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

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Abstract

Introduction: Previous psychological studies using questionnaires have consistently reported that athletes have superior motor imagery ability, both for sports-specific movements and general movements. However, regarding general motor imagery, no physiological studies have demonstrated differences in neural activity between athletes and non-athletes. Gymnasts may be a suitable population for investigating this issue because they are likely to have particularly superior motor imagery ability due to their frequent usage of motor imagery as part of daily practice. **Purpose**: The purpose of the present study was to examine differences in bioelectric sensorimotor rhythms during kinesthetic motor imagery of general movements between gymnasts and non-gymnasts. **Methods**: Healthy young participants (16 gymnasts and 16 non-gymnasts) performed repeated motor execution and motor imagery of general movements (wrist dorsiflexion and shoulder abduction of the dominant hand). Scalp electroencephalogram (EEG) was recorded over the contralateral sensorimotor cortex. During motor execution and motor imagery, 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. **Results**: ERD magnitude during motor imagery was significantly greater in gymnasts, who subjectively evaluated their motor imagery as being more vivid. In particular, αERDmax was greater in gymnasts compared with non-gymnasts for both motor

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

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).

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 (12–15). 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 general movements such as raising the arm and jumping (14,16). 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 general motor imagery.

However, in the field of applied physiology, to the best of our knowledge, no studies have demonstrated differences in neural activity during general motor imagery between athletes and non-athletes, although some studies using electroencephalogram (EEG) (16),

66 functional magnetic resonance imaging (fMRI) (17,18) and transcranial magnetic stimulation
67 (TMS) (19) 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 (19). 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) (20). 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 (21,22), which is known to reflect increased neuronal excitability in the
82 corticospinal system (23). 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

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 (24); 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) (20,25). Briefly, the KVIQ-20 tests how vividly a person is able to imagine their own movements subjectively, using two types of motor imagery: kinesthetic 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 (20,26). 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, 0.5–200 Hz; EMG,

5–1000 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 software originally designed using MATLAB software (The MathWorks, Inc., Antic, MA, United States).

Procedures

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

The physiological data recordings during motor execution and KMI were performed after several practice trials. Visual feedback was presented on the screen, with a red cursor to represent muscle contraction level as a relative value in %iEMGmax and a vertical blue line to represent a target value. Furthermore, instructions for each phase, including “Rest”, “Relax”, “Ready”, “Contraction”, or “Imagery”, were displayed on the monitor. In the wrist dorsiflexion task, participants’ dominant hand was positioned on the armrest and fixed by a belt with the palm down. In the shoulder abduction task, the dominant upper limb was lowered to the side 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 (27).

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.

Analyses

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

emphasize cortical activity originating below the electrode of interest (28). If Laplacian-derived EEG included potentials exceeded 50 μV, we considered the trial to contain an artifact, and excluded the data from future analyses. Additionally, visual inspection was performed to reject additional artifacts missed by the automatic inspection.

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

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

where A is the EEG PSDs at time t, frequency f, and R is the mean PSDs of the baseline period (last 1 s in the relax phase). This equation indicates that the positively greater the ERD value, the larger the decrease in EEG PSD during motor execution or KMI compared with the relax phase. Because the most reactive frequency band of ERD was slightly different across participants (29), we determined an electrode and the 3 Hz-frequency width showing the largest ERD in each of the α-band (8–15 Hz) and β-band (16–35 Hz) during motor execution. Because it has been suggested that the functional roles played by ERD differ between the α- and β-

218 bands (30,31), we analyzed ERDs from these two frequency bands separately. The magnitude
219 of ERD in the α-band (αERDmax) and β-band (βERDmax) were measured by calculating the
220 peak value of ERD for motor execution and KMI of each task, respectively (27,32).

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, EEGα-PSD
228 and EEGβ-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 αERDmax and βERDmax 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

