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► To cite this version:

Dylan Rannaud Monany, Charalambos Papaxanthis, Aymeric Guillot, Florent Lebon. Motor imagery and action observation following immobilization-induced hypoactivity: A narrative review. *Annals of Physical and Rehabilitation Medicine*, 2022, 65 (4), pp.101541. 10.1016/j.rehab.2021.101541 . hal-04185314

HAL Id: hal-04185314

<https://u-bourgogne.hal.science/hal-04185314>

Submitted on 22 Aug 2023

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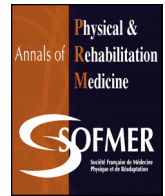


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Review

Motor imagery and action observation following immobilization-induced hypoactivity: A narrative review



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ARTICLE INFO

Article history:

Received 1st March 2020

Accepted 22 April 2021

ABSTRACT

Background: In sports, the risk of pathology or event that leads to an injury, a cessation of practice or even to an immobilization is high. The subsequent reduction of physical activity, or hypoactivity, induces neural and muscular changes that adversely affect motor skills and functional motor rehabilitation. Because the implementation of physical practice is difficult, if not impossible, during and immediately following injury or immobilization, complementary techniques have been proposed to minimize the deleterious impact of hypoactivity on neuromuscular function.

Objective: The current narrative review aimed to discuss the contributions of motor imagery and action observation, which enhance motor (re)learning and induce neural adaptations in both healthy individuals and injured athletes.

Methods: Online literature research for studies of the effects of motor imagery, action observation and their combination on hypoactivity, extracting relevant publications within the last decade (2009–2020).

Results: From published studies and the authors' knowledge of both motor imagery and action observation, some elements are provided for developing applied protocols during and after the immobilization period. Such interventions consist of associating congruent action observation with kinesthetic motor imagery of different movements, organized in increasing difficulty. The aim is to maintain motor functions and promote motor relearning by activating sensorimotor cortical areas and corticomotor pathways of the injured effector.

Conclusion: This narrative review supports the implementation of combined motor imagery and action observation protocols in the context of sports rehabilitation.

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1. Introduction

In sports, at both professional and recreational levels, the risk of accidents that leads to injuries or musculoskeletal pathologies is high (e.g., muscle tears, fractures, sprains). These events are likely to induce a training cessation or, in some cases, a prolonged period of physical inactivity (e.g., bed rest and/or immobilization). Even if necessary, this reduction in physical activity, or hypoactivity, can be problematic when considering sports practice and rehabilitation. Indeed, in addition to its harmful effects on physical (e.g. fatigability) and psychological health (e.g., depression), hypoactivity adversely and globally affects motor functions, decreasing athletic performance [1]. Thus, the rehabilitation protocols must

consider the impairments in motor function at the local (injury location zone) and general levels, caused by the traumatic event, but also the subsequent period of hypoactivity.

A recent review explored the association between hypoactivity and central lesions [2], so here we focus on hypoactivity induced by peripheral disabling events. The undesirable effects of hypoactivity differ according to the nature of the disuse: hypoactivity caused by prolonged bed rest (e.g., fracture of a leg bone during a ski descent) primarily affects walking and postural balance [3], whereas immobilization of the upper limb (sprained wrist during a tennis match) has deleterious effects on arm motor skills [4]. To understand the neurophysiological changes leading to such motor impairments in injured people, the most common method is to reproduce hypoactivity in healthy individuals (e.g., immobilization of the arm for an acute or prolonged time). The experimental model in healthy participants minimizes the impact of confounding variables (e.g., immobilization duration, immobilization cause,

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associated pain, potential comorbidities), bringing clear information about the exclusive hypoactivity-induced effects on neurophysiological processes. As presented below, the current results demonstrate that hypoactivity affects cortical activity, corticospinal excitability, neuromuscular properties and motor behavior.

At the cortical level, functional imaging reveals the presence of structural and functional changes due to hypoactivity [5–8]. For instance, Koppelmans et al. [5] reported a regular decrease in grey matter volume in areas involved in movement planning and execution, such as the primary motor cortex, the somatosensory cortex and the cerebellum, throughout the bed rest period (8.5, 50.5 and 66 days after the procedure started). This significant structural decrease was associated with functional degradation of postural balance and mobility, as measured after bed rest. Impaired interhemispheric inhibitory balance between primary motor cortices was also reported [9,10]. Crucially, Avanzino et al. [9] revealed that the imbalance depends on the over-use of the non-immobilized arm, inducing deeper inhibition in the immobilized arm-related primary motor cortex.

At the corticospinal level, by means of transcranial magnetic stimulation, Roberts et al. [6] observed a decrease in corticospinal excitability in leg muscles right after and 2 weeks after a 90-day bed rest period. These results are consistent with Karita et al. [11], who found a decrease in corticospinal excitability with shorter immobilization duration (24 hr). However, these results are challenged by Zanette et al. and Leukel et al. [12,13], who observed an increase in corticospinal excitability following limb immobilization. Modification at the spinal level may preferentially explain the increased corticospinal excitability. Nonetheless, the specific spinal pathway (direct monosynaptic or indirect polysynaptic) is still debated because of contradictory findings.

At the muscular level, decreased strength after immobilization is accompanied by changes in muscle properties, such as fiber atrophy (reduction of the cross-sectional area) and slowing duration of the maximum M-wave [14]. This latter finding may be explained by changes in muscle fiber conduction velocity, increased temporal dispersion between the responses of different motor units, and/or alterations in the muscle cell membrane properties. The authors also claimed that neural factors (primarily deficits in central activation) explained 48% of the variability in strength loss, whereas muscular factors (primarily sarcolemma function) explained 39% of the variability, thereby attesting that both components are affected by immobilization.

