Motor imagery during action observation increases eccentric hamstring force: An acute non-physical intervention

Matthew Scott [a], Stephen Taylor [a], Paul Chesterton [a], Stefan Vogt [b] & Daniel L. Eaves [a*]

[a] Sport and Exercise Science Section,

Teesside University, Middlesbrough, United Kingdom

[b] Department of Psychology, Lancaster University, United Kingdom

<u>Corresponding author</u>:

*Daniel L. Eaves

Sport and Exercise Science Section,

Teesside University, Middlesbrough, United Kingdom

e-mail: d.eaves@tees.ac.uk

Tel.: +44 (0) 1642 342380

Fax: +44 (0) 1642 342399

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Abstract

Purpose: Rehabilitation professionals typically use motor imagery (MI) *or* action observation (AO) to increase physical strength for injury prevention and recovery. Here we compared hamstring force gains for MI *during* AO (AO+MI) against two pure MI training groups. **Materials and methods:** Over a three-week intervention physically-fit adults imagined Nordic hamstring exercises in both legs simultaneously, and synchronised this with a demonstration of the same action (AO+MI), or purely imagined this action (pure MI), or imagined upper-limb actions (pure MI-control). Eccentric hamstring strength gains were assessed using ANOVAs, and magnitude-based inference (MBI) analyses determined the likelihood of clinical/practical benefits for the interventions. **Results:** Hamstring strength only increased significantly following AO+MI training. This effect was lateralised to the right leg, potentially reflecting a left-hemispheric dominance in motor simulation. MBIs: The right leg within-group treatment effect size for AO+MI was moderate and *likely* beneficial (d = 0.36), and only small and *possibly* beneficial for pure MI (0.23). Relative to pure MI-control, effects were *possibly* beneficial and moderate for AO+MI (0.72), though small for pure MI (0.39). **Conclusions:** Since hamstring strength predicts injury prevalence, our findings point to the advantage of combined AO+MI interventions, over and above pure MI, for injury prevention and rehabilitation.

Key words: action simulation; observational learning; mental practice; motor rehabilitation; Nordic hamstring eccentric exercises; hamstring strain injury.

Implications for rehabilitation

- While hamstring strains are the most common injury across the many sports involving sprinting and jumping, Nordic hamstring exercises are one of the most effective ways to build eccentric hamstring strength, for injury prevention and rehabilitation.
- In the acute injury phase it is crucial not to overload damaged soft tissues, and so non-physical rehabilitation techniques are well-suited to this phase.
- Rehabilitation professionals typically use either motor imagery or action observation techniques to safely improve physical strength, but our study shows that motor imagery *during* observation of Nordic hamstring exercises offers a safe, affordable and more effective way to facilitate eccentric hamstring strength gains, compared to purely imagining this action.
- Despite using bilateral imagery and observation training conditions in the present study, strength gains were restricted to the right leg, potentially due to a left hemispheric dominance in motor simulation.

INTRODUCTION

Hamstring strains are the most prevalent injury in sports that involve sprinting and jumping [1-2]. The most common mechanism of this injury is a forceful eccentric contraction during the terminal swing phase in high-speed running [3]. Many intervention studies now show Nordic hamstring training is one of the most effective methods for improving eccentric hamstring strength [4-7]. This training can reduce the frequency of hamstring injuries and mitigate other risk factors, such as advancing age and previous injuries associated with hamstring pathology [8]. Physical immobilisation over 3 weeks, however, which often occurs immediately post-injury, can result in a 47% reduction in eccentric, concentric and isometric hamstring strength [9]. In this initial recovery phase the challenge is to undertake rehabilitation exercises without overloading the damaged soft tissues. We addressed this issue in the present study. Our aim was to develop a relatively novel mental practice (i.e., non-physical) intervention, to both increase peak eccentric hamstring strength in a practical and cost effective way, and also to complement existing physical rehabilitation techniques. Our main intervention group engaged in concurrent action observation with motor imagery (AO+MI) of Nordic hamstring exercises. We compared this intervention to two other groups: pure motor imagery of this action (pure MI), and pure motor imagery of an upper-limb action (pure MI-control). We briefly review the evidence for motor imagery and action observation as different forms of non-physical practice, before discussing the recent evidence advocating the use of combined AO+MI interventions.

Practitioners who work in sports training and/or functional motor rehabilitation typically use motor imagery (MI) instructions and movement demonstrations *separately* to develop physical strength and improve motor skills [10]. MI is a form of mental practice involving the internal generation of visual and kinaesthetic aspects of movement in the absence of physical execution [11]. A now well-established finding is that MI can increase isometric force production [12-15], but without incurring additional neuromuscular fatigue alongside physical training [16]. MI is therefore recommended as either an accompaniment to physical practice, or an alternative during immobilisation resulting from injury [17-19]. During sports injury rehabilitation the advantages of MI are clear: this technique does not overload the soft tissues and can accelerate the return to play [17].

