Title: Gymnasts' ability to modulate bioelectric sensorimotor rhythms during kinesthetic motor imagery of sports non-specific movements

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Running head:

Gymnasts' ability of motor imagery evaluated by EEG

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Abstract

Previous psychological studies using questionnaires have consistently reported that athletes have superior motor imagery ability, both for sports-specific and sports non-specific movements. However, regarding motor imagery of sports non-specific movements, no physiological studies have demonstrated differences in neural activity between athletes and non-athletes. The purpose of the present study was to examine differences in bioelectric sensorimotor rhythms during kinesthetic motor imagery (KMI) of sports non-specific movements between gymnasts and non-gymnasts. We selected gymnasts as an example population because they are likely to have particularly superior motor imagery ability due to frequent usage of motor imagery including KMI as part of daily practice. Healthy young participants (16 gymnasts and 16 non-gymnasts) performed repeated motor execution and KMI of sports non-specific movements (wrist dorsiflexion and shoulder abduction of the dominant hand). Scalp electroencephalogram (EEG) was recorded over the contralateral sensorimotor cortex. During motor execution and KMI, sensorimotor EEG power is known to decrease in the α- (8–15 Hz) and β-bands (16–35 Hz), referred to as event-related desynchronization (ERD). We calculated the maximal peak of ERD both in the α- (αERDmax) and β-bands (βERDmax) as a measure of changes in corticospinal excitability. αERDmax was significantly greater in gymnasts, who subjectively evaluated their KMI as being more vivid, for both KMI tasks. On the other hand, βERDmax was greater in gymnasts only for shoulder abduction KMI. These findings suggest gymnasts' signature of flexibly modulating sensorimotor rhythm with no movements, which may be the basis of their superior ability of KMI for sports non-specific movements.

New & Noteworthy

Kinesthetic motor imagery of sports non-specific movements was compared between gymnasts and non-gymnasts (i.e., healthy controls) from both physiological and psychological approaches. The EEG sensorimotor rhythms during kinesthetic motor imagery were more desynchronized in gymnasts who subjectively imaged their own movements as being more vivid. The work reveals novel ability in gymnasts to flexibly control their sensorimotor rhythms with no actual movements, which would be the basis of their superior ability of motor imagery.

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

Introduction

Motor imagery is regularly used by athletes to improve performance (1,2). Previous studies have shown that performing motor imagery in training improves performance in various tasks, including sequence learning (3,4), jump height (5) and free-throw shooting (6). To explain these performance gains, several neuroscience studies have provided evidence that motor imagery activates some neural substrates in common with actual movement, including the primary motor cortex, supplementary motor area, and inferior parietal lobe (7–10), as well as inducing neural plasticity in these areas (11–13).

In the field of sports psychology, several cross-sectional questionnaire studies have consistently reported that athletes have superior motor imagery ability compared with non-athletes (14–16). Furthermore, previous studies have indicated that athletes can perform motor imagery more vividly than non-athletes, not only for specialized movements in their own sports but also for sports non-specific movements such as raising the arm and jumping (15,17). The findings of these studies suggest that the neural activity underlying motor imagery ability may differ between athletes and non-athletes, not only for sports-specific imagery but also for motor imagery of sports non-specific movements.

However, in the field of applied physiology, to the best of our knowledge, no studies have demonstrated differences in neural activity during motor imagery of sports non-specific movements between athletes and non-athletes, although some studies using electroencephalogram (EEG) (17), magnetoencephalography(MEG) (18), functional magnetic resonance imaging (fMRI) (19) and transcranial magnetic stimulation (TMS) (20) have reported signature neural activity patterns during sports-specific motor imagery in athletes. For instance, when tennis players imagined movements specifically related to tennis, their corticospinal excitability became higher than that of non-athletes, whereas such a difference between athletes and non-athletes was not observed when they imagined other movements

including non-tennis specific movements(20). Thus, there is currently a gap in findings between psychological and physiological studies regarding differences in motor imagery ability, particularly for sports non-specific movements between athletes and non-athletes.

To clarify this issue, the present study investigated differences in motor imagery ability of sports non-specific movements between gymnasts and healthy adults (i.e., non-gymnasts) from both psychological and physiological points of view. As a psychological indicator, we evaluated the subjective vividness of motor imagery using The Kinesthetic and Visual Imagery Questionnaire (KVIQ-20) (21). As a physiological indicator, we evaluated sensorimotor rhythms using EEG. Event-related desynchronization (ERD) is a measure of decreases in power of the EEG sensorimotor rhythm within the α- and β-bands from the resting-state to the motor execution or kinesthetic motor imagery (KMI) state (22,23), which is known to reflect increased neuronal excitability in the corticospinal system (24). We chose gymnasts as a population of athletes for the following reasons: 1) gymnasts perform motor imagery including KMI frequently as a part of their daily practices because of the high risk of serious injury in their performance; 2) gymnasts were assumed to have higher motor imagery abilities than athletes engaged in other sports, because it has been reported that motor imagery is more vivid in athletes engaged in individual and/or non-contact sports compared with athletes engaged in team and/or contact sports (25); 3) to the best of our knowledge, no previous studies have measured neural activity during motor imagery in gymnasts.

