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Acquisition and consolidation of sequential footstep movements with physical and motor imagery practice

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Sleep-dependent performance enhancement has been consistently reported after explicit sequential finger learning, even using motor imagery practice (MIP), but whether similar sleep benefits occur after explicit sequential gross motor learning with the lower limbs has been addressed less often. Here, we investigated both acquisition and consolidation processes in an innovative sequential footstep task performed either physically or mentally. Forty-eight healthy young participants were tested before and after physical practice (PP) or MIP on the footstep task, following either a night of sleep (PPsleep and MIPsleep groups) or an equivalent daytime period (PPday and MIPday groups). Results showed that all groups improved motor performance following the acquisition session, albeit the magnitude of enhancement in the MIP groups remained lower relative to the PP groups. Importantly, only the MIPsleep group further improved performance after a night of sleep, while the other groups stabilized their performance after consolidation. Together, these findings demonstrate a sleep-dependent gain in performance after MIP in a sequential motor task with the lower limbs but not after PP. Overall, the present study is of particular importance in the context of motor learning and functional rehabilitation.

KEYWORDS

learning, lower-limb movement, mental training, motor imagery, sleep

1 | INTRODUCTION

Motor learning refers to the practice of a new skill within an acquisition session (ie, fast-learning phase), whereby a memory trace is established and then subsequently consolidated between practice sessions (ie, slow-learning phase).¹ Using the well-known explicit sequential finger-tapping task (SFTT), accumulated evidence has reported fast improvement of performance during acquisition and sleep-dependent gain in performance.² Contrasting with this extensive literature on SFTTs, only a few studies have been devoted to exploring the acquisition and consolidation effects in sequential gross movements and even fewer when the lower limbs

were involved.³ This lack in the motor learning literature is surprising, as many of our daily activities require sequential lower-limb movements, and these become even more important in both sport and clinical contexts (eg, functional rehabilitation). Therefore, there is a crucial need to examine whether findings from SFTTs may be generalized to other sequential gross motor tasks using different effectors and closer to an ecological context.

To address this issue, various fundamental and ecological gross motor paradigms have been used, from uni- and bimanual to whole-body movements.³ The plurality of gross motor paradigms developed so far has revealed inconsistencies in the findings, especially related

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to sleep-dependent consolidation.⁴⁻⁶ For instance, Genzel et al⁷ reported sleep-dependent gains in performance following sequential motor learning with the lower limbs (ie, dance choreography), while no-sleep benefits were observed following whole-body motor adaptation (ie, learning to ride an inverted-steering bicycle).⁴ Nevertheless, it has been postulated that gross motor learning has to be sequentially structured, sufficiently challenging, and acquired explicitly in order to benefit from the sleep consolidation effect.² Based on these requirements, and in an attempt to test for the generalization of SFTT data, it may be relevant to examine sequential explicit gross motor learning with the lower limbs, following the same goal (ie, an eight-item sequence executed with accuracy and velocity) and structure of practice (ie, practice blocks followed by a short rest). Most importantly, and as SFTT, the gross motor paradigm should be reproducible in other laboratories in a low-cost and easy-making manner. Therefore, in the present study, acquisition and consolidation processes were tested using an innovative footstep paradigm that was well suited to a straightforward comparison with the SFTT.

There is now ample evidence that motor imagery practice (MIP) is a valuable complement to physical practice (PP) in enhancing motor performance.⁸ Motor imagery is the process of mentally rehearsing a motor act without overt body movements.⁹ Many studies have provided evidence that mental and physical execution of the same movement share several characteristics at the temporal, neural, and behavioral levels.¹⁰ Numerous functional brain-imaging studies have demonstrated that both executed and imagined goal-directed movements recruit overlapping, though not strictly identical, neural networks.¹¹ In the same vein, mental rehearsal of movement typically results in performance enhancement but in a lower extent compared with physical practice of the corresponding motor task.¹²⁻¹⁴ Interestingly, MIP has been reported to improve performance during explicit sequential finger and foot tasks^{15,16} and, furthermore, has resulted in similar enhancement of performance after sleep consolidation as that reported with PP.^{15,16} Despite several findings that demonstrated the beneficial effect of MIP in lower-limb movements—mostly emphasized in sport and stroke/amputee rehabilitation^{17,18}—nothing is known regarding the acquisition and consolidation processes per se.