A growing number of studies has also shown that force production can be modulated by observing effortful actions [20-25]. For example, Wrightson et al. [25] recently found that the maximum cadence increased in an arm cranking exercise when simultaneously observing a faster-than-maximal arm cranking action. A strong body of research has also demonstrated the effectiveness of action observation (AO) for increasing the mobility of an affected limb in stroke and brain-injured patients [26]. On these grounds, AO is a well-substantiated therapeutic treatment in neurorehabilitation.

In terms of the associated neural substrates, MI and AO involve motor and motor-related brain areas that at least partially overlap both with one another, and with the regions involved in motor execution [27-30]. Despite these commonalities, it is surprising that the majority of research has studied MI and AO in isolation from one another [31]. Accordingly, the findings from this vast body of research generally advocate both MI and AO as two *independent* techniques that are (in the main) useful for improving motor abilities. It is important to note, however, that research does not unanimously support the benefits of either purely imagining or purely observing actions in motor rehabilitation [32-33]. Furthermore, investigations into the relative advantages of MI versus AO, as assessed via neurophysiological and force-related variables, have produced mixed and therefore inconclusive results [22, 27-28, 34-36].

More recently, research has instead begun to investigate the effects of motor imagery *during* action observation (AO+MI), with markedly positive and consistent results [31, 37]. A growing body of multimodal brain imaging studies has recently shown that observing while imagining the same action (AO+MI) yields significantly stronger activations in cortico-motor regions, compared to when the same action is either purely observed or purely imagined [37-46]. In those studies, the authors frequently suggest AO+MI methods should be advantageous in motor rehabilitation, but the behavioural evidence to support this claim is currently sparse [37]. While the few studies into AO+MI effects on motor behaviour do not directly inform on the issue of force production, the available evidence is encouraging. For example, AO+MI instructions can increase automatic imitation effects in movement kinematics [39, 47-48]. They can also reduce balance variability [49], and develop grip strength and dexterity of the affected limb in stroke patients [50]. Taken together these neurophysiological and behavioural experiments demonstrate that AO+MI instructions have a greater impact on motor processes than either MI or AO alone.

From a theoretical perspective, Jeannerod's [11] influential proposal was that MI and AO are two 'functionally equivalent' modes of action simulation. It is remarkable, however, that this approach did not address the potential effects for MI *during* AO. More recently, AO+MI effects have been conceptualised within the related framework of *dual-action simulation* [31, 37, 39, 48]. We provide an extended account of this theory in the discussion section, as a basis for interpreting our findings.

The cogent findings from the previous studies into AO+MI instructions now warrant a more comprehensive examination of AO+MI effects on force production variables. In the present study, we were interested in whether an acute (3-week) non-physical AO+MI intervention could increase maximal voluntary eccentric contractions (MVEC) in the hamstrings of physically-fit adults, who regularly undertake recreational sport and exercise. Here we sought a 'proof of concept' for the intervention, prior to studying these effects in a clinical population in subsequent work. We compared the training effects for three groups:

observing while imagining Nordic exercises (AO+MI), purely imagining these exercises (pure MI), and purely imagining a task-irrelevant upper-limb action (pure MI-control). We predicted significant increases in MVEC over time for both AO+MI and pure MI, with larger increases for AO+MI, and no changes for pure MI-control. If successful, this AO+MI training method would represent a novel, practical and affordable tool for preventing one of the most prolific injuries in dynamic sports, reducing recovery times, and complementing traditional physical rehabilitation approaches.

Nordic exercises involve contractions in both legs simultaneously. In physical training this should produce equitable gains in peak force production across both legs. For mental practice, however, two neurophysiological studies have identified a left-hemispheric dominance for MI processes, regardless of the laterality of the effector involved [51-52]. To our knowledge no experiments have examined the behavioural impact of such lateralised MI processes in the brain. Thus it is unclear if our task of mentally simulating Nordic exercises in both legs simultaneously (i.e., via AO+MI or pure MI) will produce either lateralised or bilateral gains in peak hamstring strength. We investigated this issue by recording MVECs in each leg independently at both the baseline and the post-intervention stages.

MATERIALS AND METHODS

Participants

Participants were recruited from the undergraduate and postgraduate Sport and Exercise Science courses at Teesside University and were allocated via minimisation procedures (see section 'Procedures' for details) to one of three groups: AO+MI (n = 9; with 7 male, mean age = 25.7, SD = 3.7), pure MI (n = 9; with 4 male, mean age = 24.6, SD = 4.4), or pure MI-control (n = 8; with 5 male, mean age = 20.6, SD = 2.1). All participants had either normal or correctedto-normal vision and reported no history of hamstring, lower back, or knee pathology in the previous 12 months. All participants were physically-fit and regularly undertook recreational (i.e., not professional) sports and/or physical activity between 2 and 4 times per week. During the intervention we asked all participants to continue their weekly exercise routine as normal, and refrain from making any adjustments to this in terms of either increasing or reducing their physical workload. They provided written informed consent prior to participation, and Teesside University's ethics committee approved the study.