At the behavioral level, studies reported deteriorated motor performance in various tasks after upper-limb immobilization [7,8,15–18]. These deteriorations were mainly characterized by increased movement duration and loss in movement accuracy as well as loss of tactile acuity. The decrease in motor performances has been associated with impaired feedback and feedforward mechanisms of motor control, affecting motor command implementation, postural anticipations and on-line movement corrections.

To counteract hypoactivity effects, rehabilitation programs based on physical practice are implemented during and after immobilization [19]. Physical practice preserves motor abilities because of its positive effects on both neural and musculoskeletal structures as well as on sensorimotor representations. However, physical practice is not always possible, or sufficient. Moreover, immobilization is likely to limit the use of physical training (e.g., locomotion exercise with immobilized legs), which implies the development of complementary and alternative techniques. Because motor imagery (MI) and action observation (AO) are frequently used in clinical settings, this narrative review focuses on the efficiency of MI and AO interventions to counteract hypoactivity effects and discusses the benefits of combining MI and AO in a rehabilitation protocol.

2. Method

The main objective of the current narrative review was to examine the efficiency of MI and AO interventions to counteract hypoactivity effects and to discuss the benefits of combining MI and AO in a rehabilitation protocol. We conducted an online search in PubMed/MEDLINE, Web of Science and Google scholar electronic databases for English-language original studies and review articles of relevance. Search terms included “hypoactivity”, “immobilization”, “injury”, “motor imagery”, “action observation” and/or “combined motor imagery and action observation”. In addition, related publications were manually extracted by cross-referencing. Given past reviews [20,21] and the increasing number of subsequent studies, we focused on publications published during the last decade (2009–2020).

3. Results

3.1. Motor imagery, action observation and immobilization

3.1.1. Motor imagery

MI is the internal simulation of a movement without its concomitant production. Different modalities frame MI; the 2 most used are kinesthetic MI (the focus on sensorial and muscular aspects of action) and visual MI (the self-visualization of a movement). According to Jeannerod [22] and Decety [23], MI and actual execution are neurofunctionally equivalent (Table 1). At the cortical level, MI and actual execution share overlapping neural substrates [24]. Moreover, transcranial magnetic stimulation studies have shown an effector- and temporal-specific increase in corticospinal excitability during MI [25]. Behaviorally, MI shares the temporal properties associated with the corresponding gesture execution (isochrony) as well as a similar integration of biomechanical and environmental constraints [26]. From a computational perspective, the common properties would be due to an equivalent solicitation of the sensorimotor mechanisms involved in motor planning.

The neurofunctional equivalence between MI and actual execution may explain motor skill learning without gesture execution. Corroborating that idea, numerous studies showed beneficial effects of MI on motor acquisition, consolidation and retention [27]. MI-induced neuroplastic changes may explain these benefits at least in part (see [28] for a detailed review). Since the pioneering work of Pascual-Leone et al. [29], 3 mechanisms underlying MI-induced plasticity have been identified [28]: (1) MI contributes to a somatotopically dependent reorganization of cortical maps [30]; (2) MI also contributes to the strengthening of intersynaptic communication, at both cortical and spinal levels [31,32]; and (3) MI reduces presynaptic inhibition at the spinal level, facilitating the signal transmission [33].

3.1.2. Action observation

AO solicits the brain regions responsible for the corresponding motor execution in the observer's brain via the frontoparietal mirror network [34,35]. Similar to MI, AO increases corticospinal excitability in an effector-specific manner [36]. The activation of the sensorimotor system during AO helps the observer understand the actions of others. From a mechanistic point of view, Jeannerod [22] proposed that AO implicitly generates an internal simulation of the action. That mechanism, called motor resonance, would modulate the motor behavior of the observer and promote imitation learning (Table 1).

Several studies demonstrated that AO contributes to improve the learning of a wide variety of motor tasks, from simple (e.g., pointing) to complex (e.g., sport, poly-articular) movements

Table 1
Main processes and effects of motor imagery and action observation.

| | Motor imagery | Action observation |
|-------------------------------|--|--|
| Main processes | Explicit Implication of predictive neural mechanisms Effector-specific activation of corticospinal pathways, associated with cortical activations of the sensorimotor system | Implicit Motor resonance, possible implication of predictive neural mechanisms Effector-specific activation of corticospinal pathways, associated with cortical activations of the sensorimotor system |
| Behavioral effects | Motor skill enhancement: Muscle strength Balance Gait mobility Upper limb functionality | Motor skill enhancement: Balance Gait mobility Upper limb functionality |
| Neurophysiological mechanisms | Brain activations of frontoparietal areas, putamen and cerebellum regions Modulation of pre-synaptic spinal activity Corticospinal excitability increase | Brain activations of frontoparietal areas Corticospinal excitability increase |

[37]. As for MI, motor learning through AO can be explained by AO-induced neuroplastic reorganizations [38]. These beneficial effects on motor learning have been observed in both healthy and injured participants (e.g., post-stroke), thereby enhancing the development of AO-based treatments to facilitate motor (re)learning [20].

3.1.3. Potential interest of motor imagery and action observation for sports rehabilitation

MI and AO induce corticospinal adaptations and promote (re)learning with or without actual execution, so they are assumed to be efficient in a sport rehabilitation framework. Such an approach could indeed have implications for treating sports-related pathologies leading to movement restrictions or immobilization (e.g., muscle injury, sprain, ligament injury, dislocation, fracture).

However, and even if MI and AO are promising and complementary alternatives to physical exercise, one must first evaluate the effects of an experimentally induced and controlled hypoactivity on these processes. Indeed, if actual execution is impaired after immobilization, MI and AO would likely be affected as well. Of note, the potential impairment of MI and AO after immobilization should not be considered an impediment to their implementation in a rehabilitative context. Indeed, Ruffino et al. [39] recently demonstrated that MI quality improved after a single session of MI practice in healthy individuals. Before being excluded from the experiment, the participant/patient should be familiarized with the intervention modalities.