Methods

Ethical Approval

This study was conducted in accordance with the Declaration of Helsinki. All experimental protocols and procedures were approved by the Research Ethics Committee in Shonan Fujisawa Campus, Keio University (Approval Number 167). The examiners provided

a detailed explanation of the purpose, experimental procedures, potential benefits, and risks involved. After receiving all of the relevant information, participants provided written informed consent before participating in the experiment.

Participants

We recruited 16 gymnasts (11 men, 5 women, aged 18–24 years) and 16 healthy adults (8 men, 8 women, aged 19–22 years) as a non-gymnast group. All participants were right-handed. All gymnasts had been practicing at least for 7 years (range: 7–16 years) and had participated in an all-Japan intercollegiate gymnastic championship at least once. Note that two gymnasts were members of the Japanese national gymnastics team. The non-gymnasts group had no experience of gymnastic training. None of the participants had experienced any neurological and musculoskeletal disorders.

Psychological assessments

Procedures

Motor imagery ability was tested using a psychological questionnaire translated into Japanese: The Kinesthetic and Visual Imagery Questionnaire (KVIQ-20) (21,26). Briefly, the KVIQ-20 tests how vividly a person is able to imagine their own movements subjectively, using two types of motor imagery: KMI and visual motor imagery (VMI). KMI involves imagining the feeling when we perform actual motor tasks. Conversely, VMI involves imagining to see ourselves or the field of vision where we perform the tasks (21,27). Participants sat comfortably in a chair next to the examiner and watched the examiner's example once. Then, they actually performed the exercise, followed by VMI or KMI of the exercise they had just performed. Participants were then asked to evaluate the vividness of the motor imagery on a five-point ordinal scale (the more vivid the motor imagery, the higher the

scale score). This procedure was repeated for 10 different simple exercises: neck flexion/extension, shoulder elevation, forward shoulder flexion, elbow flexion/extension, thumb-fingers opposition, forward trunk flexion, knee extension, hip abduction, foot tapping, and foot external rotation.

Analyses

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

Physiological assessments

Recordings

Scalp EEG signals were recorded with eight passive Ag/AgCl electrodes around the sensorimotor area related to right upper limbs (Cz, C1, C3, C5, FC1, FC3, CP1, and CP3) in accord with the extended international 10-20 system. Electrodes with a diameter of 18 mm were mounted on an electrode cap (g.GAMMAcap 1027; Guger Technologies, Graz, Austria). Reference and ground electrodes were placed on the right and left earlobes, respectively. Surface electromyogram (EMG) signals were recorded from the right deltoid muscle (DEL) and the right extensor carpi radials muscle (ECR). Two passive Ag/AgCl electrodes with a diameter of 10 mm were placed over each muscle belly with inter-electrode distances of 20 mm. All EEG and EMG signals were amplified and bandpass-filtered (EEG, 0.5–1000 Hz; EMG, 2–1000 Hz) using a linked biosignal recording system (g.BSamp 0201a; Guger Technologies, Graz, Austria). All analog EEG and EMG signals were converted to digital signals at a sample rate of 1000 Hz using an AD converter with 16-bit resolution (NI USB-6259, National Instruments, Austin, TX, United States) that was controlled by data-logger

158 software originally designed using MATLAB software (The MathWorks, Inc., Antic, MA,
159 United States).
160
161 **Procedures**
162 Following the psychological assessment, we performed physiological EEG and EMG
163 measurements. The participants sat comfortably in the seat. A computer monitor for visual
164 feedback was placed 2 m in front of participants' eyes. First, resting-state EEG was recorded
165 over 60 s. Participants relaxed and fixated their eyes on a cross (+) displayed at the center of
166 the monitor during recording. Participants then performed several practice trials of maximal
167 voluntary contractions (MVCs) of wrist dorsiflexion and shoulder abduction. After these
168 movements were practiced, participants performed MVC once each for wrist dorsiflexion and
169 shoulder abduction. When performing each MVC, EMG activity of the contracting muscle was
170 recorded. The EMG signals were full-wave rectified. We found a 0.5-s period of stable force
171 exertion during MVC and calculated the integrated EMG value (iEMGmax) in this period. In
172 the following experiment, 20% of this iEMGmax value was used as a target value for visual
173 feedback.
174 The physiological data recordings during motor execution and KMI were performed
175 after several practice trials. Visual feedback was presented on the screen, with a red cursor to
176 represent muscle contraction level as a relative value in %iEMGmax and a vertical blue line to
177 represent a target value. Furthermore, instructions for each phase, including "Rest", "Relax",
178 "Ready", "Contraction", or "Imagery", were displayed on the monitor. In the wrist dorsiflexion
179 task, participants' dominant hand was positioned on the armrest and fixed by a belt with the
180 palm down. In the shoulder abduction task, the dominant upper limb was lowered to the side
181 of the body while bending the elbow lightly, and the arm was fixed by a belt. In both the wrist

dorsiflexion and shoulder abduction tasks, participants performed repeated motor execution and KMI according to the procedure used in our previous study (28).