Research design

We used a pre-post parallel groups research design. For the three groups (AO+MI, pure MI, and pure MI-control) we assessed maximal voluntary eccentric contraction (MVEC) in the right and left hamstrings both at the baseline and after the three-week imagery intervention. We assed MI ability pre-post intervention using the Movement Imagery Questionnaire-3 (MIQ-3; [53]).

Procedures

Video creation, equipment and protocol

We filmed a demonstration of the Nordic hamstring exercise in the sagittal plane (see figure 1). This was altered using video editing software (Adobe, Premier Pro 1.5), and displayed using a standard iPad (Apple, USA). Prior to baseline testing, all participants completed a standardised warm-up, comprising 5 min exercise on a cycle ergometer (Technogym; Cesena, Italy) at 65-75% of age-predicted maximal heart rate [54], followed by dynamic hamstring mobility and activation exercises [55].

--- Insert figure 1 about here ---

To assess both submaximal and maximal eccentric hamstring contractions, participants were seated upright on the Biodex System 3.0 Isokinetic Dynamometer (Biodex Medical Systems; New York, USA). Both feet were situated on the footplate, with the ankles in a neutral position. The crank axis was aligned with the axis of rotation of the knee, and a cuff was fitted 2 cm superior to the lateral malleolus. Restraints were applied across the test thigh, proximal to the knee joint so as not to restrict movement, and across the chest and waist, while participants gripped a bar with their hands, which was fixed to the machine at the side of each thigh.

Participants self-selected a moderate resistance before executing 5 sub-maximal eccentric hamstring contractions (approx. 50% MVEC) at $60°\cdot s^{-1}$. Next they performed a set of 8 single-leg maximal voluntary eccentric contractions (i.e., 100% MVEC) at $60°\cdot s^{-1}$, first using their right and then their left leg [56], separated by a minimum recovery period of 2 min [54]. The data were sampled at 2000Hz. We applied a high-pass Butterworth filter (5^{th} order) with a 50Hz cut-off to eliminate artefacts and low signal noise, before further smoothing using the root mean squared technique. The highest peak torque value (N.m.) provided the baseline score for each leg individually. We provided verbal encouragement throughout, but gave no feedback about force attainment.

Participants were allocated to one of the three groups via minimisation procedures using a customised Microsoft Excel spreadsheet published by Hopkins [57], which incorporated their baseline MIQ-3 and MVEC scores for each leg separately. Minimisation is a technique that allows group allocation based on multiple variables. The usual approach of randomized allocation can produce substantial differences among the population and between-group means, whereas minimization allocation serves to reduce these, thus improving the precision in the estimation of a treatment effect [57].

All procedures for the baseline test were replicated three weeks later at the post-intervention test. This was conducted on the same day as dissemination of the final MI session, and at roughly the same time of day as the baseline test to reduce variations resulting from circadian rhythms.

Motor imagery interventions: AO+MI, pure MI, and pure MI-control

For each participant we read aloud a MI script incorporating the PETTLEP principles (physical, environment, timing, task, learning, emotion, perspective [58]). The main instruction was to mentally simulate the *physical* effort and sensation involved in performing the movement *task* from a 1st person *perspective*, but without performing any actual movement. Participants were instructed to simulate their performance in real *time* and within their normal training *environment*, while including any *emotions* typically associated with this performance. These scripts were designed to help participants generate a vivid imagery experience involving all aspects of the task. They were also designed to foster *learning* by increasing the complexity and clarity of the imagery during the intervention period.

The structure and quantity of the sessions was designed in accordance with Schuster et al.'s [59] guidelines for best practice in motor imagery. Over a three-week period, participants performed three imagery sessions per week, each lasting 20 mins in duration. Each session was separated by a minimum of 48 hours rest to avoid fatigue and/or boredom. MI duration was equitable across groups, totalling approximately 3 hours per participant. We delivered the MI instructions to participants verbally in the laboratory. Individual debriefings investigated adherence to the MI instructions and any difficulties in imagery generation (none reported).

The three experimental groups differed primarily in their imagery and observation content. The *AO+MI* group were instructed to imagine the effort and sensation involved in executing the Nordic exercise with eyes open, and to additionally synchronise their motor simulation with the demonstration of this action [39, 48]. In the *pure MI* group participants were instructed to imagine (with eyes closed) the effort and sensation involved in executing the Nordic exercise. The pure MI-control group imagined an upper-limb action with eyes closed. They imagined the effort and sensation of writing the alphabet with their dominant hand on the wall in front of them. Thus, while MI ability should improve similarly across all three groups, any imagery improvements for pure MI-control should occur in the absence of meaningful increments in hamstring MVEC. In each session the timing of imagined movements was paced via the observed movement in the display during AO+MI, or via an auditory metronome during both pure MI and pure MI-control, which matched the timing of the movements shown during AO+MI.