3.1.4. Effect of immobilization on motor imagery and action observation

First focusing on MI, studies reported that the short-term immobilization of a limb (<1 day) affected isochrony and vividness (i.e., the clarity of simulated action) at the level of this limb [40]. These impairments are due to the somatotopic- and laterally-dependent effects of short immobilization on sensorimotor representations [41,42]. In a multimodal study combining transcranial magnetic stimulation, magnetoencephalography and functional MRI, Burianova et al. [43] sought to observe the effect of 24-hr hand immobilization on MI-associated neural and corticospinal responses. For MI of the constrained hand, data showed decreased neural activation, disturbed event-related synchronization and desynchronization and decreased corticospinal excitability after immobilization. From their findings, the authors proposed that the attenuation of MI-associated neural responses after immobilization relies on a decrease of sensorimotor representation specificity, also called dedifferentiation. For longer immobilization durations (e.g., 48 hr), Meugnot et al. [44] reported a transfer to the unconstrained contralateral limb. Because no impairments were observed for MI of other body parts (i.e., foot),

the authors suggested that immobilization effects remained restricted to the effector network. As a consequence of immobilization effects on MI neural substrates, the neural state of the patients should be considered to provide individual MI instructions. To our knowledge, the question remains of whether a longer immobilization also affects sensorimotor representations in a broader manner. To the best of our knowledge, no study has addressed the question of immobilization effects on AO. Therefore, we are limited in our understanding of the impact of hypoactivity on this process.

3.2. Benefits of motor imagery and action observation during hypoactivity

In the current section, we focused on the effect of acute and chronic MI and AO interventions on neurophysiological parameters and motor function in both healthy individuals and patients.

3.2.1. Motor imagery

Because kinesthetic and visual MI have different effects on corticospinal excitability and learning [19], MI modality deserves consideration. In Meugnot et al. [45], participants were subjected to an acute mental training (15 min) after 24 hr of brachial immobilization and were assessed on a laterality judgement task (mental rotation). MI training consisted of 4 distinct tasks: (1) finger tapping, (2) adduction/abduction of the wrist, (3) flexion/extension of the wrist, and (4) hand clenching and unclenching, with 25 trials each. MI modality varied among groups (i.e., kinesthetic vs. visual vs. no training). Kinesthetic MI training maintained response time duration after immobilization, with an increase for other groups. For the authors, kinesthetic MI would therefore contribute to the reactivation of sensorimotor representations. In another study, Stenekes et al. [46] aimed to characterize the effects of kinesthetic MI training on the preservation of hand function after a longer immobilization period (6 months). After finger flexor surgery, patients of the MI and control groups imagined or not 80 finger flexions per day, respectively. Primarily interested by the central aspects of hand function, the authors compared finger flexion of the uninjured hand before immobilization to those of the injured hand after immobilization. They reported a smaller increase in reaction time between the 2 hands for the MI group than for the control group ($F = 5.901$, $P = 0.024$), which suggests that MI training helped to conserve the central properties of motion control. In the same study, Stenekes et al. [46] reported no effects of MI on muscle strength and kinematic analysis. These results are in part contradictory to those of Frenkel et al. [47]. In that experiment [47], MI performed during immobilization preserved dorsal extension (1.77% loss) and ulnar abduction (7.71% loss) of the

wrist joint as compared with the immobilized control group (11.88% and 29.42% loss, respectively), in agreement with previous results [48]. We suggest that the differences in results could be explained in part by the dissimilarities in samples (surgical participants in [46] vs. healthy participants in [47]) and by the duration of immobilization (6 weeks for [46] vs. 3 weeks for [47]). Despite the presence of these contradictory results, the effectiveness of kinesthetic MI on the maintenance of muscular strength after immobilization has been the subject of a recent systematic review [49]. The results of that review strongly pointed to the positive effects of MI to reduce strength loss for both healthy participants and patients.

The results presented in the previous section may be due in part to the effects of MI at both cortical and corticospinal levels. In the study by Clark et al. [50], participants were immobilized at the wrist and hand for 4 weeks and were assigned or not to an MI training (immobilization group with and without MI). The training consisted of 52 imagined maximal contractions of wrist flexor muscles 5 times a week. In addition to muscle strength measures, the authors studied the effect of MI on cortical silence period duration, reflecting corticospinal inhibition. The immobilization group with MI showed a smaller decrease of muscle strength than the immobilization group without MI ($23.8 \pm 5.6\%$ vs. $45.1 \pm 5.0\%$ reduction). A silence period extension, observed for the immobilization group without MI, was not observed for the immobilization group with MI, which suggests that MI allows for relative preservation of the intracortical balance. In another experiment, Debarnot et al. [51] studied the effect of MI training on both corticospinal excitability and MI performance (hand laterality task) during short-term immobilization (11 hr). For the imagery group, MI training was divided into 5 distinct sessions of 15 min, every 2 hr and consisted of imagining mono-articular (e.g., wrist extension) movement during the first 2 sessions, then imagining both mono- and poly-articular movements (e.g., throwing a ball) during the 3 last sessions. Both corticospinal excitability and MI performances were preserved for the group that performed MI practice.

To briefly conclude, the above articles suggest that MI helps restrain the deleterious effects of hypoactivity. These benefits could rely on MI-induced intracortical and corticospinal modulations.

3.2.2. Action observation

As a reminder, immobilization affects cortical structures and modulates corticospinal excitability relative to the constrained limb. Bassolino et al. [52] sought to compare the effectiveness of AO (and MI) practice on corticospinal excitability maintained after immobilization. All participants had immobilized forearm and fingers for 10 hr. They were instructed to observe manual grasping actions (AO group), imagine a grasping movement with their constrained arm (MI group), or watch a documentary (control group). Measurements of corticospinal excitability, before and after immobilization, provided evidence of maintenance for the AO group only, which suggests that AO benefits cortical plasticity during immobilization. The authors suggested that MI might be less effective than AO owing to the frailty of predictive internal loops elicited by immobilization. Considering internal model theories, the correct estimation of MI features depends on information available at the action initiation. In the context of forearm immobilization, the initial state cannot be consistently considered when imagining grasping movement. Hence, MI would be less effective, whereas AO, relying on another mechanism (i.e., motor resonance), would not be affected by this interference.