The experimental paradigm is shown in Figure 1. In detail, each trial was started from the rest phase and the word “Rest” was displayed on the monitor for 7 s. During the rest phase, participants were able to adjust their posture freely and/or blink their eyes strongly. After the rest phase, the word “Relax” was displayed on the monitor for 3 s. During the relax phase, participants were instructed to relax as much as possible, without performing any movement. The word “Ready” was then displayed for 3 s, accompanied by a short sound presented every second. During the ready phase, participants prepared for the next instruction. After the ready phase, the word “Contraction” was displayed for 5 s. During the contraction phase, participants performed isometric voluntary contraction (wrist dorsiflexion or shoulder abduction) at 20% of iEMGmax by their dominant hand. In the contraction phase, participants were instructed to contract their muscle so that the cursor could follow the target line as accurately as possible. After the contraction phase, the word “Relax” was displayed for 2 s. In this relax phase, participants were instructed to relax as much as possible, without any movement. After the rest, relax, and ready phases, the imagery phase was started, and participants performed KMI of the preceding contraction for 5 s with their eyes open, and without any movement. During the imagery phase, we checked that no EMG activity occurred. When the imagery phase finished, the relax phase was presented again for 2 s. This flow was conducted for each trial, including motor execution and KMI, and five trials were repeated within each set. Six sets were performed for each task. Thus, a total 30 trials were performed for both wrist flexion and shoulder abduction tasks. We set the wrist dorsiflexion and the shoulder abduction task in a randomized order across participants. The duration of the set interval was longer than 2 min, to provide sufficient rest for participants.

207 **Analyses**

208 To remove noise arising from the electric power, the EEG and EMG signals were
209 notch-filtered at 50 Hz. The EEG signals over C1 and C3 were derived with a four-neighbor
210 Laplacian spatial filter. For example, in the case of C3, the EEG signal over C3 was subtracted
211 by an average of C1, C5, FC3 and CP3. The Laplacian derivation method is known to strongly
212 emphasize cortical activity originating below the electrode of interest (29). If Laplacian-
213 derived EEG included potentials exceeded 50 μV, we considered the trial to contain an artifact,
214 and excluded the data from future analyses. Additionally, visual inspection was performed to
215 reject additional artifacts missed by the automatic inspection.

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

223 $$ERD(f,t) = \frac{R(f) - A(f,t)}{R(f)} \times 100\%, \qquad \text{(eq. 1)}$$

224 where A is the EEG PSDs at time t, frequency f, and R is the mean PSDs of the baseline period
225 (last 1 s in the relax phase). This equation indicates that the positively greater the ERD value,
226 the larger the decrease in EEG PSD during motor execution or KMI compared with the relax
227 phase. Because the most reactive frequency band of ERD was slightly different across
228 participants (30), we determined an electrode and the 3 Hz-frequency width showing the largest
229 ERD in each of the α-band (8–15 Hz) and β-band (16–35 Hz) during motor execution. Because
230 it has been suggested that the functional roles played by ERD differ between the α- and β-

231 bands (31,32), we analyzed ERDs from these two frequency bands separately. The magnitude
232 of ERD in the α-band (αERDmax) and β-band (βERDmax) were measured by calculating the
233 peak value of ERD for motor execution and KMI of each task, respectively (28,33).
234 To compare the features of EEG during the relax phase in the task with continuous
235 resting-state for a prolonged period, we also analyzed the α-band or β-band PSDs for both
236 data sets. For the relax phase EEG, the final 1 s periods in the relax phase, which were used
237 as the baseline periods for ERD analyses, were extracted from all trials, and combined to
238 create a 60 s relax phase EEG signal. For the resting-state EEG, a continuous 60 s period with
239 few artefacts was extracted. We then calculated the ratio of the sum of EEG power within the
240 α-band or β-band PSD to that of the entire frequency range (4–50 Hz) (named, EEGα-PSD
241 and EEGβ-PSD) for both data sets, and compared these values between relax phase EEG
242 during tasks and resting-state EEG.
243
244 **Statistical analyses**
245 Two-side unpaired t-tests were performed on VMI and KMI scores of KVIQ between
246 groups (non-gymnasts vs. gymnasts), to confirm differences in the subjective vividness of
247 motor imagery between them. To test differences in αERDmax and βERDmax during motor
248 execution or KMI, we performed two-way mixed-model analysis of variance (ANOVA)
249 between participant groups (gymnasts and non-gymnasts) and tasks (wrist dorsiflexion and
250 shoulder abduction). If the interaction was significant, we performed a two-sided unpaired t-
251 test for groups (gymnasts vs. non-gymnasts) and a two-sided paired t-test for tasks (wrist
252 dorsiflexion vs. shoulder abduction). To test differences in the EEGα-PSD or EEGβ-PSD
253 between resting-state EEG and relax phase EEG during tasks, we also performed two-way
254 ANOVA between participant groups (gymnasts and non-gymnasts) and conditions (resting-
255 sate and relax phase). The p-values of 0.05 were used to indicate statistical significance. All

256 statistical analyses were performed using SPSS statistics software (IBM SPSS Statistics 25,
257 IBM developerWorks, Tokyo, Japan).
258

