Regional brain gray matter volume in world-class artistic gymnasts

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Abstract
The relationship between long-term intensive training and brain plasticity in gymnasts has recently been reported. However, the relationship between abilities in different gymnastic events and brain structural changes has not been explored. This study aimed to evaluate the correlation between world-class gymnasts (WCGs)’ specific abilities in different gymnastics events and their gray matter (GM) volume. Ten right-handed Japanese male WCGs and 10 right-handed gender- and age-matched controls with no history of gymnastic training participated in this study. Whole brain three-dimensional T1-weighted images (magnetization-prepared rapid gradient-echo sequence) with 0.90 mm3 voxels were obtained using a 3 T-MRI scanner from each subject. Volume-based morphometry (VolBM) was used to compare GM volume differences between WCGs and controls. We then explored the correlation between specific gymnastic abilities using different gymnastic apparatuses, and GM volume. Significantly higher GM volumes (false discovery rate-corrected $p < 0.05$) in the inferior parietal lobule, middle temporal gyrus, precentral gyrus, rostral middle frontal gyrus, and superior frontal gyrus were demonstrated in WCGs, compared with controls using VolBM. Moreover, significant positive correlations were observed between brain regions and the difficulty scores for each gymnastic event, for example, rings and inferior parietal lobule and parallel bars and rostral middle frontal gyrus. These results may reflect the neural basis of an outstanding gymnastic ability resulting from brain plasticity in areas associated with spatial perception, vision, working memory, and motor control.

Keywords: Magnetic resonance imaging, Volume-based morphometry, Brain plasticity, Difficulty score

Introduction
Artistic gymnastics is a major competition in the Summer Olympic Games that has attracted increasing interest worldwide (International Gymnastics Federation: FIG, https://www.gymnastics.sport/site/). Japan is one such country with an increasing interest in artistic gymnastics. Artistic gymnastics is usually divided into men's and women's gymnastics. Men perform on 6 events: floor exercise, pommel horse, rings, vault, parallel bars, and horizontal bar. Gymnastics performances in competitions are evaluated by a panel of judges using two different scores, the D-score (difficulty of the routine) and the E-score (execution of the routine). The D-score is mainly assessed according to the difficulty of the elements performed within a routine under the conditions required for each event, whereas the E-score is defined by evaluating technical errors in the routine. The total score is calculated by adding the D-score and the E-score (FIG, https://www.gymnastics.sport/site/).

Gymnasts belonging to gymnastics clubs train to increase their skills using conventional and newly developed techniques. The amount of research on artistic gymnastics has increased in recent years, mainly focused on technical aspects or coaching/teaching methods.
Until now, little is known about the anatomical and physiological characteristics of gymnasts. However, it is well known that many brain areas are activated during exercise and that neuronal plasticity, defined as the ability of neurons to change in structure and function in response to environment and experience, is induced by long-term training [1–4]. Through this process, athletes can acquire exceptional abilities in perception, stimulus discrimination, decision-making, motor preparation, and execution [1]. Indeed, evidence suggests that athletes’ brains are characterized by specific functional and anatomical adaptations that facilitate information processing relevant to their specific sport [5–10].

Gymnasts at the top level begin training from childhood. Such long-term intensive training with specific movements may cause specific adaptations in brain structure and function. In fact, it has been demonstrated that Chinese gymnasts exhibit higher gray matter (GM) volume in somatosensory and visuospatial areas compared with non-gymnasts using voxel-based morphometry (VBM) analysis [11]. GM includes neurons, which consist of cell bodies, dendrites, axons, and synapses, as well as glial cells like oligodendrocytes, astrocytes, and microglia. Any microstructural changes to these cells may affect GM volume and function [2, 11]. However, the relationship between abilities in different gymnastic events and structural brain changes is unknown. Better understanding the neural basis of elite gymnastics performance may inform future training strategies and, moreover, it may provide a new method of identifying talent and assessing the development process [12].