Statistical analyses

First we ran mixed-measures analyses of variance (ANOVAs) on both the MIQ-3 and the MVEC data to investigate the between-subjects factor of group (AO+MI vs. pure MI vs. pure MI-control) and the within-subjects factor of time (baseline vs. post-intervention). We assessed the within-subjects factor of leg (left vs. right) in the MVEC data only. These analyses were conducted using SPSS Statistics 22 (IBM). Where appropriate, we adjusted for any violation of the homogeneity of variance assumption using the Greenhouse–Geisser correction. Alpha levels were set to 0.05, and effect sizes were calculated as partial eta squared values (η_p^2). To reduce type I error rates, we used pairwise comparisons to explore the data further [60]. In line with the main aim of the paper, we report pre-planned contrasts to investigate the MVEC change scores within each group separately.

Second, we complement the above reports with magnitude-based inference (MBI) analyses. This approach offers a theoretically justified and practically useful approach to behavioural research [61], and is particularly suited to quantifying changes in human performance over time. MBI describes the likelihood for an intervention to provide clinical/practical benefits for the population [62]. In athletic performance research it is important to know how big an effect is, and using the P value alone provides no information about the size of the effect, or the range of feasible values [63]. Therefore, uncertainty of the estimates, shown as 90% confidence intervals for the change scores with *SD*, were calculated using Hopkins' [64] pre-post parallel groups spreadsheet in Microsoft Excel. The between-groups difference in mean percent change scores was also calculated with *SD*s. The standardized effect size (*d*) was calculated for each difference score. The smallest worthwhile effect was defined as 0.2 times the between-subject *SD* of the baseline value [62].

The qualitative inferences were based on the disposition of the confidence interval for the mean difference in relation to the smallest worthwhile effect. The probability (percent chances) that the true population difference between the conditions was substantial (beneficial/harmful) or negligible was calculated as per the magnitude-based inference approach [65]. These percent chances were qualified via probabilistic terms assigned using the following scale: <0.5% = most unlikely or almost certainly not; 0.5 – 4.9% = very unlikely; 5 – 24.9% = unlikely or probably not; 25 – 74.9% = possibly; 75 – 94.9% = likely or probably; 95 – 99.5% = very likely; and >99.5% = most likely or almost certainly. Effect sizes were categorised as follows: 0.00 – 0.19 = negligible; 0.20 – 0.59 = small; 0.60 – 1.19 = moderate; 1.20 – 1.99 = large; 2.00 – 3.99 = very large; ≥ 4.0 = extremely large.

RESULTS

Motor imagery ability

The two-factorial ANOVAs run on the MIQ-3 data revealed a main effect of time. Imagery ability increased over time for each imagery sub-scale: kinaesthetic (4.4 vs. 5.7; $F(1, 23) = 26.94$; $p < 0.001$; $\eta^2 = 0.54$), visual 1st person (5.2 vs. 5.7; $F(1, 23) = 6.99$; $p < 0.05$; $\eta^2 = 0.23$), and visual 3rd person perspective (5.4 vs. 5.8, $F(1, 23) = 4.76$; $p < 0.05$; $\eta^2 = 0.17$). The main effect of group and the interaction was not significant in each analysis.

Maximal voluntary eccentric contraction of the hamstrings

ANOVA results

The three-factorial ANOVA identified a significant main effect of leg, $F(1, 23) = 10.42$; $p < 0.01$; $\eta^2 = 0.31$. Overall, MVEC was greater in the right compared to the left leg (180.2 vs. 171.4 N.m.). The main effects of both time and group were not significant, $F(1, 23) = 2.62$; $p > 0.05$ $\eta^2= 0.10$, and $F(2, 23) = 0.08$; $p > 0.05$; $\eta^2= 0.10$, respectively. However, the interaction between leg and time was significant, $F(1, 23) = 4.45$; $p < 0.05$; $\eta^2 = 0.16$. Pairwise comparisons revealed MVEC was significantly greater in the right compared to the left leg at both the baseline and post-intervention ($p < 0.05$ and $p < 0.01$, respectively). Importantly, MVEC increased significantly in the right leg between the baseline and the post-intervention test ($p < 0.01$). This comparison was not significant in the left leg ($p > 0.05$). All other interactions, including that between leg and group, were not significant.

Running pre-planned contrasts on the right leg data revealed a significant increase in MVEC from the baseline to post-intervention for AO+MI only ($p < 0.01$). See figure 2. This comparison approached significance for pure MI ($p = 0.10$), and was not significant for pure MI-control. In the left leg data these three comparisons were not significant.

