J Korean Med Sci. 2022 Mar 21;37(11):e86
https://doi.org/10.3346/jkms.2022.37.e86
eISSN 1598-6357·pISSN 1011-8934

JKMS

Original Article
Basic Medical Sciences

Check for updates

Cerebral Cortex Changes in Basketball Players

Ji Hyun Kim [1*], **Jin Woo Park** [1*], **Woo Suk Tae** [2] and **Im Joo Rhyu** [1,3]

[1]Department of Anatomy, College of Medicine, Korea University, Seoul, Korea
[2]Brain Convergence Research Center, College of Medicine, Korea University, Seoul, Korea
[3]Department of Biomedical Sciences, Brain Korea 21 FOUR, College of Medicine, Korea University, Seoul, Korea

OPEN ACCESS

Received: Jan 10, 2022
Accepted: Feb 17, 2022
Published online: Mar 10, 2022

Address for Correspondence:
Woo Suk Tae, PhD
Brain Convergence Research Center, College of Medicine, Korea University, 73 Goryeodae-ro, Seongbuk-gu, Seoul 02841, Korea.
Email: wstae@korea.ac.kr

Im Joo Rhyu, MD, PhD
Department of Anatomy, College of Medicine, Korea University, 73 Goryeodae-ro, Seongbuk-gu, Seoul 02841, Korea.
Email: irhyu@korea.ac.kr

*Ji Hyun Kim and Jin Woo Park contributed equally to this work.

ORCID iDs
Ji Hyun Kim
https://orcid.org/0000-0003-4449-7269
Jin Woo Park
https://orcid.org/0000-0001-6719-5947
Woo Suk Tae
https://orcid.org/0000-0003-0451-0713
Im Joo Rhyu
https://orcid.org/0000-0002-5558-6278

ABSTRACT

Background: Plastic changes to brain structure and function have been reported in elite athletes of various sports. Interestingly, different regions of the brain were engaged according to the type of sports analyzed. Our laboratory reported no difference in total cerebellar volume of basketball players compared to that in the control group using the manual segmentation method. Further detailed analyses showed that elite basketball players had increased volume of the striatum and vermian lobules VI–VII of the cerebellum. We analyzed the brain magnetic resonance imaging (MRI) of basketball players to understand their cerebral cortical plasticity through automatic analysis tools for MRI.
Methods: Brain MRI data were collected from 19 male university basketball players and 20 age-, sex-, and height-matched control groups. In order to understand the changes in the cerebral cortices of basketball players, we employed automated MRI brain analysis techniques, including voxel-based morphometry (VBM) and surface-based morphometry (SBM).
Results: VBM showed increased gray and white matter volume in both precentral gyri, paracentral lobules and increased gray matter volume in the right anterior superior temporal gyrus. SBM revealed a left dominant increase in both pericentral gyri. Fractal dimensional analysis showed an increase in the area of both precentral gyri, the left subcallosal gyrus, and the right posterior cingulate gyrus. These results suggest a significant role not only for the primary motor cortex, but also for the cingulate gyrus during basketball.
Conclusion: Plastic changes of both precentral gyri, the pericentral area, paracentral lobules, and the right superior temporal gyrus were observed in elite basketball players. There was a strong increase of fractal complexity in both precentral gyri and a weak increase in the right posterior cingulate gyrus and left collateral gyrus. In this study, plastic regions linked to functional neuroanatomy were related to the competence required to play basketball.

Keywords: Sports; Plasticity; Motor Skill; MRI; Spatial Perception

INTRODUCTION

All movements we perform are controlled by the brain. The motor system controls complex neuromuscular networks. The motor system includes cortical and subcortical gray matter (GM); descending tracts including corticobulbar, corticospinal, rubrospinal, reticulospinal,

Disclosure

The authors have no potential conflicts of interest to disclose.

