

1 Motor imagery during action observation increases eccentric hamstring force:

2 An acute non-physical intervention

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## Abstract

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**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.

46 **Implications for rehabilitation**

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

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## 69 INTRODUCTION

70 Hamstring strains are the most prevalent injury in sports that involve sprinting and jumping  
71 [1-2]. The most common mechanism of this injury is a forceful eccentric contraction during  
72 the terminal swing phase in high-speed running [3]. Many intervention studies now show  
73 Nordic hamstring training is one of the most effective methods for improving eccentric  
74 hamstring strength [4-7]. This training can reduce the frequency of hamstring injuries and  
75 mitigate other risk factors, such as advancing age and previous injuries associated with  
76 hamstring pathology [8]. Physical immobilisation over 3 weeks, however, which often occurs  
77 immediately post-injury, can result in a 47% reduction in eccentric, concentric and isometric  
78 hamstring strength [9]. In this initial recovery phase the challenge is to undertake  
79 rehabilitation exercises without overloading the damaged soft tissues. We addressed this issue  
80 in the present study. Our aim was to develop a relatively novel mental practice (i.e., non-  
81 physical) intervention, to both increase peak eccentric hamstring strength in a practical and  
82 cost effective way, and also to complement existing physical rehabilitation techniques. Our  
83 main intervention group engaged in concurrent action observation with motor imagery  
84 (AO+MI) of Nordic hamstring exercises. We compared this intervention to two other groups:  
85 pure motor imagery of this action (pure MI), and pure motor imagery of an upper-limb action  
86 (pure MI-control). We briefly review the evidence for motor imagery and action observation  
87 as different forms of non-physical practice, before discussing the recent evidence advocating  
88 the use of combined AO+MI interventions.

89 Practitioners who work in sports training and/or functional motor rehabilitation  
90 typically use motor imagery (MI) instructions and movement demonstrations *separately* to  
91 develop physical strength and improve motor skills [10]. MI is a form of mental practice  
92 involving the internal generation of visual and kinaesthetic aspects of movement in the  
93 absence of physical execution [11]. A now well-established finding is that MI can increase

94 isometric force production [12-15], but without incurring additional neuromuscular fatigue  
95 alongside physical training [16]. MI is therefore recommended as either an accompaniment to  
96 physical practice, or an alternative during immobilisation resulting from injury [17-19].  
97 During sports injury rehabilitation the advantages of MI are clear: this technique does not  
98 overload the soft tissues and can accelerate the return to play [17].

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

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

117         More recently, research has instead begun to investigate the effects of motor imagery  
118 *during* action observation (AO+MI), with markedly positive and consistent results [31, 37]. A

119 growing body of multimodal brain imaging studies has recently shown that observing while  
120 imagining the same action (AO+MI) yields significantly stronger activations in cortico-motor  
121 regions, compared to when the same action is either purely observed or purely imagined [37-  
122 46]. In those studies, the authors frequently suggest AO+MI methods should be advantageous  
123 in motor rehabilitation, but the behavioural evidence to support this claim is currently sparse  
124 [37]. While the few studies into AO+MI effects on motor behaviour do not directly inform on  
125 the issue of force production, the available evidence is encouraging. For example, AO+MI  
126 instructions can increase automatic imitation effects in movement kinematics [39, 47-48].  
127 They can also reduce balance variability [49], and develop grip strength and dexterity of the  
128 affected limb in stroke patients [50]. Taken together these neurophysiological and  
129 behavioural experiments demonstrate that AO+MI instructions have a greater impact on  
130 motor processes than either MI or AO alone.

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

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

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

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

160

## 161 **MATERIALS AND METHODS**

### 162 **Participants**

163 Participants were recruited from the undergraduate and postgraduate Sport and Exercise  
164 Science courses at Teesside University and were allocated via minimisation procedures (see  
165 section ‘Procedures’ for details) to one of three groups: AO+MI ( $n = 9$ ; with 7 male, mean age  
166 = 25.7,  $SD = 3.7$ ), pure MI ( $n = 9$ ; with 4 male, mean age = 24.6,  $SD = 4.4$ ), or pure MI-control  
167 ( $n = 8$ ; with 5 male, mean age = 20.6,  $SD = 2.1$ ). All participants had either normal or corrected-

168 to-normal vision and reported no history of hamstring, lower back, or knee pathology in the  
169 previous 12 months. All participants were physically-fit and regularly undertook recreational  
170 (i.e., not professional) sports and/or physical activity between 2 and 4 times per week. During  
171 the intervention we asked all participants to continue their weekly exercise routine as normal,  
172 and refrain from making any adjustments to this in terms of either increasing or reducing their  
173 physical workload. They provided written informed consent prior to participation, and Teesside  
174 University's ethics committee approved the study.

