● IMAGING IN NEURAL REGENERATION

Activation of less affected corticospinal tract and poor motor outcome in hemiplegic pediatric patients: a diffusion tensor tractography imaging study

Jin Hyun Kim, Su Min Son*

Department of Physical Medicine and Rehabilitation, College of Medicine, Yeungnam University, Daemyungdong, Namku, Daegu, Republic of Korea

***Correspondence to:**
Su Min Son, M.D., Ph.D.,
sumin430@hanmail.net.

orcid:
0000-0003-2818-3884 (Su Min Son)

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Abstract

The less affected hemisphere is important in motor recovery in mature brains. However, in terms of motor outcome in immature brains, no study has been reported on the less affected corticospinal tract in hemiplegic pediatric patients. Therefore, we examined the relationship between the condition of the less affected corticospinal tract and motor function in hemiplegic pediatric patients. Forty patients with hemiplegia due to perinatal or prenatal injury (13.7 ± 3.0 months) and 40 age-matched typically developing controls were recruited. These patients were divided into two age-matched groups, the high functioning group (20 patients) and the low functioning group (20 patients) using functional level of hemiplegia scale. Diffusion tensor tractography images showed that compared with the control group, the patient group of the less affected corticospinal tract showed significantly increased fiber number and significantly decreased fractional anisotropy value. Significantly increased fiber number and significantly decreased fractional anisotropy value in the low functioning group were observed than in the high functioning group. These findings suggest that activation of the less affected hemisphere presenting as increased fiber number and decreased fractional anisotropy value is related to poor motor function in pediatric hemiplegic patients.

Key Words: *nerve regeneration; unaffected hemisphere; hemiplegia; corticospinal tract; diffusion tensor imaging; motor function; neural regeneration*

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Introduction

Brain plasticity plays an important role in the motor recovery mechanism in an injured brain (Broderick et al., 2004). In particular, immature brain of pediatric patients has greater potential for plasticity than mature brain during the recovery phase (Johnston et al., 2003). Understanding the recovery mechanism using brain plasticity is essential in terms of prediction of functional outcome and establishment of rehabilitative treatment. Several motor recovery mechanisms have been proposed in previous studies: recovery of a damaged lateral corticospinal tract (CST), subcortical peri-lesional reorganization, contributions of ipsilateral motor pathway from unaffected motor cortex to the affected extremities, and the other motor areas, and among them, the ipsilateral motor pathway is significant because it can change with time and it can be influenced by rehabilitative management (Colebatch et al., 1989; Kim et al., 1993; Chen et al., 1997; Jang, 2009a, 2011). It is also known that sustained activation of the ipsilateral motor pathway results in poor motor outcome in adult hemiplegic patients with stroke (Chen et al., 1997a, b; Netz et al., 1997; Kim et al., 2004; Serrien et al., 2004; Kwon et al., 2007). Several previous studies have reported contribution of the ipsilateral motor pathway from the unaffected hemisphere in mature brains, using transcranial magnetic stimulation (TMS) (Chollet et al., 1991; Farmer et al., 1991; Carr et al., 1993, 1996; Maegaki et al., 1995; Caramia et al., 1998), conventional magnetic resonance imaging (MRI) (Staudt et al., 2005), functional MRI (Cramer et al., 1997), positron emission tomography (Jang et al., 2001), transcranial Doppler ultrasonography (Silvestrini et al., 1995), and autopsy study (Scales et al., 1972; Schachenmayr et al., 1978).

Diffusion tensor imaging (DTI) allows the estimation of neural tracts quantitatively by virtue of its ability to quantify water diffusion properties (Basser et al., 1996; Mori et al., 1999; Arzoumanian et al., 2003; Drobyshevsky et al., 2007; Ludeman et al., 2008; Yoshida et al., 2010). Diffusion tensor tractography (DTT), which is derived from DTI, provides three-dimensional visualization of the neural pathways (Basser et al., 1996; Mori et al., 1999; Arzoumanian et al., 2003; Drobyshevsky et al., 2007; Ludeman et al., 2008; Yoshida et al., 2010). Some DTT studies in adult hemiplegic patients have demonstrated the compensation of the ipsilateral CST from the unaffected hemisphere as a recovery mechanism (Jang et al., 2005a, 2009; Kwak et al., 2010). However, regarding pediatric hemiplegic patients, only two DTT studies with small numbers of patients have been reported (Thomas et al., 2005; Wakamoto et al., 2006), and no DTT studies have demonstrated the relationship between ipsilateral CST of the less affected hemisphere and motor function in pediatric patients with hemiplegia.