Challenging the above-presented results of Debarnot et al. [51], these opposite results lead to considering certain features of the MI protocols. Indeed, the MI protocol used by Debarnot et al. [51] involved different movements of increasing difficulty, whereas the

protocol by Bassolino et al. [52] involved grasping movements. Moreover, in Debarnot et al. [51], participants could physically practice the movement with their non-immobilized arm before MI practice, which might have a positive effect on reactivation of the corticomotor pathways specific to the imagined movement. These results suggest that imagery content and protocol instructions are important to help maintain motor functions.

3.3. Combined motor imagery and action observation

MI and AO have been separately studied for years, but recent studies provided clear evidence that these 2 forms of practice should rather be used complementarily. Indeed, a growing body of neurophysiological and behavioral studies pointed out that combined AO and MI led to a greater activity of the motor execution network as well as better performance as compared with MI or AO alone ([53], for review). In Marusic et al. [54], the authors observed the effectiveness of a combined MI and AO protocol, applied during (4 to 6 days) and 2 months after immobilization induced by total hip arthroplasty. The protocol consisted of observing an action on a screen and concomitantly imagining the movement with a focus on kinesthetic action features (AO + MI). The observed and imagined actions consisted of locomotor movement of increasing difficulty (e.g., slow walking at first, then walking on unstable surfaces or on stairs). As compared with the group that benefited from only the standard rehabilitation protocol, the combination of MI and AO resulted in greater performance gains for gait speed, swing-time variability and better scores on behavioral tests (Timed Up and Go and Four Square Step Test). The authors suggested that AO allows for visual guidance, permitting a better focus on MI kinesthetic features [55]. By doing so, internal representation updating would be enhanced, leading to motor performance improvement. Although the superiority of the MI and AO protocol compared to MI or AO alone was not directly tested, these results suggest the possibility of combining both MI and AO as a complementary rehabilitative technique after post-surgical immobilization.

4. Discussion and recommendations for practice

In this review, we aimed to identify the single and combined contributions of MI and AO to counteract the effects of immobilization-induced hypoactivity and to provide practical implications in sport rehabilitation. The included studies (Table 2) underline the efficiency of MI, AO, and their combined use, to maintain motor functions during and after immobilization. In the following section, we discuss the main recommendations that should be considered for designing the optimal use of MI and AO in a sport rehabilitation context.

Our main recommendation concerns the implementation of a protocol combining MI and AO in sports rehabilitation. Combining MI and AO in a single protocol would have a positive effect on sensorimotor representations, promoting relearning after immobilization more effectively than an isolated MI or AO protocol. To our knowledge, there are no contraindications to the application of such a protocol. Moreover, it would be beneficial in a large number of cases; from simple sprain to immobilization following a fracture. Consequently, it would be applicable in many sport rehabilitation contexts. Aware of the temporal, ergonomic and human resource limits in the rehabilitation field, the application of MI and AO combined would not be time-consuming (in accordance with Marusic et al. [54]; 20 to 30 min per day in the hospital, then 3 times per week at home).

To the best of our knowledge, there are no clear data as to when these protocols should ideally start. However, because motor

Table 2
Classification of studies by research aim.

| Reference number | Effects of hypoactivity on motor functions | Effects of motor imagery | Effects of action observation | Effects of motor imagery and action observation |
|------------------|--|--------------------------|-------------------------------|---|
| | [1–18,40–44] | [45–51] | [52] | [53] |

function decreases quickly during the immobilization procedure (see introduction section), we recommend starting the protocols as soon as possible/convenient for the patient during the immobilization and/or rest procedure. Because improvements following mental practice might depend on motor imagery quality, assessment could be relevant to discriminate participants who could directly benefit from the protocol from those who will need to improve MI quality in a first time. Indeed, one can improve MI quality after one or a few sessions [39]; therefore, the assessment at the first session should not be directly excluded from the study/intervention for participants/patients with initial low MI quality.

The protocol should include a familiarization phase for the proper integration of instructions related to MI. Movements should be presented in increasing difficulty [51], gradually adding contextual elements involving subtle movement modifications (e.g., walking on slippery ground, then on a downward- or upward-slope, with obstacles). In addition, MI is more effective when imagined in an ecological setting [56]. However, the patient may be constrained to stay still during recovery. During that time, the presentation of ecological images/videos could help the patient recall vivid motor representations. As recently evidenced [57–60], we recommend using AO in a first perspective for isolated body-part movements (e.g., hand exercise) and using AO in a third perspective for whole-body movements (e.g., locomotor exercise). Concerning more specifically a third perspective AO, we recommend to not use mirror movements (e.g., not observing a person coming toward the subject, but observing a person walking in front of the subject) in order to minimize additional mental rotation. Moreover, biological similarities between the actor and the observer (e.g., action observation of a woman for a female patient) would maximize AO efficiency. Transitive and meaningful movements are also recommended, allowing for greater solicitation of AO neural substrates [61]. Finally, patient’s compliance with the treatment should be carefully controlled [30].

Designing the appropriate content and recommendations for MI requires specific attention. As evidenced in Meugnot et al. [45], the use of kinesthetic rather than visual MI would be preferable to reactivate sensorimotor representations. Because of the effect of circadian rhythms on MI performance, MI quality assessment and MI training should ideally be performed at the same time of day (between 14:00 and 16:00 for adults) to ensure consistent results [62]. If possible, an actual execution of the unconstrained contralateral effector during interventions would also be welcome

to ease the reactivation of the corticomotor pathways specific to the imagined movement. When actual movement is possible, the person’s initial position should be congruent with the imagined movement (e.g., standing for a locomotion exercise) [63]. The incorporation of physical movements between MI trials is also relevant owing to their positive effect on motor performance, MI quality and mental fatigue minimization [64]. Therefore, we recommend series of 10 imagined trials interspersed with 1 to 5 actual trials, when feasible (Table 3).