259 ## Results

260 ### KVIQ

261 Figure 2 shows group data (mean ± S.D.) for KVIQ scores obtained from VMI and
262 KMI tasks between gymnasts and non-gymnasts. The KVIQ scores were significantly greater
263 in gymnasts, both in VMI (gymnasts, 42.68 ± 6.22; non-gymnasts, 35.44 ± 8.73, $p = 0.011$)
264 (Figure 2A) and KMI (gymnasts, 43.50 ± 6.78; non-gymnasts, 35.94 ± 8.24, $p = 0.008$) (Figure
265 2B). The KVIQ results indicate that gymnasts subjectively evaluated how vividly they could
266 imagine their own movements.
267

268 ### ERD magnitude

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

274 Figure 3C shows group data for αERDmax during wrist dorsiflexion and shoulder
275 abduction motor execution. An ANOVA on αERDmax during motor execution revealed no
276 significant effects of group ($F_{1,30} = 0.209$, $p = 0.651$) and task ($F_{1,30} = 0.831$, $p = 0.369$), while
277 a significant interaction was obtained ($F_{1,30} = 4.654$, $p = 0.0391$). An unpaired t-test for group
278 revealed no significant difference in αERDmax between gymnasts and non-gymnasts for wrist
279 dorsiflexion (gymnasts, 64.41 ± 20.96; non-gymnasts, 65.58 ± 13.97, $p = 0.855$) and shoulder
280 abduction task (gymnasts, 70.13 ± 21.07; non-gymnasts, 63.26 ± 16.77, $p = 0.316$). A paired t-

281 test for task revealed no significant difference in αERDmax between wrist dorsiflexion and
282 shoulder abduction execution both for non-gymnasts (wrist dorsiflexion, 65.58 ± 13.97;
283 shoulder abduction, 63.26 ± 16.77, $p = 0.303$) and gymnasts (wrist dorsiflexion, 64.41 ± 20.96;
284 shoulder abduction, 70.13 ± 21.07, $p = 0.078$). Figure 3D shows group data for βERDmax
285 during wrist dorsiflexion and shoulder abduction motor execution. An ANOVA on the
286 βERDmax during motor execution with groups and task revealed no significant effects of
287 group ($F_{1,30} = 0.571$, $p = 0.456$) and task ($F_{1,30} = 1.249$, $p = 0.273$), and interaction ($F_{1,30} =$
288 1.815, $p = 0.188$). The results revealed no effects of sports experience and body part on ERD
289 magnitude during motor execution.

290 Typical examples of EEG signals, EEG time-frequency maps and ERD time courses
291 during wrist dorsiflexion KMI from a non-gymnast and a gymnast are shown in Figure 4A and
292 4B, respectively. From the time-frequency maps for a non-gymnast participant, we did not
293 observe clear ERD in the imagery phase (0 to 5 s) compared with the relax phase (−6 to −3 s)
294 in both the α-band and β-band. (Figure 4A). Conversely, clear ERD can be observed in the
295 time-frequency-map for the gymnast participant around 12 Hz and 22 Hz (Figure 4B).

296 Figure 4C shows group data for the αERDmax during wrist dorsiflexion and shoulder
297 abduction KMI. An ANOVA on αERDmax during KMI showed significant effects of group
298 ($F_{1,30} = 5.437$, $p = 0.027$) and task ($F_{1,30} = 10.975$, $p = 0.002$). No significant interaction effect
299 ($F_{1,30} = 0.266$, $p = 0.610$) was observed. Figure 4C shows group data for βERDmax during
300 wrist dorsiflexion and shoulder abduction KMI. An ANOVA on βERDmax during KMI
301 showed no significant effects of group ($F_{1,30} = 0.876$, $p = 0.357$), but significant effects of task
302 ($F_{1,30} = 8.019$, $p = 0.008$) and a significant interaction ($F_{1,30} = 7.421$, $p = 0.010$). An unpaired
303 t-test for group revealed a significant difference in βERDmax between gymnasts and non-
304 gymnasts for the shoulder abduction task (gymnasts, 46.08 ± 18.09; non-gymnasts, 32.27 ±
305 17.84, $p = 0.021$) but not for the wrist dorsiflexion task (gymnasts, 46.42 ± 22.76; non-

306 gymnasts, 49.56 ± 17.84, $p = 0.666$). A paired t-test for task revealed a significant difference
307 in βERDmax between the wrist dorsiflexion and shoulder abduction KMI conditions for non-
308 gymnasts (wrist dorsiflexion, 49.56 ± 17.84; shoulder abduction, 32.27 ± 17.84, $p = 0.002$) but
309 not for gymnasts (wrist dorsiflexion, 46.42 ± 22.76; shoulder abduction, 46.08 ± 18.09, $p =$
310 0.938). These results indicated that gymnastics experience affected ERD magnitude during
311 KMI of sports non-specific movements.
312

313 **Comparison of EEGα-PSD and EEGβ-PSD between resting-state EEG and relax phase**
314 **EEG during tasks**

