model in
13 sport: a review and theoretical investigation of motor imagery use. *International Review of*
14 *Sport and Exercise Psychology* **1**, 31-44.
- 15 Guillot, A., Collet., C, Nguyen, V.A., Malouin, F., Richards, C. and Doyon, J. (2009) Brain
16 activity during visual versus kinesthetic imagery: An fMRI study. *Human Brain Mapping*
17 **30**, 2157-2172.
- 18 Hale, B.D. (1982) The effects of internal and external imagery on muscular and ocular
19 concomitants. *Journal of Sport Psychology* **4**, 379-387.
- 20 Hall, C.R., Rodgers, W.M. and Barr, K.A. (1990) The use of imagery by athletes in selected
21 sports. *Sport Psychologist* **4**, 1-10.
- 22 Hammoudi-Nassib, S., Chtara, M., Nassib, S., Briki, W., Hammoudi-Riahi, S., Tod, D. and
23 Chamari, K. (2014) Time interval moderates the relationship between psyching-up and
24 actual sprint performance. *Journal of Strength and Conditioning Research* **28**, 3245-54.

- 1 Harris, D.V., and Robinson, W.J. (1986) The effects of skill level on EMG activity during
2 internal and external imagery. *Journal of Sport Psychology* **8**, 105-111.
- 3 Hardy, L. and Nelson, D. (1988) Self-control training in sport and work. *Ergonomics* **31**,
4 1573-1585.
- 5 Hardy, L. and Callow, N. (1999) Efficacy of external and internal visual imagery perspectives
6 for the enhancement of performance on tasks in which form is important. *Journal of Sport
7 and Exercise Psychology* **21**, 95-112.
- 8 Hardy, L. (1997) The Coleman Robert Griffiths address: Three myths about applied
9 consultancy work. *Journal of Applied Sport Psychology* **9**, 277-294.
- 10 Hatzigeorgiadis, A., Zourbanos, N., Galanis, E. and Theodorakis, Y. (2011) Self-talk and
11 sports performance: A meta-analysis. *Perspectives on Psychological Science* **6**, 348-356.
- 12 Herbert, R.D., Dean, C. and Gandevia, S.C. (1998) Effects of real and imagined training on
13 voluntary muscle activation during maximal isometric contractions. *Acta Physiologica
14 Scandinavica* **163**, 361-368.
- 15 Hetu, S., Gregoire, M., Saimpont, A., Coll, M.P., Eugene, F., Michon, P.E. and Jackson, P.L.
16 (2013) The neural network of motor imagery: an ALE meta-analysis. *Neuroscience and
17 Biobehavioral Reviews* **37**, 930-949.
- 18 Highlen, P.S. and Bennet, B.B. (1983) Elite divers and wrestlers: A comparison between open-
19 and closed-skill athletes. *Journal of Sport Psychology* **5**, 390-409.
- 20 Ievleva, L. and Orlick, T. (1991) Mental links to enhanced healing: An exploratory study.
21 *Sport Psychologist* **5**, 25-40.
- 22 Jackson, P.L., Lafleur, M.F., Malouin, F., Richards, C.L. and Doyon, J. (2003) Functional
23 cerebral reorganization following motor sequence learning through mental practice with
24 motor imagery. *Neuroimage* **20**, 1171-1180.

- 1 Jacobson, E. (1932) Electrophysiology of mental activities. *American Journal of Psychology*
2 **44**, 677-694.
- 3 Jeannerod, M. (1994) The representing brain: Neural correlates of motor intention and
4 imagery. *Behavioral and Brain Sciences* **17**, 187-245.
- 5 Jeannerod, M. (1995) Mental imagery in the motor context. *Neuropsychology* **33**, 1419-32.
- 6 Jeannerod, M. (2001) Neural simulation of action: A unifying mechanism for motor cognition.
7 *Neuroimage* **14**, 103-109.
- 8 Jones, G.E. and Johnson, H.J. (1980) Heart rate and somatic concomitants of mental imagery.
9 *Psychophysiology* **174**, 339-447.
- 10 Jones, L. and Stuth, G. (1997) The uses of mental imagery in athletics: An overview. *Applied*
11 *and Preventive Psychology* **6**, 101-115.
- 12 Kawakami, Y., Akima, H., Kubo, K., Muraoka, Y., Hasegawa, H., Kouzaki, M., Imai, M.,
13 Suzuki, Y. and Gunji, A. (2001) Changes in muscle size, architecture, and neural activation
14 after 20 days of bed rest with and without resistance exercise. *European Journal of Applied*
15 *Physiology* **84**, 7-12.
- 16 Kell, R.T., Bell, G. and Quinney, A. (2001) Musculoskeletal fitness, health outcomes and
17 quality of life. *Sports Medicine* **31(12)**, 863-73.
- 18 Khaled, T. (2004) The effects of mental imagery on the acquisition of motor skills and
19 performance: A literature review with theoretical implications. *Journal of Mental Imagery*
20 **28(1-2)**, 79-114.
- 21 Khan, K.S., Ter Riet, G., Glanville, J., Sowden, A.J. and Kleijnen, J. (2000) *Undertaking*
22 *Systematic Reviews of Research on Effectiveness*. CRD's Guidance for Carrying Out or
23 Commissioning Reviews. 2nd ed. New York: NHS Centre for Reviews and Dissemination,
24 University of York, NHS Centre for Reviews and Dissemination.