In this study, we investigated the relationship between the state of the ipsilateral CST and motor function in pediatric hemiplegic patients using DTT.

Subjects and Methods

Subjects

Sixty hemiplegic patients were recruited in accordance with the following criteria: (1) patients with spastic hemiplegia examined by two pediatric neurologists, (2) DTI performance at physiologic age of 10–20 months, (3) patients who underwent rehabilitation therapy in our hospital for at least 6 months. The patients were excluded in accordance with the following criteria: (1) diagnosed chromosomal anomaly, congenital brain anomaly, or genetic syndrome, (2) severe mental retardation or intractable seizure, (3) history of postnatal brain injury such as traumatic event, hypoxic brain injury, brain surgery, or postnatal neonatal stroke, (4) upper limb joint contracture which may affect the function of the hand, (5) dyskinetic or hypotonic movement pattern. Three patients with chromosomal anomaly and two patients showing congenital brain anomaly such as pachygyria or schizencephaly were excluded. Three patients with intractable epilepsy and one patient who underwent brain surgery were also excluded. In addition, five patients could not be included in this study due to motion artifact on DTI images. All subjects were patients who visited Pediatric Rehabilitation Center of Yeungnam University Hospital, Korea, and they were volunteers and their parents volunteered for this study.

Hemiplegic upper extremity motor function of all patients was evaluated using functional level of hemiplegia (FxL) (House et al., 1981; Romain et al., 1999; Fluet et al., 2010) by two pediatric neurologists who did not know the results of other evaluations. The patients were divided into two age-matched groups according to the FxL (0, has no use; 1, use as stabilizing weight only; 2, can hold objects placed in hand; 3, can hold object and stabilize it for use in other hand; 4, can actively grasp object and hold it weakly; 5, can actively grasp object and stabilize it well; 6, can actively grasp object and manipulate it against other hand; 7, can perform bimanual activities easily and occasionally use the hand spontaneously; 8, use the hand with complete independence). The high functioning group included patients who showed FxL ≥ 6, and the low functioning group included patients who showed FxL ≤ 5. In this study, the criteria to distinguish between high functioning group and low functioning group was whether the patient can perform bimanual activities or not, because bimanual activity is usually required to perform the functional activity of hands.

One patient whose results from two neurologists did not match and five patients who were not age-matched were excluded. Therefore, 40 patients were recruited in the final analysis (**Figure 1**). We also recruited 40 age-matched typically developing control subjects whose parents volunteered for this study. The parents of control subjects applied for this study and the results of DTT were provided free of charge. The control subjects had no medical history or diagnosis of neurological or psychological disease including brain trauma or delayed development. Informed consents were obtained from the parents of all subjects, and this study was approved by the Institutional Review Board at Yeungnam University Hospital, Korea.

DTI

Within an interval of less than 3 days from FxL assessment, DTI scanning was performed at an average of 13.65 ± 3.0 months (range 10–20 months) using a six-channel head coil on a 1.5 Tesla Philips Gyroscan Intera unit (Philips Medical Systems, Best, The Netherlands) with single-shot echo-planar imaging. Sixty-seven adjacent slices were obtained for the 32 non-collinear diffusion sensitizing gradients. Imaging parameters were as follows: field of view = 221 × 221 mm^2, acquisition matrix = 96 × 96, reconstructed matrix = 128 × 128, echo time = 76 mm, repetition time = 10,726 ms, echo planar imaging factor = 59, sensitivity encoding factor = 2, b = 1,000 s/mm^2, number of excitations = 1, and a slice thickness of 2.3 mm. Oxford Centre for Functional Magnetic Resonance Imaging of Brain (FMRIB) Software Library (FSL; www.fmrib.ox.ac.uk/fsl) was used to remove distorted images from Eddy current using multi-scale two-dimensional registration. Fiber Assignment by Continuous Tracking (FACT) in Philips PRIDE software (Philips Medical Systems), which is three-dimensional fiber reconstruction algorithm, was used to evaluate fiber connectivity. The termination standard of fiber tracking was fractional anisotropy (FA) threshold < 0.2 and angle change > 45°. On an FA axial color slice, a seed region of interest (ROI) was placed in the anterior mid-pons (the CST portion). On each of the FA axial color slices, another ROI was drawn in the anterior low-pons (the CST portion). The tracts passing through both ROIs were selected as final tracts. The ROI size was set between 5 and 10 voxels to include only the CST (Son, 2009) (**Figure 2**). Fiber number (FN), mean value of FA, and mean diffusivity (MD) of both sides of the entire CST were measured. In the control group, there was no definite difference of values between the two hemispheres; therefore, the mean values of diffusion parameters of both CSTs were measured.

