

1 **Title:** Gymnasts' ability for general motor imagery evaluated by bioelectric sensorimotor

2 rhythms

3

4 **Authors:** Hirotaka Sugino¹, Junichi Ushiyama^{2,3}

5

6 **Affiliation:**

7 ¹Graduate School of Media and Governance, Keio University, 5322 Endo, Fujisawa,

8 Kanagawa 252-0882, Japan; ²Faculty of Environment and Information Studies, Keio

9 University, 5322 Endo, Fujisawa, Kanagawa 252-0882, Japan; ³Department of Rehabilitation

10 Medicine, Keio University School of Medicine, Shinanomachi, Shinjuku, Tokyo 160-8582,

11 Japan

12

13 **Corresponding Author:**

14 Junichi Ushiyama, Ph.D.

15 Faculty of Environment and Information Studies, Keio University, 5322 Endo, Fujisawa,

16 Kanagawa 252-0882, Japan

17 Tel & Fax: +81-466-49-3525

18 Email: ushiyama@sfc.keio.ac.jp

19

20 **Abstract**

21 **Introduction:** Previous psychological studies using questionnaires have consistently reported
22 that athletes have superior motor imagery ability, both for sports-specific movements and
23 general movements. However, regarding general motor imagery, no physiological studies have
24 demonstrated differences in neural activity between athletes and non-athletes. Gymnasts may
25 be a suitable population for investigating this issue because they are likely to have particularly
26 superior motor imagery ability due to their frequent usage of motor imagery as part of daily
27 practice. **Purpose:** The purpose of the present study was to examine differences in bioelectric
28 sensorimotor rhythms during kinesthetic motor imagery of general movements between
29 gymnasts and non-gymnasts. **Methods:** Healthy young participants (16 gymnasts and 16 non-
30 gymnasts) performed repeated motor execution and motor imagery of general movements
31 (wrist dorsiflexion and shoulder abduction of the dominant hand). Scalp electroencephalogram
32 (EEG) was recorded over the contralateral sensorimotor cortex. During motor execution and
33 motor imagery, sensorimotor EEG power is known to decrease in the α - (8–15 Hz) and β -bands
34 (16–35 Hz), referred to as event-related desynchronization (ERD). We calculated the maximal
35 peak of ERD both in the α - (α ERD_{max}) and β -bands (β ERD_{max}) as a measure of changes in
36 corticospinal excitability. **Results:** ERD magnitude during motor imagery was significantly
37 greater in gymnasts, who subjectively evaluated their motor imagery as being more vivid. In
38 particular, α ERD_{max} was greater in gymnasts compared with non-gymnasts for both motor

39 imagery tasks, whereas β ERDmax was greater in gymnasts only for shoulder abduction
40 imagery. **Conclusion:** We observed gymnasts' signature of flexibly modulating sensorimotor
41 rhythm with no movement, which may be the basis of their superior general motor imagery
42 ability.

43

44 **Keywords:** athletes, kinesthetic motor imagery (KMI), electroencephalogram (EEG), event-
45 related desynchronization (ERD), the Kinesthetic and Visual Imagery Questionnaire (KVIQ)

46

47 **Introduction**

48 Motor imagery is regularly used by athletes to improve performance (1). Previous
49 studies have shown that performing motor imagery in training improves performance in various
50 tasks, including sequence learning (2,3), jump height (4) and free-throw shooting (5). To
51 explain these performance gains, several neuroscience studies have provided evidence that
52 motor imagery activates some neural substrates in common with actual movement, including
53 the primary motor cortex, supplementary motor area, and inferior parietal lobe (6–9), as well
54 as inducing neural plasticity in these areas (10).

55 In the field of sports psychology, several cross-sectional questionnaire studies have
56 consistently reported that athletes have superior motor imagery ability compared with non-
57 athletes (11–14). Furthermore, previous studies have indicated that athletes can perform motor
58 imagery more vividly than non-athletes, not only for specialized movements in their own sports
59 but also for general movements such as raising the arm and jumping (13,15). The findings of
60 these studies suggest that the neural activity underlying motor imagery ability may differ
61 between athletes and non-athletes, not only for sports-specific imagery but also for general
62 motor imagery.

63 However, in the field of applied physiology, to the best of our knowledge, no studies
64 have demonstrated differences in neural activity during general motor imagery between
65 athletes and non-athletes, although some studies using electroencephalogram (EEG) (15),

66 functional magnetic resonance imaging (fMRI) (16,17) and transcranial magnetic stimulation
67 (TMS) (18) have reported signature neural activity patterns during sports-specific motor
68 imagery in athletes. For instance, when tennis players imagined movements specifically related
69 to tennis, their corticospinal excitability became higher than that of non-athletes, whereas such
70 a difference between athletes and non-athletes was not observed when they imagined other
71 general movements (18). Thus, there is currently a gap in findings between psychological and
72 physiological studies regarding differences in motor imagery ability, particularly for general
73 movements between athletes and non-athletes.

74 To clarify this issue, the present study investigated differences in general motor
75 imagery ability between gymnasts and healthy adults (i.e., non-gymnasts) from both
76 psychological and physiological points of view. As a psychological indicator, we evaluated the
77 subjective vividness of motor imagery using The Kinesthetic and Visual Imagery Questionnaire
78 (KVIQ-20) (19). As a physiological indicator, we evaluated sensorimotor rhythms using EEG.
79 Event-related desynchronization (ERD) is a measure of decreases in power of the EEG
80 sensorimotor rhythm within the α - and β -bands from the resting-state to the motor execution
81 or motor imagery state (20,21), which is known to reflect increased neuronal excitability in the
82 corticospinal system (22). We chose gymnasts as a population of athletes for the following
83 reasons: 1) gymnasts perform motor imagery frequently as a part of their daily practices
84 because of the high risk of serious injury in their performance; 2) gymnasts were assumed to

85 have higher motor imagery abilities than athletes engaged in other sports, because it has been
86 reported that motor imagery is more vivid in athletes engaged in individual and/or non-contact
87 sports compared with athletes engaged in team and/or contact sports (23); 3) to the best of our
88 knowledge, no previous studies have measured neural activity during motor imagery in
89 gymnasts.

90

91 **Methods**

92 **Ethical Approval**

93 This study was conducted in accordance with the Declaration of Helsinki. All
94 experimental protocols and procedures were approved by the Research Ethics Committee in
95 Shonan Fujisawa Campus, Keio University (Approval Number 167). The examiners provided
96 a detailed explanation of the purpose, experimental procedures, potential benefits, and risks
97 involved. After receiving all of the relevant information, participants provided written informed
98 consent before participating in the experiment.