In this study, we compare GM volume differences between Japanese world-class gymnasts (WCGs) and healthy controls with no history of intensive exercise training. Furthermore, we evaluated the correlation of WCGs’ specific abilities in different gymnastics events and GM volume. Since the E-score is more susceptible to mental and physical conditions during competition than the D-score and is influenced by the referees’ subjectivity, the D-score was used as an index of the gymnasts’ specific physical abilities acquired through long-term training. We applied volume-based morphometry (VolBM) to compare with VBM, which explores hundreds of thousands of voxel-wise GM concentrations, VolBM demonstrates a higher level of accuracy by evaluating volumes of particular regions of interest in the brain (e.g., atlas-based regions) [13].

Materials and methods
Subjects
Ten right-handed Japanese WCGs (10 males; mean age, 19.9±1.3 years; age range, 18–22 years; mean years of training, 13.6 ± 2.2 years; years of training range, 10–19 years) and ten right-handed gender- and age-matched healthy controls (10 males; mean age, 20.6±1.7 years; age range, 16–22 years) without any history of gymnastics training or competition participated in this study. All WCGs in this study have won medals at gymnastics world championships. Their best D-score and E-score for each gymnastics event (floor exercise, horizontal bar, rings, vault, parallel bars, and pommel horse) obtained at a recent world gymnastics competition, are listed in Table 1. The D-score evaluates the content of a routine using three criteria: difficulty, composition requirements, and connection value, whereas the E-score evaluates technical errors in the routine. The D-score was used as an objective indicator of gymnastic ability in this study. There were no participants with a history of neurological or brain injuries or psychiatric disease. The study protocol was approved by the Ethic Committee of the Juntendo University and participants provided written informed consent before scanning.

MRI acquisition
Magnetic resonance imaging (MRI) data were obtained using a 3-T scanner (MAGNETOM Prisma, Siemens Healthcare, Erlangen, Germany) equipped with a 64-channel head coil. T1-weighted images (T1-WI) were acquired by a three-dimensional (3D) magnetization-prepared rapid gradient-echo sequence (MPRAGE). The acquisition parameters were: repetition time, 2300 ms; echo time, 2.32 ms; inversion time, 900 ms; voxel size, 0.90×0.90×0.90 mm³; and acquisition time, 5.31 min.

GM volume measurement methods
VolBM
VolBM was performed using FreeSurfer version 5.3.0 (freesurfer-Linux-centos6_x86_64-stable-pub-v5.3.0; https://surfer.nmr.mgh.harvard.edu/fswiki), as previously described [14]. FreeSurfer was run with the recon-all pipeline using the default analysis settings on each T1-WI. Briefly, this pipeline included motion correction and intensity normalization of T1-WI, removal of
Table 1 Characteristics of world-class gymnasts who participated in this study