Statistical analysis

For detection of the demographic differences between the patient and control groups, chi-square test was used for gender and independent *t*-test for age. For comparison of DTI parameters (FN, FA and MD) between the patient and control groups, one-way analysis of variance was conducted. When a significant difference was found between these two groups, Bonferroni *post-hoc* test was used to assess pairwise

Table 1 Demographic data for hemiplegic patients and controls

	Patient group	Control group
Patient (*n*)	40	40
Age (month)	13.7±3.0	13.7±3.0
Gender (male/female, *n*)	28/12	25/15

Values of age are presented as the mean ± SD.

Table 2 Demographic and clinical data for the high functioning and low functioning groups

	High functioning group	Low functioning group
Patient (*n*)	20	20
Age (month)	13.7±3.0	13.7±3.0
Gender (male/female, *n*)	14/6	14/6
Full-term/preterm (*n*)	13/7	2/18
FxL score	7.5±0.7	3.7±1.5
Brain lesion		
Periventricular leukomalacia (*n*)	3	6
Intra-cerebral hemorrhage (*n*)	0	2

Values of age and FxL score are presented as the mean ± SD. FxL: Functional level of hemiplegia.

Table 4 Diffusion parameters of the less affected CSTs in hemiplegic patients with high and low upper extremity function

	High functioning group (*n* = 20)	Low functioning group (*n* = 20)
Fiber number	1,203.15±278.32*	1,394.95±343.22
Fractional anisotropy	0.4888±0.022*	0.4658±0.026
Mean diffusivity (× 10^{-3} mm^2/s)	0.9010±0.056	0.9214±0.034

Values are expressed as the mean ± SD. *$P < 0.05$, *vs*. low functioning group. Independent *t*-test was used. CST: Corticospinal tract.

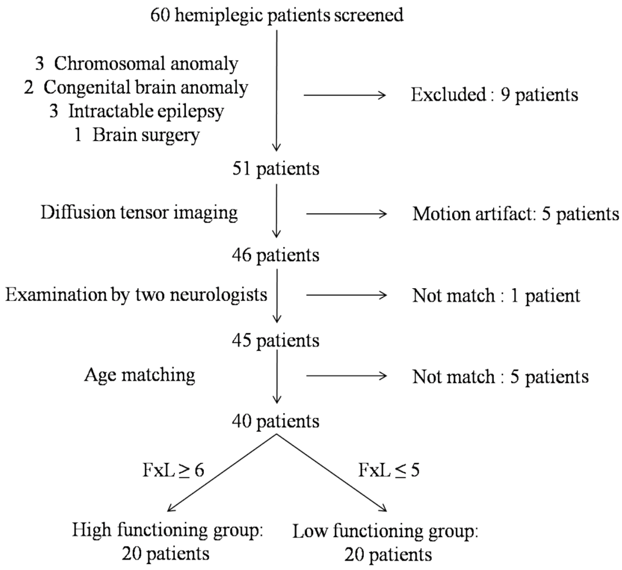

Figure 1 Flow chart of patient grouping.
FxL: Functional level of hemiplegia.

Table 3 Diffusion parameters of CST in hemiplegic patients and controls

	More affected CST in the patient group (*n* = 40)	Less affected CST in the patient group (*n* = 40)	Mean values of both CSTs in the control group (*n* = 40)
Fiber number	809.53±320.49*	1,299.05± 323.06†	1,185.14±193.49
Fractional anisotropy	0.4506±0.042*	0.4773±0.027†	0.4943±0.013
Mean diffusivity (× 10^{-3} mm^2/s)	0.9506±0.072*	0.9157±0.044	0.9022±0.032

Values are expressed as the mean ± SD. *$P < 0.05$, *vs*. the less affected side in the patient group and the control group; †$P < 0.05$, *vs*. control group. One-way analysis of variance followed by Bonferroni *post-hoc* test was used. CST: Corticospinal tract.

comparisons. Independent *t*-test was used for comparison of DTI parameters in the less affected CST between the high functioning and low functioning groups. SPSS 18.0 software (SPSS, Chicago, IL, USA) was used. A level of $P < 0.05$ was considered statistically significant.

