

## CASE REPORT

# Feasibility Case Study for Treating a Patient with Sensory Ataxia Following a Stroke with Kinesthetic Illusion Induced by Visual Stimulation

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**Background:** Sensory ataxia is a disorder of movement coordination caused by sensory deficits, especially in kinesthetic perception. Visual stimulus-induced kinesthetic illusion (KINVIS) is a method used to provide vivid kinesthetic perception without peripheral sensory input by using a video showing pre-recorded limb movements while the actual limb remains stationary. We examined the effects of KINVIS intervention in a patient with sensory ataxia. **Case:** The patient was a 59-year-old man with a severe proprioceptive deficit caused by left thalamic hemorrhage. During KINVIS intervention, a computer screen displayed a pre-recorded mirror image video of the patient's unaffected hand performing flexion–extension movements as if it were attached to the patient's affected forearm. Kinematics during the flexion–extension movements of the paretic hand were recorded before and after 20-min interventions. Transcranial magnetic stimulation was applied to the affected and non-affected hemispheres. The amplitude of the motor-evoked potential (MEP) at rest was recorded for the muscles of both hands. After the intervention, the total trajectory length and the rectangular area bounding the trajectory of the index fingertip decreased. The MEP amplitude of the paretic hand increased, whereas the MEP amplitude of the non-paretic hand was unchanged. **Discussion:** The changes in kinematics after the intervention suggested that KINVIS therapy may be a useful new intervention for sensory ataxia, a condition for which few effective treatments are currently available. Studies in larger numbers of patients are needed to clarify the mechanisms underlying this therapeutic effect.

**Key words:** body ownership; kinesthetic illusion; sensory ataxia, stroke; transcranial magnetic stimulation

## INTRODUCTION

Sensory ataxia is a disorder of movement coordination caused by sensory deficits, especially deficits in kinesthetic perception. Previous studies have shown that sensory ataxia occurs in patients with peripheral neuropathy<sup>1,2)</sup> and fol-

lowing thalamic stroke.<sup>3)</sup> Several studies have shown that rehabilitation can improve some sensory functions, such as tactile sensation and positional sense,<sup>4,5)</sup> but a systematic review by Doyle et al.<sup>6)</sup> concluded that there is insufficient evidence to support its effectiveness in improving sensory impairment. Furthermore, there have been very few reports

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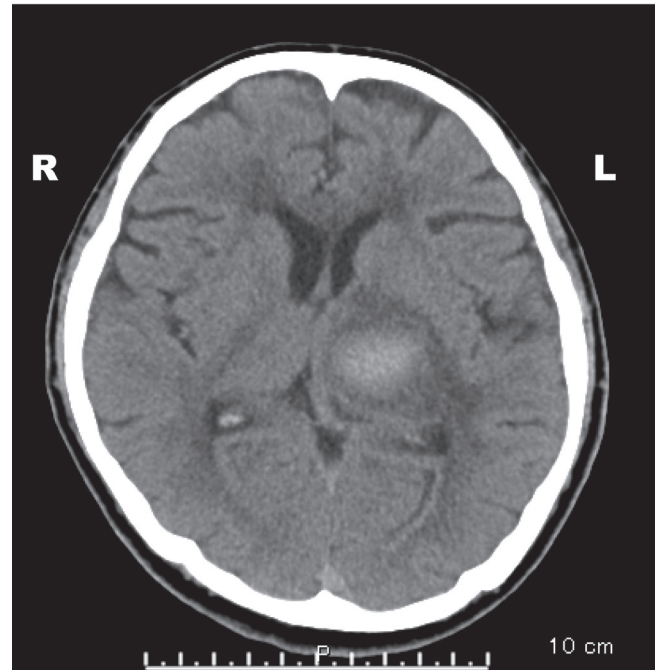
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regarding rehabilitation for sensory ataxia.<sup>2,7)</sup> Because sensory ataxia is caused by impairments in kinesthetic perception, providing appropriate kinesthetic feedback may help to improve sensory ataxia. However, if sensory pathways are severely impaired, peripheral sensory input may not be sufficient to adjust the movement trajectory. Notably, kinesthetic perception is also generated by top-down modulation within brain networks involved in motor planning and sensory–motor integration that do not rely on peripheral sensory afferent projections.<sup>8–10)</sup> Kinesthetic illusion induced by visual stimulation (KINVIS) is one potential method for providing kinesthetic perception without peripheral sensory inputs.<sup>9–13)</sup> To investigate this method, we developed a box-type virtual reality system to induce KINVIS, termed the KiNvis™ system. During KINVIS, a video of finger movement is shown on a computer screen located directly above an individual's actual hand. This intervention induces body ownership and vivid kinesthetic perception of the “artificial body” on the screen.<sup>13)</sup> Furthermore, it selectively increases corticomotor excitability corresponding to control of the involved muscles<sup>12,13)</sup> and activates brain regions including the dorsal and ventral premotor cortices and left superior and inferior parietal lobules.<sup>10)</sup> These studies demonstrated that KINVIS generates neural activity similar to that observed during motor execution, even in the absence of the peripheral kinesthetic inputs. Consequently, KINVIS may be considered a stimulation paradigm for the embodied cognitive brain system.