The present study aimed to investigate the effect of PP and MIP on the acquisition of sequential footstep movements, and the subsequent sleep and daytime consolidation processes. We first hypothesized that both types of practice would enhance motor performance during the acquisition session, but to a lesser extent after MIP than after PP. We further expected that the consolidation of motor memory following both types of practice would be greater after a night of sleep compared with wakefulness.

2 | METHODS

2.1 | Participants

A total of 48 healthy volunteers aged 20 to 35 years (mean age: 21.8 ± 2.2 years; 24 women) took part in this study. They were right-footed, as assessed by the Waterloo Footedness Questionnaire-Revised 10.43 ± 5.4 .¹⁹ All were good sleepers, as assessed by the Pittsburgh Sleep Quality Index cutoff < 5 ²⁰; and had a neutral/moderate chronotype rhythm range from 31 to 59.²¹ None had any prior history of drug or alcohol abuse or neurologic, psychiatric, or sleep disorders, and they were instructed to be drug, alcohol, and caffeine free for 24 hours prior to and during the experiment. Participants who either took regular dance classes or played virtual dancing games were excluded. This study was approved by the Institutional Review Board (IRB, #2018_03) of the University of Lyon, and all participants signed an informed consent form. Participants were not aware of the hypotheses of the study.

2.2 | Instrumentation and footstep motor task

The system was composed of a customized mat of 1 m², which was divided into nine squares (with sides of 33 cm each), as illustrated in Figure 1. Pressure sensors of 16 cm² (Interlink FSR402 short) were fixed under the center of each square (ie, on the underside of the mat) and corresponded to visible red circles/targets on the upper side. The task consisted of performing continuously an eight-step sequence (ie, sequence 3-1-9-8-4-7-6-5; see Figure 1 for target locations) using the right and left feet alternately, over blocks of 30 s.

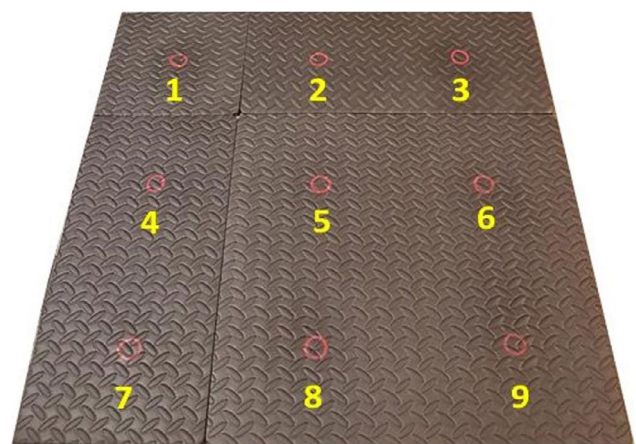


FIGURE 1 Sequential footstep device. The mat was composed by nine red circles, under which pressure sensors were fixed. The footstep motor task was performed by moving alternatively the right and left foot over the following targets: 3-1-9-8-4-7-6-5. Yellow numbers were not visible to the participant

Both the timing and accuracy of each step over the red targets were recorded during each block (PowerLab, ADInstrument, Australia). At the beginning of each practice block, participants stood at the center of the mat (Target 5). The experimenter used a digital timer (1/100 s, XL-013 anytime®) and said “go” and “stop” to indicate the start and end of each block.

2.3 | Experimental procedure

Participants were pseudo-randomized based on their gender, which allowed equal allocation of women and men into the four groups ($n = 12$ with 6 women each). Experimental groups were determined with respect to the nature of the practice (PP vs. MIP) and the type of consolidation period (sleep vs. day): PPsleep, PPday, MIPsleep, and MIPday groups. The experiment was scheduled to begin at 19:00 for the PPsleep and MIPsleep groups and 08:00 for the PPday and MIPday groups.