175

## 176 **Research design**

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

182

## 183 **Procedures**

### 184 *Video creation, equipment and protocol*

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

191

--- Insert figure 1 about here ---



192 To assess both submaximal and maximal eccentric hamstring contractions, participants  
193 were seated upright on the Biodex System 3.0 Isokinetic Dynamometer (Biodex Medical  
194 Systems; New York, USA). Both feet were situated on the footplate, with the ankles in a neutral  
195 position. The crank axis was aligned with the axis of rotation of the knee, and a cuff was fitted  
196 2 cm superior to the lateral malleolus. Restraints were applied across the test thigh, proximal  
197 to the knee joint so as not to restrict movement, and across the chest and waist, while  
198 participants gripped a bar with their hands, which was fixed to the machine at the side of each  
199 thigh.

200 Participants self-selected a moderate resistance before executing 5 sub-maximal  
201 eccentric hamstring contractions (approx. 50% MVEC) at  $60^{\circ}\cdot\text{s}^{-1}$ . Next they performed a set  
202 of 8 single-leg maximal voluntary eccentric contractions (i.e., 100% MVEC) at  $60^{\circ}\cdot\text{s}^{-1}$ , first  
203 using their right and then their left leg [56], separated by a minimum recovery period of 2 min  
204 [54]. The data were sampled at 2000Hz. We applied a high-pass Butterworth filter (5<sup>th</sup> order)  
205 with a 50Hz cut-off to eliminate artefacts and low signal noise, before further smoothing using  
206 the root mean squared technique. The highest peak torque value (N.m.) provided the baseline  
207 score for each leg individually. We provided verbal encouragement throughout, but gave no  
208 feedback about force attainment.

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

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

220

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

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

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

238 The three experimental groups differed primarily in their imagery and observation  
239 content. The *AO+MI* group were instructed to imagine the effort and sensation involved in

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

251

## 252 **Statistical analyses**

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

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

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

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## 287 **RESULTS**

### 288 **Motor imagery ability**

289 The two-factorial ANOVAs run on the MIQ-3 data revealed a main effect of time. Imagery  
290 ability increased over time for each imagery sub-scale: kinaesthetic (4.4 vs. 5.7;  $F(1, 23) =$   
291  $26.94; p < 0.001; \eta^2 = 0.54$ ), visual 1<sup>st</sup> person (5.2 vs. 5.7;  $F(1, 23) = 6.99; p < 0.05; \eta^2 =$   
292  $0.23$ ), and visual 3<sup>rd</sup> person perspective (5.4 vs. 5.8,  $F(1, 23) = 4.76; p < 0.05; \eta^2 = 0.17$ ). The  
293 main effect of group and the interaction was not significant in each analysis.

294

### 295 **Maximal voluntary eccentric contraction of the hamstrings**

#### 296 *ANOVA results*

297 The three-factorial ANOVA identified a significant main effect of leg,  $F(1, 23) = 10.42; p <$   
298  $0.01; \eta^2 = 0.31$ . Overall, MVEC was greater in the right compared to the left leg (180.2 vs.  
299 171.4 N.m.). The main effects of both time and group were not significant,  $F(1, 23) = 2.62; p$   
300  $> 0.05; \eta^2 = 0.10$ , and  $F(2, 23) = 0.08; p > 0.05; \eta^2 = 0.10$ , respectively. However, the  
301 interaction between leg and time was significant,  $F(1, 23) = 4.45; p < 0.05; \eta^2 = 0.16$ .  
302 Pairwise comparisons revealed MVEC was significantly greater in the right compared to the  
303 left leg at both the baseline and post-intervention ( $p < 0.05$  and  $p < 0.01$ , respectively).  
304 Importantly, MVEC increased significantly in the right leg between the baseline and the post-  
305 intervention test ( $p < 0.01$ ). This comparison was not significant in the left leg ( $p > 0.05$ ). All  
306 other interactions, including that between leg and group, were not significant.

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

311

--- Insert figure 2 ---

312

### 313 *Magnitude-based inference results*

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

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

326

--- Insert table 1 about here ---

327

## 328 **DISCUSSION**

329 Hamstring strains are especially common across the large number of sports involving  
330 sprinting and jumping [1-2]. Nordic exercises are a well-established method of increasing  
331 eccentric hamstring strength for both preventing and rehabilitating this injury [4-9]. A  
332 particular challenge, however, is to avoid an excessive eccentric workload during the acute  
333 injury phase, for fear of further damaging the soft tissues. For this reason, in the present study  
334 we investigated non-physical training methods as an alternative approach to acute hamstring

335 rehabilitation. Our core aim was to assess hamstring strength gains for combined AO+MI  
336 training, compared to two pure imagery groups (pure MI and pure MI-control). The  
337 ANOVAs (with post-hoc tests) showed a significant improvement only in the right leg  
338 MVEC scores for the AO+MI group, and not for the other two groups. The MBI results  
339 revealed a similar pattern, highlighting the practical advantage for AO+MI instructions,  
340 compared to both purely imagining the Nordic exercises, and purely imagining upper-limb  
341 actions. Since imagery ability improved equally across groups, we rule this out as a  
342 potentially limiting factor. The present study therefore provides the first empirical evidence  
343 showing combined AO+MI instructions can produce a modest but practically important  
344 advantage in hamstring strength development, over an acute non-physical intervention.