5. Perspectives

The current review points out the relevance of combining MI and AO in a motor rehabilitation context. Despite the promising effects observed in the included studies, the methodological heterogeneities (e.g., healthy or patient participants, immobilization durations) call for some caution in interpreting the results. Moreover, many questions remain and need to be addressed to provide appropriate and effective care assistance. First, the greater benefits of a combined MI and AO protocol compared to MI or AO alone must be explicitly tested. Although the benefits can be reasonably assumed from reports in other framework (e.g., stroke), this has not been studied in the case of peripherally induced immobilization. Also, the effect of immobilization-induced hypoactivity on AO should be examined, as studied for MI. Next, whether circadian rhythms affect AO must be investigated to determine optimal training periods. When movement is possible, a protocol combining MI and AO might be improved by a recent and innovative technique, called dynamic MI [65]. Dynamic MI consists of performing simple movements concomitant to the imagination of a more complex one, involving the same effector (e.g., oscillate on legs while imagining locomotor movements). This method led to better performance (i.e., more congruent results between actual motion and MI) as compared with static motor imagery (i.e., without concomitant movement) [65]. When actual movement is possible, one could reasonably assume that MI use would be enhanced with that technique. Sports-specific assessment of the efficiency of these techniques as well as comparative studies regarding time to return to sport and time to return to initial level should be assessed to contextually adjust rehabilitation protocols. Given the effects of peripheral nerve stimulation on MI- or AO-induced motor learning and motor performances [66,67], whether

Table 3
Main recommendations for MI, AO and AO + MI protocol.

| General protocol recommendations | MI recommendations | AO recommendations | AO + MI recommendations |
|---|---|---|---|
| Frequency Hospital: every day At home: 3 times a week | MI quality assessment Kinesthetic rather than visual MI to activate sensorimotor representations | Use AO in a 1st perspective for body-part movements and in a 3rd perspective for whole-body movements | Congruency between AO and MI movements Present videos in ecological and familiar settings (e.g., to observe someone uses cutlery rather than isolated finger movements) to improve motor imagery quality |
| Duration 20–30 min | When actual movement is possible: congruence between body position and imagined movement | Use transitive and meaningful movements | |
| Time of day Ideally between 14:00 and 16:00 | Interspersed MI trials with actual trials | Execute actual movements in reaction to the observed movement | |
| Difficulty Increase across sessions | | | |

AO: action observation; MI: motor imagery.

peripheral nerve stimulation can enhance motor learning induced by a combined AO + MI protocol should be assessed.

As mentioned previously, immobilization can induce an intracortical imbalance in favour of intracortical facilitation. If AO maintains corticospinal excitability after short-term immobilization [49], MI would maintain the intracortical imbalance by increasing the activity of intracortical inhibitory networks. Testing the intracortical dynamics associated with MI and AO before, during, and after immobilization would help better picture their respective effects on intracortical balance. Given the effects of hypoactivity on corticospinal excitability, the effects of MI and AO at the spinal level also could be investigated. Although the modulation of spinal excitability by MI and AO has been observed in other contexts [68], there is very little information concerning the potential influence of MI and AO to counteract immobilization effects at the spinal level.

6. Conclusions

This current narrative review supports the implementation of combined MI and AO protocols in the context of sports rehabilitation. These protocols aim to minimize the loss of motor functions induced by hypoactivity and to promote the recovery of motor function during rehabilitation. Further investigations should help in developing individual protocols for ecological sport tasks.

Funding

This work was supported by the French-German ANR program in human and social sciences (contract ANR-17-FRAL-0012-01).

Author contributions

RMD wrote the manuscript; PC, GA and LF provided feedback on the manuscript; all authors read and approved the submitted version.

Disclosure of interest

The authors declare that they have no competing interest.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <https://doi.org/10.1016/j.rehab.2021.101541>.