315 Figure 5A shows group data for the EEGα-PSD in resting-state EEG and relax phase
316 EEG during the tasks. An ANOVA examining EEGα-PSD data revealed no significant effects
317 of group ($F_{1,30} = 0.486$, $p = 0.491$) or condition ($F_{1,30} = 4.135$, $p = 0.051$); however, a significant
318 interaction ($F_{1,30} = 6.382$, $p = 0.017$) was observed. An unpaired t-test for group revealed no
319 significant difference in EEGα-PSD during resting-state EEG (gymnasts, 0.473 ± 0.155; non-
320 gymnasts, 0.482 ± 0.166, $p = 0.878$) and that during the relax phase (gymnasts, 0.482 ± 0.155;
321 non-gymnasts, 0.403 ± 0.125, $p = 0.878$; $p = 0.122$) between gymnasts and non-gymnasts. In
322 non-gymnasts, a paired t-test revealed significant differences in the EEGα-PSD between
323 conditions (resting-state, 0.482 ± 0.166; relax phase, 0.403 ± 0.125, $p = 0.008$). However, in
324 gymnasts, no significant differences in EEGα-PSD were observed between conditions (resting-
325 state, 0.473 ± 0.155; relax phase, 0.481 ± 0.155, $p = 0.715$). Figure 5B shows group data for
326 EEGβ-PSD. An ANOVA on EEGβ-PSD showed no significant effects of group ($F_{1,30} = 0.106$,
327 $p = 0.747$) and condition ($F_{1,30} = 1.787$, $p = 0.191$), and no significant interaction ($F_{1,30} = 0.063$,
328 $p = 0.804$). These results indicate that, in non-gymnasts, the EEGα-PSD was smaller in the
329 relax phase EEG than during resting-state EEG, while such a difference was not observed in

330 gymnasts. Conversely, EEGβ-PSD did not differ between resting-state EEG and relax phase
331 EEG in both gymnasts and non-gymnasts.
332
333 ## Discussion
334 The purpose of the present study was to clarify differences in bioelectric sensorimotor
335 rhythm during KMI of sports non-specific movements between gymnasts and non-gymnasts.
336 The results revealed that, when required to repeatedly switch between relaxing and motor
337 execution or KMI of sports non-specific movements, the ERD magnitude during KMI was
338 significantly greater in gymnasts, who subjectively evaluated their imagery including KMI as
339 more vivid, while no difference between groups was observed during motor execution. In
340 particular, the ERD magnitude in the α-band was greater in gymnasts compared with non-
341 gymnasts, both in wrist dorsiflexion and shoulder abduction KMIs, whereas the ERD
342 magnitude in the β-band was greater in gymnasts only in shoulder abduction KMI.
343
344 **Difference in KMI ability of sports non-specific movements between gymnasts and non-**
345 **gymnasts**
346 We evaluated ERD as a physiological indicator of KMI ability in the present study,
347 because it is considered to reflect changes in corticospinal excitability (24) and is associated
348 with subjective vividness of KMI measured by KVIQ (28). It should be noted that the present
349 results revealed greater ERD magnitude during KMI of sports non-specific movements in
350 gymnasts than in non-gymnasts, although differences in neural activity between athletes and
351 non-athletes have not been reported in motor imagery of sports non-specific movements in
352 previous studies using EEG (17), MEG (18), TMS (20) or fMRI (19). This may be related to
353 the fact that gymnasts perform motor imagery including KMI frequently as a part of their daily
354 practice to reduce the risk of serious injury in their practice. Furthermore, a previous

355 psychological study showed that the vividness of motor imagery of sports non-specific
356 movements was higher in athletes engaged in individual and/or non-contact sports compared
357 with athletes engaged in team and/or contact sports (25). Thus, as gymnasts have superior
358 motor imagery ability among athletes, they may provide a particularly suitable population for
359 highlighting differences in neural activity during KMI of sports non-specific movements
360 compared with non-athletes.

361 It is possible that the present task protocol, in which participants performed KMI
362 following motor execution repeatedly in the order of seconds, led to the current finding of
363 greater ERD magnitude in gymnasts. In psychological questionnaires, the conventional
364 procedure for measuring motor imagery ability is to examine participants while they perform
365 motor execution then motor imagery in one trial, and subjectively evaluate the vividness of the
366 motor imagery of the preceding movement (21). In physiological experiments, however, the
367 conventional procedure involves evaluating neural activity while participants perform only
368 motor imagery (17–20). Thus, there has been a methodological gap in the approach for
369 examining of motor imagery between psychological questionnaire studies and experimental
370 physiological studies. In response to direct questioning in the current study, gymnasts reported
371 that they usually perform actual movements and KMIs alternately in their daily practice.
372 Therefore, the method for measuring KMI in the present physiological experiment was
373 designed in accord with the procedure of psychological questionnaire measurement. The
374 current physiological findings may have been due to differences between gymnasts and non-
375 gymnasts in the ability to flexibly modulate corticospinal excitability when imagining their
376 own movements, by referring to the actual movement.