99

100 **Participants**

101 We recruited 16 gymnasts (11 men, 5 women, aged 18–24 years) and 16 healthy adults
102 (8 men, 8 women, aged 19–22 years) as a non-gymnast group. All participants were right-
103 handed. All gymnasts had been practicing at least for 7 years (range: 7–16 years) and had

104 participated in an all-Japan intercollegiate gymnastic championship at least once. Note that two
105 gymnasts were members of the Japanese national gymnastics team. The non-gymnasts group
106 had no experience of gymnastic training. None of the participants had experienced any
107 neurological and musculoskeletal disorders.

108

109 **Psychological assessments**

110 **Procedures**

111 Motor imagery ability was tested using a psychological questionnaire translated into
112 Japanese: The Kinesthetic and Visual Imagery Questionnaire (KVIQ-20) (19,24). Briefly, the
113 KVIQ-20 tests how vividly a person is able to imagine their own movements subjectively,
114 using two types of motor imagery: kinesthetic motor imagery (KMI) and visual motor imagery
115 (VMI). KMI involves imagining the feeling when we perform actual motor tasks. Conversely,
116 VMI involves imagining to see ourselves or the field of vision where we perform the tasks
117 (19,25). Participants sat comfortably in a chair next to the examiner and watched the
118 examiner's example once. Then, they actually performed the exercise, followed by VMI or
119 KMI of the exercise they had just performed. Participants were then asked to evaluate the
120 vividness of the motor imagery on a five-point ordinal scale (the more vivid the motor imagery,
121 the higher the scale score). This procedure was repeated for 10 different simple exercises: neck
122 flexion/extension, shoulder elevation, forward shoulder flexion, elbow flexion/extension,

123 thumb-fingers opposition, forward trunk flexion, knee extension, hip abduction, foot tapping,
124 and foot external rotation.

125

126 **Analyses**

127 We evaluated the vividness of motor imagery by summing all KVIQ scores for KMI
128 and VMI, respectively. If a participant could imagine their movements perfectly, the score was
129 50 points.

130

131 **Physiological assessments**

132 **Recordings**

133 Scalp EEG signals were recorded with eight passive Ag/AgCl electrodes around the
134 sensorimotor area related to right upper limbs (Cz, C1, C3, C5, FC1, FC3, CP1, and CP3) in
135 accord with the extended international 10-20 system. Electrodes with a diameter of 18 mm
136 were mounted on an electrode cap (g.GAMMAcap 1027; Guger Technologies, Graz, Austria).
137 Reference and ground electrodes were placed on the right and left earlobes, respectively.
138 Surface electromyogram (EMG) signals were recorded from the right deltoid muscle (DEL)
139 and the right extensor carpi radialis muscle (ECR). Two passive Ag/AgCl electrodes with a
140 diameter of 10 mm were placed over each muscle belly with inter-electrode distances of 20
141 mm. All EEG and EMG signals were amplified and bandpass-filtered (EEG, 0.5–200 Hz; EMG,

142 5–1000 Hz) using a linked biosignal recording system (g.BSamp 0201a; Guger Technologies,
143 Graz, Austria). All analog EEG and EMG signals were converted to digital signals at a sample
144 rate of 1000 Hz using an AD converter with 16-bit resolution (NI USB-6259, National
145 Instruments, Austin, TX, United States) that was controlled by data-logger software originally
146 designed using MATLAB software (The MathWorks, Inc., Antic, MA, United States).

147

148 **Procedures**

149 Following the psychological assessment, we performed physiological EEG and EMG
150 measurements. The participants sat comfortably in the seat of the dynamometer device. A
151 computer monitor for visual feedback was placed 2 m in front of participants' eyes. First,
152 resting-state EEG was recorded over 60 s. Participants relaxed and fixated their eyes on a cross
153 (+) displayed at the center of the monitor during recording. Participants then performed several
154 practice trials of maximal voluntary contractions (MVCs) of wrist dorsiflexion and shoulder
155 abduction. After these movements were practiced, participants performed MVC once each for
156 wrist dorsiflexion and shoulder abduction. When performing each MVC, EMG activity of the
157 contracting muscle was recorded. The EMG signals were full-wave rectified. We found a 0.5-
158 s period of stable force exertion during MVC and calculated the integrated EMG value
159 (iEMGmax) in this period. In the following experiment, 20% of this iEMGmax value was used
160 as a target value for visual feedback.

161 The physiological data recordings during motor execution and KMI were performed
162 after several practice trials. Visual feedback was presented on the screen, with a red cursor to
163 represent muscle contraction level as a relative value in %iEMGmax and a vertical blue line to
164 represent a target value. Furthermore, instructions for each phase, including “Rest”, “Relax”,
165 “Ready”, “Contraction”, or “Imagery”, were displayed on the monitor. In the wrist dorsiflexion
166 task, participants’ dominant hand was positioned on the armrest and fixed by a belt with the
167 palm down. In the shoulder abduction task, the dominant upper limb was lowered to the side
168 of the body while bending the elbow lightly, and the arm was fixed by a belt. In both the wrist
169 dorsiflexion and shoulder abduction tasks, participants performed repeated motor execution
170 and KMI according to the procedure used in our previous study (26).

171 The experimental paradigm is shown in Figure 1. In detail, each trial was started from
172 the rest phase and the word “Rest” was displayed on the monitor for 7 s. During the rest phase,
173 participants were able to adjust their posture freely and/or blink their eyes strongly. After the
174 rest phase, the word “Relax” was displayed on the monitor for 3 s. During the relax phase,
175 participants were instructed to relax as much as possible, without performing any movement.
176 The word “Ready” was then displayed for 3 s, accompanied by a short sound presented every
177 second. During the ready phase, participants prepared for the next instruction. After the ready
178 phase, the word “Contraction” was displayed for 5 s. During the contraction phase, participants
179 performed isometric voluntary contraction (wrist dorsiflexion or shoulder abduction) at 20%

180 of iEMGmax by their dominant hand. In the contraction phase, participants were instructed to
181 contract their muscle so that the cursor could follow the target line as accurately as possible.
182 After the contraction phase, the word “Relax” was displayed for 2 s. In this relax phase,
183 participants were instructed to relax as much as possible, without any movement. After the rest,
184 relax, and ready phases, the imagery phase was started, and participants performed KMI of the
185 preceding contraction for 5 s with their eyes open, and without any movement. During the
186 imagery phase, we checked that no EMG activity occurred. When the imagery phase finished,
187 the relax phase was presented again for 2 s. This flow was conducted for each trial, including
188 motor execution and KMI, and five trials were repeated within each set. Six sets were
189 performed for each task. Thus, a total 30 trials were performed for both wrist flexion and
190 shoulder abduction tasks. We set the wrist dorsiflexion and the shoulder abduction task in a
191 randomized order across participants. The duration of the set interval was longer than 2 min,
192 to provide sufficient rest for participants.