- 1 Kossert, A.L. and Munroe-Chandler, K. (2007) Exercise imagery: A systematic review of the
2 empirical literature. *Journal of Imagery Research in Sport and Physical Activity* **2**, 1-32.
- 3 Kremer, J.M.D. and Scully, D.M. (1994) Psychology in sport London: Taylor & Francis.
- 4 Kukulka, C.G. and Clamann, H.P. (1981) Comparison of the recruitment and discharge
5 properties of motor units in human brachial biceps and adductor pollicis during isometric
6 contractions. *Brain Research* **219**, 45-55.
- 7 Lang, P.J. (1979) A bio-informational theory of emotional imagery. *Psychophysiology* **16**,
8 495-512.
- 9 Lang, P.J., Kozak, M.J., Miller, G.A., Levin, D.N. and McLean, A. (1980) Emotional imagery:
10 Conceptual structure and pattern of somatic-visceral response. *Psychophysiology* **17**, 179-
11 192.
- 12 Lanning, W. and Hisanga, B. (1983) A study of the relation between the reduction of
13 competition anxiety and an increase in athletic performance. *International Journal of*
14 *Sports Psychology* **14**, 219-227.
- 15 Lebon, F., Guillot, A. and Collet, C. (2012) Increased muscle activation following motor
16 imagery during the rehabilitation of the anterior cruciate ligament. *Applied*
17 *Psychophysiology and Biofeedback* **37**, 45-51.
- 18 Leung, M.C.M., Spittle, M. and Kidgell, D.J. (2013) Corticospinal excitability following
19 short-term motor imagery training of a strength task. *Journal of Imagery Research in*
20 *Sport and Physical Activity* **8(1)**, 1-10.
- 21 Levy, A.R., Perry, J., Nicholls, A.R., Larkin, D. and Davies, J. (2015) Sources of sport
22 confidence, imagery type and performance among competitive athletes: the mediating role
23 of sports confidence. *The Journal of Sports Medicine and Physical Fitness* **55(7-8)**, 835-
24 44.

- 1 Liu, K.P., Chan, C.C., Lee, T.M. and Hui-Chan, C.W. (2004) Mental imagery for promoting
2 relearning for people after stroke: a randomized controlled trial. *Archives of Physical*
3 *Medicine and Rehabilitation* **85(9)**, 1403-1408.
- 4 Mahoney, M. and Avenier, M. (1977) Psychology of the elite athlete: an exploratory study.
5 *Cognitive Therapy and Research* **1**, 135-141.
- 6 Maher, C.G., Sherrington, C., Herbert, R.D., Moseley, A.M. and Elkins, M. (2003) Reliability
7 of the PEDro scale for rating quality of randomized controlled trials. *Physical Therapy*
8 **83(8)**, 713-21.
- 9 Martin, K.A. and Hall, C.R. (1995) Using mental imagery to enhance intrinsic motivation.
10 *Journal of Sport and Exercise Psychology* **17**, 54-69.
- 11 McCormick, A., Meijen, C. and Marcora, S. (2015) Psychological determinants of whole-
12 body endurance performance. *Sports Medicine* **45**, 997-1015.
- 13 McKenzie, A.D. and Howe, B.L. (1997) The effects of imagery on self-efficacy for a motor
14 skill. *International Journal of Sports Psychology* **28**, 196-210.
- 15 Mellet, E., Petit, L., Mazoyer, B., Denis, M. and Tzourio, N. (1998) Reopening the mental
16 imagery debate: Lessons from functional anatomy. *Neuroimage* **8**, 129-139.
- 17 Meugnot, A., Almecija, Y. and Toussaint, L. (2014) The embodied nature of motor imagery
18 processes highlighted by short-term limb immobilization. *Experimental Psychology* **61**,
19 180-186.
- 20 Moher, D., Liberati, A., Tetzlaff, J., Altman, D.G. and The PRISMA Group. (2009) Preferred
21 reporting items for systematic reviews and meta-analyses: the PRISMA statement. *PLoS*
22 *Medicine* **21;6(7)**, e1000097.
- 23 Morris, T., Spittle, M. and Watt, A.P. (2005) Imagery in sport. Champaign, IL: Human
24 Kinetics.