Author Contributions

Conceptualization: Kim JH, Park JW, Tae WS, Rhyu IJ. Data curation: Kim JH, Park JW, Tae WS, Rhyu IJ. Formal analysis: Kim JH, Park JW, Tae WS, Rhyu IJ. Funding acquisition: Rhyu IJ. Investigation: Kim JH, Park JW, Tae WS, Rhyu IJ. Methodology: Kim JH, Park JW, Tae WS, Rhyu IJ. Project administration: Rhyu IJ. Resources: Rhyu IJ. Visualization: Tae WS. Writing - original draft: Kim JH, Park JW, Tae WS, Rhyu IJ. Writing - review & editing: Kim JH, Park JW, Tae WS, Rhyu IJ

vestibulospinal, and tectospinal tracts; the spinal cord GM; spinal nerves; and the cerebellum and basal ganglia. In addition, modulation based on sensory inputs is important for fine movement.[1]

The motor system allows people to perform various kinds of sports. The structural brain plasticity of elite athletes has been reported in several studies. Hänggi et al.[2] reported structural brain changes in handball players and reviewed structural changes in ballet dancers, golf players, basketball players, speed skaters, high diving athletes, badminton players, mountaineers, Judo wrestlers, slackline dancers, gymnasts, climbers, martial artists, and endurance athletes. Structural changes were different according to specific sports, although sample size and analysis method also differed by sport.

Our laboratory has focused on basketball players since 2000. There was no overall volume difference in the cerebellum between basketball players and the control group.[3] Nonetheless, a detailed analysis of the cerebellum in subdivisions[4] showed a difference in vermian lobules VI–VII (declive, folium, and tuber) of elite basketball athletes, which resulted from an increase in white matter (WM) volume.[5] In addition, the striatum volume was larger in the athletes group.[6]

The aforementioned studies from our laboratory showed structural changes in the cerebellum and striatum based on manual segmentation.[7] Nevertheless, changes in the cerebral cortex of basketball players were not assessed. In this study, we analyzed structural changes in the cerebral cortex of basketball players using fully automated magnetic resonance imaging (MRI) brain analysis techniques.

METHODS

Subjects

The raw MRI data in this study were the same as those used in a study previously published.[3] Briefly, MRI was performed on 19 male college basketball players (athlete group, AG) and 20 age-, sex- and height-matched controls who did not exercise regularly (control group, CG). All subjects had healthy general medical and neurological profiles. Individuals in the AG had played basketball for 8 years on average and had practiced for 5 hours daily on average.

MRI acquisition

MRI images were scanned on a 1.5-T Magnetom vision instrument (Siemens, Erlangen, Germany) using T1-weighted magnetization using a rapid acquisition gradient echo sequence (repetition time = 9.7 msec, echo time = 4 msec, flip angle = 12 degrees, slice thickness 2.0 mm without gap, field of view 250 mm, number of slices 90, and matrix 256 × 256).

CAT12 processing

The volumetric 3D T1 MRIs of all participants were processed using the Computational Anatomy Toolbox (CAT12, http://www.neuro.uni-jena.de/cat) in SPM12 (http://www.fil.ion.ucl.ac.uk/spm) for voxel-based morphometry (VBM) and surface-based morphometry (SBM, estimation of cortical thickness [CT], and fractal dimension [FD]).

For VBM, MRIs were bias-corrected and spatially normalized to the DARTEL template by DARTEL high-dimensional spatial normalization.[8] The accuracy of spatial normalization was visually checked using the Check Registration tool with the Montreal Neurological

Institute (MNI) template image. Normalized MRI images were segmented into GM, WM, and cerebrospinal fluid (CSF) using an adaptive maximum a posteriori technique. The voxel values of the GM partitions were multiplied by the nonlinear components, which were derived only from the normalization matrix to preserve the actual GM values locally (modulation process). Modulated GM was smoothed using an 8-mm full width at half maximum (FWHM) isotropic gaussian kernel (IGK). The values of individual intracranial cavity volume (ICV) were automatically calculated from the GM, WM, and CSF partitions.

Analysis of covariance (ANCOVA), controlled for age and ICV, was applied for analyses of regional volume changes of GM and WM.[9] To exclude edge effects between the boundaries of different tissue types, an absolute threshold masking value of 0.15 was applied. The statistical threshold level was set to uncorrected $P < 0.001$, and the extent threshold was set to $k_E > 100$ voxels (338 mm^3; 1 voxel = 3.375 mm^3).