377 As shown in equation (1), we were able to confirm that the ERD was determined by
378 both the degree of synchronization during the relax phase ($R(f)$) and the degree of
379 desynchronization during KMI ($A(f, t)$). As shown in Fig. 5, first, gymnasts could return their

380 sensorimotor α-rhythm during the relax phase in the task to the same power level as during the
381 resting-state for 60 s, whereas non-gymnasts could not. Thus, gymnasts appeared to be good at
382 relaxing deeply by making their sensorimotor rhythms more synchronized within a short period
383 of time. However, higher EEGα-PSD during the relax phase does not appear to be the only
384 factor involved in gymnasts' greater ERD magnitude in the α-band. As shown in Fig. 2, second,
385 differences in αERDmax between groups were not observed in motor execution but were found
386 in KMI. Thus, gymnasts also appeared to be good at increasing corticospinal excitability by
387 making their sensorimotor rhythms more desynchronized, even in KMI. Overall, the present
388 results demonstrate that gymnasts have the ability to generate a clear contrast in the state of the
389 sensorimotor cortex, when required to repeatedly switch across relaxing, motor execution and
390 KMI conditions. On the basis of the current findings, we believe that the ability to modulate
391 the brain state without any movement is a core aspect of superior KMI ability in gymnasts.
392
393 **Difference in functional role of ERD between α- and β-band**
394 Interestingly, the present study demonstrated different results between ERD
395 magnitude in the α-band and β-band. Several previous studies reported that functional roles
396 played by the sensorimotor rhythm are different between frequency bands. During actual
397 muscle contraction with weak-to-moderate intensity, the sensorimotor rhythm is known to be
398 coherent with EMG activity only in the β-band, with no significant coherence in the α-band
399 (34–36). When focusing on oscillatory power itself, the EEG spectral power in the
400 sensorimotor area contralateral to the contracted/imagined limb was decreased in both the α-
401 and β-bands, while that in task-irrelevant cortical regions was increased in the α-band (22,37),
402 but not in the β-band (31). During KMI, the ERD magnitude was increased by increasing task
403 demand in the β-band, but not in the α-band (32,38). Taken together, these findings suggest

404 that the functional roles of sensorimotor rhythms for movement/imagery should be
405 distinguished between the α-band and β-band.

406 First, αERDmax was larger in gymnasts than non-gymnasts during both KMI tasks
407 (i.e., wrist dorsiflexion and shoulder abduction). In task-relevant cortical regions, neural
408 populations are assumed to be disinhibited by the ERD of the sensorimotor area in the α-band,
409 which would allow reallocation of computational resources (32). However, task-irrelevant
410 cortical regions are assumed to be inhibited by enhancing their α-oscillations (23). As
411 gymnasts are required to perform skilled movements successively, they are trained to quickly
412 switch their attention across their body parts by facilitating task-relevant regions and inhibiting
413 task-irrelevant regions. The present results regarding ERD in the α-band would reflect such an
414 ability of gymnasts.

415 Second, βERDmax was larger in gymnasts only during shoulder abduction KMI, but
416 not during wrist dorsiflexion KMI. This task-specificity in βERDmax may be caused by ERD
417 in the β-band playing a role in the calculation of specific motor commands. In general, wrist
418 movement is used frequently in daily life, which makes it easy for most people to perform wrist
419 dorsiflexion KMI. Thus, βERDmax would not be differed between gymnasts and non-
420 gymnasts in the wrist dorsiflexion KMI task. However, as isometric shoulder abduction is a
421 movement rarely used in daily life, it may be difficult for most people to perform this KMI.
422 Conversely, gymnasts are well-trained to move their upper limbs, including the shoulder joints,
423 both dynamically (i.e., giant swing) and statically (i.e., handstand and rings). Therefore, it
424 would be easy for gymnasts to imagine shoulder abduction because they are skilled at adjusting
425 the movement parameters of their shoulder joints. We assume that ERD in the β-band is an
426 indicator for how precisely a person can imagine their own movement kinesthetically.

427

428 **Limitations**

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

The present study is the first to observe differences in physiological indices between athletes and non-athletes. This means that the present study can bridge the gap between psychology and physiology studies regarding differences in KMI ability of sports non-specific movements between athletes and non-athletes. However, because only gymnasts participated in this study, it is unclear whether the present results are specific to gymnasts or apply generally to athletes performing any sports. Because differences in motor imagery ability of sports non-specific movements would be expected among athletes, further investigation is needed to elucidate sports-specific differences in motor imagery ability for sports non-specific movements. In any case, the present study indicated the importance of comparing corticospinal excitability measured by ERD for evaluating KMI ability. In future studies, imagery training using bioelectrical signals may provide a useful tool for improving the motor imagery ability of athletes.

Conclusion

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

Author Contributions

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

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For all authors, no conflicts of interest were declared.