- 1 Mulder, T. (2007) Motor imagery and action observation: cognitive tools for rehabilitation.
2 *Journal of Neural Transmission* **114(10)**, 1265-1278.
- 3 Naito, E., Kochiyama, T., Kitada, R., Nakamura, S., Matsumura, M., Yonekura, Y. and Sadato,
4 N. (2002) Internally simulated movement sensations during motor imagery activate
5 cortical areas and the cerebellum. *Journal of Neuroscience* **22**, 3683-3691.
- 6 Newsom, J., Knight, P. and Balnave, R. (2003) Use of mental imagery to limit strength loss
7 after immobilization. *Journal of Sport Rehabilitation* **12**, 249-258.
- 8 Nordin, S. and Cumming, J. (2005) Professional dancers describe their imagery: Where,
9 when, what, why, and how. *Sport Psychologist* **19**, 395-416.
- 10 Olsson, C.J., Jonsson, B. and Nyberg, L. (2008) Internal imagery training in active high
11 jumpers. *Scandinavian Journal of Psychology* **49(2)**, 133-40.
- 12 Paccalin, C. and Jeannerod, M. (2000) Changes in breathing during observation of effortful
13 actions. *Brain Research* **862**, 194-200.
- 14 Page, S.J., Levine, P., and Leonard, A. (2007) Mental practice in chronic stroke: results of a
15 randomized, placebo-controlled trial. *Stroke* **38(4)**, 1293-1297.
- 16 Paivio, A. (1985) Cognitive and motivational functions of imagery in human performance.
17 *Canadian Journal of Applied Sport Sciences* **10**, 223-28s.
- 18 Patrick, T. and Hrycaiko, D. (1998) Effects of a mental training package on an endurance
19 performance. *Sport Psychologist* **12**, 283-299.
- 20 Pitcher, J.B., Robertson, A.L., Clover, E.C. and Jaberzadeh, S. (2005) Facilitation
21 of depression of corticospinal excitability. *Experimental Brain Research* **160**, 409-17.
- 22 Porro, C.A., Cettolo, V., Fancescato, A.V. and Baraldi, P. (2000) Ipsilateral involvement of
23 primary motor cortex during motor imagery. *European Journal of Neuroscience* **12**, 3059-
24 3063.

- 1 Pyndt, H.S. and Nielsen, J.B. (2003) Modulation of transmission in the corticospinal and
2 group Ia afferent pathways to soleus motoneurons during bicycling. *Journal of*
3 *Neurophysiology* **89(1)**, 304-14.
- 4 Ranganathan, V.K., Kuykendall, T., Siemionow, V. and Yue, G.H. (2002) Level of mental
5 effort determines training-induced strength increases. *Abstracts - Society for Neuroscience*
6 **32**, 768.3.
- 7 Ranganathan, V.K., Siemionow, V., Liu, J.Z., Sahgal, V. and Yue, G. (2004) From mental
8 power to muscle power- gaining strength by using the mind. *Neuropsychology* **42**, 994-
9 956.
- 10 Reiser, M., Büsch, D., and Munzert, J. (2011) Strength gains by motor imagery with different
11 ratios of physical to mental practice. *Frontiers in Psychology* **2**, 1-8.
- 12 Roth, M., Decety, J., Raybaudi, M., Massarelli, R., Delon-Martin, C., Segebarth, C., Morand,
13 S., Rozand, V., Lebon, F., Papaxanthis, C. and Lepers, R. (2014) Does a Mental Training
14 Session Induce Neuromuscular Fatigue? *Medicine and Science in Sports and Exercise*
15 **46(10)**, 1981-1989.
- 16 Ruby, P. and Decety, J. (2001) Effect of subjective perspective taking during simulation of
17 action: a PET investigation of agency. *Nature Neuroscience* **4**, 546-550.
- 18 Shackell, E. and Standing, L. (2007) Mind over matter: Mental training increases physical
19 strength. *North American Journal of Psychology* **9**, 189-200.
- 20 Sidaway, B. and Trzaska, A. (2005) Can mental practice increase ankle dorsiflexor torque?
21 *Physical Therapy* **85**, 1053-1060.
- 22 Slimani, M., Chamari, K., Boudhiba, D. and Cheour, F. (2016) Mediator and moderator
23 variables of imagery use-motor learning and sport performance relationships: a narrative
24 review. *Sport Sciences for Health* **12**, 1-9.