| World-class gymnasts | Recent medal records | Age (years) | Years of training (years) | D-score | E-score |
|----------------------|----------------------|------------|---------------------------|---------|---------|
|                      |                      |            |                           | Floor exercise | Pommel horse | Rings | Vault | Parallel bars | Horizontal bar | Mean±SD |         | Floor exercise | Pommel horse | Rings | Vault | Parallel bars | Horizontal bar | Mean±SD |
| 1                    | DTB team challenge 2017, bronze medal | 20         | 14                        | 5.3     | 6.0     | 5.6  | 52   | 58           | 56                   | 5.58±0.30 |         | 8.066   | 8.500   | 8.400 | 7.666 | 8.466           | 7.433                   | 8.089±0.451 |
| 2                    | WC 2018 Tokyo cup, silver medal | 21         | 14                        | 6.0     | 5.8     | 6.0  | 56   | 62           | 51                   | 5.78±0.39 |         | 8.633   | 8.233   | 8.233 | 9.433 | 8.633           | 7.900                   | 8.511±0.331 |
| 3                    | WGC 2015, gold medal | 21         | 12                        | 5.9     | 6.4     | 6.1  | 52   | 63           | 5.7                  | 5.93±0.44 |         | 8.566   | 8.566   | 8.200 | 8.833 | 8.866           | 8.300                   | 8.555±0.270 |
| 4                    | Asian Games 2018, silver medal | 21         | 19                        | 6.0     | 6.0     | 5.7  | 52   | 62           | 5.7                  | 5.80±0.35 |         | 8.300   | 8.366   | 8.200 | 8.833 | 8.866           | 8.300                   | 8.422±0.348 |
| 5                    | WGC 2015, gold medal | 22         | 13                        | 6.2     | 5.4     | 5.3  | 52   | 54           | 5.9                  | 5.57±0.39 |         | 8.166   | 8.500   | 8.166 | 8.900 | 8.733           | 8.100                   | 5.65±0.42 |
| 6                    | DTB team challenge 2018, bronze medal | 20         | 10                        | 5.9     | 6.3     | 5.6  | 52   | 57           | 5.2                  | 5.57±0.39 |         | 8.566   | 8.566   | 8.200 | 8.833 | 8.866           | 8.300                   | 5.57±0.39 |
| 7                    | DTB team challenge 2018, bronze medal | 19         | 14                        | 5.5     | 5.1     | 5.6  | 52   | 59           | 6.1                  | 5.57±0.39 |         | 8.300   | 8.300   | 8.200 | 8.833 | 8.866           | 8.300                   | 5.57±0.39 |
| 8                    | Voronin cup 2016, gold medal | 19         | 14                        | 5.6     | 5.8     | 5.5  | 48   | 60           | 5.8                  | 5.58±0.42 |         | 8.266   | 8.433   | 8.200 | 8.833 | 8.866           | 8.300                   | 5.42±0.43 |
| 9                    | UGC 2015, gold medal | 18         | 14                        | 5.9     | 5.7     | 5.0  | 56   | 55           | 4.8                  | 5.42±0.43 |         | 7.866   | 7.133   | 8.000 | 7.566 | 8.033           | 7.766                   | 7.633±0.313 |
| 10                   | Asian Games 2018, silver medal | 18         | 12                        | 5.9     | 6.1     | 5.3  | 52   | 60           | 5.6                  | 5.68±0.38 |         | 8.300   | 8.433   | 8.200 | 8.833 | 8.866           | 8.300                   | 8.305±0.354 |
|                      | All Japan 2018, gold medal | 18         | 12                        | 5.9     | 6.1     | 5.3  | 52   | 60           | 5.6                  | 5.68±0.38 |         | 8.320   | 8.270   | 8.200 | 8.833 | 8.866           | 8.300                   | 8.344±0.199 |

Mean±SD 19.9±1.4 13.6±2.3 5.82±0.27 5.86±0.39 5.57±0.33 5.24±0.23 5.90±0.30 5.55±0.40

Correlations between D (or E)-scores and mean values in each event are also indicated. *p<0.05, **p<0.001, ***p<0.0001
All WCGs in this study have won medals in gymnastics world championships since 2015
D-score difficulty score, E-score execution score, DTB Deutscher Turnen-Bund, WGC World Gymnastics Championships, WC World Cup, IJGC International Junior Gymnastics Competition, SD standard deviation
non-brain tissue, automated Talairach transformation, segmentation of the subcortical WM and deep GM volumetric structures (including the hippocampus, amygdala, caudate, putamen, and ventricles), tessellation of the GM–WM boundary, and derivation of cortical thickness. After image processing, we extracted volumes for the cortical structures of the 34 bilateral Desikan–Killiany atlas [15] regions. Volumes of structures were then measured by multiplying the size of each voxel by the number of voxels.

**Statistical analysis**

All statistical analyses were performed using IBM SPSS Statistics for Windows, Version 22.0 (IBM Corporation, Armonk, NY, USA). The Shapiro–Wilk test was used to assess the normality of the data, whereas the data on demographics were analyzed using an unpaired Student’s t-test and χ² test for continuous and categorical variables, respectively. Statistical significance was set to 0.05.

During the VolBM analysis, the Mann–Whitney U test was used to compare the mean (bilateral hemispheres) normalized GM volumes (nGM; GM volume/intracranial volume) between the WCGs and controls. Then, the Benjamini–Hochberg false discovery rate (FDR) correction was applied to correct for multiple testing (34 regions of interest) with the level of significance for two-tailed p values set to 0.05. The relationship between the D-scores for individual gymnastic events (floor exercise, horizontal bar, rings, vault, parallel bars, and pommel horse) or the average D-scores from these individual scores and areas showing significant FDR-corrected p-values in group comparisons were evaluated using the Spearman’s rank correlation test, with the level of significance set to FDR-corrected p<0.05. The relationship between the D-scores from individual gymnastic events and average D-scores was also evaluated using Pearson correlation analysis at a significance level of p<0.05.