Results

Demographic data

Age at MRI scans and clinical evaluations were adjusted based on physiologic age. Out of 40 patients, 20 patients were included in the high functioning group (14 males, 6 females; mean age 13.7 ± 3.0 months; 13 full-term delivery, 7 preterm delivery) and another 20 patients in the low functioning group (14 males, 6 females; mean age 13.7 ± 3.0 months; 2 full-term delivery, 18 preterm delivery). The mean age of the control group was 13.7 ± 3.0 months (25 males, 15 females; 40 full-term delivery). There were no significant differences in demographic data between the patient and control groups (**Table 1**). The mean FxL score of the high and low functioning groups was 7.5 ± 0.7 and 3.7 ± 1.5, respectively. On conventional MRI, three patients had lesions (three periventricular leukomalacia) in the high functioning group, and eight patients had lesions (two intra-cerebral hemorrhages and six periventricular leukomalacia) in the low functioning group. The other patients showed no abnormal brain lesions on conventional MRI (**Table 2**).

DTI parameters

The more affected CST of the patient group showed significantly decreased FN and FA value, significantly increased MD value compared with the less affected CSTs and that of the control group ($P < 0.05$). The less affected CST of the patient group showed significantly increased FN and significantly decreased FA value compared with that of the control group ($P < 0.05$). However, there was no significant difference in MD value between the less affected CST of the patient group and the control group ($P > 0.05$) (**Table 3**).

The low functioning group showed significantly increased FN and significantly decreased FA value than the high functioning group ($P < 0.05$). There was no significant difference