193

194 **Analyses**

195 To remove noise arising from the electric power, the EEG and EMG signals were
196 notch-filtered at 50 Hz. The EEG signals over C1 and C3 were derived with a four-neighbor
197 Laplacian spatial filter. For example, in the case of C3, the EEG signal over C3 was subtracted
198 by an average of C1, C5, FC3 and CP3. The Laplacian derivation method is known to strongly

199 emphasize cortical activity originating below the electrode of interest (27). If Laplacian-
200 derived EEG included potentials exceeded 50 μ V, we considered the trial to contain an artifact,
201 and excluded the data from future analyses. Additionally, visual inspection was performed to
202 reject additional artifacts missed by the automatic inspection.

203 ERDs during motor execution and KMI of each task were calculated as follows. After
204 separating the data into motor execution and KMI periods, we extracted the 30 1 s data
205 windows in the same period from the data for each trial. Then, fast Fourier transformation was
206 performed using Welch's method for the data (window length, 1 s; window function, Hanning-
207 window; overlap, 0), and the power spectrum densities (PSDs) of the EEG signal were
208 calculated. This process was repeated by sliding the 1 s data window in 50 ms steps. The ERDs
209 were calculated using the following equation:

$$210 \quad ERD(f, t) = \frac{R(f) - A(f, t)}{R(f)} \times 100\%, \quad (\text{eq. 1})$$

211 where A is the EEG PSDs at time t , frequency f , and R is the mean PSDs of the baseline period
212 (last 1 s in the relax phase). This equation indicates that the positively greater the ERD value,
213 the larger the decrease in EEG PSD during motor execution or KMI compared with the relax
214 phase. Because the most reactive frequency band of ERD was slightly different across
215 participants (28), we determined an electrode and the 3 Hz-frequency width showing the largest
216 ERD in each of the α -band (8–15 Hz) and β -band (16–35 Hz) during motor execution. Because
217 it has been suggested that the functional roles played by ERD differ between the α - and β -

218 bands (29,30), we analyzed ERDs from these two frequency bands separately. The magnitude
219 of ERD in the α -band (α ERDmax) and β -band (β ERDmax) were measured by calculating the
220 peak value of ERD for motor execution and KMI of each task, respectively (26,31).

221 To compare the features of EEG during the relax phase in the task with continuous
222 resting-state for a prolonged period, we also analyzed the α -band or β -band PSDs for both
223 data sets. For the relax-phase EEG, the final 1 s periods in the relax phase, which were used
224 as the baseline periods for ERD analyses, were extracted from all trials, and combined to
225 create a 60 s relax-phase EEG signal. For the resting-state EEG, a continuous 60 s period with
226 few artefacts was extracted. We then calculated the ratio of the sum of EEG power within the
227 α -band or β -band PSD to that of the entire frequency range (4–50 Hz) (named, EEG α -PSD
228 and EEG β -PSD) for both data sets, and compared these values between relax-phase EEG
229 during tasks and resting-state EEG.

230

231 **Statistical analyses**

232 Two-side unpaired t-tests were performed on VMI and KMI scores of KVIQ between
233 groups (non-gymnasts vs. gymnasts), to confirm differences in the subjective vividness of
234 motor imagery between them. To test differences in α ERDmax and β ERDmax during motor
235 execution or KMI, we performed two-way mixed-model analysis of variance (ANOVA)
236 between participant groups (gymnasts and non-gymnasts) and tasks (wrist dorsiflexion and

237 shoulder abduction). If the interaction was significant, we performed a two-sided unpaired t-
238 test for groups (gymnasts vs. non-gymnasts) and a two-sided paired t-test for tasks (wrist
239 dorsiflexion vs. shoulder abduction). To test differences in the EEG α -PSD or EEG β -PSD
240 between resting-state EEG and relax-phase EEG during tasks, we also performed two-way
241 ANOVA between participant groups (gymnasts and non-gymnasts) and conditions (resting-sate
242 and relax-phase). The p-values of 0.05 were used to indicate statistical significance. All
243 statistical analyses were performed using SPSS statistics software (IBM SPSS Statistics 25,
244 IBM developerWorks, Tokyo, Japan).

245

246 **Results**

247 **KVIQ**

248 Figure 2 shows group data (mean \pm S.D.) for KVIQ scores obtained from VMI and
249 KMI tasks between gymnasts and non-gymnasts. The KVIQ scores were significantly greater
250 in gymnasts, both in VMI (gymnasts, 42.68 ± 6.22 ; non-gymnasts, 35.44 ± 8.73 , $p = 0.011$)
251 (Figure 2A) and KMI (gymnasts, 43.50 ± 6.78 ; non-gymnasts, 35.94 ± 8.24 , $p = 0.008$) (Figure
252 2B). The KVIQ results indicate that gymnasts subjectively evaluated how vividly they could
253 imagine their own movements.

254

255 **ERD magnitude**

256 Typical examples of EEG signals, EEG time-frequency maps and ERD time courses
257 during wrist dorsiflexion ME from a non-gymnast and a gymnast are shown in Figure 3A and
258 3B, respectively. From these time-frequency maps, a decrease of EEG power can be observed
259 around 12 Hz and 22 Hz in the contraction phase (0 to 5 s) compared with the relax phase (–6
260 to –3 s) in both participants when performing motor execution.

261 Figure 3C shows group data for α ERDmax during wrist dorsiflexion and shoulder
262 abduction motor execution. An ANOVA on α ERDmax during motor execution revealed no
263 significant effects of group ($F_{1,30} = 0.209$, $p = 0.651$) and task ($F_{1,30} = 0.831$, $p = 0.369$), while
264 a significant interaction was obtained ($F_{1,30} = 4.654$, $p = 0.0391$). An unpaired t-test for group
265 revealed no significant difference in α ERDmax between gymnasts and non-gymnasts for wrist
266 dorsiflexion (gymnasts, 64.41 ± 20.96 ; non-gymnasts, 65.58 ± 13.97 , $p = 0.855$) and shoulder
267 abduction task (gymnasts, 70.13 ± 21.07 ; non-gymnasts, 63.26 ± 16.77 , $p = 0.316$). A paired t-
268 test for task revealed no significant difference in α ERDmax between wrist dorsiflexion and
269 shoulder abduction execution both for non-gymnasts (wrist dorsiflexion, 65.58 ± 13.97 ;
270 shoulder abduction, 63.26 ± 16.77 , $p = 0.303$) and gymnasts (wrist dorsiflexion, 64.41 ± 20.96 ;
271 shoulder abduction, 70.13 ± 21.07 , $p = 0.078$). Figure 3D shows group data for β ERDmax
272 during wrist dorsiflexion and shoulder abduction motor execution. An ANOVA on the
273 β ERDmax during motor execution with groups and task revealed no significant effects of group
274 ($F_{1,30} = 0.571$, $p = 0.456$) and task ($F_{1,30} = 1.249$, $p = 0.273$), and interaction ($F_{1,30} = 1.815$, $p =$

275 0.188). The results revealed no effects of sports experience and body part on ERD magnitude
276 during motor execution.