First, all participants were asked to warm-up for approximately 2 minutes by making random footstep movements on the mat. Then, the experimenter showed the sequence three times on the mat and asked participants to perform trials at self-speed until the correct execution of three consecutive sequences had been achieved. Immediately afterward, participants were asked to execute the correct sequence by putting their feet over the center of each square (where the sensors were fixed) as fast as possible during a pre-test consisting of two blocks of 30 seconds each, separated by 15 seconds of rest. Then, participants performed either a PP or an MIP training session over 12 blocks of 30 seconds, separated by 15 seconds of rest; a 1-min rest was further imposed after the 4th, 8th, and 12th blocks. MIP participants were equipped with two electromyogram (EMG) surface electrodes (Trigno Wireless EMG, Delsys, MA, USA; 1,000 Hz) stuck onto the right vastus medialis and gastrocnemius muscles. During MIP, the experimenter carefully controlled the background EMG activity online. Whenever muscle activities were detected in the signal, the experimenter waited for the rest period before asking participants to avoid moving physically during MIP. To assess the number of imagined sequences, MIP participants were also equipped with an accelerometer over the right extensor indicis muscle (Trigno Wireless accelerometer, Delsys, MA, USA; 300 Hz). An imagery script was read to the MIP participants at the beginning of the experiment (for details see, in Supporting Information) and shortly repeated immediately before the MIP training, hence ensuring that they followed similar instructions throughout MIP sessions. Briefly, MIP groups were asked to imagine themselves performing the motor sequence using a combination of visual and kinesthetic imagery (ie, visualizing movements from within one's body and feeling the corresponding

sensations induced by executing the sequence). During the first and last blocks of MIP training, they were asked to make a slight extension of the right index finger when they finished a sequence mentally (ie, right foot over Target 5). Following the 4th, 8th, and 12th blocks, MIP participants were required to auto-evaluate the difficulty and quality of their imagery using a Liker-type scale (from 1 = very difficult, no images/no sensations, to 5 = very easy, image as clear as seeing/sensation as intense as during actual performance).

A physical post-test was performed 1 minute after the PP or MIP training session and consisted of two blocks of 30 seconds separated by 15 seconds of rest. Then, the PPsleep and MIPsleep participants were equipped with an actigraph (wGT3X-BT, Pensacola, USA) to control for sleep efficiency of the subsequent night of sleep.

Finally, a retest was administered following either 12 hours of consolidation that included a night of sleep (PPsleep and MIPsleep groups) or a daytime period (PPday and MIPday groups). All participants had a 2-min warm-up (ie, random footstep movements on the mat), before performing the retest over two blocks of 30 seconds separated by 15 seconds of rest. Importantly, the experimenter repeated the instructions (accuracy and speed) before the post-test and retest sessions.

The timing of each sensor-press was recorded by means of a homemade MATLAB program (The Mathworks, Inc, Natick, MA, USA). Practically, this program allowed us to detect skillful steps performed over the center of the correct square, as recorded by the sensors, and following the order of the motor sequence. We selected the number of correct steps rather than the number of correct sequences for our main dependent variable as it provided a more representative measure of performance (for details, see Supporting Information).

2.4 | Complementary measures

The short version of the kinesthetic and visual imagery questionnaire (KVIQ,²² was administered before the beginning of the experiment to measure the individual's ability to form kinesthetic sensations and visual images of movements. Participants assessed on a five-point ordinal scale the clarity of the images (from 1, no image, to 5, image as clear as seeing) and the intensity of the sensations (from 1, no sensation, to 5, sensation as intense as during actual performance) elicited during the imagination of five simple movements. Visual and kinesthetic scores were calculated by summing the respective levels of MIP vividness for the five movements. The Corsi Block Test²³ was also administered to evaluate the individual visuospatial working memory capacity. The visuospatial span was assessed as the maximum number of blocks (presented in random sequences of increasing length) that subjects could correctly recall. Subjective measures of alertness and fatigue were collected using the Stanford Sleepiness

Score (SSS,²⁴ before the pre-test and the retest sessions. The SSS is a 7-point scale, with 1 being the most alert state.

2.5 | Data analysis

To assess performance during the tests (ie, pre-test, post-test, and retest), the number of skillful steps performed over targets following the correct ordinal sequence within each block of 30 seconds was computed, and the mean of the two blocks for each test was calculated for analysis.