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

Results

KVIQ

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

ERD magnitude

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

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

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

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

Figure 4C shows group data for the αERDmax during wrist dorsiflexion and shoulder abduction KMI. An ANOVA on αERDmax during KMI showed significant effects of group ($F_{1,30} = 5.437$, $p = 0.027$) and task ($F_{1,30} = 10.975$, $p = 0.002$). No significant interaction effect ($F_{1,30} = 0.266$, $p = 0.610$) was observed. Figure 4C shows group data for βERDmax during wrist dorsiflexion and shoulder abduction KMI. An ANOVA on βERDmax during KMI showed no significant effects of group ($F_{1,30} = 0.876$, $p = 0.357$), but significant effects of task ($F_{1,30} = 8.019$, $p = 0.008$) and a significant interaction ($F_{1,30} = 7.421$, $p = 0.010$). An unpaired t-test for group revealed a significant difference in βERDmax between gymnasts and non-gymnasts for the shoulder abduction task (gymnasts, 46.08 ± 18.09; non-gymnasts, 32.27 ± 17.84, $p = 0.021$) but not for the wrist dorsiflexion task (gymnasts, 46.42 ± 22.76; non-gymnasts, 49.56 ± 17.84, $p = 0.666$). A paired t-test for task revealed a significant difference in βERDmax 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 EEGα-PSD and EEGβ-PSD between resting-state EEG and relax phase**
300 **EEG during tasks**

301 Figure 5A shows group data for the EEGα-PSD in resting-state EEG and relax phase
302 EEG during the tasks. An ANOVA examining EEGα-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 EEGα-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 EEGα-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 EEGα-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 EEGβ-PSD. An ANOVA on EEGβ-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 EEGα-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, EEGβ-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

present study, because it is considered to reflect changes in corticospinal excitability (23) and is associated with subjective vividness of motor imagery measured by KVIQ (27). It should be noted that the present results revealed greater ERD magnitude during general KMI in gymnasts than in non-gymnasts, although differences in neural activity between athletes and non-athletes have not been reported in general motor imagery in previous studies using EEG (16), magnetoencephalography (18), TMS (19) or fMRI (17). This may be related to the fact that gymnasts perform motor imagery frequently as a part of their daily practice to reduce the risk of serious injury in their practice. Furthermore, a previous psychological study showed that the vividness of general motor imagery was higher in athletes engaged in individual and/or non-contact sports compared with athletes engaged in team and/or contact sports (13). Thus, as gymnasts have superior motor imagery ability among athletes, they may provide a particularly suitable population for highlighting differences in neural activity during general motor imagery compared with non-athletes.

It is possible that the present task protocol, in which participants performed KMI following motor execution repeatedly in the order of seconds, led to the current finding of greater ERD magnitude in gymnasts. In psychological questionnaires, the conventional procedure for measuring motor imagery ability is to examine participants while they perform motor execution then motor imagery in one trial, and subjectively evaluate the vividness of the motor imagery of the preceding movement (20). In physiological experiments, however, the

351 conventional procedure involves evaluating neural activity while participants perform only
352 motor imagery (16–19). 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 EEGα-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 αERDmax 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 (33–35). 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 (22,36,37), but not in the β-band (30). During KMI, the ERD magnitude was increased by
388 increasing task demand in the β-band, but not in the α-band (31,38). 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, αERDmax 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 (31). However, task-irrelevant
395 cortical regions are assumed to be inhibited by enhancing their α-oscillations (22). 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, βERDmax was larger in gymnasts only during shoulder abduction KMI, but
401 not during wrist dorsiflexion KMI. This task-specificity in βERDmax 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, βERDmax 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

psychology and physiology studies regarding differences in general motor imagery ability 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 general motor imagery ability would be expected among athletes, further investigation is needed to elucidate sports-specific differences in ability for general movement imagery. In any case, the present study indicated the importance of comparing corticospinal excitability measured by ERD for evaluating motor imagery 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 general KMI, the corticospinal excitability measured by ERD magnitude was significantly greater in gymnasts compared with non-gymnasts. These results are consistent with higher subjective vividness 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 general motor imagery ability in gymnasts.

Author Contributions

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

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Conflicts of interest

None declared.

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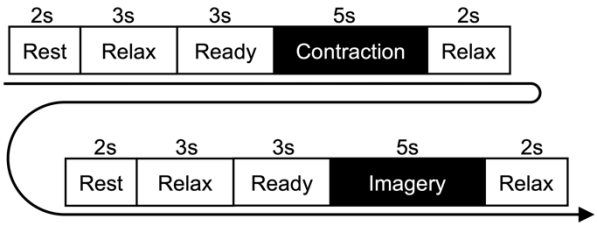
566 **Figures**