A preliminary study revealed increased upper limb muscle activity and joint movement in stroke patients immediately following KINVIS.<sup>14)</sup> However, no study has observed the effects of KINVIS in stroke patients with sensory ataxia. The current study investigated whether visually induced kinesthetic perception in the absence of peripheral kinesthetic inputs affects sensory ataxia symptoms. To explore the feasibility of this technique, the kinematic, neurophysiological, and electromyographic changes after KINVIS were examined in a patient with sensory ataxia resulting from thalamic hemorrhage. Because kinesthetic perception plays a crucial role in motor execution and learning,<sup>1,15,16)</sup> we hypothesized that KINVIS may effectively reduce upper limb sensory ataxia.

## CASE

A 59-year-old, right-handed, male stroke patient participated in this study. The patient had displayed sensory ataxia for 5 months in his paretic right hand as a result of severe



**Fig. 1.** Computed tomography image of the patient 14 days after stroke onset showing left thalamic hemorrhage.

proprioceptive deficits following a thalamic hemorrhage. His only neurological disease was stroke. The location of the brain lesion and the patient's clinical characteristics are shown in **Fig. 1** and **Table 1**, respectively. The patient had severe deep sensory loss and mild superficial sensory loss. The sensory subscore on the Stroke Impairment Assessment Set (SIAS) for the upper limb was 0 for position sense and 2 for touch sense. During the two-point discrimination test on the pulp of the index finger, the patient failed to distinguish the points even at a separation distance of 20 mm.

The patient provided prior written informed consent to participate in the study in accordance with the Declaration of Helsinki. The present study was approved by the local Ethics Committee of the Ibaraki Prefectural University of Health Sciences (approval number: e202). Written informed consent was also obtained from the patient for publication of this case report.

## INTERVENTION

The patient was seated in a comfortable chair with his paretic right forearm on a table. Before the intervention, we filmed the participant executing hand flexion–extension movements (3-s flexion and 3-s extension) with the non-paretic left hand. During the intervention (KiNvis Therapy

**Table 1.** Patient characteristics

Characteristic	Value
Age (years)	59
Sex	Male
Time since stroke (months)	5
Diagnosis	Cerebral hemorrhage
Lesion location	Left thalamus
Motor function	
Brunnstrom stage (I–VI)	
UE	IV
Finger	IV
LE	III
SIAS finger-function test (0–5)	3
FMA UE (0–66)	29
ARAT (0–57)	20
MAS finger flexor (0–4)	1
Sensory function	
SIAS UE touch (0–3)	2
SIAS UE position (0–3)	0
Two-point discrimination	>20 mm

UE, upper extremity; LE, lower extremity; SIAS, Stroke Impairment Assessment Set; FMA, Fugl-Meyer Assessment; ARAT, Action Research Arm Test; MAS, Modified Ashworth Scale.

System™; Inter Reha, Tokyo, Japan), the patient remained fully relaxed and was instructed to keep his both hands still. A computer display showing the mirror image of the patient's left hand was positioned over the right forearm. The position and size of the image were appropriately adjusted so that the paretic hand mimicked the feeling that an artificial hand belonged to the patient's own body. KINVIS was performed for 20 min by repeatedly showing the 6-s video of the hand flexion–extension movement. The kinematics and muscle activity during hand flexion–extension movements and corticomotor excitability using transcranial magnetic stimulation (TMS) were evaluated before and after the 20-min intervention.