277 Typical examples of EEG signals, EEG time-frequency maps and ERD time courses
278 during wrist dorsiflexion KMI from a non-gymnast and a gymnast are shown in Figure 4A and
279 4B, respectively. From the time-frequency maps for a non-gymnast participant, we did not
280 observe clear ERD in the imagery phase (0 to 5 s) compared with the relax phase (-6 to -3 s)
281 in both the α -band and β -band. (Figure 4A). Conversely, clear ERD can be observed in the
282 time-frequency-map for the gymnast participant around 12 Hz and 22 Hz (Figure 4B).

283 Figure 4C shows group data for the α ERDmax during wrist dorsiflexion and shoulder
284 abduction KMI. An ANOVA on α ERDmax during KMI showed significant effects of group
285 ($F_{1,30} = 5.437$, $p = 0.027$) and task ($F_{1,30} = 10.975$, $p = 0.002$). No significant interaction effect
286 ($F_{1,30} = 0.266$, $p = 0.610$) was observed. Figure 4C shows group data for β ERDmax during
287 wrist dorsiflexion and shoulder abduction KMI. An ANOVA on β ERDmax during KMI showed
288 no significant effects of group ($F_{1,30} = 0.876$, $p = 0.357$), but significant effects of task ($F_{1,30} =$
289 8.019 , $p = 0.008$) and a significant interaction ($F_{1,30} = 7.421$, $p = 0.010$). An unpaired t-test for
290 group revealed a significant difference in β ERDmax between gymnasts and non-gymnasts for
291 the shoulder abduction task (gymnasts, 46.08 ± 18.09 ; non-gymnasts, 32.27 ± 17.84 , $p = 0.021$)
292 but not for the wrist dorsiflexion task (gymnasts, 46.42 ± 22.76 ; non-gymnasts, 49.56 ± 17.84 ,
293 $p = 0.666$). A paired t-test for task revealed a significant difference in β ERDmax between the

294 wrist dorsiflexion and shoulder abduction imagery conditions for non-gymnasts (wrist
295 dorsiflexion, 49.56 ± 17.84 ; shoulder abduction, 32.27 ± 17.84 , $p = 0.002$) but not for gymnasts
296 (wrist dorsiflexion, 46.42 ± 22.76 ; shoulder abduction, 46.08 ± 18.09 , $p = 0.938$). These results
297 indicated that sports experience affected ERD magnitude during KMI.

298

299 **Comparison of EEG α -PSD and EEG β -PSD between resting-state EEG and relax-phase** 300 **EEG during tasks**

301 Figure 5A shows group data for the EEG α -PSD in resting-state EEG and relax-phase
302 EEG during the tasks. An ANOVA examining EEG α -PSD data revealed no significant effects
303 of group ($F_{1,30} = 0.486$, $p = 0.491$) or condition ($F_{1,30} = 4.135$, $p = 0.051$); however, a significant
304 interaction ($F_{1,30} = 6.382$, $p = 0.017$) was observed. An unpaired t-test for group revealed no
305 significant difference in EEG α -PSD during resting-state EEG (gymnasts, 0.473 ± 0.155 ; non-
306 gymnasts, 0.482 ± 0.166 , $p = 0.878$) and that during the relax phase (gymnasts, 0.482 ± 0.155 ;
307 non-gymnasts, 0.403 ± 0.125 , $p = 0.878$; $p = 0.122$) between gymnasts and non-gymnasts. In
308 non-gymnasts, a paired t-test revealed significant differences in the EEG α -PSD between
309 conditions (resting-state, 0.482 ± 0.166 ; relax-phase, 0.403 ± 0.125 , $p = 0.008$). However, in
310 gymnasts, no significant differences in EEG α -PSD were observed between conditions (resting-
311 state, 0.473 ± 0.155 ; relax-phase, 0.481 ± 0.155 , $p = 0.715$). Figure 5B shows group data for
312 EEG β -PSD. An ANOVA on EEG β -PSD showed no significant effects of group ($F_{1,30} = 0.106$,

313 $p = 0.747$) and condition ($F_{1,30} = 1.787$, $p = 0.191$), and no significant interaction ($F_{1,30} = 0.063$,
314 $p = 0.804$). These results indicate that, in non-gymnasts, the EEG α -PSD was smaller in the
315 relax-phase EEG than during resting-state EEG, while such a difference was not observed in
316 gymnasts. Conversely, EEG β -PSD did not differ between resting-state EEG and relax phase
317 EEG in both gymnasts and non-gymnasts.

318

319 **Discussion**

320 The purpose of the present study was to clarify differences in bioelectric sensorimotor
321 rhythm during general motor imagery (i.e., non-sports specific motor imagery) between
322 gymnasts and non-gymnasts. The results revealed that, when required to repeatedly switch
323 between relaxing and motor execution or KMI, the ERD magnitude during general KMI was
324 significantly greater in gymnasts, who subjectively evaluated their motor imagery as more
325 vivid, while no difference between groups was observed during motor execution. In particular,
326 the ERD magnitude in the α -band was greater in gymnasts compared with non-gymnasts, both
327 in wrist dorsiflexion and shoulder abduction KMIs, whereas the ERD magnitude in the β -band
328 was greater in gymnasts only in shoulder abduction KMI.

329

330 **Difference in general KMI ability between gymnasts and non-gymnasts**

331 We evaluated ERD as a physiological indicator of motor imagery ability in the

332 present study, because it is considered to reflect changes in corticospinal excitability (22) and
333 is associated with subjective vividness of motor imagery measured by KVIQ (26). It should be
334 noted that the present results revealed greater ERD magnitude during general KMI in gymnasts
335 than in non-gymnasts, although differences in neural activity between athletes and non-athletes
336 have not been reported in general motor imagery in previous studies using EEG (15),
337 magnetoencephalography (17), TMS (18) or fMRI (16). This may be related to the fact that
338 gymnasts perform motor imagery frequently as a part of their daily practice to reduce the risk
339 of serious injury in their practice. Furthermore, a previous psychological study showed that the
340 vividness of general motor imagery was higher in athletes engaged in individual and/or non-
341 contact sports compared with athletes engaged in team and/or contact sports (12). Thus, as
342 gymnasts have superior motor imagery ability among athletes, they may provide a particularly
343 suitable population for highlighting differences in neural activity during general motor imagery
344 compared with non-athletes.

345 It is possible that the present task protocol, in which participants performed KMI
346 following motor execution repeatedly in the order of seconds, led to the current finding of
347 greater ERD magnitude in gymnasts. In psychological questionnaires, the conventional
348 procedure for measuring motor imagery ability is to examine participants while they perform
349 motor execution then motor imagery in one trial, and subjectively evaluate the vividness of the
350 motor imagery of the preceding movement (19). In physiological experiments, however, the

351 conventional procedure involves evaluating neural activity while participants perform only
352 motor imagery (15–18). Thus, there has been a methodological gap in the approach for
353 examining of motor imagery between psychological questionnaire studies and experimental
354 physiological studies. In response to direct questioning in the current study, gymnasts reported
355 that they usually perform actual movements and KMIs alternately in their daily practice.
356 Therefore, the method for measuring motor imagery in the present physiological experiment
357 was designed in accord with the procedure of psychological questionnaire measurement. The
358 current physiological findings may have been due to differences between gymnasts and non-
359 gymnasts in the ability to flexibly modulate corticospinal excitability when imagining their
360 own movements, by referring to the actual movement.