--- Insert figure 2 ---

Magnitude-based inference results

See table 1 for the MBI analyses on the MVEC data. In the right leg, the within-group treatment effect size for AO+MI was moderate and *likely* beneficial as an applied intervention (d = 0.36). For both pure MI and pure MI-control the effect sizes were small and only *possibly* beneficial (ds = 0.23 and 0.13, respectively). Compared to the pure MI-control group, the treatment effect size for AO+MI was moderate and *possibly* beneficial (d = 0.74), while for pure MI this effect was only small and *possibly* beneficial (d = 0.50).

In the left leg, the within-group change scores were negligible and trivial for AO+MI (d = 0.00), negligible and unclear for pure MI (d = 0.05), while small and *possibly* harmful for pure MI-control (d = -0.29). Compared to pure MI-control, the treatment effect for AO+MI and pure MI was small and *possibly* beneficial (ds = 0.44 and 0.50, respectively). When contrasting the AO+MI and pure MI groups in both the right and left leg data, the effects were small and negligible, respectively, and unclear (ds = 0.34 and -0.10).

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DISCUSSION

Hamstring strains are especially common across the large number of sports involving sprinting and jumping [1-2]. Nordic exercises are a well-established method of increasing eccentric hamstring strength for both preventing and rehabilitating this injury [4-9]. A particular challenge, however, is to avoid an excessive eccentric workload during the acute injury phase, for fear of further damaging the soft tissues. For this reason, in the present study we investigated non-physical training methods as an alternative approach to acute hamstring rehabilitation. Our core aim was to assess hamstring strength gains for combined AO+MI training, compared to two pure imagery groups (pure MI and pure MI-control). The ANOVAs (with post-hoc tests) showed a significant improvement only in the right leg MVEC scores for the AO+MI group, and not for the other two groups. The MBI results revealed a similar pattern, highlighting the practical advantage for AO+MI instructions, compared to both purely imagining the Nordic exercises, and purely imagining upper-limb actions. Since imagery ability improved equally across groups, we rule this out as a potentially limiting factor. The present study therefore provides the first empirical evidence showing combined AO+MI instructions can produce a modest but practically important advantage in hamstring strength development, over an acute non-physical intervention.

Across the following sections we first discuss the effects for the combined AO+MI intervention, relative to pure MI and pure MI-control. We then contextualise these findings from the theoretical perspective of *dual-action simulation*. We subsequently consider the questions raised by the right-lateralised effects for AO+MI training, before outlining both a series of avenues for future research, and the implications for professionals in applied rehabilitation and sports training.

AO+MI and pure MI effects on eccentric hamstring force development

The within-group improvement in peak hamstring torque was significant only for the combined AO+MI intervention. For this group the treatment effect size was moderate and *likely* beneficial as an applied training / rehabilitation intervention. Compared to the pure MI control group, the effect size was moderate and *possibly* beneficial for AO+MI ($d = 0.72$). These data clearly argue in favour of modest but practically important benefits for AO+MI training. In contrast, we did not find compelling support for the positive effects of pure MI on hamstring MVEC development. For pure MI the within-group analysis of peak torque gains approached but did not reach levels of significance (p = 0.10), with a small treatment effect size that was only *possibly* beneficial. Compared to pure MI-control, the effect size for pure MI was small (d = 0.39), almost half of that for AO+MI in the same comparison, and *possibly* beneficial. It is important to note, however, that we did not optimise the intervention duration to ensure strength gains via pure MI. We instead focused on a time period (3-weeks) that represented the immediate stages post-injury, in which it is crucial to undertake rehabilitation, but necessary to avoid overloading the soft tissues [8]. In line with previous literature [12-13, 16-19, 58-59], we would expect more robust effects for pure MI over an extended training period. Considering this design restriction within our study, however, it is then particularly compelling that we did identify a significant and practically important advantage for combined AO+MI procedures within the same acute time period. Thus our analyses revealed overall that combined AO+MI procedures offer favourable strength training conditions during a short period of mental training.

A defining and potentially limiting characteristic of pure MI is the absence of a visual guide. By contrast, AO+MI instructions require close attention to the observed action, which presumably offers continuous and helpful opportunities for refining and updating the internal motor representation. Given the large number of studies that have advocated pure MI training methods for more than two decades [10-19, 59], we hope our findings now pave the way for further investigations into if, when, and how AO+MI instructions can offer advantages in force production tasks, for improving injury prevention and rehabilitation.