References

- [1] Canu MH, Fourneau J, Coq JO, Dannhoffer L, Cieniewski-Bernard C, Stevens L, et al. Interplay between hypoactivity, muscle properties and motor command: How to escape the vicious deconditioning circle? *Ann Phys Rehabil Med* 2019;62:122–7. <http://dx.doi.org/10.1016/j.rehab.2018.09.009>.
- [2] Coleman ER, Moudgal R, Lang K, Hyacinth HI, Awosika OO, Kissela BM, et al. Early rehabilitation after stroke: a narrative review. *Curr Atheroscler Rep* 2017;19. <http://dx.doi.org/10.1007/s11883-017-0686-6>.
- [3] Mulder E, Linnarsson D, Paloski WH, Rittweger J, Wuyts FL, Zange J, et al. Effects of five days of bed rest with and without exercise countermeasure on postural stability and gait. *J Musculoskelet Neuronal Interact* 2014;14:359–66.
- [4] Lundbye-Jensen J, Nielsen JB. Central nervous adaptations following 1 wk of wrist and hand immobilization. *J Appl Physiol* 2008;105:139–51. <http://dx.doi.org/10.1152/jappphysiol.00687.2007>.
- [5] Koppelmans V, Bloomberg JJ, De Dios YE, Wood SJ, Reuter-Lorenz PA, Kofman IS, et al. Brain plasticity and sensorimotor deterioration as a function of 70 days head down tilt bed rest. *PLoS One* 2017;12:1–23. <http://dx.doi.org/10.1371/journal.pone.0182236>.
- [6] Roberts DR, Ramsey D, Johnson K, Kola J, Ricci R, Hicks C, et al. Cerebral cortex plasticity after 90 days of bed rest: data from TMS and fMRI. *Aviat Sp Environ Med* 2010;81:30–40. <http://dx.doi.org/10.3357/ASEM.2532.2009>.
- [7] Huber R, Ghilardi MF, Massimini M, Ferrarelli F, Riedner BA, Peterson MJ, et al. Arm immobilization causes cortical plastic changes and locally decreases sleep slow wave activity. *Nat Neurosci* 2006;9:1169–76. <http://dx.doi.org/10.1038/nn1758>.
- [8] Lissek S, Wilimzig C, Stude P, Pleger B, Kalisch T, Maier C, et al. Immobilization impairs tactile perception and shrinks somatosensory cortical maps. *Curr Biol* 2009;19:837–42. <http://dx.doi.org/10.1016/j.cub.2009.03.065>.
- [9] Avanzino LMB, Pozzo T, Bove M. Use-dependent hemispheric balance. *J Neurosci* 2011;31:3423–8. <http://dx.doi.org/10.1523/JNEUROSCI.4893-10.2011>.
- [10] Avanzino L, Pelosin E, Abbruzzese G, Bassolino M, Pozzo T, Bove M. Shaping motor cortex plasticity through proprioception. *Cereb Cortex* 2014;24:2807–14. <http://dx.doi.org/10.1093/cercor/bht139>.
- [11] Karita T, Matsuura A, Kondo Y, Tomimura K, Nakada N, Mori F. Time course of changes in corticospinal excitability after short-term forearm/hand immobilization. *Neuroreport* 2017;28:1092–6. <http://dx.doi.org/10.1097/WNR.0000000000000891>.
- [12] Zanette G, Manganotti P, Fiaschi A, Tamburin S. Modulation of motor cortex excitability after upper limb immobilization. *Clin Neurophysiol* 2004;115:1264–75. <http://dx.doi.org/10.1016/j.clinph.2003.12.033>.
- [13] Leukel C, Taube W, Rittweger J, Gollhofer A, Ducos M, Weber T, et al. Changes in corticospinal transmission following 8 weeks of ankle joint immobilization. *Clin Neurophysiol* 2015;126:131–9. <http://dx.doi.org/10.1016/j.clinph.2014.04.002>.
- [14] Clark BC, Fernhall B, Ploutz-Snyder LL. Adaptations in human neuromuscular function following prolonged unweighting: I. Skeletal muscle contractile properties and applied ischemia efficacy. *J Appl Physiol* 2006;101:256–63. <http://dx.doi.org/10.1152/jappphysiol.01402.2005>.
- [15] Bassolino M, Bove M, Jacomo M, Fadiga L, Pozzo T. Functional effect of short-term immobilization: kinematic changes and recovery on reaching-to-grasp. *Neuroscience* 2012;215:127–34. <http://dx.doi.org/10.1016/j.neuroscience.2012.04.019>.
- [16] Moissello C, Bove M, Huber R, Abbruzzese G, Battaglia G, Tononi G, et al. Short-term limb immobilization affects motor performance. *J Mot Behav* 2008;40:165–76. <http://dx.doi.org/10.3200/JMBR.40.2.165-176>.
- [17] Bolzoni F, Bruttini C, Esposti R, Cavallari P. Hand immobilization affects arm and shoulder postural control. *Exp Brain Res* 2012;220:63–70. <http://dx.doi.org/10.1007/s00221-012-3115-7>.
- [18] Scotto CR, Meugnot A, Casiez G, Toussaint L. Short-term sensorimotor deprivation impacts feedforward and feedback processes of motor control. *Front Neurosci* 2020;14. <http://dx.doi.org/10.3389/fnins.2020.00696>.
- [19] Rausch Osthoff AK, Juhl CB, Knittle K, Dagfinrud H, Hurkmans E, Braun J, et al. Effects of exercise and physical activity promotion: meta-analysis informing the 2018 EULAR recommendations for physical activity in people with rheumatoid arthritis, spondyloarthritis and hip/knee osteoarthritis. *RMD Open* 2018;4:e000713. <http://dx.doi.org/10.1136/rmdopen-2018-000713>.
- [20] Buccino G. Action observation treatment: a novel tool in neurorehabilitation. *Philos Trans R Soc B Biol Sci* 2014;369. <http://dx.doi.org/10.1098/rstb.2013.0185>.
- [21] Malouin F, Richards CL, Durand A. Normal aging and motor imagery vividness: implications for mental practice training in rehabilitation. *Arch Phys Med Rehabil* 2010;91:1122–7. <http://dx.doi.org/10.1016/j.apmr.2010.03.007>.
- [22] Jeannerod M. The representing brain: neural correlates of motor intention and imagery. *Behav Brain Sci* 1994;17:1–31.
- [23] Decety J. The neurophysiological basis of motor imagery. *Behav Brain Res* 1996;77:45–52. [http://dx.doi.org/10.1016/0166-4328\(95\)00225-1](http://dx.doi.org/10.1016/0166-4328(95)00225-1).
- [24] Gerardin E, Sirigu A, Léhericy S, Poline JB, Gaymard B, Marsault C, et al. Partially overlapping neural networks for real and imagined hand movements. *Cereb Cortex* 2000;10:1093–104. <http://dx.doi.org/10.1093/cercor/10.11.1093>.
- [25] Grosprêtre S, Ruffino C, Lebon F. Motor imagery and cortico-spinal excitability: a review. *Eur J Sport Sci* 2016;16:317–24. <http://dx.doi.org/10.1080/17461391.2015.1024756>.
- [26] Kilteni K, Andersson BJ, Houborg C, Ehrsson HH. Motor imagery involves predicting the sensory consequences of the imagined movement. *Nat Commun* 2018;9. <http://dx.doi.org/10.1038/s41467-018-03989-0>.
- [27] Collet C, Guillot A, Lebon F, MacIntyre T, Moran A. Measuring motor imagery using psychometric, behavioral, and psychophysiological tools. *Exerc Sport Sci Rev* 2011;39:85–91.
- [28] Ruffino C, Papaxanthis C, Lebon F. Neural plasticity during motor learning with motor imagery practice: review and perspectives. *Neuroscience* 2017;341:61–78. <http://dx.doi.org/10.1016/j.neuroscience.2016.11.023>.
- [29] Pascual-Leone A, Dang N, Cohen LG, Brasil-Neto JP, Cammarota A, Hallett M. Modulation of muscle responses evoked by transcranial magnetic stimulation during the acquisition of new fine motor skills. *J Neurophysiol* 1995;74:1037–45. <http://dx.doi.org/10.1152/jn.1995.74.3.1037>.
- [30] Gandola M, Zapparoli L, Saetta G, De Santis A, Zerbi A, Banfi G, et al. Thumbs up: Imagined hand movements counteract the adverse effects of post-surgical hand immobilization. Clinical, behavioral, and fMRI longitudinal observations. *NeuroImage Clin* 2019;23:101838. <http://dx.doi.org/10.1016/j.nicl.2019.101838>.
- [31] Jackson PL, Lafleur MF, Malouin F, Richards CL, Doyon J. Functional cerebral reorganization following motor sequence learning through mental practice with motor imagery. *Neuroimage* 2003;20:1171–80. [http://dx.doi.org/10.1016/S1053-8119\(03\)00369-0](http://dx.doi.org/10.1016/S1053-8119(03)00369-0).
- [32] Lacourse MG, Turner JA, Randolph-Orr E, Schandler SL, Cohen MJ. Cerebral and cerebellar sensorimotor plasticity following motor imagery-based mental practice of a sequential movement. *J Rehabil Res Dev* 2004;41:505–23. <http://dx.doi.org/10.1682/JRRD.2004.04.0505>.
- [33] Grosprêtre S, Lebon F, Papaxanthis C, Martin A. New evidence of corticospinal network modulation induced by motor imagery. *J Neurophysiol* 2016;115:1279–88. <http://dx.doi.org/10.1152/jn.00952.2015>.