361 As shown in equation (1), we were able to confirm that the ERD was determined by
362 both the degree of synchronization during the relax phase ($R(f)$) and the degree of
363 desynchronization during KMI ($A(f, t)$). As shown in Fig. 5, first, gymnasts could return their
364 sensorimotor α -rhythm during the relax phase in the task to the same power level as during the
365 resting-state for 60 s, whereas non-gymnasts could not. Thus, gymnasts appeared to be good at
366 relaxing deeply by making their sensorimotor rhythms more synchronized within a short period
367 of time. However, higher EEG α -PSD during the relax phase does not appear to be the only
368 factor involved in gymnasts' greater ERD magnitude in the α -band. As shown in Fig. 2, second,
369 differences in α ERDmax between groups were not observed in motor execution but were found

370 in KMI. Thus, gymnasts also appeared to be good at increasing corticospinal excitability by
371 making their sensorimotor rhythms more desynchronized, even in KMI. Overall, the present
372 results demonstrate that gymnasts have the ability to generate a clear contrast in the state of the
373 sensorimotor cortex, when required to repeatedly switch across relaxing, motor execution and
374 motor imagery conditions. On the basis of the current findings, we believe that the ability to
375 modulate the brain state without any movement is a core aspect of superior motor imagery
376 ability in gymnasts.

377

378 **Difference in functional role of ERD between α - and β -band**

379 Interestingly, the present study demonstrated different results between ERD
380 magnitude in the α -band and β -band. Several previous studies reported that functional roles
381 played by the sensorimotor rhythm are different between frequency bands. During actual
382 muscle contraction with weak-to-moderate intensity, the sensorimotor rhythm is known to be
383 coherent with EMG activity only in the β -band, with no significant coherence in the α -band
384 (32–34). When focusing on oscillatory power itself, the EEG spectral power in the
385 sensorimotor area contralateral to the contracted/imagined limb was decreased in both the α -
386 and β -bands, while that in task-irrelevant cortical regions was increased in the α -band
387 (21,35,36), but not in the β -band (29). During KMI, the ERD magnitude was increased by
388 increasing task demand in the β -band, but not in the α -band (30,37). Taken together, these

389 findings suggest that the functional roles of sensorimotor rhythms for movement/imagery
390 should be distinguished between the α -band and β -band.

391 First, α ERDmax was larger in gymnasts than non-gymnasts during both KMI tasks
392 (i.e., wrist dorsiflexion and shoulder abduction). In task-relevant cortical regions, neural
393 populations are assumed to be disinhibited by the ERD of the sensorimotor area in the α -band,
394 which would allow reallocation of computational resources (30). However, task-irrelevant
395 cortical regions are assumed to be inhibited by enhancing their α -oscillations (21). As gymnasts
396 are required to perform skilled movements successively, they are trained to quickly switch their
397 attention across their body parts by facilitating task-relevant regions and inhibiting task-
398 irrelevant regions. The present results regarding ERD in the α -band would reflect such an
399 ability of gymnasts.

400 Second, β ERDmax was larger in gymnasts only during shoulder abduction KMI, but
401 not during wrist dorsiflexion KMI. This task-specificity in β ERDmax may be caused by ERD
402 in the β -band playing a role in the calculation of specific motor commands. In general, wrist
403 movement is used frequently in daily life, which makes it easy for most people to imagine wrist
404 dorsiflexion. Thus, β ERDmax would not be differed between gymnasts and non-gymnasts in
405 the wrist dorsiflexion task. However, as isometric shoulder abduction is a movement rarely
406 used in daily life, it may be difficult for most people to imagine this movement. Conversely,
407 gymnasts are well-trained to move their upper limbs, including the shoulder joints, both

408 dynamically (i.e., giant swing) and statically (i.e., handstand and rings). Therefore, it would be
409 easy for gymnasts to imagine shoulder abduction because they are skilled at adjusting the
410 movement parameters of their shoulder joints. We assume that ERD in the β -band is an
411 indicator for how precisely a person can imagine their own movement kinesthetically.

412

413 **Limitations**

414 In the present study, only upper limb movements (i.e., wrist-dorsiflexion and shoulder
415 abduction) were examined. Gymnasts use their upper limb muscles specifically as anti-gravity
416 muscles for postural non-gymnastic movements, such as handstand and pommel horse. This
417 usage of the upper limbs is unique relative to the movements of non-gymnasts. The uniqueness
418 of gymnasts' upper limb usage may lead to superior motor imagery ability regarding upper
419 limb movements. Thus, we cannot clearly predict whether similar results would be obtained
420 when performing similar experiments for other body parts. However, the KVIQ results
421 demonstrated that gymnasts tended to show higher scores for all movements. In addition, we
422 found that most gymnasts performed motor imagery of various body parts in their daily practice.
423 On the basis of these findings, we speculate that gymnasts have superior motor imagery ability
424 irrespective of body parts, although confirming this possibility will require further investigation.

425 The present study is the first to observe differences in physiological indices between
426 athletes and non-athletes. This means that the present study can bridge the gap between

427 psychology and physiology studies regarding differences in general motor imagery ability
428 between athletes and non-athletes. However, because only gymnasts participated in this study,
429 it is unclear whether the present results are specific to gymnasts or apply generally to athletes
430 performing any sports. Because differences in general motor imagery ability would be expected
431 among athletes, further investigation is needed to elucidate sports-specific differences in ability
432 for general movement imagery. In any case, the present study indicated the importance of
433 comparing corticospinal excitability measured by ERD for evaluating motor imagery ability.
434 In future studies, imagery training using bioelectrical signals may provide a useful tool for
435 improving the motor imagery ability of athletes.

436

437 **Conclusion**

438 The present study demonstrated that, during general KMI, the corticospinal
439 excitability measured by ERD magnitude was significantly greater in gymnasts compared with
440 non-gymnasts. These results are consistent with higher subjective vividness in gymnasts
441 measured using the KVIQ psychological questionnaire. The observed signature of flexibly
442 modulating sensorimotor rhythm with no movement would be the basis of their superior
443 general motor imagery ability in gymnasts.

444

445 **Author Contributions**

446 H.S. and J.U. conceptualized and designed the study, interpreted data, wrote the manuscript,
447 and acquired funding. H.S. acquired and analyzed data. J.U. supervised the study.