A commonly accepted framework for conceptualising MI and AO processes is Jeannerod's [11] 'functional equivalence' hypothesis of action simulation. From this perspective both MI and AO can be regarded as two forms of motor simulation, which both involve the motor system but typically do not include motor execution. A limitation of this account, however, is that it did not explicitly consider the possibility of MI *during* AO. To address this pertinent issue, a related and more recent proposal is the *dual-action simulation* account of AO+MI effects [31, 37, 39, 48]. This view submits that both an observed and an imagined action can be represented simultaneously, in the sense of two concurrent sensorimotor streams. These two streams could either merge or compete with one another, depending on their contents and usefulness for on-going actions plans. This proposal is (in part) grounded in the growing evidence showing AO+MI can: (i) elicit increased cortical activity in various motor regions of the brain; (ii) facilitate corticospinal excitability, measured through the amplitudes of motor evoked potentials in the muscles after applying transcranial magnetic stimulation to the motor cortex; and (iii) influence motor behaviour more directly than either AO or MI alone [37]. The particular match between the contents of MI during AO (i.e., congruent vs. conflicting) can also significantly modulate motor outputs [39,48]. Taken together these findings show the unique effects for AO+MI instructions (compared to both AO and MI) on different neurophysiological and behavioural indices of motor planning and execution. The present study strengthens this evidence further, being the first to show beneficial *practice* effects on motor outputs (i.e., increased peak hamstring torque) for congruent AO+MI training.

Helm et al. [22] previously suggested that both AO and MI processes can strengthen motor commands by potentiating the recruitment and synchronization of motor neurons, leading to increased force generation. From a dual-action simulation perspective, it is most likely that under AO+MI conditions the individual AO and MI processes serve to complement one another, to produce the overall advantage found here in force development. That is, the combined impact of both the internally-generated motor simulation *plus* the externally-induced visuomotor representation of the same action most likely coalesced to both increase and expedite motor processing.

Within the dual-action simulation framework, two further, interesting variations are: coordinating one's own imagined action with the actions of an imagined partner (i.e., MI+MI [66]), and observing the actions of two interacting partners (i.e., AO+AO). These everyday scenarios raise intriguing questions from a dual-action simulation perspective and are, at present, clearly under-researched.

AO+MI effects lateralised to the right leg

We instructed MI in both legs simultaneously, yet strength gains for AO+MI (and to a lesser extent, pure MI) were lateralised to the right leg. Our method replicated the approach of Whiteley et al. [56] in testing each leg individually in a given order. Since we first tested the right and then the left leg at both the baseline and post-intervention, we cannot completely rule out a potential order effect within our data. We do, however, suggest this explanation of our findings is unlikely. Any differences in MVEC resulting from order effects should present themselves equitably at both the baseline and post-intervention test, in which the testing procedures were identical. Contrariwise, we obtained a larger difference between the right vs. left leg MVECs post-intervention, compared to the baseline. We therefore submit that our findings do indeed support a genuine training effect.

At the baseline, peak hamstring torque was significantly higher in the right compared to the left leg, indicating a right leg dominance in this population. One possibility is that the lateralisation effect observed at the post-test could result from a spontaneous attentional focus during AO+MI training on the dominant, rather than non-dominant leg, producing an imbalance in the allocation of imagery processes across the two legs during training. This was despite clear and regular instructions for a bilateral motor representation of the task throughout every imagery training session for both AO+MI and pure MI. This finding is also counterintuitive to the fact that participants mainly observed the left leg in the demonstration (see figure 1). To our knowledge no behavioural studies have investigated this issue. It will be interesting to address this topic further in future research, by manipulating the attentional focus of the imagery to involve simulating either the dominant or non-dominant leg, ideally using a within-subjects pre-post cross-over design. Delayed retention tests could also be included to examine the time-course of the effects in each leg.

While more research is clearly needed to understand the role of leg-dominance in our task, we next outline a further explanation based on neurophysiological data showing task-specific and left-lateralised effects for MI processes in the brain. In their recent meta-analysis Hétu et al. [30] report that imagining simple gait patterns produces bilateral activations of primary sensorimotor regions in the brain, while MI of the dominant vs. non-dominant hand does not modulate the laterality of neural activations. Hétu and colleagues do, however, point out that the majority of studies in their meta-analysis employed simple rather than complex tasks. Using the limited data available they further concluded that increasing task complexity can result in greater left-hemispheric involvement during MI. The Nordic exercise is a fairly complex whole-body action to imagine, and so neural involvement may well have been predominantly left-lateralised during training. In addition to our earlier explanation of the right-lateralised effects in peak hamstring torque on the basis of leg-dominance, it is at least conceivable these effects might also relate to a left-hemispheric dominance for MI processes, resulting from task complexity. This conjecture is further supported by two studies not included in the meta-analysis by Hétu et al. [30].

Stinear et al. [52] investigated corticospinal excitability during MI of a phasic thumb movement. Their results showed a significant temporal modulation of motor evoked potentials in the *right* thumb abductor muscle during *both* bilateral and unilateral imagery of either the dominant or non-dominant hand. Baraldi and colleagues [51] also found a similar pattern of results using functional magnetic resonance imaging techniques. These two studies thus identified a left-hemispheric dominance for MI processes, regardless of the laterality of the imagined effector. On these grounds the participants in our study presumably had difficulties in representing both limbs simultaneously and/or to the same degree, which might have resulted in a spontaneous and perhaps unconscious allocation of MI predominantly to their right leg. Our findings therefore highlight a potential limitation for imagery (including with observation) in bilateral strength training and rehabilitation exercises.