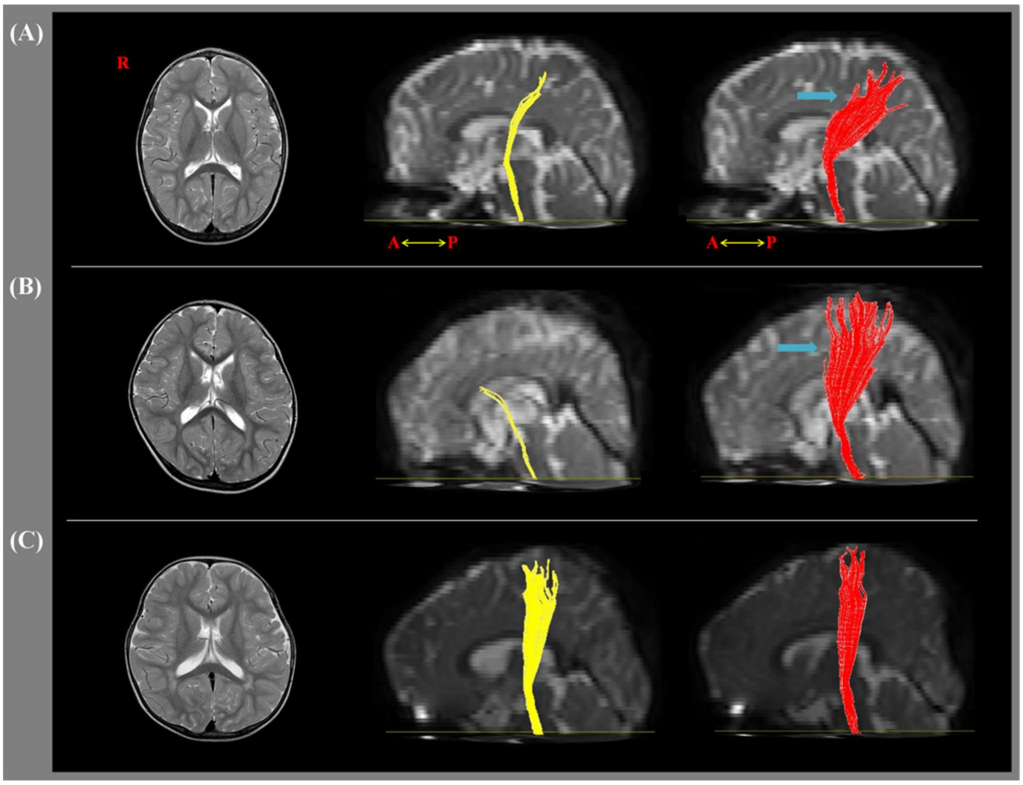

Figure 2 Conventional T2-weighted brain magnetic resonance images and diffusion tensor images for the corticospinal tract (CST) of a patient in the high functioning group (A), low functioning group (B), and a control subject (C).
(A) The less affected CST (red colored) of a patient with better upper extremity function. (B) The less affected CST of a patient with worse upper extremity function. (C) The CST of a control subject. The fiber number of the less affected CST of a high functioning patient (A) was increased compared with that of a control subject (C), however it was decreased compared with that of a low functioning patient (B). In A and B, red colored tract (sky blue arrow) indicates less affected CST, and yellow colored tract indicates more affected CST. R: Right; A: anterior; P: posterior.

in MD value between the high functioning and low functioning groups ($P > 0.05$) (**Table 4**).

Discussion

In the current study, significantly increased FN and decreased FA value of the less affected CST were observed in hemiplegic patients than in the controls. The comparative result for the less affected CST showed significantly increased FN and decreased FA value in the low functioning group than in the high functioning group.

In the current study, we used FxL for functional evaluation of participants. FxL is an observational description of hemiplegic upper extremity use in pediatric patients, and has been widely used in several previous studies on the therapeutic effect of rehabilitation on motor dysfunction (House et al., 1981; Romain et al., 1999; Fluet et al., 2010). Because the CST is highly related to the fine motor coordination of the upper extremities (Jang, 2009b; Cho et al., 2012), we used FxL, which can focus on the more affected upper extremity use instead of Bayley Scales of Infant Development (BSID) or Erhardt Developmental Prehension Assessment (EDPA), which cannot assess the function of the more affected extremity, particularly in hemiplegic patients.

Among DTI parameters, FN represents the quantitative information on connectivity within a white matter tract (Wilson-Costello et al., 2005; Son et al., 2009; Faria et al., 2010; Jang, 2010; Kwak et al., 2010; Yoshida et al., 2010). FA value represents the degree of unidirectionality of a well-organized white matter tract (Basser et al., 1996; Mori et al., 1999; Assaf et al., 2008; Neil, 2008). MD value represents the magnitude of water diffusion (Basser et al., 1996; Mori et al., 1999; Assaf et al., 2008; Neil, 2008). Therefore, increased FN and decreased FA value of the less affected CST appear to indicate a regenerative activation for compensatory action following brain injury (Kawk et al., 2010). Although the mechanism of activation of the unaffected motor cortex after brain damage has not been fully addressed, disinhibition hypothesis is currently the most acceptable (Netz et al., 1997; Liepert et al., 2000; Manganotti et al., 2002; Duque et al., 2005). Normal motor cortices in both hemispheres are balanced by interhemispheric transcallosal inhibition against each other. However, brain injury in one hemisphere can cause off-balance between two hemispheres due to the decreased power of inhibition from the injured hemisphere. As a result, unaffected motor cortex can be activated more than the balanced state. This hypothesis is believed to be the scientific basis for the recovery mechanism through the ipsilateral motor pathway.

In the comparative analysis according to motor function, the low functioning group showed significantly increased

FN and significantly decreased FA value of the less affected CST than the high functioning group. This finding indicates greater activation of the less affected motor cortex in the low functioning group than in the high functioning group. Although the ipsilateral motor pathway is a momentous motor recovery mechanism, many previous studies in adult stroke patients have reported that patients who had ipsilateral motor pathway recovery showed poor motor (hand) function, and sustained activation of the unaffected hemisphere is related to poor motor function (Turton et al., 1996; Jang et al., 2005b; Jang, 2007, 2009b; Netz et al., 1997; Kim et al., 2004; Serrien et al., 2004; Kwon et al., 2007). Other studies in adult stroke patients showed that the ipsilateral motor pathway was less effective compared to other recovery mechanisms such as the recovery of damaged lateral CST or peri-lesional reorganization (Colebatch et al., 1989; Kim et al., 1993; Chen et al., 1997; Jang, 2009a, 2011). Our results are consistent with those of previous studies. We demonstrated the relationship between the state of the less affected CST and motor function. In detail, high contribution from the ipsilateral motor pathway also showed relevance to poor motor (hand) function in pediatric patients with hemiplegia. Therefore, suppression of less affected motor cortex and facilitation of more affected motor cortex could be a scientific rehabilitative strategy for better motor outcome in pediatric patients with hemiplegia.