448

449 **Acknowledgements**

450 This work was supported by grants from the Grant-in-Aid for Scientific Research (B) (Japan
451 Society for the Promotion of Science, JSPS) (grant number 20H04091) to JU, a designated
452 donation from Living Platform, Ltd, Japan to JU, and Taikichiro Mori Memorial Research
453 Grants to H.S. We thank Ms. Tomomi Hamaoka, Ms. Kana Iijima, and Ms. Chieko Matsuda
454 for their secretarial assistance and Mr. Hisato Toriyama, Mr. Ryoichiro Yamazaki, Mr. Takuya
455 Ideriha, Ms. Rina Suzuki and all other members of our laboratory for their useful comments on
456 the work. We thank Mr. Hisashi Mizutori for his practical comments on the work. We thank
457 Benjamin Knight, MSc., from Edanz (<https://www.jp.edanz.com/ac>), for editing a draft of this
458 manuscript.

459

460

461 **References**

- 462 1. Cumming J, Hall C. Deliberate imagery practice: the development of imagery skills in
463 competitive athletes. *J Sports Sci.* 2002;20(2):137–45.
- 464 2. Sobierajewicz J, Przekoracka-Krawczyk A, Jaśkowski W, Verwey WB, van der Lubbe
465 R. The influence of motor imagery on the learning of a fine hand motor skill. *Exp*
466 *Brain Res.* 2017;235(1):305–20.
- 467 3. Lebon F, Horn U, Domin M, Lotze M. Motor imagery training: Kinesthetic imagery
468 strategy and inferior parietal fMRI activation. *Hum Brain Mapp.* 2018;39(4):1805–13.
- 469 4. Battaglia C, D’Artibale E, Fiorilli G, Piazza M, Tsopani D, Giombini A, et al. Use of
470 video observation and motor imagery on jumping performance in national rhythmic
471 gymnastics athletes. *Hum Mov Sci.* 2014;38:225–34.
- 472 5. Peynircioğlu ZF, Thompson JLW, Tanielian TB, Tanielian TB. Improvement
473 strategies in free-throw shooting and grip-strength tasks. *J Gen Psychol.*
474 2000;127(2):145–56.
- 475 6. Decety J, Grèzes J. Neural mechanisms subserving the perception of human actions.
476 *Trends Cogn Sci.* 1999;3(5):172–8.
- 477 7. Guillot A, Collet C, Nguyen VA, Malouin F, Richards C, Doyon J. Brain activity
478 during visual versus kinesthetic imagery: An fMRI study. *Hum Brain Mapp.*
479 2009;30(7):2157–72.

- 480 8. Hanakawa T. Functional Properties of Brain Areas Associated With Motor Execution
481 and Imagery. *J Neurophysiol.* 2002;89(2):989–1002.
- 482 9. Zabicki A, De Haas B, Zentgraf K, Stark R, Munzert J, Krüger B. Imagined and
483 executed actions in the human motor system: Testing neural similarity between
484 execution and imagery of actions with a multivariate approach. *Cereb Cortex.*
485 2017;27(9):4523–36.
- 486 10. Hashimoto R, Rothwell JC. Dynamic changes in corticospinal excitability during
487 motor imagery. *Exp Brain Res.* 1999;125(1):75–81.
- 488 11. Di Corrado D, Guarnera M, Quartiroli A. Vividness and transformation of mental
489 images in karate and ballet. *Percept Mot Skills.* 2014;119(3):764–73.
- 490 12. Di Corrado D, Guarnera M, Vitali F, Quartiroli A, Coco M. Imagery ability of elite
491 level athletes from individual vs. Team and contact vs. No-contact sports. *PeerJ.*
492 2019;7:1–14.
- 493 13. Isaac AR, Marks DF. Individual differences in mental imagery experience:
494 Developmental changes and specialization. *Br J Psychol.* 1994;85(4):479–500.
- 495 14. Jansen P, Lehmann J. Mental rotation performance in soccer players and gymnasts in
496 an object-based mental rotation task. *Adv Cogn Psychol.* 2013;9(2):92–8.
- 497 15. Di Nota PM, Chartrand JM, Levkov GR, Montefusco-Siegmund R, DeSouza JFX.
498 Experience-dependent modulation of alpha and beta during action observation and

- 499 motor imagery. *BMC Neurosci.* 2017;18(1):28.
- 500 16. Wei G, Luo J. Sport expert's motor imagery: Functional imaging of professional motor
501 skills and simple motor skills. *Brain Res.* 2010;1341:52–62.
- 502 17. Kraeutner SN, McWhinney SR, Solomon JP, Dithurbide L, Boe SG. Experience
503 modulates motor imagery-based brain activity. *Eur J Neurosci.* 2018;47(10):1221–9.
- 504 18. Fourkas AD, Bonavolont V, Avenanti A, Aglioti SM. Kinesthetic imagery and tool-
505 specific modulation of corticospinal representations in expert tennis players. *Cereb*
506 *Cortex.* 2008;18(10):2382–90.
- 507 19. Malouin F, Richards CL, Jackson PL, Lafleur MF, Durand A, Julien D. The
508 Kinesthetic and Visual Imagery Questionnaire (KVIQ) for Assessing Motor Imagery
509 in Persons with Physical Disabilities: A Reliability and Construct Validity Study. *J*
510 *Neurol Phys Ther.* 2007;31(1):20–9.
- 511 20. Pfurtscheller G, Lopes da Silva FH. Event-related EEG/MEG synchronization and
512 desynchronization: basic principles. *Clin Neurophysiol.* 1999;110(11):1842–57.
- 513 21. Pfurtscheller G, Neuper C, Andrew C, Edlinger G. Foot and hand area mu rhythms. *Int*
514 *J Psychophysiol.* 1997;26(1–3):121–35.
- 515 22. Takemi M, Masakado Y, Liu M, Ushiba J. Event-related desynchronization reflects
516 downregulation of intracortical inhibition in human primary motor cortex. *J*
517 *Neurophysiol.* 2013;110(5):1158–66.