2.6 | Statistical analysis

Linear mixed models were used to assess the interaction effect of GROUP (MIPsleep vs MIPday vs PPsleep vs PPday) and SESSION (pre-test vs post-test vs retest) (fixed effects) on the mean number of correct steps. Participants were entered as random intercepts. The F and P -values were obtained from likelihood ratio tests, which were conducted by testing the full model against the model without the effect tested. In the case of interaction effects, the two fixed effects were tested independently within each category of the other effect, and the alpha error was corrected by a Bonferroni procedure to compensate for multiple comparisons, leading to a significance of $P < .007$ (0.05/7).

To assess the reach of asymptotic performance during PP training, we applied a linear mixed model to the mean number of correct steps with group (PPsleep and PPday) and block (blocks 8-12 of training) as fixed effects. The temporal accuracy of motor imagery during training was controlled by comparing the number of steps (ie, number of sequences x eight steps) performed mentally during the first and last training blocks relative to those performed physically in the second block of the pre-test and the first block of the post-test, respectively, with Student paired t tests. The difference between the four groups in the Corsi test and the SSS scores were analyzed by an analysis of variance for repeated measures (ANOVARM), while the KVIQ and actigraphy data were also analyzed using a Student paired t test. Normal distribution of all data was assessed using the Shapiro-Wilk test. All models were performed using the software package lme4 of R (R 3.5.0, RCore Team, Vienna, Austria).

3 | RESULTS

3.1 | Acquisition and consolidation

Application of the linear mixed model to the mean number of correct steps yielded a main effect of GROUP ($F_{3,86} = 26.8$, $P < .0001$) and SESSION ($F_{2,86} = 224.1$, $P < .0001$), as well as a

GROUP X SESSION interaction ($F_{6,86} = 12.1$, $P < .0001$). We first checked whether the four groups were comparable in terms of performance during the pre-test session. In this session, subjects from the PPsleep, PPday, MIPsleep, and MIPday groups, respectively, performed 54.4 ± 3.4 , 54.2 ± 2.3 , 49.3 ± 2.8 , and 44.5 ± 3.9 correct steps; post hoc comparison did not show differences between groups ($P = .08$, Cohen's $d = [0.02-0.94]$) (Figure 2).

In the post-test, the mean number of correct steps significantly increased to 84.3 ± 4.8 , 81.2 ± 4.1 , 61.7 ± 3.2 , and 52.6 ± 4.4 in the PPsleep ($P < .001$, Cohen's $d = 2.16$), PPday ($P < .001$, Cohen's $d = 2.42$), MIPsleep ($P < .001$, Cohen's $d = 1.23$), and MIPday ($P < .001$, Cohen's $d = 0.62$) groups, respectively. These results indicate that MIP improved motor performance after training, albeit to a lower extent compared with PP ($P < .001$, Cohen's $d = [1.58-2.10]$), while no difference was found between the two PP groups ($P = .94$, Cohen's $d = 0.21$) or between the two MIP groups ($P = .67$, Cohen's $d = 0.73$).

Notably, analyses of the step numbers during last five blocks of PP training showed a main effect of BLOCK ($F_{4,88} = 6.94$, $P < .001$) but no main effect of GROUP ($F_{1,22} = 0.31$, $P = .58$), nor a GROUP X BLOCK interaction ($F_{4,88} = 0.76$, $P = .55$). Post hoc tests revealed that the number of correct steps did not continue to increase from the 9th to the 12th blocks of PP (8th vs. 9th block $P < .01$; all comparisons between blocks 9, 10, 11, and 12 non-significant), which may demonstrate the reach of asymptotic performance in the last three blocks of training.

In the retest session (Figure 2), the mean number of correct steps stabilized relative to the post-test in the PPsleep (89.9 ± 3.8 , $P = .08$, Cohen's $d = 0.39$), PPday (88.0 ± 4.1 , $P = .06$, Cohen's $d = 0.50$), and MIPday (55.8 ± 3.4 , $P = .27$, Cohen's $d = 0.25$) groups. In contrast, analysis of the MIPsleep group showed that performance significantly improved (73.3 ± 2.9 , $P < .001$, Cohen's $d = 1.13$). There was no difference between the PPsleep and PPday groups at retest ($P = .98$, Cohen's $d = 0.14$), while both had a higher performance compared with the MIPsleep ($P < .007$, Cohen's $d = [1.23-1.45]$) and MIPday ($P < .007$, Cohen's $d = [2.55-2.81]$) groups. Besides, the MIPsleep group had significantly higher performance than the MIPday group ($P < .006$, Cohen's $d = 1.66$).