Coordinates were defined by the MNI coordinate system. The cluster regions were localized using information about their local maxima, based on the standardized template and defined by visual comparison with the atlas of Henri M. Duvernoy.[10]

For SBM, the CAT12 toolbox included the calculation of CT and the central surface of the bilateral hemisphere based on projection-based thickness.[11] The pipeline of surface analysis included topological correction, spherical mapping, spherical registration, and FD.[12] After GM and WM segmentations, the WM distance was calculated, and the local maxima were projected to other GM voxels calculated by the WM distance. The estimated GM and WM boundaries were constructed by classifying all WM voxels in the MRI. After computing the curvature of the surface, the surface representation was reconstructed to obtain the finest scale of the local surface curvature. The CTs of individuals in the AG and CG were calculated using the closest distance between the vertices of the two reconstructed surfaces. Additional surface parameters, such as the local gyrification index and FD, were extracted using the surface tool of CAT12.

The group differences of CT and FD were tested separately using ANCOVA, using the confounder of age with 5,000 permutations. The significance level was set to an uncorrected $P < 0.001$.

RESULTS

In the VBM of GM, increased GMV (**Fig. 1**) were found in the both precentral gyri and paracentral lobules (left, x, y, z= −2, −12, 72; $k_E = 344$, $P_{unc} = 0.001$; right, x, y, z = 10, −26,78; $k_E = 165$, $P_{unc} = 0.001$) and right antero-superior temporal gyrus (x, y, z = 51, 16, −16; $k_E = 1,404$, $P_{unc} = 0.0012$) of basketball players. In the VBM of WM (**Fig. 2**), the both precentral gyri (left, x, y, z = −14, −28, 62; $k_E = 406$, $P_{unc} = 0.0008$; right, x, y, z = 33, −30, 57; $k_E = 241$, $P_{unc} = 0.001$) of basketball players were shown the increased WM volumes.

In the SBM, the CT of basketball players was left dominantly increased in the both pericentral area including paracentral lobules (**Fig. 3**, left, x, y, z = −6, −26, 74; $k_E = 991$, $P_{unc} = 0.0007$; right, x, y, z = 8, −24, 75; $k_E = 755$, $P_{unc} = 0.0009$). Basketball players had increased FD in both precentral gyri, the left subcallosal gyrus, and the right posterior cingulate gyrus (**Fig. 4**, FDR < 0.05), according to the region of interest analysis, defined by Destrieux atlas.[13]

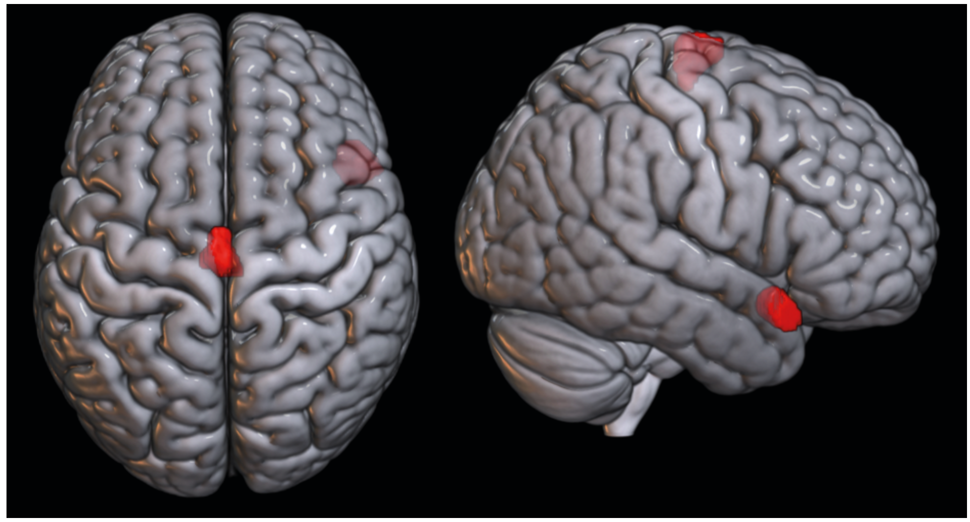

Fig. 1. Increased GM volumes in basketball players. Increased GM volumes are observed (uncorrected $P < 0.001$) in both precentral gyri, paracentral lobules and right antero-superior temporal gyrus of basketball players. GM = gray matter.