- 518 23. Brickwedde M, Krüger MC, Dinse HR. Somatosensory alpha oscillations gate
519 perceptual learning efficiency. *Nat Commun.* 2019;10(1):263.
- 520 24. Nakano H, Kodama T, Ukai K, Kawahara S, Horikawa S, Murata S. Reliability and
521 validity of the Japanese version of the kinesthetic and visual imagery questionnaire
522 (KVIQ). *Brain Sci.* 2018;8(5).
- 523 25. Hall C, Pongrac J, Buckholz E. The measurement of imagery ability. *Hum Mov Sci.*
524 1985;4(2):107–18.
- 525 26. Toriyama H, Ushiba J, Ushiyama J. Subjective Vividness of Kinesthetic Motor
526 Imagery Is Associated With the Similarity in Magnitude of Sensorimotor Event-
527 Related Desynchronization Between Motor Execution and Motor Imagery. *Front Hum*
528 *Neurosci.* 2018;12(July):1–10.
- 529 27. McFarland DJ, McCane LM, David S V., Wolpaw JR. Spatial filter selection for EEG-
530 based communication. *Electroencephalogr Clin Neurophysiol.* 1997;103(3):386–94.
- 531 28. Pfurtscheller G, Neuper C. Future prospects of ERD/ERS in the context of brain-
532 computer interface (BCI) developments. *Prog Brain Res.* 2006. p. 433–7.
- 533 29. Stolk A, Brinkman L, Vansteensel MJ, Aarnoutse E, Leijten FS, Dijkerman CH, et al.
534 Electrocorticographic dissociation of alpha and beta rhythmic activity in the human
535 sensorimotor system. *Elife.* 2019;8:1–24.
- 536 30. Brinkman L, Stolk A, Dijkerman HC, de Lange FP, Toni I. Distinct Roles for Alpha-

- 537 and Beta-Band Oscillations during Mental Simulation of Goal-Directed Actions. *J*
538 *Neurosci.* 2014;34(44):14783–92.
- 539 31. Takemi M, Masakado Y, Liu M, Ushiba J. Is event-related desynchronization a
540 biomarker representing corticospinal excitability? *Proc Annu Int Conf IEEE Eng Med*
541 *Biol Soc EMBS.* 2013;281–4.
- 542 32. Ushiyama J, Takahashi Y, Ushiba J. Muscle dependency of corticomuscular coherence
543 in upper and lower limb muscles and training-related alterations in ballet dancers and
544 weightlifters. *J Appl Physiol.* 2010;109(4):1086–95.
- 545 33. Ushiyama J, Yamada J, Liu M, Ushiba J. Individual difference in β -band
546 corticomuscular coherence and its relation to force steadiness during isometric
547 voluntary ankle dorsiflexion in healthy humans. *Clin Neurophysiol.* 2017;128(2):303–
548 11.
- 549 34. Suzuki R, Ushiyama J. Context-Dependent Modulation of Corticomuscular Coherence
550 in a Series of Motor Initiation and Maintenance of Voluntary Contractions. *Cereb*
551 *Cortex Commun.* 2020;1(1):1–14.
- 552 35. Lopes da Silva FH, Pfurtscheller G. Event-related EEG/MEG synchronization and
553 desynchronization: basic principles. *Clin Neurophysiol.* 1999;110(11):1842–57.
- 554 36. Pfurtscheller G. Event-related synchronization (ERS): an electrophysiological
555 correlate of cortical areas at rest. *Electroencephalogr Clin Neurophysiol.*

556 1992;83(1):62–9.

557 37. van Elk. Semantics in the motor system: motor-cortical beta oscillations reflect

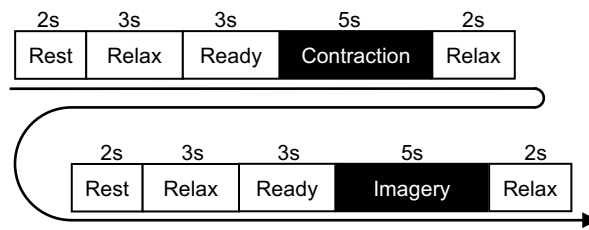
558 semantic knowledge of end-postures for object use. *Front Hum Neurosci*.

559 2010;4(February):1–12.

560

561

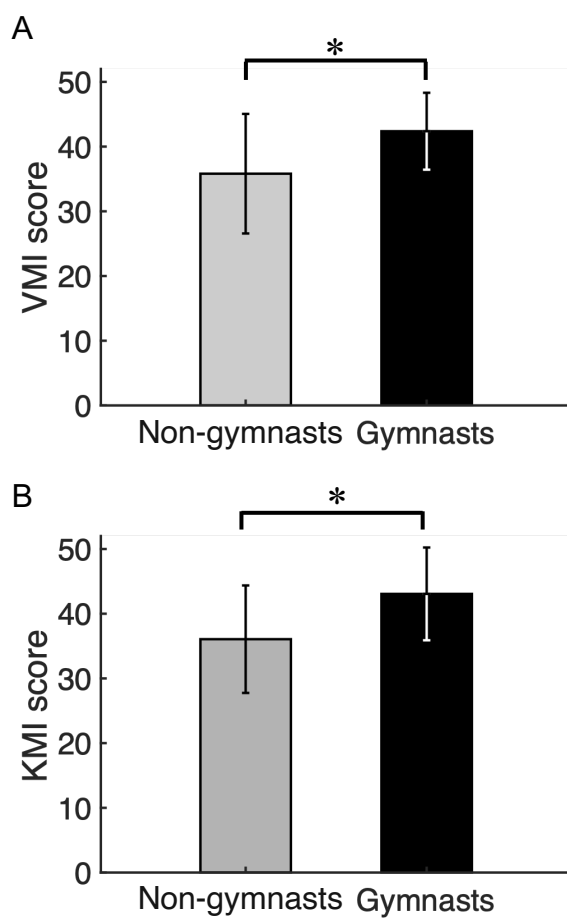
562 **Figures**



563

564 Figure 1. Experimental paradigm of physiological experiment. Participants performed
565 isometric contraction in the contraction phase and performed motor imagery of the same
566 movement in the imagery phase. The diagram shows the flow in each trial, which was repeated
567 five times within each set. Six sets were performed for each of the wrist flexion and shoulder
568 abduction tasks.