Regarding pediatric patients with hemiplegia, Wakamoto et al. (2006) performed a study based on seven patients who experienced hemispherectomy and age matched normal control subjects, indicating no significant change of the unaffected CST. Another DTT study by Thomas el al. (2005) showed significant increase of fiber count of the unaffected corticobulbar tract in five hemiplegic pediatric patients compared with those of age- matched control subjects. However, these studies recruited a small number of heterogeneous patients, and did not evaluate clinical motor function either. Therefore, for more homogeneous recruitment of subjects, we recruited a larger number of subjects and set a narrower range of subject age. In addition, we demonstrated the relationship between motor (hand) function and the contribution of the ipsilateral motor pathway. However, limitations of this study should be considered. First, the onset time of brain lesions such as periventricular leukomalacia and intra-cerebral hemorrhage was unclear. We evaluated patients during the recovery phase, so that recruitment of homogeneous subjects was very important. However, it was impossible to confirm the duration time after onset in cases of perinatal or prenatal injury. Therefore, to reduce bias from heterogeneity of duration time and to maintain homogeneity of the subjects, we recruited the subjects according to the physiologic age of 10–20 months rather than corrected age. DTT is a valuable neural imaging modality which can show false positive and false negative results because of volume effect or crossing fiber (Yamada et al., 2009; Fillard et al., 2011). Further functional MRI and/or TMS guided complementary studies will be required. Finally, other clinical evaluations that may influence motor function such as sensory or cognitive dysfunction were not conducted. Further complementary studies involving more detailed clinical parameters will be warranted.

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Peer review: *This paper was double-blinded and stringently reviewed by international expert reviewers.*

References

Arzoumanian Y, Mirmiran M, Barnes PD, Woolley K, Ariagno RL, Moseley ME, Fleisher BE, Atlas SW (2003) Diffusion tensor brain imaging findings at term-equivalent age may predict neurologic abnormalities in low birth weight preterm infants. AJNR Am J Neuroradiol 24:1646-1653.

Assaf Y, Pasternak O (2008) Diffusion tensor imaging (dti)-based white matter mapping in brain research: A review. J Mol Neurosci 34:51-61.

Basser PJ, Pierpaoli C (1996) Microstructural and physiological features of tissues elucidated by quantitative-diffusion-tensor MRI. J Magn Reson B 111:209-219.

Broderick JP, William M. Feinberg L (2004) Stroke therapy in the year 2025: Burden, breakthroughs, and barriers to progress. Stroke 35:205-211.

Caramia MD, Telera S, Palmieri MG, Wilson-Jones M, Scalise A, Iani C, Giuffre R, Bernardi G (1998) Ipsilateral motor activation in patients with cerebral gliomas. Neurology 51:196-202.

Carr LJ, Harrison LM, Evans AL, Stephens JA (1993) Patterns of central motor reorganization in hemiplegic cerebral palsy. Brain 116:1223-1247.

Carr LJ (1996) Development and reorganization of descending motor pathways in children with hemiplegic cerebral palsy. Acta Paediatr Suppl 416:53-57.

Chen R, Cohen LG, Hallett M (1997a) Role of the ipsilateral motor cortex in voluntary movement. Can J Neurol Sci 24:284-291.

Chen R, Gerloff C, Hallett M, Cohen LG (1997b) Involvement of the ipsilateral motor cortex in finger movements of different complexities. Ann Neurol 41:247-254.

Cho HM, Choi BY, Chang CH, Kim SH, Lee J, Chang MC, Son SM, Jang SH (2012) The clinical characteristics of motor function in chronic hemiparetic stroke patients with complete corticospinal tract injury. NeuroRehabilitation 31:207-213.

Chollet F, DiPiero V, Wise RJ, Brooks DJ, Dolan RJ, Frackowiak RS (1991) The functional anatomy of motor recovery after stroke in humans: A study with positron emission tomography. Ann Neurol 29:63-71.

Colebatch JG, Gandevia SC (1989) The distribution of muscular weakness in upper motor neuron lesions affecting the arm. Brain 112:749-763.

Cramer SC, Nelles G, Benson RR, Kaplan JD, Parker RA, Kwong KK, Kennedy DN, Finklestein SP, Rosen BR (1997) A functional MRI study of subjects recovered from hemiparetic stroke. Stroke 28:2518-2527.