In the present study there was also a small trend for greater peak torque at the baseline in the right leg compared to the left leg for AO+MI and pure MI, but not in the pure MI-control group (see table 1). The interaction between the factors of leg and group was, however, not significant at the baseline.

Future research opportunities

Since strength gains are typically strongest via physical practice itself, future research should now contrast AO+MI training against physical practice effects on a range of force development variables. The effects of different ratios of physical and AO+MI training can also be explored, as has previously been the case for physical and pure MI schedules [67]. A further line of enquiry could be to study the effects of AO+MI instructions within the practical framework of layered stimulus response training [68]. This method involves reducing the mental imagery content down to those components that a participant is able to generate with ease. The complexity and realism of the imagery is then gradually increased across trials by incorporating participant-generated stimulus, response and meaning propositions, such as sights, sounds or feelings associated with the movement task [68]. Over multiple AO+MI trials participants could make the experience more realistic each time by incorporating self-selected response and/or meaning propositions to layer over the observed action [37].

In the present study we did not include a pure AO condition because it is difficult to control for the potential confound of spontaneous MI occurring in a supposedly ‘pure’ AO condition [31]. Indeed, it is likely that concurrent AO+MI states are actually a common, rather than exceptional feature of daily life [37]. Future research could now compare AO+MI training effects against different cognitive strategies that can influence motor processes during observation, such as action prediction and observing with the intent to imitate [47] vs. no instructions at all.

Here we sought a ‘proof of concept’ for the effectiveness of the AO+MI intervention in physically active and healthy individuals. Given that the requirements for fitness improvements and strength gains in this population were generic (i.e., not sport-specific), we assessed peak hamstring torque only. Future research could now explore the potential benefits of this intervention in more specific populations, such as those recovering from hamstring injuries in a particular sport, or receiving treatment for neurological impairment. Depending on the population under investigation, there will be other force-related variables suitable for investigation. For example, reducing time-to-peak hamstring torque is important in hamstring rehabilitation, as it can indicate muscular strength for explosive aspects of sprinting.

In our physically-fit sample population, the variability in the data was considerable, and we would only expect this to increase in a clinical population. To some degree this might reflect the variability inherent in any repeated test of human performance, which can be caused by natural fluctuations in factors such as diet, sleep and motivation. A related and unexpected result in our study was that MVEC actually reduced in the pure MI-control group in the left leg only. Since the pre-planned contrasts revealed this effect was not significant, we do not consider this as problematic for our main interpretations of the data outlined above.

The application of AO+MI protocols in rehabilitation settings

While hamstring strains remain one of the most prolific injuries in dynamic sports, the rehabilitation of these injuries continues to present the clinician with numerous challenges. Despite strong evidence supporting the benefits of Nordic training for preventing hamstring injuries [5], coaches, clinicians and athletes still report poor compliance with this exercise, typically because of the tight time constraints in training schedules. During the acute phases of hamstring injury, the crucial challenge is also in deciding how best to facilitate rehabilitation without overloading damaged tissues. For these purposes, AO+MI instructions now offer a well-suited addendum to current practice in sports training and injury rehabilitation.

For professionals who work in these disciplines, our AO+MI method is extremely practical, affordable, accessible and safe to administer. It could, for example, be readily employed by displaying pre-recorded movements on an iPad or other hand-held device in a training or clinical setting. Following the appropriate guidance, athletes could also self-administer this protocol, to complement their face-to-face activities with rehabilitation and strength training professionals.

Overall, observing while imagining Nordic exercises offers an attractive method for maintaining and/or developing eccentric hamstring strength. AO+MI training should now be considered alongside traditional training and rehabilitation methods for reducing hamstring injury prevalence, mitigating hamstring strength loss during immobilisation, and for safely improving the rehabilitation of this challenging and troublesome injury.

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Declarations of interest

We declare that we have no potential competing interests with respect to the research, authorship and/or publication of this article. This research was conducted without any funding.