Concerning the temporal accuracy of MIP during training, there were no significant differences between the number of physical and mental steps performed by the MIP groups at pre-test relative to the 1st block of MIP ($P = .18$, Cohen's $d = 0.40$), and between the 12th block of MIP relative to the post-test ($P = .12$, Cohen's $d = 0.11$). This result indicates that the speed of imagination of the sequence was similar to that of physically performed sequences at the beginning and at the end of MIP training. Moreover, there was a significant difference in the ease of MIP between blocks 4 and 8 (1.83 ± 0.91 and 1.91 ± 0.82 , respectively; $P < .001$) but

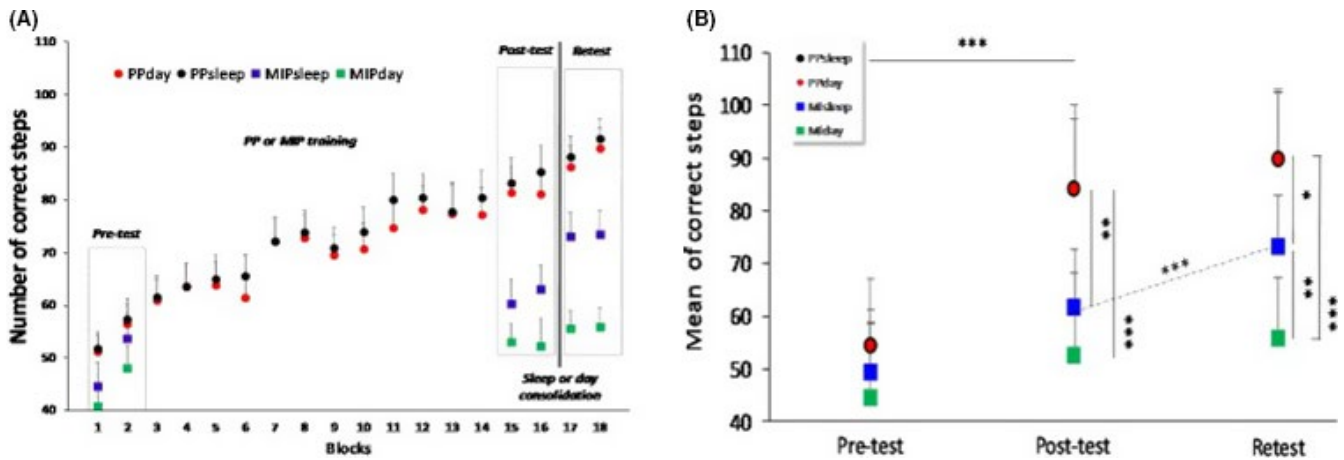


FIGURE 2 A, Mean number of correct steps per block in the PPsleep, PPday, MIPsleep and MIPday. All participants performed two physical blocks at pre-test, then they either physically or mentally trained on the task (blocks 3 to 14), and they all performed two physical blocks at post-test (blocks 15-16). After either 12 hours of sleep or daytime consolidation, all participants performed again two physical blocks at retest (blocks 17-18). B, Mean number of correct steps of the two blocks in the pre-test, post-test and retest sessions. Effects of PP and MIP on acquisition and consolidation of sequential footstep movements. The mean number of correct footsteps for the two blocks performed during the pre-test, post-test and retest have been computed for the four groups of participants. There was no difference between groups at pre-test, and all groups significantly increased their performance at post-test, but MIP groups' performance was lower compared to that of the PP groups. During retest, the two PP groups and the MIPday groups stabilized their performance, while the MIPsleep group showed delayed gains in performance after a night of sleep

TABLE 1 Summary of the actigraphy data for the MIPsleep and PPsleep groups. Values for actigraphy are reported in hours/percentages as indicated