**Results**

No significant difference was observed with regard to age (p=0.35) and sex (p=1.00) between the WCG and control groups. In the WCGs, the best D-scores for each gymnastic event and the average of the D-scores from a recent world gymnastics competition are shown in Table 1. Significant correlations between the average D-score and the
D-scores from the rings event ($p=0.0016$, $R^2=0.73$) or the parallel bars event ($p=0.0029$, $R^2=0.69$) were found in the WCGs.

VolBM analysis showed statistically significant increases in mean nGM volumes (FDR-corrected $p<0.05$) in the inferior parietal lobule (IPL; $p=0.036$), middle temporal gyrus (MTG; $p=0.044$), precentral gyrus (PrG; $p=0.044$), rostral middle frontal gyrus (RMFG; $p=0.044$), and superior frontal gyrus (SFG; $p=0.047$) of WCGs compared to controls (Fig. 1, Table 2). Furthermore, the nGM volume of IPL was positively correlated with the D-score from the rings event ($p=0.015$, $R^2=0.76$) and the average D-scores ($p=0.041$, $R^2=0.73$), and that of the RMFG was also positively correlated with the D-score from the parallel bars event ($p=0.006$, $R^2=0.54$) and average D-scores ($p=0.036$, $R^2=0.35$) (Fig. 2).

Table 2 Normalized gray matter (nGM) volume of controls and world-class gymnast (WCGs) obtained using volume-based morphometry analysis

| Normalized gray matter volume | Controls | WCGs | $p$ value | FDR-corrected $p$ value |
|------------------------------|----------|------|-----------|-------------------------|
|                              | Mean     | SD   | Mean      | SD                      |
| Banksts                      | 0.34     | 0.06 | 0.36      | 0.04                    | 0.353  | 0.631 |
| Caudal anterior cingulate    | 0.27     | 0.04 | 0.27      | 0.03                    | 0.684  | 0.895 |
| Caudal middle frontal        | 0.74     | 0.07 | 0.73      | 0.13                    | 0.912  | 0.971 |
| Cuneus                       | 0.41     | 0.04 | 0.43      | 0.07                    | 0.684  | 0.895 |
| Entorhinal                   | 0.22     | 0.04 | 0.22      | 0.02                    | 0.796  | 0.933 |
| Fusiform                     | 1.50     | 0.14 | 1.50      | 0.10                    | 0.529  | 0.817 |
| Inferior parietal            | 1.92     | 0.15 | 2.18      | 0.13                    | 0.001  | 0.036*|
| Inferior temporal            | 1.46     | 0.14 | 1.68      | 0.17                    | 0.009  | 0.051 |
| Isthmus cingulate            | 0.39     | 0.02 | 0.38      | 0.05                    | 0.143  | 0.406 |
| Lateral occipital            | 1.49     | 0.14 | 1.58      | 0.12                    | 0.247  | 0.526 |
| Lateral orbito-frontal       | 0.91     | 0.06 | 0.98      | 0.06                    | 0.035  | 0.121 |
| Lingual                      | 0.91     | 0.11 | 1.00      | 0.12                    | 0.190  | 0.498 |
| Medial orbito-frontal        | 0.64     | 0.07 | 0.64      | 0.03                    | 0.684  | 0.895 |
| Middle temporal              | 1.55     | 0.15 | 1.72      | 0.12                    | 0.005  | 0.044*|
| Parahippocampal              | 0.31     | 0.03 | 0.33      | 0.04                    | 0.280  | 0.560 |
| Pariacentral                 | 0.47     | 0.04 | 0.54      | 0.06                    | 0.035  | 0.121 |
| Pars opercularis             | 0.60     | 0.06 | 0.57      | 0.06                    | 0.579  | 0.856 |
| Pars orbitalis               | 0.28     | 0.02 | 0.32      | 0.03                    | 0.011  | 0.056 |
| Pars triangularis            | 0.54     | 0.06 | 0.54      | 0.07                    | 0.971  | 0.971 |
| Pericalcarine                | 0.28     | 0.05 | 0.29      | 0.05                    | 0.481  | 0.779 |
| Postcentral                  | 1.24     | 0.21 | 1.35      | 0.09                    | 0.063  | 0.195 |
| Posterior cingulate          | 0.48     | 0.07 | 0.49      | 0.04                    | 0.971  | 0.971 |
| Precentral                   | 1.42     | 0.14 | 1.46      | 0.08                    | 0.003  | 0.044*|
| Precuneus                    | 0.33     | 0.04 | 0.32      | 0.03                    | 0.247  | 0.526 |
| Rostral anterior cingulate   | 1.75     | 0.17 | 1.76      | 0.12                    | 0.315  | 0.595 |
| Rostral middle frontal       | 1.62     | 0.15 | 1.62      | 0.15                    | 0.005  | 0.044*|
| Superior frontal             | 1.51     | 0.17 | 1.48      | 0.11                    | 0.007  | 0.047*|
| Superior parietal            | 0.10     | 0.02 | 0.11      | 0.02                    | 0.971  | 0.971 |
| Superior temporal            | 0.28     | 0.04 | 0.33      | 0.04                    | 0.796  | 0.933 |
| Supramarginal                | 0.16     | 0.03 | 0.14      | 0.03                    | 0.971  | 0.971 |
| Frontal pole                 | 0.89     | 0.05 | 0.89      | 0.06                    | 0.393  | 0.668 |
| Temporal pole                | 0.34     | 0.06 | 0.36      | 0.04                    | 0.015  | 0.062 |
| Transverse temporal          | 0.27     | 0.04 | 0.27      | 0.03                    | 0.218  | 0.526 |
| Insula                       | 0.74     | 0.07 | 0.73      | 0.13                    | 0.796  | 0.933 |