- [34] Vogt S, Thomaschke R. From visuo-motor interactions to imitation learning: behavioural and brain imaging studies. *J Sports Sci* 2007;25:497–517. <http://dx.doi.org/10.1080/02640410600946779>.
- [35] Lapenta OM, Ferrari E, Boggio PS, Fadiga L, D'Ausilio A. Motor system recruitment during action observation: no correlation between mu-rhythm desynchronization and corticospinal excitability. *PLoS One* 2018;13:1–15. <http://dx.doi.org/10.1371/journal.pone.0207476>.
- [36] Sakamoto M, Muraoka T, Mizuguchi N, Kanosue K. Execution-dependent modulation of corticospinal excitability during action observation. *Exp Brain Res* 2009;199:17–25. <http://dx.doi.org/10.1007/s00221-009-1962-7>.
- [37] Mattar AAG, Gribble PL. Motor learning by observing. *Neuron* 2005;46:153–60. <http://dx.doi.org/10.1016/j.neuron.2005.02.009>.
- [38] Rocca MA, Meani A, Fumagalli S, Pagani E, Gatti R, Martinelli-Boneschi F, et al. Functional and structural plasticity following action observation training in multiple sclerosis. *Mult Scler J* 2019;25:1472–87. <http://dx.doi.org/10.1177/1352458518792771>.
- [39] Ruffino C, Papaxanthis C, Lebon F. The influence of imagery capacity in motor performance improvement. *Exp Brain Res* 2017;235:3049–57. <http://dx.doi.org/10.1007/s00221-017-5039-8>.
- [40] Meugnot A, Toussaint L. Functional plasticity of sensorimotor representations following short-term immobilization of the dominant versus non-dominant hands. *Acta Psychol (Amst)* 2015;155:51–6. <http://dx.doi.org/10.1016/j.actpsy.2014.11.013>.
- [41] Debarnot U, Huber C, Guillot A, Schwartz S. Sensorimotor representation and functional motor changes following short-term arm immobilization. *Behav Neurosci* 2018;132:595–603. <http://dx.doi.org/10.1037/bne0000274>.
- [42] Malouin F, Richards CL, Durand A, Descent M, Poiré D, Frémont P, et al. Effects of practice, visual loss, limb amputation, and disuse on motor imagery vividness. *Neurorehabil Neural Repair* 2009;23:449–63. <http://dx.doi.org/10.1177/1545968308328733>.
- [43] Burianova H, Sowman PF, Marsteller L, Rich AN, Williams MA, Savage G, et al. Adaptive motor imagery: a multimodal study of immobilization-induced brain plasticity. *Cereb Cortex* 2016;26:1072–80. <http://dx.doi.org/10.1093/cercor/bhu287>.
- [44] Meugnot A, Agbangla NF, Toussaint L. Selective impairment of sensorimotor representations following short-term upper-limb immobilization. *Q J Exp Psychol* 2016;69:1842–50. <http://dx.doi.org/10.1080/17470218.2015.1125376>.
- [45] Meugnot A, Agbangla NF, Almcicija Y, Toussaint L. Motor imagery practice may compensate for the slowdown of sensorimotor processes induced by short-term upper-limb immobilization. *Psychol Res* 2015;79:489–99. <http://dx.doi.org/10.1007/s00426-014-0577-1>.
- [46] Stenekes MW, Geertzen JH, Nicolai JPA, De Jong BM, Mulder T. Effects of motor imagery on hand function during immobilization after flexor tendon repair. *Arch Phys Med Rehabil* 2009;90:553–9. <http://dx.doi.org/10.1016/j.apmr.2008.10.029>.
- [47] Frenkel MO, Herzig DS, Gebhard F, Mayer J, Becker C, Einsiedel T. Mental practice maintains range of motion despite forearm immobilization: a pilot study in healthy persons. *J Rehabil Med* 2014;46:225–32. <http://dx.doi.org/10.2340/16501977-1263>.
- [48] Newsom J, Knight P, Balnave R. Use of mental imagery to limit strength loss after immobilization. *J Sport Rehabil* 2003;12:249–58. <http://dx.doi.org/10.1123/jsr.12.3.249>.
- [49] Teo WP, Chew E. Is motor-imagery brain-computer interface feasible in stroke rehabilitation? *PM R* 2014;6:723–8. <http://dx.doi.org/10.1016/j.pmrj.2014.01.006>.
- [50] Clark BC, Mahato NK, Nakazawa M, Law TD, Thomas JS. The power of the mind: the cortex as a critical determinant of muscle strength/weakness. *J Neurophysiol* 2014;112:3219–26. <http://dx.doi.org/10.1152/jn.00386.2014>.
- [51] Debarnot U, Perrault A, Sterpenich V, Legendre G, Huber C, Guillot A, Schwartz S. Motor imagery practice benefits during arm-immobilization on sensorimotor cortical networks and sleep features. *Sci Rep* 2021;11:8928.