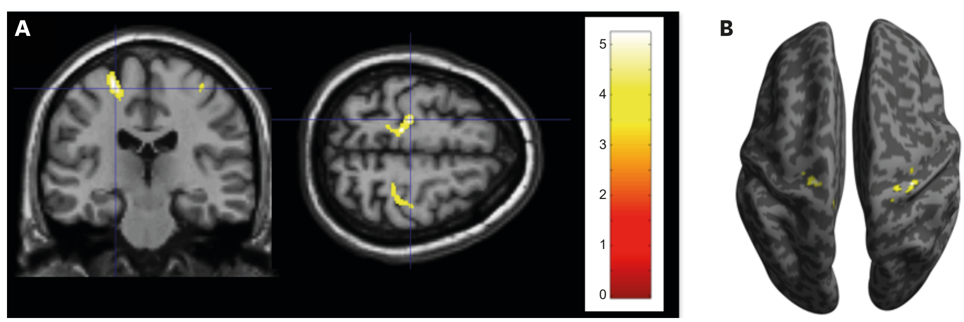

Fig. 2. Increased WM volumes in basketball players. Increased WM volumes are observed (uncorrected $P < 0.001$) in both precentral gyri of basketball players. (**A**) The left dominantly has increased WM volumes (radiological view). (**B**) The increased WM volumes are overlaid on the inflated brain surface. The color bar represents t values. WM = white matter.

DISCUSSION

This study showed an increase of gray and white mater volumes in both primary motor area including superior part of precentral gyri and anterior paracentral lobules of the basketball players. In addition, we observed increased fractal complexity in the bilateral precentral gyri and, and increased CT of both pericentral areas and paracentral lobules. These findings imply that primary motor cortices are well developed in the basketball players. The motor homunculus map shows that anterior paracentral lobule controls lower extremity (thigh, leg, and foot), and small superior portion of precentral gyrus controls hip.[14] Therefore, **Figs. 1** and **3** suggest that the important role of the lower extremity motor control in elite basketball players. Optimal eye-hand coordination requires rapid processing of sensory information coming from external stimuli, and control of continuous movement in the arms, legs, and torso.[4] These skills can be improved with practice, subsequently activating the neural circuit and related brain regions, including the motor cortices, the primary motor, premotor, and supplementary motor cortex, thereby enhancing the plasticity of a basketball player's precentral gyrus. The pericentral area includes a portion of the precentral gyrus and of the postcentral gyrus. Somatosensory input is essential for precise motor performance based on

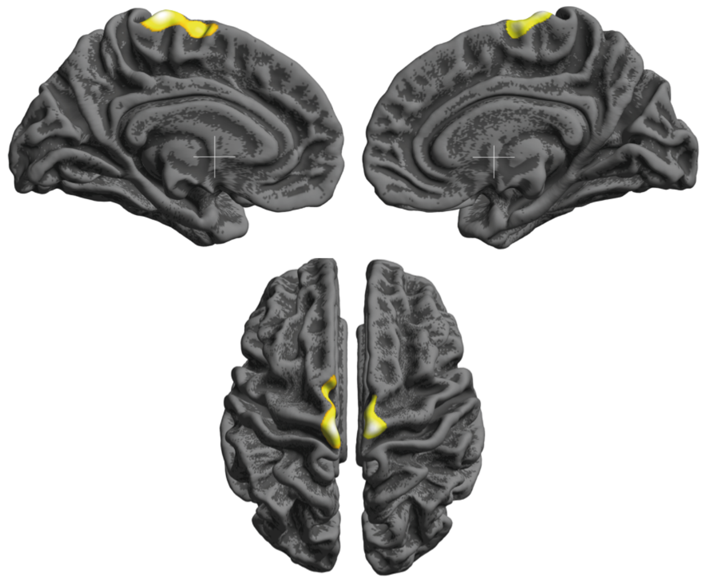

Fig. 3. Increased CTs in basketball players. Compared to control group, both pericentral gyri and paracentral lobules are observed in basketball players (uncorrected $P < 0.001$).
CT = cortical thickness.