- 1 Slimani, M. and Cheour, F. (2016) Effects of cognitive training strategies on muscular force
2 and psychological skills in healthy striking combat sports practitioner. *Sport Sciences for*
3 *Health* 1-9.
- 4 Smirmaul, B.P.C, Dantas, J.L., and Nakamura, F.Y., et al. (2013) The psychobiological model:
5 a new explanation to intensity regulation and (in) tolerance in endurance exercise. *Revista*
6 *Brasileira de Educação Física e Esporte* **27(2)**, 333-40.
- 7 Smith, D., Collins, D., and Hale, B. (1998) Imagery perspectives and karate performance.
8 *Journal of Sports Sciences* **16**, 98-99.
- 9 Smith, D. and Collins, D. (2004) Mental practice, motor performance, and the late CNV.
10 *Journal of Sport and Exercise Psychology* **26**, 412-426.
- 11 Solodkin, A., Hlustik, P., Chen, E.E. and Small, S.L. (2004) Fine modulation in network
12 activation during motor execution and motor imagery. *Cerebral Cortex* **14**, 1246-55.
- 13 Spittle, M. and Morris, T. (2007) Internal and external imagery perspective measurement and
14 use in imagining open and closed sport skills. *Perceptual and Motor Skills* **104**, 387-404.
- 15 Spittle, M. and Morris, T. (2011) Can internal and external imagery perspectives be trained?
16 *Journal of Mental Imagery* **35**, 81-104.
- 17 Stinear, C.M., Byblow, W.D., Steyvers, M., Levin, O. and Swinnen, S.P. (2006) Kinesthetic,
18 but not visual, motor imagery modulates corticomotor excitability. *Experimental Brain*
19 *Research* **168**, 157-64.
- 20 Stenekes, M.W., Geertzen, J.H., Nicolai, J.P., De Jong, B.M. and Mulder, T. (2009) Effects of
21 motor imagery on hand function during immobilization after flexor tendon repair. *Archives*
22 *of Physical Medicine and Rehabilitation* **90**, 553-559.
- 23 Tenenbaum, G., Bar-Eli, M., Hoffman, J.R., Jablonovski, R., Sade, S. and Shitrit, D. (1995)
24 The effect of cognitive and somatic psyching-up techniques on isokinetic leg strength
25 performance. *Journal of Strength and Conditioning Research* **9**, 3-7.

- 1 Thelwell, R.C. and Maynard, I.W. (2003) The effects of a mental skills package on 'repeatable
2 good performance' in cricketers. *Psychology of Sport and Exercise* **4**, 377-396.
- 3 Tod, D., Edwards, C., McGuigan, M. and Lovell, G. (2015) A Systematic review of the effect
4 of cognitive strategies on strength performance. *Sports Medicine* **45(11)**, 1589-602.
- 5 Tod, D., Hardy, J. and Oliver, E. (2011) Effects of self-talk: A systematic review. *Journal of*
6 *Sport and Exercise Psychology*, **33(5)**, 666-687.
- 7 Tod, D., Iredale, F. and Gill, N. (2003) 'Psyching-up' and muscular force production. *Sports*
8 *Medicine* **33**, 47-58.
- 9 Topp, R., Fahlman, M. and Boardley, D. (2004) Healthy aging: health promotion and disease
10 prevention. *Nursing Clinics of North America* **39**, 411-22.
- 11 Ungerleider, S. and Golding, J.M. (1991) Mental practice among Olympic athletes.
12 *Perceptual and Motor Skills* **72**, 1007-1017.
- 13 Vadoaab, E.A., Halla, C.R. and Moritzab, S.E. (1997) The relationship between competitive
14 anxiety and imagery use. *Journal of Applied Sport Psychology* **2**, 241-253.
- 15 Wakefield, C. and Smith, D. (2011) From Strength to Strength: A Single-Case Design Study
16 of PETTLEP Imagery Frequency. *Sport Psychologist* **25**, 305-320.
- 17 Wang, Y. and Morgan, W.P. (1992) The effect of imagery perspectives on the
18 psychophysiological responses to imagined exercise. *Behavioural Brain Research* **52**, 167-
19 174.
- 20 Weinberg, R. (2008) Does Imagery Work? Effects on performance and mental skills. *Journal*
21 *of Imagery Research in Sport and Physical Activity* **3**, 193-219.
- 22 White, A. and Hardy, L. (1995) Use of different imagery perspectives on the learning and
23 performance of different motor skills. *British Journal of Psychology* **86**, 169-180.
- 24 Williamson, J.W., McColl, R., Mathews, D., Mitchell, J.H., Raven, P.B. and Morgan, W.P.
25 (2002) Brain activation during central command during actual and imagined handgrip
26 under hypnosis. *Journal of Applied Physiology* **92**, 1317-1324.