Sleep measures	MIsleep	PPsleep	<i>P</i>
<i>Actigraphy</i> (hh:mm)			
Bed time	23:08 ± 01:25	23:32 ± 01:30	<i>P</i> = .59
Sleep latency	00:07 ± 00:10	00:07 ± 00:07	<i>P</i> = .12
Sleep start	23:16 ± 01:29	23:38 ± 01:34	<i>P</i> = .60
Sleep end	07:17 ± 01:03	07:51 ± 01:07	<i>P</i> = .22
Get up time	07:26 ± 01:13	07:58 ± 01:31	<i>P</i> = .25
Total sleep time (min)	07:05 ± 01:21	07:35 ± 01:09	<i>P</i> = .36
Sleep efficiency (%)	87,14% ± 0,05	87,89% ± 0,07	<i>P</i> = .82

not between blocks 8 and 12 (2.08 ± 1.05 ; $P > .05$), suggesting that MIP became easier with training. In addition, there was no difference in the mean vividness scores between block 4 (2.93 ± 0.13), block 8 (2.85 ± 0.17), and block 12 (2.87 ± 0.19) ($P > .09$ for each comparison).

3.2 | Questionnaires and sleep assessment

First, no group differences emerged from the comparison of the visuospatial spans ($F_{3,43} = 0.03$, $P = .80$), showing that all subjects had similar visuospatial working memory

capacities. Results from the KVIQ did not show a main effect of MODALITY ($F_{1,22} = 3.72$, $P = .06$; visual 18.26 ± 4.35 and kinesthetic 17.26 ± 3.89 scores) nor a GROUP \times MODALITY interaction ($F_{1,22} = 2.15$, $P = .15$), indicating that the ability to imagine movements was similar between MIP groups. The ANOVA on the mean SSS ratings did not reveal any differences between GROUPS ($F_{3,44} = 1.82$, $P = .15$), nor SESSION effect ($F_{1,44} = 3.43$, $P = .07$) or GROUP \times SESSION interaction ($F_{3,44} = 0.98$, $P = .40$), showing that the four groups were identical in terms of alertness during the two experimental sessions. Finally, analysis of actigraphy data combined with subjective assessment of the night of sleep did not reveal any significant differences between the PPsleep and MIPsleep groups (Table 1), indicating that sleep groups were equivalent in the quantity and quality of sleep before the retest session.

4 | DISCUSSION

The present study was designed to investigate, for the first time, the effect of physical or mental practice of an explicit sequential footstep learning and the following consolidation process. Results showed that all participants improved their performance following the same amount of either physical or mental practice during the acquisition session. Importantly, only the MIPsleep group continued to improve performance at retest, while a stabilization of performance was observed in all other groups.

As expected, and consistent with the motor learning literature, both PP and MIP of sequential footstep movements

contributed to the enhancement of motor performance during the acquisition session. These results are supported by a previous neuroimaging study by Lafleur et al,²⁵ who showed that sequential foot movements, whether executed or imagined, recruit similar (albeit not totally overlapping) neural substrates and further mediate neuroplasticity. Our data demonstrated that the magnitude of performance was lower after MIP relative to PP, which is also consistent with the large body of evidence emphasizing that MIP enhances motor performance more than no practice, although generally not to the same extent as PP.^{13,26}

After physical acquisition in the explicit sequential footstep task, both PPsleep and PPday stabilized their performance following 12 hours of consolidation. Such findings may seem inconsistent with the extensive literature from the motor consolidation domain documenting that performance improvement in an explicit SFTT is sleep dependent.² However, there is a growing body of contrary research demonstrating that sleep benefits after such a type of motor paradigm, as well as more gross upper-limb movements, may result instead from the effect of confounding factors,²⁷⁻²⁹ especially the fatigue and circadian effects. In controlling the former, Rickard et al³⁰ reported stabilization rather than sleep-dependent enhancement of performance in an explicit finger-tapping task. Here, in an attempt to prevent the fatigue effect, 1 minute of rest was implemented after four blocks of practice (each separated by 15 seconds of rest). In a seminal meta-analysis, the same authors highlighted the influence of circadian rhythm effects on performance using varied time design or PM/AM design,³¹ as employed here (ie, wake group trained in the morning vs. sleep group trained at night, and both groups tested after the same delay interval).²⁷ Natural variation of the circadian rhythms is likely to influence simple motor performance in a 24-h cycle, leading to low performance in the early morning, improved across the early afternoon, and worse into the late evening.³² Nonetheless, factors such as alertness, motivation, and task constraints (complexity and duration) have been showed to prevail over that of circadian modulation,³³ see Debarnot et al.³⁴ Here, we may hypothesize that motor performance may be less vulnerable to circadian confounding, because the footstep paradigm is more complex (compared with simple finger tapping) and fun, as it resembles to the video-game paradigm employed by Genzel et al.⁷ Regarding alertness, the results did not yield a difference between the start of pre-test and retest in the wake and night groups, hence alleviating any confounding effect of alertness.