567

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

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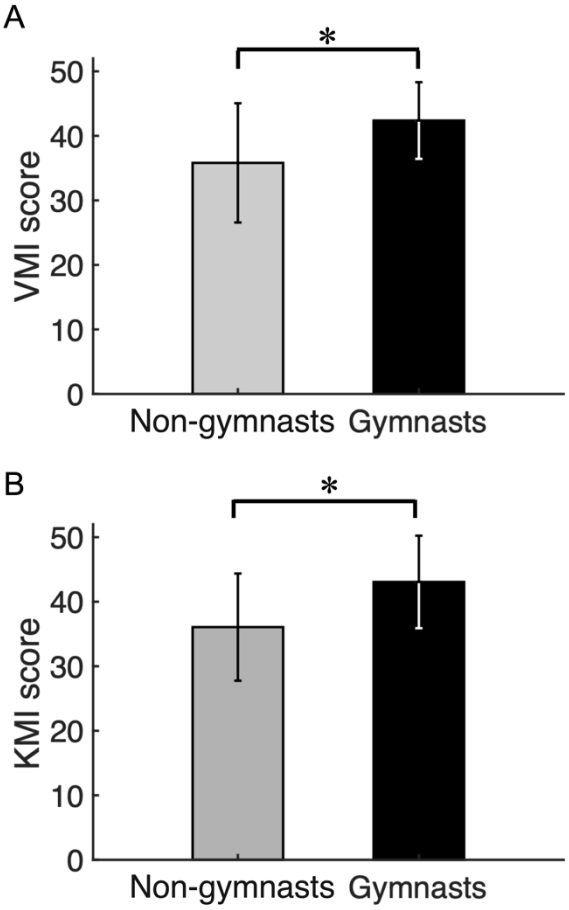


Figure 2. Results of psychological experiment. Group data (Mean ± S.D.) for visual motor imagery (VMI) (A) and kinesthetic motor imagery (KMI) scores (B) obtained from the Kinesthetic and Visual Imagery Questionnaire (KVIQ) are shown for both groups. The gray bar represents data for non-gymnasts, while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

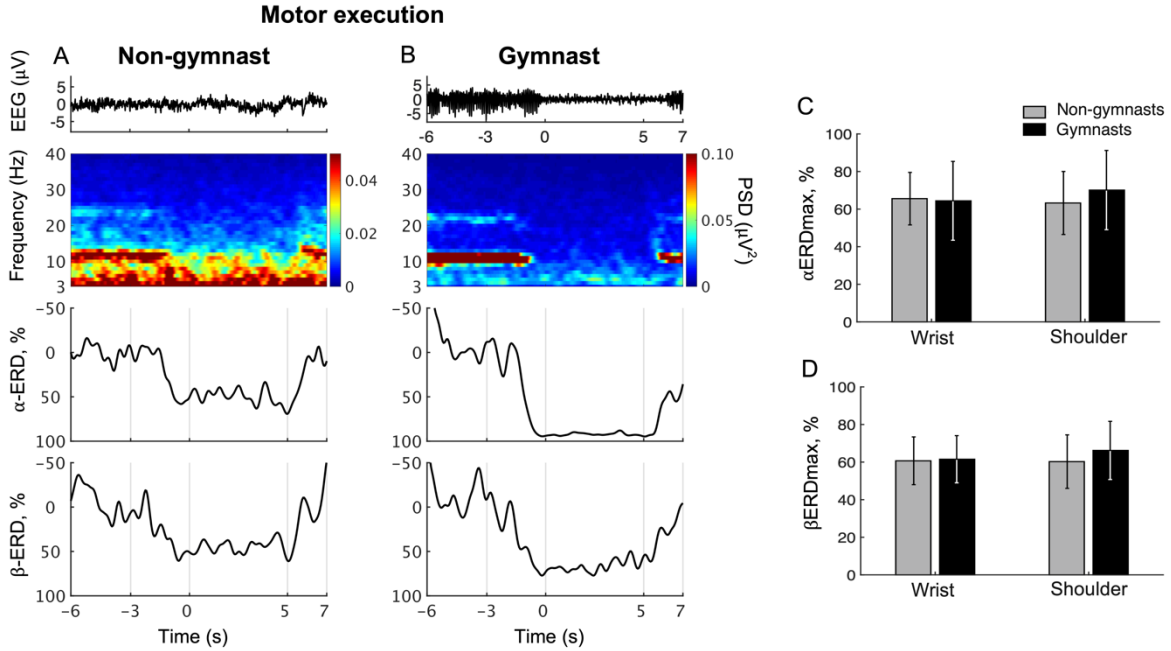
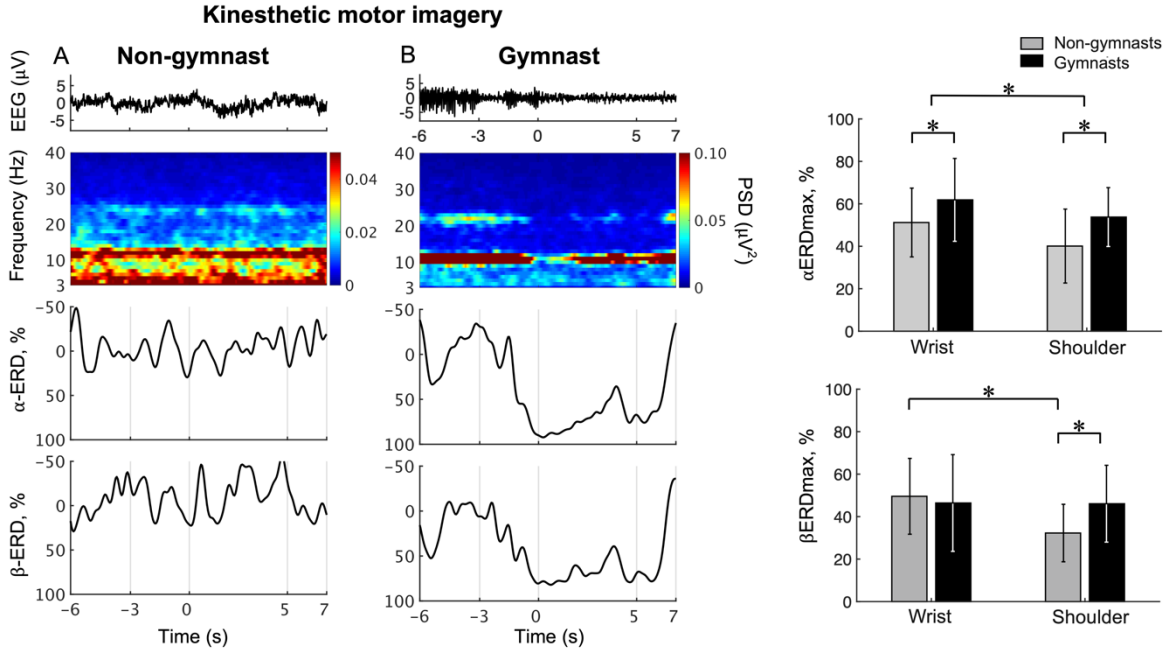