- [52] Bassolino M, Campanella M, Bove M, Pozzo T, Fadiga L. Training the motor cortex by observing the actions of others during immobilization. *Cereb Cortex* 2014;24:3268–76. <http://dx.doi.org/10.1093/cercor/bht190>.
- [53] Eaves DL, Riach M, Holmes PS, Wright DJ. Motor imagery during action observation: a brief review of evidence, theory and future research opportunities. *Front Neurosci* 2016;10:1–10. <http://dx.doi.org/10.3389/fnins.2016.00514>.
- [54] Marusic U, Grosprêtre S, Paravlic A, Kovač S, Taube W. Motor imagery during action observation of locomotor tasks improves rehabilitation outcome in older adults after total hip arthroplasty. *Neural Plast* 2018;2018:1–9.
- [55] Meers R, Nuttall HE, Vogt S. Motor imagery alone drives corticospinal excitability during concurrent action observation and motor imagery. *Cortex* 2020;126:322–33. <http://dx.doi.org/10.1016/j.cortex.2020.01.012>.
- [56] Kalicinski M, Kempe M, Bock O. Motor imagery: effects of age, task complexity, and task setting. *Exp Aging Res* 2015;41:25–38. <http://dx.doi.org/10.1080/0361073X.2015.978202>.
- [57] Calvo-Merino B, Grèzes J, Glaser DE, Passingham RE, Haggard P. Seeing or doing? Influence of visual and motor familiarity in action observation. *Curr Biol* 2006;16:2277. <http://dx.doi.org/10.1016/j.cub.2006.10.065>.
- [58] Vingerhoets G, Stevens L, Meesdom M, Honoré P, Vandemaele P, Achten E. Influence of perspective on the neural correlates of motor resonance during natural action observation. *Neuropsychol Rehabil* 2012;22:752–67. <http://dx.doi.org/10.1080/09602011.2012.686885>.
- [59] Watanabe R, Higuchi T. Behavioral advantages of the first-person perspective model for imitation. *Front Psychol* 2016;7:701. <http://dx.doi.org/10.3389/fpsyg.2016.00701>.
- [60] Ge S, Liu H, Lin P, Gao J, Xiao C, Li Z. Neural basis of action observation and understanding from first- and third-person perspectives: an fMRI study. *Front Behav Neurosci* 2018;12:283. <http://dx.doi.org/10.3389/fnbeh.2018.00283>.
- [61] Decety J, Grèzes J, Costes N, Perani D, Jeannerod M, Procyk E, et al. Brain activity during observation of actions. Influence of action content and subject's strategy. *Brain* 1997;120:1763–77. <http://dx.doi.org/10.1093/brain/120.10.1763>.
- [62] Rulleau T, Mauvieux B, Toussaint L. Influence of circadian rhythms on the temporal features of motor imagery for older adult inpatients. *Arch Phys Med Rehabil* 2015;96:1229–34. <http://dx.doi.org/10.1016/j.apmr.2015.02.015>.
- [63] Saimpont A, Malouin F, Toussaint L, Jackson PL. The influence of body configuration on motor imagery of walking in younger and older adults. *Neuroscience* 2012;222:49–57. <http://dx.doi.org/10.1016/j.neuroscience.2012.06.066>.
- [64] Rozand V, Lebon F, Stapley PJ, Papaxanthis C, Lepers R. A prolonged motor imagery session alter imagined and actual movement durations: potential implications for neurorehabilitation. *Behav Brain Res* 2016;297:67–75. <http://dx.doi.org/10.1016/j.bbr.2015.09.036>.
- [65] Fusco A, Iasevoli L, Iosa M, Gallotta MC, Padua L, Tucci L, et al. Dynamic motor imagery mentally simulates uncommon real locomotion better than static motor imagery both in young adults and elderly. *PLoS One* 2019;14:e0218378. <http://dx.doi.org/10.1371/journal.pone.0218378>.
- [66] Bonassi G, Biggio M, Bisio A, Ruggeri P, Bove M, Avanzino L. Provision of somatosensory inputs during motor imagery enhances learning-induced plasticity in human motor cortex. *Sci Rep* 2017;7:1–10. <http://dx.doi.org/10.1038/s41598-017-09597-0>.
- [67] Bisio A, Avanzino L, Biggio M, Ruggeri P, Bove M. Motor training and the combination of action observation and peripheral nerve stimulation reciprocally interfere with the plastic changes induced in primary motor cortex excitability. *Neuroscience* 2017;348:33–40. <http://dx.doi.org/10.1016/j.neuroscience.2017.02.018>.
- [68] Kaneko N, Masugi Y, Usuda N, Yokoyama H, Nakazawa K. Modulation of Hoffmann reflex excitability during action observation of walking with and without motor imagery. *Neurosci Lett* 2018;684:218–22. <http://dx.doi.org/10.1016/j.neulet.2018.07.041>.