569



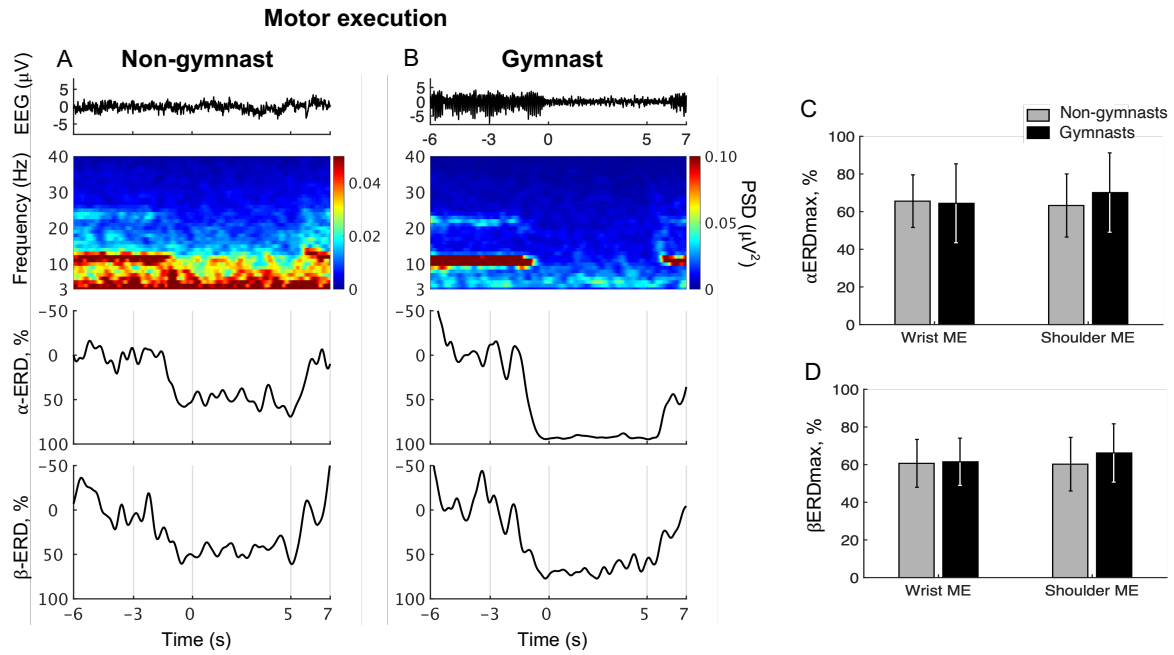
570

571 Figure 2. Results of psychological experiment. Group data (Mean \pm S.D.) for VMI (A) and

572 KMI scores (B) obtained from KVIQ are shown for both groups. The gray bar represents data

573 for non-gymnasts, while the black bar represents data for gymnasts. *P < 0.05.

574



575

576 Figure 3. Results from physiological experiments for ME. Typical time courses of single trial

577 EEG, time-frequency map, α -band ERD, and β -band in wrist dorsiflexion ME are shown for

578 non-gymnast (A) and gymnast (B) participants. Note that participants performed wrist

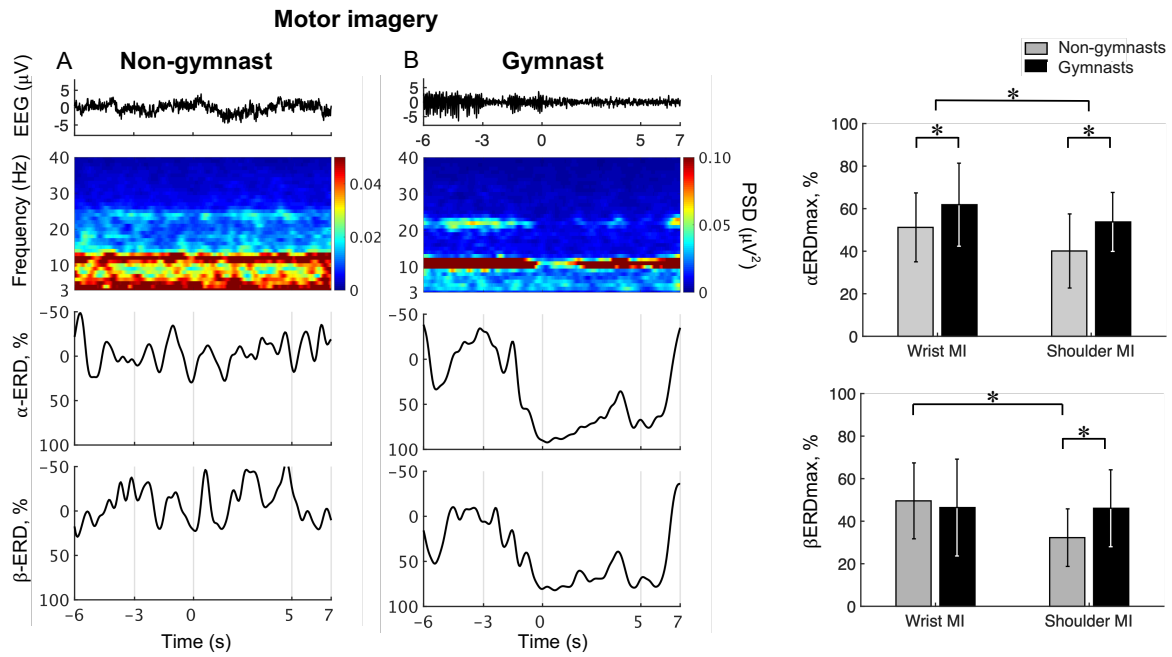
579 dorsiflexion ME from 0 s to 5 s. Group data (Mean \pm S.D.) for αERDmax (C) and βERDmax

580 (D) during ME are shown across groups and tasks. The gray bar represents data for non-

581 gymnasts, while the black bar represents data for gymnasts. No significant differences were

582 observed across groups and tasks.

583



584

585 Figure 4. Results from physiological experiments for KMI. Typical time courses of single trial

586 EEG, time-frequency map, α -band ERD, and β -band in wrist dorsiflexion KMI are shown for

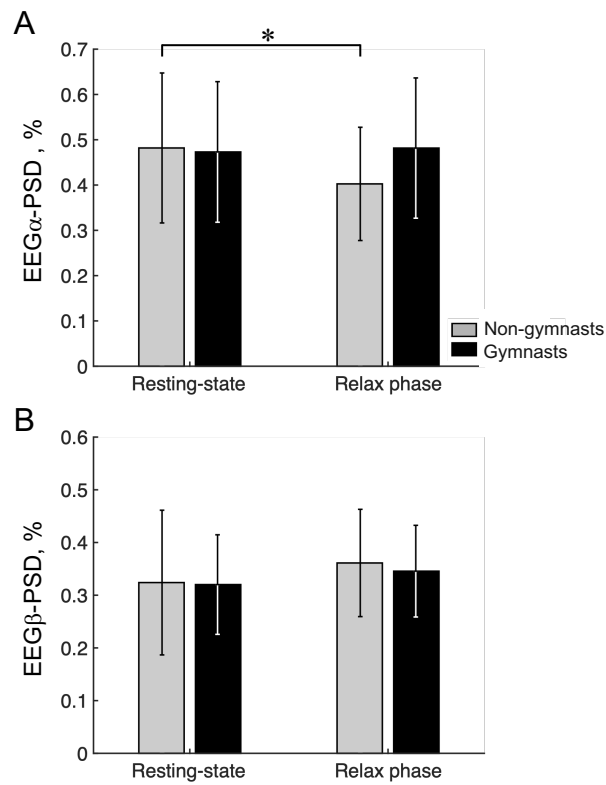
587 non-gymnast (A) and gymnast (B) participants. Note that participants performed wrist

588 dorsiflexion KMI from 0 s to 5 s. Group data (Mean \pm S.D.) for αERDmax (C) and βERDmax

589 (D) during KMI are shown across groups and tasks. The gray bar represents data for non-

590 gymnasts, while the black bar represents data for gymnasts. * $P < 0.05$.

591



592

593 Figure 5. Results of the ratio of the α -band and β -band (EEG β -PSD) PSDs. Group data (Mean

594 \pm S.D.) for the ratio of the α -band (A) and β -band PSDs (B) are shown for both groups. The

595 gray bar represents data for non-gymnasts, while the black bar represents data for gymnasts.

596 * $P < 0.05$.