## OUTCOME MEASUREMENT

### Transcranial Magnetic Stimulation

A Magstim 200<sup>2</sup> stimulator (Magstim, Whitland, UK) connected to a figure-of-eight coil was used to elicit motor-evoked potentials (MEP) from the paretic and non-paretic first dorsal interosseous muscle (FDI), the paretic flexor digitorum superficialis muscle (FDS), and the paretic extensor digitorum muscle (ED). The handle of the coil was

positioned pointing backward and laterally at an angle of 45° from the midline to induce an anteromedial-directed current in the brain to trans-synaptically activate pyramidal neurons.<sup>17,18</sup> Hot spots in each hemisphere that elicited the most consistent MEP amplitude from the contralateral FDI muscles were determined by moving the coil in 1-cm increments around the hand motor area. After determination of the hot spots, test stimuli were administered at least five times. The test stimulus intensities were set at 50% and 60% of the maximum stimulator output (MSO). The interval between the previous and subsequent stimuli was set to at least 8 s. To determine whether corticomotor excitability was changed by KINVIS, MEP amplitudes of the hand muscles in the resting condition were measured before and after the intervention. The location and intensity of the stimulation were the same before and after the intervention. Trials in which the root mean square of the electromyograph (EMG) activity exceeded 0.01 mV within 100 ms prior to TMS were rejected.<sup>19</sup>

### Electromyography

The skin at the electrode site was swabbed with alcohol and prepared using abrasive skin-prepping gel. Surface Ag–AgCl electrodes were placed over the paretic FDS, paretic ED, and bilateral first dorsal FDI. The positions of the electrodes were maintained throughout the experiment, including before and after the intervention. EMG signals were amplified (Neuropack MEB2300; Nihon Kohden, Saitama, Japan) at a gain of 1000 or 2000 and band-pass filtered at 5–5000 Hz. All signals were stored on a laboratory computer for offline analysis. The sampling frequency was set at 10 kHz during the TMS experiment and 2 kHz during the hand motor task.

### Motor Task with Kinematic and EMG Analysis

The patient put his paretic hand in a neutral position and performed the 6-s hand flexion–extension movement task (3-s flexion and 3-s extension) with the paretic hand four times. To focus on the kinematic analysis of hand movements, the experimenter fixed the patient's distal forearm during the motor task. Reflective markers were placed on the patient's index fingertip, distal interphalangeal joint, proximal interphalangeal (PIP) joint, metacarpophalangeal (MP) joint, and radial styloid process. The positions of the reflective markers were maintained throughout the experiment, including before and after the intervention. Hand flexion–extension movements were captured from above using a digital video camera (EX-FH100, 30 frames/s; Casio, Tokyo, Japan). The recorded images were digitized to obtain coordinates for

the five reflective markers using a motion analysis system (Frame DIAS V; DKH, Tokyo, Japan). Two-dimensional (2D) coordinates for each marker were processed using a fourth-order, zero-lag, low-pass, Butterworth filter with a cut-off frequency of 6 Hz. The changes in flexion angles of the PIP and MP joints were calculated from the 2D coordinate data based on the reflective markers. For each hand flexion–extension movement, the flexion–extension angle ranges for the PIP and MP joints were calculated and averaged. Additionally, we used the indices of the total trajectory length and its rectangular area, which are often used to assess tremor of the trajectory of the hand movement and sway of the center of pressure in ataxic patients,<sup>20–23</sup> to determine whether the extent of tremor of the trajectory of the fingertip during hand flexion and extension movement was different before and after the intervention.