1 Yao, W.X., Ranganathan, V.K., Allexandre, D., Siemionow, V. and Yue, G.H. (2013)
2 Kinesthetic imagery training of forceful muscle contractions increases brain signal and
3 muscle strength. *Frontiers in Human Neuroscience* **7**, 561.

4 Yue, G. and Cole, K.J. (1992) Strength increases from the motor program: Comparison of
5 training with maximal voluntary and imagines muscle contractions. *Journal of*
6 *Neurophysiology* **67**, 1114-1123.

7 Zijdwind, I., Toering, S.T., Bessem, B., Van Der Laan, O. and Diercks, R.L. (2003) Effects of
8 imagery motor training on torque production of ankle plantar flexor muscles. *Muscle and*
9 *Nerve* **28**, 168-173.

10 Zimmermann-Schlatter, A., Schuster, C., Puhan, M.A., Siekierka, E. and Steurer, J. (2008)
11 Efficacy of motor imagery in post-stroke rehabilitation: a systematic review. *Journal of*
12 *Neuro Engineering and Rehabilitation* **5**, 8.

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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	Mental imagery PG	-Maximal isometric contractions (elbow flexor) ↑6.8 ↑17.8	7
Leung et al. (2013)	18-35; 18; Male and female; Healthy participants	No injury	Motor imagery (3 wks/3 dys)	-Voluntary grip strength ↑8.9 ↑2.1 (NSDG)	6
Smith et al. (2007)	<i>Study 1:</i> 20.37±3.26; 48; Male and female; Healthy student athletes <i>Study 2:</i> 7-14; 40; Female; Healthy athletes	No injury	PETTLEP-based imagery Traditional imagery (6 wks/1 dys)	Field hockey penalty flic ↑15.11 ↑5.59	6
Wright and Smith (2009)	20.74±3.71; 50; NR; Healthy students	No injury	PETTLEP-based imagery (6 wks/3 dys)	Straight jump on the beam ↑36.36	6
Wright and Smith (2009)	20.74±3.71; 50; NR; Healthy students	No injury	PETTLEP imagery PETTLEP + PP Traditional imagery PG (6 wks/2 dys)	1RM: bicep curl machine ↑23.29 ↑28.03 ↑13.75 ↑26.56	6
Slimani and Chéour (2016)	23.2 ± 3.1; 45 ; Male; Healthy participants	No injury	Mental imagery PG (10 wks/3 dys)	↑13.1 1RM bench press ↑16.9 1RM half-squat ↑10.7 1RM bench press ↑8.61RM half-squat	6
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 Creator 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	Immobilization 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	Immobilization 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.

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

Study	Characteristics (Age; n; Sex; AL)	MI perspective (Weeks/sessions)	Strength task	Results	PEDr o 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 Ruiten 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.

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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: <i>makiwara</i>)	↑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 After 5 weeks After 7 weeks	↑129.6 ↑111.3 ↑136.3 ↑112.9	5
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.

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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	?

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Table 4. Results from mediation variables.

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

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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	Imagery	Leg exercise (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	Imagery	Treadmill running (3 min each condition)		NR	NR
			5 km/h	↑8.25		
			8 km/h	↑13.20		
		Actual exercise	12 km/h	↑19.45		
			5 km/h	↑44.20		
			8 km/h	↑70.72		
Fusi et al. (2005)	22-24; 14; Male and female; Healthy participants	Imagery	Walking task (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		
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.