* Significantly higher nGM volume in WCGs compared to controls (false discovery rate [FDR]-corrected $p < 0.05$)
Using VolBM analysis, this study revealed that the nGM volumes of the IPL, MTG, PrG, RMFG, and SFG were higher in WCGs than in controls. Accumulating evidence has shown that increased GM volumes found in exercise-trained subjects are associated with increased functional plasticity and cognitive performance [2, 11, 16, 17]. Our findings support the concept that long-term motor skill training is associated with a complex bihemispheric cortical–subcortical network [2, 18]. The brain areas identified in this study are functionally related to motor control (i.e., PrG) [19, 20], interpretation of sensory information (i.e., IPL) [21–23], body image (i.e., IPL) [21, 22], spatial perception (i.e., IPL and MTG) [23, 24], spatial attention (i.e., IPL) [21–23], vision (i.e., IPL and MTG) [21–24], executive function (i.e., RMFG and IPL) [22, 25–27], and working memory (i.e., RMFG and SFG) [25–28]. A unique feature of gymnastics events is that each requires acrobatic performances comprising speed, strength, and flexibility; these physiological functions are all critical to supporting elaborate body movements. The increased GM volume in the IPL, MTG, PrG, RMFG, and SFG of WCGs is likely to result from many years of intensive training. These findings support a previous report, which suggested that, compared with non-gymnasts, Chinese gymnasts exhibit higher volumes of GM in somatosensory, motor control, and visuospatial areas [11]. The underlying mechanisms associated with training-dependent GM volume increases remain unknown, but they may involve microstructural changes in brain cells, including neurons, glial cells, and endothelial cells, induced by increased blood flow, oxygenation, and the production of brain neurotrophic factors and their receptors [2, 11, 16].

In WCGs, we analyzed correlations between the D-scores for each gymnastics event and the GM volumes of particular brain areas identified as containing more GM in gymnasts than controls. The D-scores for the rings and parallel bars events were found to be related to the GM volumes of the IPL and RMFG, respectively. The IPL is known to be involved in various neural functions, including spatial attention, multimodal sensory integration, body image, oculomotor control, and hand–eye coordination [21–23]. The RMFG is critical for executive function and working memory [25–27]. Working memory is a series of memory operations that involve manipulating and utilizing information while temporarily

![Image](https://example.com/image.png)

**Fig. 2** Correlation between normalized gray matter volumes obtained using volume-based morphometry in world-class gymnasts and the average or absolute D-scores for each gymnastics event. Statistically significant positive correlation between nGM volume in the inferior parietal and rostral middle frontal regions and the D-score from the rings event and average D-scores and D-score of parallel bars event and average D-scores, respectively. nGM normalized gray matter, WCGs world-class gymnasts.
retaining it in the brain. Executive function is a cognitive system that controls thoughts and actions when performing complex tasks, and working memory is included in this process.