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Figures

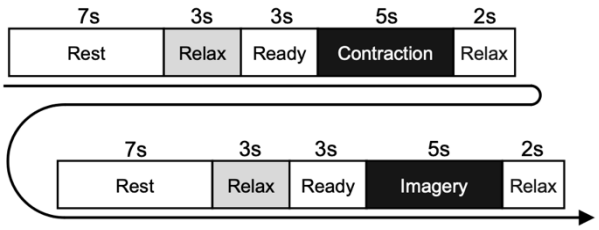

Figure 1. Experimental paradigm of physiological experiment. Participants performed isometric contraction in the contraction phase and performed motor imagery of the same movement in the imagery phase. The diagram shows the flow in each trial, which was repeated five times within each set. Six sets were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

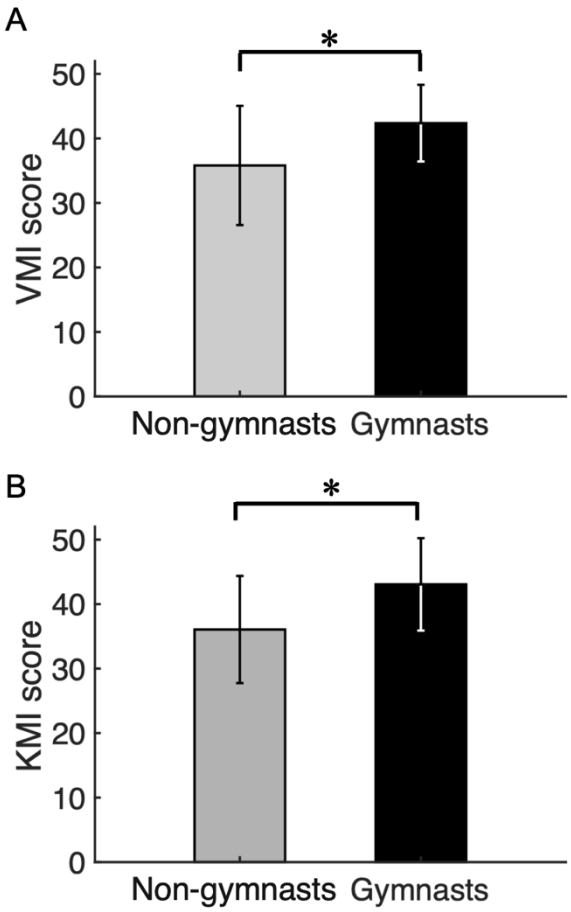

Figure 2. Results of psychological experiment. Group data (Mean ± S.D.) for visual motor imagery (VMI) (A) and kinesthetic motor imagery (KMI) scores (B) obtained from the Kinesthetic and Visual Imagery Questionnaire (KVIQ) are shown for both groups. The gray bars represent data for non-gymnasts, while the black bar represents data for gymnasts. *P < 0.05.

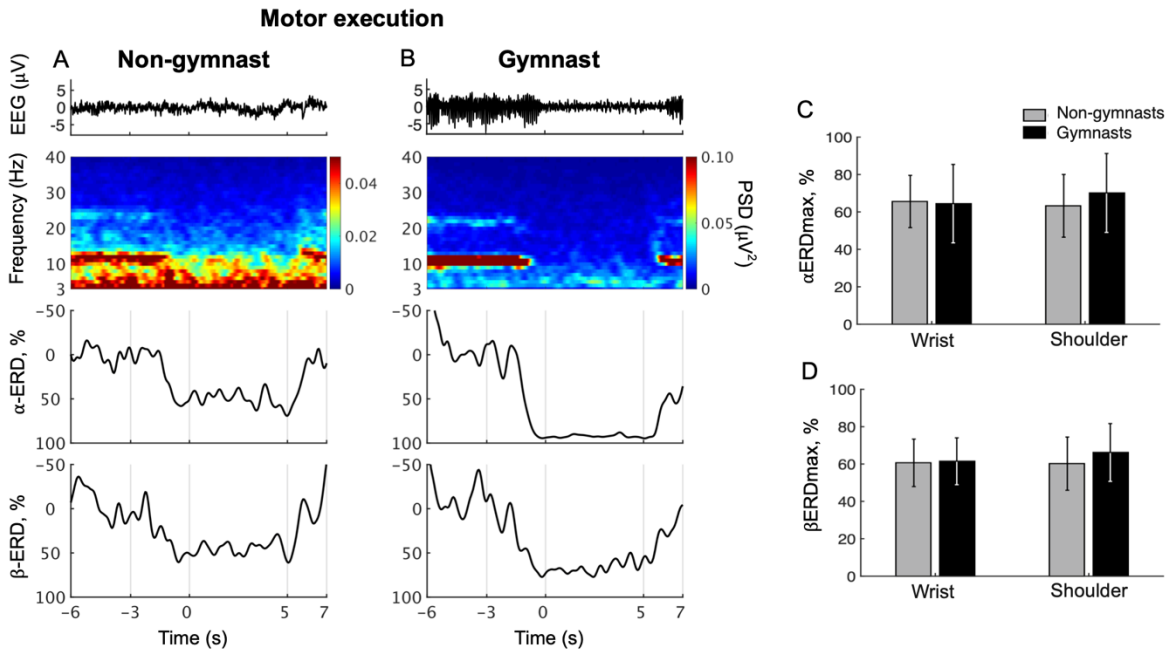

Figure 3. Results from physiological experiments for motor execution. Typical time courses of single trial electroencephalogram (EEG), time-frequency map, α-band event-related desynchronization (ERD), and β-band in wrist dorsiflexion motor execution are shown for non-gymnast (A) and gymnast (B) participants. Note that participants performed wrist dorsiflexion motor execution from 0 s to 5 s. Group data (Mean ± S.D.) for the maximal peak of ERD both in the α- (αERDmax) (C) and β-bands (βERDmax) (D) during motor execution are shown across groups and tasks. The gray bars represent data for non-gymnasts, while the black bar represents data for gymnasts. No significant differences were observed across groups and tasks.