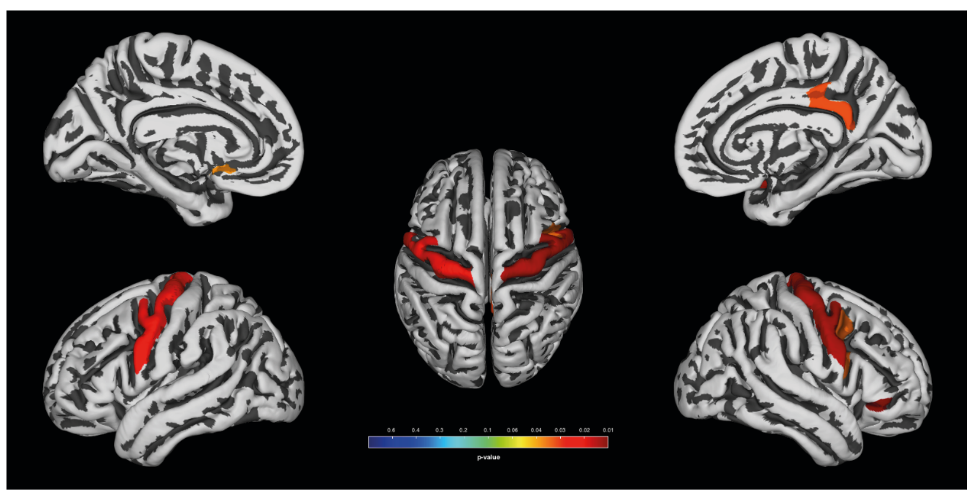

Fig. 4. High FDs in basketball players. Increased FDs are observed in both precentral gyri of basketball players (FDR $P < 0.05$). The color bar represents t values.
FD = fractal dimension.

learning and memory.[15] In this context, increased CT of the primary sensory area is expected. Changes of the precentral gyrus in response to sporting activities were also reported in the brains of Judo wrestlers, gymnasts, and handball players.[2,16,17]

The increased gray mater volume of the right antero-superior temporal gyrus is consistent with the report by Karnath et al.[18] In their report, new anatomical functional brain localization based on MRI analysis was observed on patients with lesions. Karnath et al.[18] reported that the right superior temporal cortex is closely related to spatial awareness based on patients with lesions leading to special neglect. These patients set up new functional localization of spatial awareness, which was previously considered a function of the parietal lobe.[18] The specific increase in the right superior temporal lobe of basketball players could be understood by simulating a basketball game. Recognition of spatial information is key during a real basketball game.

The increased FD of both precentral gyri in basketball players is expected considering these areas are primary motor cortices and the plasticity observed in this study. Changes in the left subcallosal gyrus and right posterior cingulate gyrus were observed with low significance levels in this study. The posterior cingulate gyrus is activated during complex motor skill learning,[19] and relate to voluntary and involuntary memory recall.[20] The posterior cingulate cortex governs spatial attention-shifting tasks, with oculomotor approach behaviors based on internal expectancies. The neural network underlying this phenomenon is supposedly the retrosplenial-cingulate-thalamic-dorsolateral frontal cortical connectivity. Actually, patients with retrosplenial injury or an anterior thalamic stroke had driving disabilities due to impaired spatial aiming in far space.[21] Auger and Magurie[22] reported that good navigators decoded the number of permanent items in view significantly better than poor navigators, based on patterns of activity in the retrosplenial cortex. These data suggest a link between brain plasticity in basketball players and increased fractal complexity in the posterior cingulate gyrus. The functions of the subcallosal gyrus, a portion of the limbic system behind the cingulate cortex are reciprocal to those of the cingulate cortex. The subcallosal gyrus inhibits motor neuron activity, whereas the cingulate cortex enhances motor neuron functions (APA Dictionary of Psychology). This structure likely regulates movement, but more research is needed to accurately link the association with basketball play. FD was originally a mathematical index for characterizing fractal patterns of geometric objects. Currently, it is used to estimate cortical complexities in many neuropsychiatric and neurological disorders.[23] Cortical complexity calculated by FD showed a significant change with age in normal children.[24] FD is another way to measure the complexity of cortical folding and complements the gyrification index. FD renders the brain as a fractal structure and mathematically quantifies the degree of complexity.[12] An increased FD value in the cortical area could suggest a more convoluted cortex structure.