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

351

### 352 **AO+MI and pure MI effects on eccentric hamstring force development**

353 The within-group improvement in peak hamstring torque was significant only for the  
354 combined AO+MI intervention. For this group the treatment effect size was moderate and  
355 *likely* beneficial as an applied training / rehabilitation intervention. Compared to the pure MI  
356 control group, the effect size was moderate and *possibly* beneficial for AO+MI ( $d = 0.72$ ).  
357 These data clearly argue in favour of modest but practically important benefits for AO+MI  
358 training. In contrast, we did not find compelling support for the positive effects of pure MI on

359 hamstring MVEC development. For pure MI the within-group analysis of peak torque gains  
360 approached but did not reach levels of significance ( $p = 0.10$ ), with a small treatment effect  
361 size that was only *possibly* beneficial. Compared to pure MI-control, the effect size for pure  
362 MI was small ( $d = 0.39$ ), almost half of that for AO+MI in the same comparison, and *possibly*  
363 beneficial. It is important to note, however, that we did not optimise the intervention duration  
364 to ensure strength gains via pure MI. We instead focused on a time period (3-weeks) that  
365 represented the immediate stages post-injury, in which it is crucial to undertake rehabilitation,  
366 but necessary to avoid overloading the soft tissues [8]. In line with previous literature [12-13,  
367 16-19, 58-59], we would expect more robust effects for pure MI over an extended training  
368 period. Considering this design restriction within our study, however, it is then particularly  
369 compelling that we did identify a significant and practically important advantage for  
370 combined AO+MI procedures within the same acute time period. Thus our analyses revealed  
371 overall that combined AO+MI procedures offer favourable strength training conditions  
372 during a short period of mental training.

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

380         A commonly accepted framework for conceptualising MI and AO processes is  
381 Jeannerod's [11] 'functional equivalence' hypothesis of action simulation. From this  
382 perspective both MI and AO can be regarded as two forms of motor simulation, which both  
383 involve the motor system but typically do not include motor execution. A limitation of this



384 account, however, is that it did not explicitly consider the possibility of MI *during* AO. To  
385 address this pertinent issue, a related and more recent proposal is the *dual-action simulation*  
386 account of AO+MI effects [31, 37, 39, 48]. This view submits that both an observed and an  
387 imagined action can be represented simultaneously, in the sense of two concurrent  
388 sensorimotor streams. These two streams could either merge or compete with one another,  
389 depending on their contents and usefulness for on-going actions plans. This proposal is (in  
390 part) grounded in the growing evidence showing AO+MI can: (i) elicit increased cortical  
391 activity in various motor regions of the brain; (ii) facilitate corticospinal excitability,  
392 measured through the amplitudes of motor evoked potentials in the muscles after applying  
393 transcranial magnetic stimulation to the motor cortex; and (iii) influence motor behaviour  
394 more directly than either AO or MI alone [37]. The particular match between the contents of  
395 MI during AO (i.e., congruent vs. conflicting) can also significantly modulate motor outputs  
396 [39,48]. Taken together these findings show the unique effects for AO+MI instructions  
397 (compared to both AO and MI) on different neurophysiological and behavioural indices of  
398 motor planning and execution. The present study strengthens this evidence further, being the  
399 first to show beneficial *practice* effects on motor outputs (i.e., increased peak hamstring  
400 torque) for congruent AO+MI training.

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

409           Within the dual-action simulation framework, two further, interesting variations are:  
410 coordinating one's own imagined action with the actions of an imagined partner (i.e., MI+MI  
411 [66]), and observing the actions of two interacting partners (i.e., AO+AO). These everyday  
412 scenarios raise intriguing questions from a dual-action simulation perspective and are, at  
413 present, clearly under-researched.