Joint kinematic analysis during paretic hand movement in the motor task was performed simultaneously with EMG recordings. The EMG activity of the paretic FDI, FDS, and ED muscles were band-pass filtered (zero-lag Butterworth filter, 20–500 Hz), and EMG recordings were then full-wave rectified and smoothed using a fourth-order, zero-lag, low-pass filter (cut-off frequency: 6 Hz). The maximum value of the average muscle activity for 1 s during flexion–extension movement was calculated for each hand. The maximum value of four movements were averaged for each muscle. To further investigate the mechanism of kinematic changes resulting from the intervention, we calculated the co-contraction index<sup>24</sup> between FDS and ED, which are the agonist and antagonist muscles of hand flexion–extension movements. This index is an indicator related to the coordination of a pair of agonist–antagonist muscles and is calculated as follows:

$$\text{Co-contraction Index} = \frac{\text{EMGS}}{\text{EMGL}} \times (\text{EMGS} + \text{EMGL})$$

where EMGS is the level of activity in the less active muscle, and EMGL is the level of activity in the more active muscle. The mean value of the co-contraction index at  $\pm 500$  ms of each maximum flexion and extension angle was calculated. Then, the mean values of the co-contraction index for the four flexion–extension movements were calculated.

### Questionnaire Regarding Body Ownership and Illusory Sensation

Following the KINVIS intervention, the patient was asked to rate the sense of body ownership and illusory sensation during KINVIS using a 7-point Likert scale (–3, strongly disagree; 0, neither agree nor disagree; +3, strongly agree).

## RESULTS

### Body Ownership and Illusory Sensation

The patient rated his sense of body ownership during KINVIS as +2 (agree) and the subjective illusory sensation during KINVIS as +2 (agree).

### Paretic Hand Kinematics

The MP and PIP joint angles during hand flexion–extension movements are shown in **Fig. 2**. The average flexion–extension angle ranges for PIP and MP joint movement were slightly increased following KINVIS (**Table 2**). The trajectories of the index fingertip during hand flexion–extension movements completed before and after KINVIS are shown in **Fig. 3**. Prior to KINVIS, we observed prominent tremor in the fingertip trajectory during hand flexion–extension movements typical of the sensory ataxia with severe proprioceptive deficits present in this patient. The total trajectory length and the rectangular area bounding the trajectory of the index fingertip decreased after KINVIS (**Table 2**).

### Muscle Activity in the Paretic Hand

**Figure 2** shows the activities of the FDI, FDS, and ED muscles and the co-contraction index between FDS and ED muscles in the paretic hand during hand flexion–extension movements. Activation of the paretic FDI, FDS, and ED muscles increased after KINVIS (**Table 2**). The co-contraction index between FDS and ED muscles tended to be higher during the extension phase before the intervention but decreased after the intervention. Conversely, the co-contraction index during the finger flexion phase increased after the intervention (**Table 2**).