Figure 3. Results from physiological experiments for motor execution. Typical time courses of single trial electroencephalogram (EEG), time-frequency map, α-band event-related desynchronization (ERD), and β-band in wrist dorsiflexion motor execution are shown for non-gymnast (A) and gymnast (B) participants. 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 bar represents data for non-gymnasts, while the black bar represents data for gymnasts. No significant differences were observed across groups and tasks.



591

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

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

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

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

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

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

598

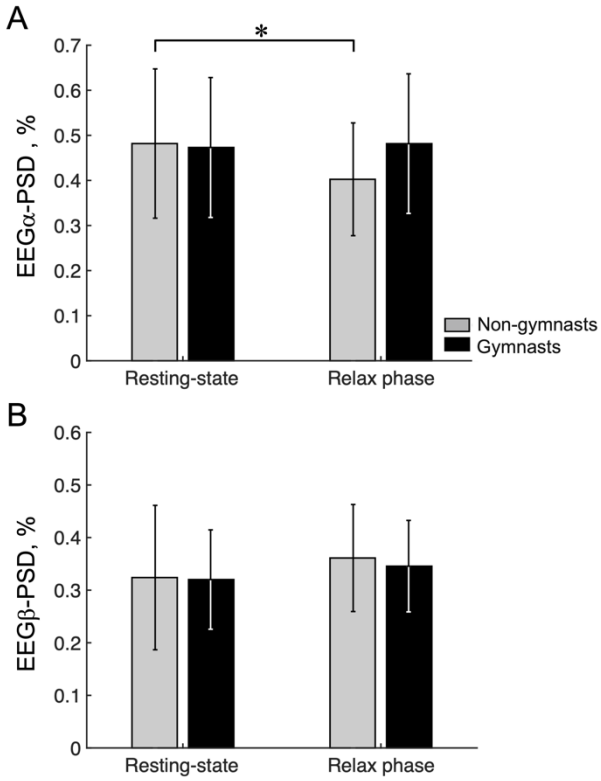


Figure 5. Results of the ratio of the α-band and β-band power spectrum densities. Group data (Mean ± S.D.) for the ratio of the α-band (A) and β-band power spectrum densities (PSD) (B) are shown for both groups. The gray bar represents data for non-gymnasts, while the black bar represents data for gymnasts.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