414

#### 415 **AO+MI effects lateralised to the right leg**

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

426           At the baseline, peak hamstring torque was significantly higher in the right compared  
427 to the left leg, indicating a right leg dominance in this population. One possibility is that the  
428 lateralisation effect observed at the post-test could result from a spontaneous attentional focus  
429 during AO+MI training on the dominant, rather than non-dominant leg, producing an  
430 imbalance in the allocation of imagery processes across the two legs during training. This  
431 was despite clear and regular instructions for a bilateral motor representation of the task  
432 throughout every imagery training session for both AO+MI and pure MI. This finding is also

433 counterintuitive to the fact that participants mainly observed the left leg in the demonstration  
434 (see figure 1). To our knowledge no behavioural studies have investigated this issue. It will  
435 be interesting to address this topic further in future research, by manipulating the attentional  
436 focus of the imagery to involve simulating either the dominant or non-dominant leg, ideally  
437 using a within-subjects pre-post cross-over design. Delayed retention tests could also be  
438 included to examine the time-course of the effects in each leg.

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

454         Stinear et al. [52] investigated corticospinal excitability during MI of a phasic thumb  
455 movement. Their results showed a significant temporal modulation of motor evoked  
456 potentials in the *right* thumb abductor muscle during *both* bilateral and unilateral imagery of  
457 either the dominant or non-dominant hand. Baraldi and colleagues [51] also found a similar

458 pattern of results using functional magnetic resonance imaging techniques. These two studies  
459 thus identified a left-hemispheric dominance for MI processes, regardless of the laterality of  
460 the imagined effector. On these grounds the participants in our study presumably had  
461 difficulties in representing both limbs simultaneously and/or to the same degree, which might  
462 have resulted in a spontaneous and perhaps unconscious allocation of MI predominantly to  
463 their right leg. Our findings therefore highlight a potential limitation for imagery (including  
464 with observation) in bilateral strength training and rehabilitation exercises.

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

469

#### 470 **Future research opportunities**

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

482 incorporating self-selected response and/or meaning propositions to layer over the observed  
483 action [37].

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

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

501 In our physically-fit sample population, the variability in the data was considerable,  
502 and we would only expect this to increase in a clinical population. To some degree this might  
503 reflect the variability inherent in any repeated test of human performance, which can be  
504 caused by natural fluctuations in factors such as diet, sleep and motivation. A related and  
505 unexpected result in our study was that MVEC actually reduced in the pure MI-control group

506 in the left leg only. Since the pre-planned contrasts revealed this effect was not significant,  
507 we do not consider this as problematic for our main interpretations of the data outlined above.

508

### 509 **The application of AO+MI protocols in rehabilitation settings**

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

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

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

530

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536

537 **Declarations of interest**

538 We declare that we have no potential competing interests with respect to the research,  
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Within-group comparisons	Left leg			Right leg		
	Action Observation + Motor Imagery	Pure Motor Imagery	Pure Motor Imagery-control	Action Observation + Motor Imagery	Pure Motor Imagery	Pure Motor Imagery-control
	(AO+MI)	(pure MI)	(pure MI-control)	(AO+MI)	(pure MI)	(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 ( <i>d</i> )	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 ( <i>d</i> )	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

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

8 contrasts. Effect sizes ( $d$  and CI) reported for both the within- and between-groups analyses,  
9 with qualitative descriptions taken from Hopkins' [65] scales: 0.0 – 0.19 = negligible; 0.2 –  
10 0.59 = small; 0.6 – 1.19 = moderate; with qualitative inference: \* = *possibly* (25–75%); \*\* =  
11 *likely* (75–95%); +ive = beneficial (positive) effect; -ive = harmful (negative) effect.

12

### 13 **Figures**

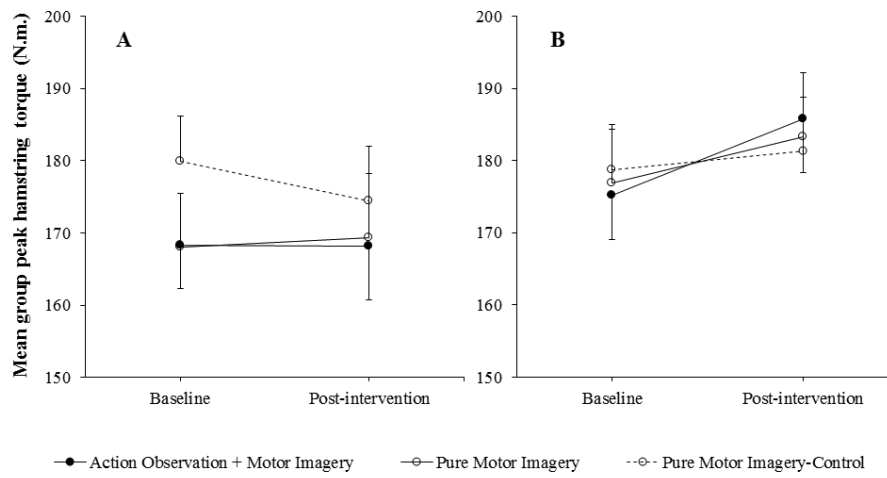


14

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

23





24

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