Drobyshevsky A, Bregman J, Storey P, Meyer J, Prasad PV, Derrick M, MacKendrick W, Tan S (2007) Serial diffusion tensor imaging detects white matter changes that correlate with motor outcome in premature infants. Dev Neurosci 29:289-301.

Duque J, Hummel F, Celnik P, Murase N, Mazzocchio R, Cohen LG (2005) Transcallosal inhibition in chronic subcortical stroke. Neuroimage 28:940-946.

Faria AV, Hoon A (2010) Caveats in diffusion tensor imaging interpretation. Dev Med Child Neurol 52:887.

Farmer SF, Harrison LM, Ingram DA, Stephens JA (1991) Plasticity of central motor pathways in children with hemiplegic cerebral palsy. Neurology 41:1505-1510.

Fillard P, Descoteaux M, Goh A, Gouttard S, Jeurissen B, Malcolm J, Ramirez-Manzanares A, Reisert M, Sakaie K, Tensaouti F, Yo T, Mangin JF, Poupon C (2011) Quantitative evaluation of 10 tractography algorithms on a realistic diffusion MR phantom. Neuroimage 56:220-234.
Fluet GG, Qiu Q, Kelly D, Parikh HD, Ramirez D, Saleh S, Adamovich SV (2010) Interfacing a haptic robotic system with complex virtual environments to treat impaired upper extremity motor function in children with cerebral palsy. Dev Neurorehabil 13:335-345.
House JH, Gwathmey FW, Fidler MO (1981) A dynamic approach to the thumb-in palm deformity in cerebral palsy. J Bone Joint Surg Am 63:216-225.
Jang SH (2007) A review of motor recovery mechanisms in patients with stroke. NeuroRehabilitation 22:253-259.
Jang SH (2009a) A review of the ipsilateral motor pathway as a recovery mechanism in patients with stroke. NeuroRehabilitation 24:315-320.
Jang SH (2009b) The role of the corticospinal tract in motor recovery in patients with a stroke: A review. NeuroRehabilitation 24:285-290.
Jang SH (2010) Prediction of motor outcome for hemiparetic stroke patients using diffusion tensor imaging: A review. NeuroRehabilitation 27:367-372.
Jang SH (2011) A review of diffusion tensor imaging studies on motor recovery mechanisms in stroke patients. NeuroRehabilitation 28:345-352.
Jang SH, Byun WM, Chang Y, Han BS, Ahn SH (2001) Combined functional magnetic resonance imaging and transcranial magnetic stimulation evidence of ipsilateral motor pathway with congenital brain disorder: A case report. Arch Phys Med Rehabil 82:1733-1736.
Jang SH, You SH, Kwon YH, Hallett M, Lee MY, Ahn SH (2005a) Cortical reorganization associated lower extremity motor recovery as evidenced by functional MRI and diffusion tensor tractography in a stroke patient. Restor Neurol Neurosci 23:325-329.
Jang SH, Ahn SH, Yang DS, Lee DK, Kim DK, Son SM (2005b) Cortical reorganization of hand motor function to primary sensory cortex in hemiparetic patients with a primary motor cortex infarct. Arch Phys Med Rehabil 86:1706-1708.
Jang SH, Park KA, Ahn SH, Cho YW, Byun WM, Son SM, Choi JH, Kwon YH (2009) Transcallosal fibers from corticospinal tract in patients with cerebral infarct. NeuroRehabilitation 24:159-164.
Johnston MV (2003) Brain plasticity in paediatric neurology. Eur J Paediatr Neurol 7:105-113.
Kim SG, Ashe J, Hendrich K, Ellermann JM, Merkle H, Ugurbil K, Georgopoulos AP (1993) Functional magnetic resonance imaging of motor cortex: Hemispheric asymmetry and handedness. Science 261:615-617.
Kim YH, Jang SH, Byun WM, Han BS, Lee KH, Ahn SH (2004) Ipsilateral motor pathway confirmed by combined brain mapping of a patient with hemiparetic stroke: A case report. Arch Phys Med Rehabil 85:1351-1353.
Kwak SY, Yeo SS, Choi BY, Chang CH, Jang SH (2010) Corticospinal tract change in the unaffected hemisphere at the early stage of intracerebral hemorrhage: A diffusion tensor tractography study. Eur Neurol 63:149-153.
Kwon YH, Lee MY, Park JW, Kang JH, Yang DS, Kim YH, Ahn SH, Jang SH (2007) Differences of cortical activation pattern between cortical and corona radiata infarct. Neurosci Lett 417:138-142.