The brain regulates every activity we perform, and it shows some plastic change from the synaptic to the behavioral level when learning is induced by continuous repetitive activity. Black et al.,[25] showed increased synapse numbers per Purkinje cell as a result of acrobat motor skill learning, whereas simple exercise such as treadmill training induced increased vascular density.[24] A few studies revealed specific strengthening of synaptic networks.[26-28] As previously mentioned, studies that analyzed the brains of elite athletes using MRI showed changes in tract, volume, or thickness of the brain region related to specific sports.[2] These kind of brain plasticity is observed in the patient recovering stroke with constraint-induced movement therapy.[29] The underlying cellular mechanisms are likely synaptogenesis, increased neuronal or glial cell volume, and axonal remodeling.[7,30]

Some limitations of this study are number of subjects and cross sectional study, the reason why we cannot describe cause and result of basketball training. We checked the training career as an athlete, but the objective data presenting motor skill related to basketball (parameters) were not checked, which should be considered in next study design like this researches.

As we hypothesized, the strong cerebral plasticity of both precentral gyri were shown by white and gray mater volume, as well as fractal complexity. The increase of CT in pericentral area and paracentral lobule was also observed bilaterally. These results suggest that motor system circuits favorably respond in basketball players. The moderate increase in fractal complexity of the right posterior cingulate gyrus implies that spatial aiming and navigation are important abilities for basketball players. Our data support the recently observed spatial awareness function of the superior temporal gyrus, which would be important in basketball payers. The plastic regions shown in this study, linked to functional neuroanatomy, were related to the competence required to play basketball. In addition, novel brain functions related to sports competency could be explored in the future.

REFERENCES

1. Waxman SG. Control of movement. In: Waxman SG, editor. *Clinical Neuroanatomy*. 28th ed. New York, NY, USA: McGraw-Hill Education; 2017.
2. Hänggi J, Langer N, Lutz K, Birrer K, Mérillat S, Jäncke L. Structural brain correlates associated with professional handball playing. *PLoS One* 2015;10(4):e0124222.
PUBMED | CROSSREF
3. Park IS, Han JW, Lee KJ, Lee NJ, Lee WT, Park KA, et al. Evaluation of morphological plasticity in the cerebella of basketball players with MRI. *J Korean Med Sci* 2006;21(2):342-6.
PUBMED | CROSSREF
4. Park IS, Lee KJ, Han JW, Lee NJ, Lee WT, Park KA, et al. Experience-dependent plasticity of cerebellar vermis in basketball players. *Cerebellum* 2009;8(3):334-9.
PUBMED | CROSSREF
5. Park IS, Lee YN, Kwon S, Lee NJ, Rhyu IJ. White matter plasticity in the cerebellum of elite basketball athletes. *Anat Cell Biol* 2015;48(4):262-7.
PUBMED | CROSSREF
6. Park IS, Lee KJ, Han JW, Lee NJ, Lee WT, Park KA, et al. Basketball training increases striatum volume. *Hum Mov Sci* 2011;30(1):56-62.
PUBMED | CROSSREF
7. Park IS, Lee NJ, Rhyu IJ. Roles of the declive, folium, and tuber cerebellar vermian lobules in sportspeople. *J Clin Neurol* 2018;14(1):1-7.
PUBMED | CROSSREF
8. Ashburner J. A fast diffeomorphic image registration algorithm. *Neuroimage* 2007;38(1):95-113.
PUBMED | CROSSREF
9. Friston KJ, Holmes AP, Worsley KJ, Poline JP, Frith CD, Frackowiak RS. Statistical parametric maps in functional imaging: a general linear approach. *Hum Brain Mapp* 1994;2(4):189-210.
CROSSREF
10. Duvernov HM. *The Human Brain: Surface, Three-Dimensional Sectional Anatomy, and MRI.* New York, NY, USA: Springer-Verlag; 1999.
11. Dahnke R, Yotter RA, Gaser C. Cortical thickness and central surface estimation. *Neuroimage* 2013;65:336-48.
PUBMED | CROSSREF
12. Yotter RA, Nenadic I, Ziegler G, Thompson PM, Gaser C. Local cortical surface complexity maps from spherical harmonic reconstructions. *Neuroimage* 2011;56(3):961-73.
PUBMED | CROSSREF
13. Destrieux C, Fischl B, Dale A, Halgren E. Automatic parcellation of human cortical gyri and sulci using standard anatomical nomenclature. *Neuroimage* 2010;53(1):1-15.
PUBMED | CROSSREF
14. Vanderah TW, Gould DJ. *Nolte's the Human Brain: An Introduction to Its Functional Anatomy*. 8th ed. Philadelphia, PA, USA: Elsevier; 2021.
15. Kumar N, Manning TF, Ostry DJ. Somatosensory cortex participates in the consolidation of human motor memory. *PLoS Biol* 2019;17(10):e3000469.
PUBMED | CROSSREF
16. Jacini WF, Cannonieri GC, Fernandes PT, Bonilha L, Cendes F, Li LM. Can exercise shape your brain? Cortical differences associated with judo practice. *J Sci Med Sport* 2009;12(6):688-90.
PUBMED | CROSSREF
17. Huang R, Lu M, Song Z, Wang J. Long-term intensive training induced brain structural changes in world class gymnasts. *Brain Struct Funct* 2015;220(2):625-44.
PUBMED | CROSSREF