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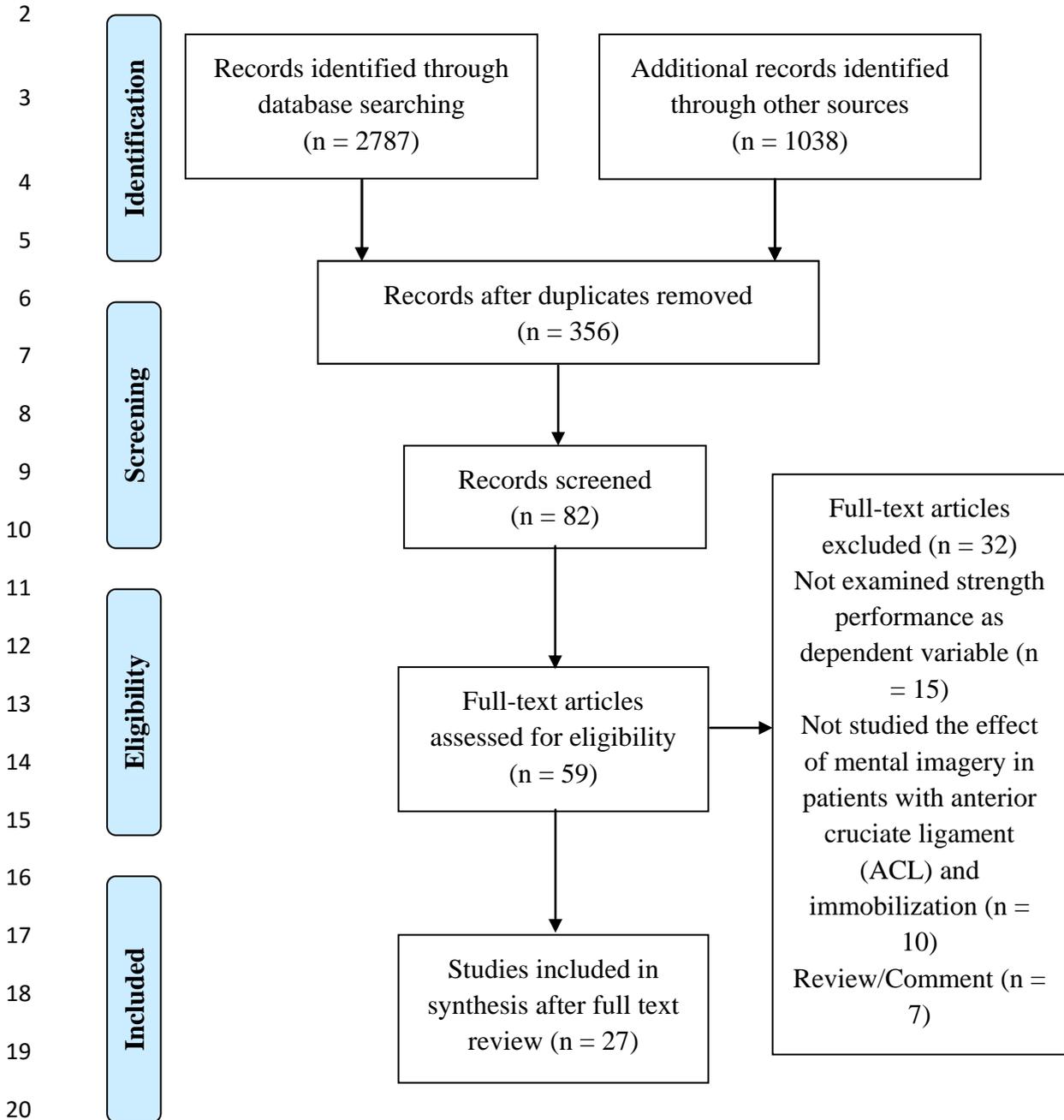
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1 **Figure 1.** PRISMA flow diagram detailing the literature search procedure.



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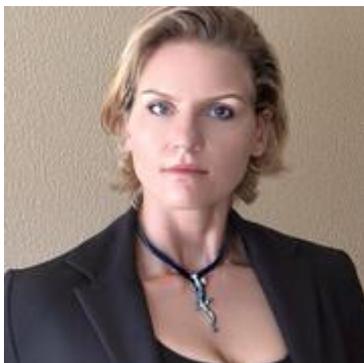
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