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Within-group comparisons	**Left leg**			**Right leg**		
	Action Observation + Motor Imagery (AO+MI)	Pure Motor Imagery (pure MI)	Pure Motor Imagery-control (pure MI-control)	Action Observation + Motor Imagery (AO+MI)	Pure Motor Imagery (pure MI)	Pure Motor Imagery-control (pure MI-control)
Baseline peak torque	168.28	168.01	179.89	175.13	176.89	178.75
SEM	11.5	9.4	5.7	10	9.4	6.3
Post-test peak torque	168.19	169.4	174.48	185.8	183.29	181.35
SEM	13.1	7.9	7.3	9.5	8.9	7.5
Change score	-0.09 (-0.8%)	1.39 (1.2%)	-5.41 (-3.3%)	10.67 (6.6%)	6.4 (3.8%)	2.6 (1.3%)
SEM	13.88	16.41	9.83	13.64	11.25	7.53
± 90% CL	8.6	10.2	6.6	8.5	7.0	5.0
Effect size (*d*)	0.00	0.05	-0.29	0.36	0.23	0.13
CI	-0.93 - 0.92	-0.87 - 0.97	-1.26 - 0.71	-0.58 - 1.28	-0.71 - 1.15	-0.85 - 1.11
Qualitative inference	negligible trivial**	negligible unclear	small –ive**	moderate +ive**	small +ive*	small +ive*

Between-group comparisons	AO+MI vs. Pure MI-control	Pure MI vs. Pure MI-control	AO+MI vs. Pure MI	AO+MI vs. Pure MI-control	Pure MI vs. Pure MI-control	AO+MI vs. Pure MI
Change score difference	5.32 (2.6%)	6.8 (4.7%)	-1.48 (-2.0%)	8.07 (5.2%)	3.8 (2.5%)	4.27 (2.7%)
SEM	5.79	6.48	7.16	5.27	4.6	5.89
± 90% CL	10.2	11.5	12.6	9.4	8.1	10.3
Effect size (*d*)	0.44	0.50	-0.10	0.72	0.39	0.34
CI	-0.55 - 1.38	-0.50 - 1.44	-1.02 - 0.83	-0.30 - 1.66	-0.59 - 1.33	-0.61 - 1.25
Qualitative inference	small +ive*	small +ive*	negligible unclear	moderate +ive*	small +ive*	small unclear

Table 1. Magnitude-based inference results for within- and between-group comparisons of percentage change in peak hamstring torque (N.m.). Key: SEM = standard error of the mean; CL = confidence limits; CI = confidence interval. Data extracted from Hopkins' [64] pre-post parallel groups spreadsheet, using 0.2 as the smallest worthwhile effect. Group mean baseline and post-test scores for peak hamstring torque (N.m) presented with SEM and change scores (SEM, % and CL) in the left and right leg within each group (AO+MI, pure MI, pure MI-control). Differences in change scores (i.e., baseline vs. post-intervention) also reported for group mean peak hamstring torque in left and right leg for the between-groups

contrasts. Effect sizes (*d* and CI) reported for both the within- and between-groups analyses, with qualitative descriptions taken from Hopkins' [65] scales: 0.0 – 0.19 = negligible; 0.2 – 0.59 = small; 0.6 – 1.19 = moderate; with qualitative inference: * = *possibly* (25–75%); ** = *likely* (75–95%); +ive = beneficial (positive) effect; -ive = harmful (negative) effect.

Figures

Figure 1. Visual demonstration of the Nordic hamstring exercise. Two people were present throughout the video: the main exerciser (left), who performed 10 repetitions of the Nordic exercise over a 50 s set, and a training partner (right) who held down and stabilised the main exerciser's ankles. As described by Arnason et al. [4], the exerciser (left) leaned forward (1) with back and legs extended, arms raised at the shoulders and elbows bent. (2) He resisted the fall forward for as long as possible using the hamstrings. (3) He landed on his hands, touched down with his chest and then forcefully pushed back up to a kneeling position using his hands, with minimal concentric loading on the hamstrings.

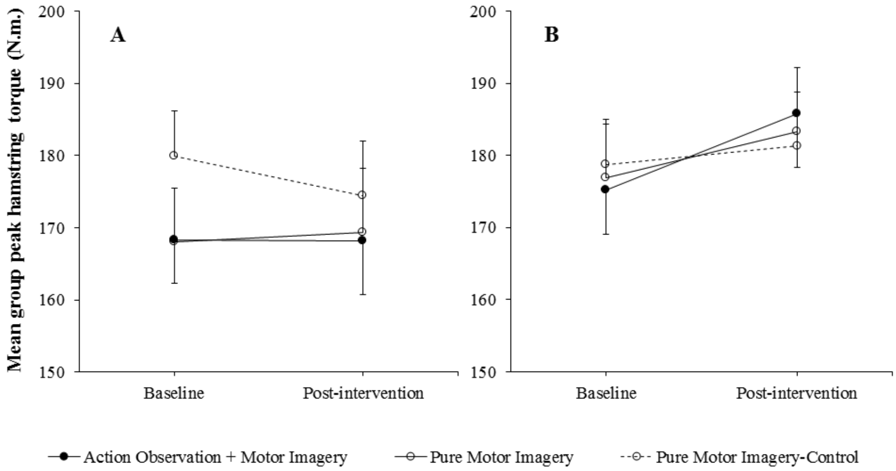

Figure 2. Group mean peak hamstring torque at both the baseline and post-intervention in both the left leg (panel A) and in the right leg (panel B) in N.m. Error bars show standard error of the mean.