18. Karnath HO, Ferber S, Himmelbach M. Spatial awareness is a function of the temporal not the posterior parietal lobe. *Nature* 2001;411(6840):950-3.
PUBMED | CROSSREF

19. Tracy J, Flanders A, Madi S, Laskas J, Stoddard E, Pyrros A, et al. Regional brain activation associated with different performance patterns during learning of a complex motor skill. *Cereb Cortex* 2003;13(9):904-10.
PUBMED | CROSSREF

20. Hall NM, Gjedde A, Kupers R. Neural mechanisms of voluntary and involuntary recall: a PET study. *Behav Brain Res* 2008;186(2):261-72.
PUBMED | CROSSREF

21. Barrett AM, Abdou A, Caulfield MD. The cingulate cortex and spatial neglect. *Handb Clin Neurol* 2019;166:129-50.
PUBMED | CROSSREF

22. Auger SD, Maguire EA. Assessing the mechanism of response in the retrosplenial cortex of good and poor navigators. *Cortex* 2013;49(10):2904-13.
PUBMED | CROSSREF

23. Im K, Lee JM, Yoon U, Shin YW, Hong SB, Kim IY, et al. Fractal dimension in human cortical surface: multiple regression analysis with cortical thickness, sulcal depth, and folding area. *Hum Brain Mapp* 2006;27(12):994-1003.
PUBMED | CROSSREF

24. Blanton RE, Levitt JG, Thompson PM, Narr KL, Capetillo-Cunliffe L, Nobel A, et al. Mapping cortical asymmetry and complexity patterns in normal children. *Psychiatry Res* 2001;107(1):29-43.
PUBMED | CROSSREF

25. Black JE, Isaacs KR, Anderson BJ, Alcantara AA, Greenough WT. Learning causes synaptogenesis, whereas motor activity causes angiogenesis, in cerebellar cortex of adult rats. *Proc Natl Acad Sci U S A* 1990;87(14):5568-72.
PUBMED | CROSSREF

26. Kim HT, Kim IH, Lee KJ, Lee JR, Park SK, Chun YH, et al. Specific plasticity of parallel fiber/Purkinje cell spine synapses by motor skill learning. *Neuroreport* 2002;13(13):1607-10.
PUBMED | CROSSREF

27. Lee KJ, Jung JG, Arii T, Imoto K, Rhyu IJ. Morphological changes in dendritic spines of Purkinje cells associated with motor learning. *Neurobiol Learn Mem* 2007;88(4):445-50.
PUBMED | CROSSREF

28. Lee KJ, Park IS, Kim H, Greenough WT, Pak DT, Rhyu IJ. Motor skill training induces coordinated strengthening and weakening between neighboring synapses. *J Neurosci* 2013;33(23):9794-9.
PUBMED | CROSSREF

29. Kim YH, Park JW, Ko MH, Jang SH, Lee PK. Plastic changes of motor network after constraint-induced movement therapy. *Yonsei Med J* 2004;45(2):241-6.
PUBMED | CROSSREF

30. Lee KJ, Rhyu IJ. Effects of exercise on structural and functional changes in the aging brain. *J Korean Med Assoc* 2009;52(9):907-19.
CROSSREF