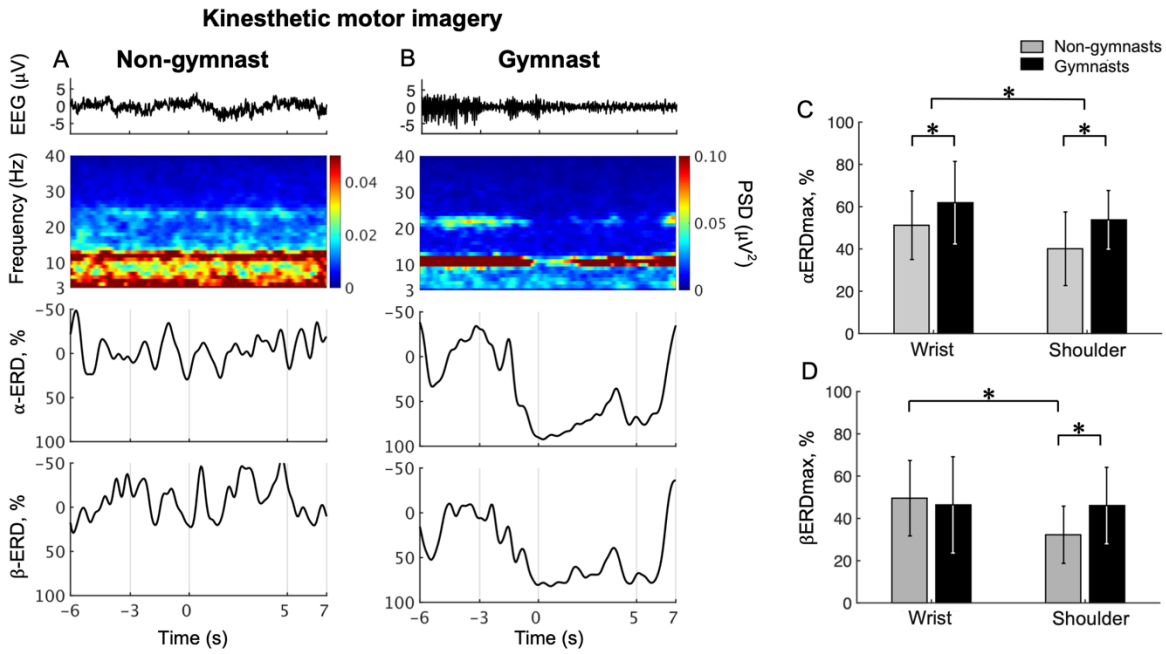

Figure 4. Results from physiological experiments for KMI. Typical time courses of single trial EEG, time-frequency map, α-band ERD, and β-band in wrist dorsiflexion KMI are shown for non-gymnast (A) and gymnast (B) participants. Note that participants performed wrist dorsiflexion KMI from 0 s to 5 s. Group data (Mean ± S.D.) for αERDmax (C) and βERDmax (D) during KMI are shown across groups and tasks. The gray bars represent data for non-gymnasts, while the black bar represents data for gymnasts. *P < 0.05.

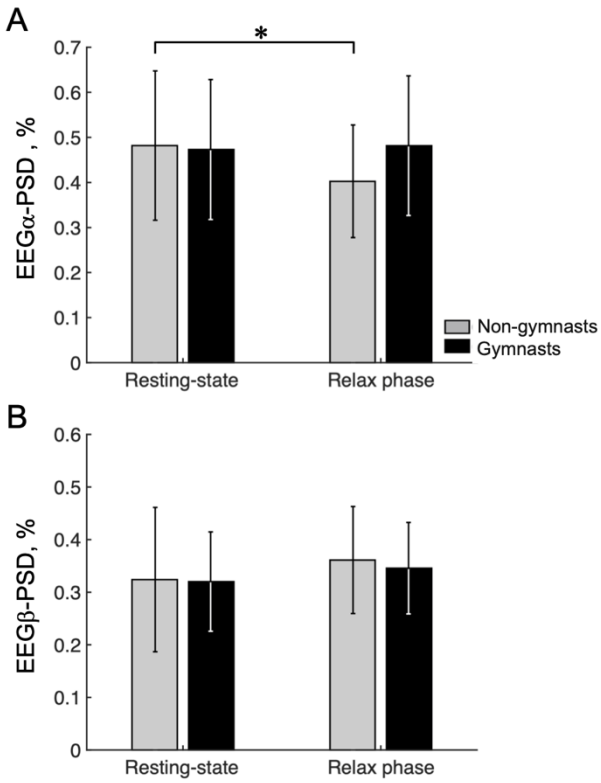

Figure 5. Results of the ratio of the α-band and β-band power spectrum densities. Group data (Mean ± S.D.) for the ratio of the α-band (A) and β-band power spectrum densities (PSD) (B) are shown for both groups. The gray bars represent data for non-gymnasts, while the black bar represents data for gymnasts. *P < 0.05.