The rings represent the only apparatus that is continually in motion. Hence, this particular event requires prodigious body balance and muscle strength to halt body movements suddenly and allow the gymnast to maintain the position. Considering our findings, a high level of IPL function may be required to follow the precise movements of the rings, adjust body balance, and hold the body in an optimal position. On the parallel bars, techniques involve hand-release from and regraping of the bars. Therefore, a high level of visuospatial working memory may be required to identify the precise location of the bar/bars to be regraped quickly, and this level of function may be associated closely with the level of competitive ability seen in WCGs. Structural changes in the IPL and RMFG are also likely to be the result of intensive training in WCGs.

Because the average D-score reflects the level of skill demonstrated in the individual all-around event, correlations were determined between the average D-score and GM volumes of particular brain areas identified as containing more GM in gymnasts than in controls. Interestingly, significant positive correlations were found only in the IPL and RMFG, indicating that the brain areas and functions associated with the D-scores from the rings and parallel bars were also involved in determining the average D-score. Indeed, the average D-scores were highly correlated with the D-scores for both the rings and parallel bars but not the other events. These characteristics of the WCGs who participated in this study may have caused the IPL and RMFG to be identified as brain areas that affect the average D-score. However, although each gymnastic event entails specific skills, all events involve common body movements, including handstands, somersaults, and twist techniques, all of which require complex motor skills, based on sensory perception–motor integration, to adjust balance and hold the body optimally. Therefore, our finding that the IPL and RMFG affect the average D-score may suggest that higher levels of spatial attention, multimodal sensory integration, body image, oculomotor control, hand–eye coordination, executive function, and working memory facilitate sensory perception–motor integration and elaborate body movements required to undertake all gymnastics events, thus enabling the competitor to obtain a higher score in the individual all-around event.

Limitations
Since the number of Japanese WCGs who are currently active is extremely limited, the sample sizes in this study were small (10 WCGs and 10 controls). However, to confirm whether genetic factors affect the GM volumes of particular brain areas in WCGs and/or whether long-term intensive training is a main factor that contributes to the structural changes, future investigations using longitudinal studies with a large number of WCGs and/or control subjects will be required.

Conclusions
Overall, we found that the GM volumes of particular brain areas play an indispensable role in gymnastic ability and are closely associated with individual D-scores for specific gymnastic events in WCGs. The increased GM volumes in these areas may represent the neural basis for outstanding gymnastics performance resulting from brain plasticity. GM volumes in these brain areas of interest could become markers for the objective evaluation of gymnastic performance. In this regard, our findings demonstrate that GM volumes in the IPL and RMFG may be potential markers for evaluating the performance of a gymnast on the rings, parallel bars, or in the individual all-around event.

Abbreviations
3D: Three-dimensional; D-score: Difficulty score; FDR: False discovery rate; FIG: International Gymnastics Federation; GM: Gray matter; MPRAGE: Magnetization-prepared rapid gradient-echo sequence; MRI: Magnetic resonance imaging; nGM: Normalized GM; T1-WI: T1-weighted images; VoBM: Volume-based morphometry; WCGs: World-class gymnasts; WM: White matter; IPL: Inferior parietal lobule; MTG: Middle temporal gyrus; PrG: Precentral gyrus; RMFG: Rostral middle frontal gyrus; SFG: Superior frontal gyrus; VBM: Voxel-based morphometry.

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Authors’ contributions
MF, KK, HW, HS, SA, and HN conceived and planned the experiments. MF, KK, MK, HT, YTan, and TM performed the experiments. MF, KK, CA, TM, HS, YTan, WU, YTak, AH, MH, KC, and MH analyzed the data. MF, KK, MK, CA, HT, TM, WU, YTak, AH, MG, and MH interpreted the results of the experiments. MF, KK, MK, CA, and HW prepared the figures. MF, KK, CA, and HW drafted the manuscript. MF, KK, CA, HW, HT, MH, SA, and HN revised the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials
The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.
Ethics approval and consent to participate
The study protocol was approved by the Ethic Committee of the Juntendo University and participants provided written informed consent before scanning.

Consent for publication
Informed consent was obtained from all individual participants included in the study.

Competing interests
The authors declare that they have no competing interest.

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