As an alternative explanation of the PP acquisition findings, our footstep paradigm required anticipated postural adjustments, balance maintenance, and adaptation skills, features that correspond to complex gross motor skill.^{35,36} Interestingly, studies which independently explored the

learning of postural adjustments and tracking movements performed with the lower limbs reported gains in performance after 24 hours of consolidation that included a night of sleep.³⁷⁻³⁹ Likewise, Lugassy et al.⁶ showed performance gains for an explicit complex motor skill (ie, fine movement) 24 hours following the acquisition session but not after a 12-h interval including or excluding a night of sleep. Therefore, it is possible that our sequential footstep paradigm would benefit from consolidation after 24 hours including a night of sleep, rather than 12 hours. Notably, our findings showed that PP groups reached an asymptotic level of performance in the 8th block of training, but it may be possible that further gains in performance may have appeared after more practice blocks (rather than the 12 here). This hypothesis is supported by studies demonstrating that gross motor learning (such as whole-body postural tasks) may need extensive training to reach asymptotic performance.^{3,40} Overall, our findings reinforce the current idea that explicit sequential knowledge is not sufficient to trigger sleep-dependent consolidation processes.² The level of complexity of the motor learning, as well as retesting at 24 hours, should be further explored in future investigations using complex motor paradigms.

The main notable and innovative finding of this study is that sleep improved motor performance after MIP, while stabilization occurred following daytime consolidation. These findings are consistent with previous evidence reporting that MIP of an explicit sequential finger task benefitted from sleep rather than daytime consolidation.^{15,16,41} Although the research of task complexity using MIP is scarce, previous reports showed that MIP of a challenging task, rather than a simple one, benefits more from sleep than daytime consolidation.^{42,43} Here, our innovative motor paradigm involved a complex pattern of movement control (eg, several skeletal muscles, degrees of freedom, and management of the gravitational force) that may have required effortful working memory process during MIP. As recent findings have demonstrated greater delayed gains in working memory following a night of sleep,^{44,45} it is possible that sleep-dependent overnight improvement following MIP may be due to prior working memory processes that reinforce the memory trace in the procedural long-term memory system. Notably, when looking at the different levels of performance reached at post-test between PP and MIP, one could attribute the sleep-dependent benefits for the MIPsleep to the simple addition of physical trials at retest. However, this assumption seems unlikely, as the MIPday group did not improve performance at retest after an equivalent consolidation period, but during the daytime. To draw definitive conclusions about the sleep-dependent performance gains following MIP associated with the working memory processes, future studies should test the effect of complexity on sequential lower-limb consolidation (eg,

fewer steps, no crossed movements) using MIP. Overall, this line of research may help to determine the best schedule to use in mental practice during motor learning and recovery of lower-limb functions.

4.1 | Perspective

This is the first evidence that explicit learning of sequential lower-limb movements is promoted by both physical and mental training. Furthermore, the present investigation demonstrated that PP elicits a stabilization of performance after a period of day- or night-time consolidation, while MIP results in performance gain after a night of sleep. In developing this novel motor paradigm, our study enables further exploration of the multifaceted nature of sleep consolidation, with a main purpose of bringing insights into the motor learning and functional rehabilitation domains. Increasing knowledge about the relationship between sleep and lower-limb movements, learnt physically or mentally, could be of relevance for physical therapy, such as the treatment of lower-limb disabilities.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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