Liepert J, Hamzei F, Weiller C (2000) Motor cortex disinhibition of the unaffected hemisphere after acute stroke. Muscle Nerve 23:1761-1763.
Ludeman NA, Berman JI, Wu YW, Jeremy RJ, Kornak J, Bartha AI, Barkovich AJ, Ferriero DM, Henry RG, Glenn OA (2008) Diffusion tensor imaging of the pyramidal tracts in infants with motor dysfunction. Neurology 71:1676-1682.
Maegaki Y, Yamamoto T, Takeshita K (1995) Plasticity of central motor and sensory pathways in a case of unilateral extensive cortical dysplasia: Investigation of magnetic resonance imaging, transcranial magnetic stimulation, and short-latency somatosensory evoked potentials. Neurology 45:2255-2261.
Manganotti P, Patuzzo S, Cortese F, Palermo A, Smania N, Fiaschi A (2002) Motor disinhibition in affected and unaffected hemisphere in the early period of recovery after stroke. Clin Neurophysiol 113:936-943.
Mori S, Crain BJ, Chacko VP, van Zijl PC (1999) Three-dimensional tracking of axonal projections in the brain by magnetic resonance imaging. Ann Neurol 45:265-269.
Neil JJ (2008) Diffusion imaging concepts for clinicians. J Magn Reson Imaging 27:1-7.
Netz J, Lammers T, Homberg V (1997) Reorganization of motor output in the non-affected hemisphere after stroke. Brain 120:1579-1586.
Romain M, Benaim C, Allieu Y, Pelissier J, Chammas M (1999) Assessment of hand after brain damage with the aim of functional surgery. Ann Chir Main Memb Super 18:28-37.
Scales DA, Collins GH (1972) Cerebral degeneration with hypertrophy of the contralateral pyramid. Arch Neurol 26:186-190.
Schachenmayr W, Friede RL (1978) Dystopic myelination with hypertrophy of pyramidal tract. J Neuropathol Exp Neurol 37:34-44.
Serrien DJ, Strens LH, Cassidy MJ, Thompson AJ, Brown P (2004) Functional significance of the ipsilateral hemisphere during movement of the affected hand after stroke. Exp Neurol 190:425-432.
Silvestrini M, Troisi E, Matteis M, Cupini LM, Caltagirone C (1995) Involvement of the healthy hemisphere in recovery from aphasia and motor deficit in patients with cortical ischemic infarction: A transcranial doppler study. Neurology 45:1815-1820.
Son SM, Park SH, Moon HK, Lee E, Ahn SH, Cho YW, Byun WM, Jang SH (2009) Diffusion tensor tractography can predict hemiparesis in infants with high risk factors. Neurosci Lett 451:94-97.
Staudt M, Krageloh-Mann I, Grodd W (2005) Ipsilateral corticospinal pathways in congenital hemiparesis on routine magnetic resonance imaging. Pediatr Neurol 32:37-39.
Thomas B, Eyssen M, Peeters R, Molenaers G, Van Hecke P, De Cock P, Sunaert S (2005) Quantitative diffusion tensor imaging in cerebral palsy due to periventricular white matter injury. Brain 128:2562-2577.
Turton A, Wroe S, Trepte N, Fraser C, Lemon RN (1996) Contralateral and ipsilateral emg responses to transcranial magnetic stimulation during recovery of arm and hand function after stroke. Electroencephalogr Clin Neurophysiol 101:316-328.
Wakamoto H, Eluvathingal TJ, Makki M, Juhasz C, Chugani HT (2006) Diffusion tensor imaging of the corticospinal tract following cerebral hemispherectomy. J Child Neurol 21:566-571.
Wilson-Costello D, Friedman H, Minich N, Fanaroff AA, Hack M (2005) Improved survival rates with increased neurodevelopmental disability for extremely low birth weight infants in the 1990s. Pediatrics 115:997-1003.
Yamada K, Sakai K, Akazawa K, Yuen S, Nishimura T (2009) Mr tractography: A review of its clinical applications. Magn Reson Med Sci 8:165-174.
Yoshida S, Hayakawa K, Yamamoto A, Okano S, Kanda T, Yamori Y, Yoshida N, Hirota H (2010) Quantitative diffusion tensor tractography of the motor and sensory tract in children with cerebral palsy. Dev Med Child Neurol 52:935-940.

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