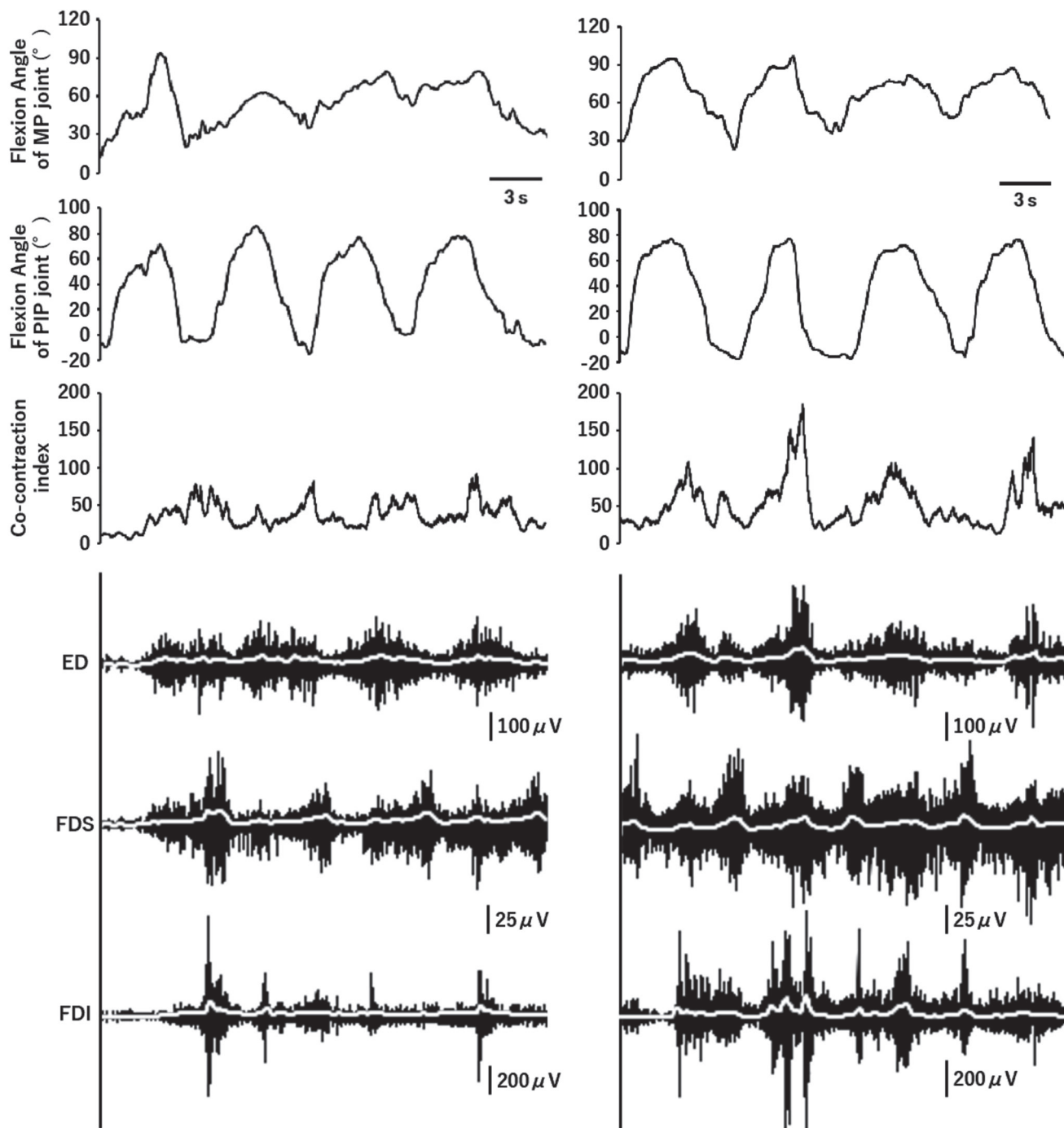
### Corticomotor Excitability

To examine corticomotor excitability before and after KINVIS, the amplitude of TMS-induced MEP was measured at two stimulation intensities (50% and 60% MSO). After KINVIS, the MEP amplitude for the FDI, FDS, and ED muscles in the paretic hand increased at both stimulus intensities (**Fig. 4**). Conversely, KINVIS did not consistently affect the MEP amplitude of the non-paretic FDI muscle.

## DISCUSSION

The results showed that, despite the patient's severe loss of kinesthetic perception, KINVIS intervention elicited virtual kinesthetic perception. In addition, tremor of the fingertip trajectory, the total trajectory length, and the rectangular





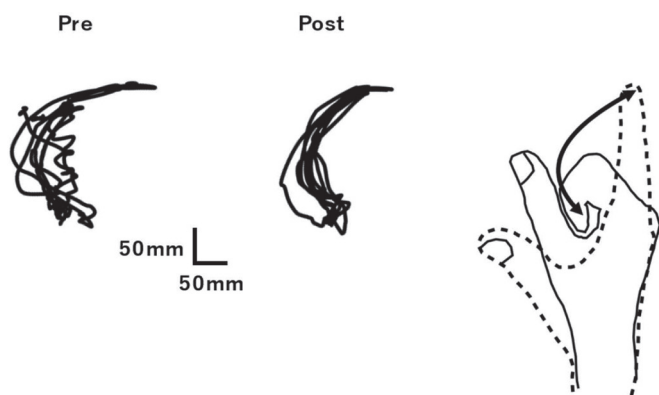
**Fig. 2.** Flexion angles of the metacarpophalangeal (MP) joint and the proximal interphalangeal (PIP) joint are shown before (left) and after (right) kinesthetic illusion induced by visual stimulus intervention. Also shown are electromyography (EMG) recordings of the activities of the extensor digitorum muscle (ED), the flexor digitorum superficialis muscle (FDS), and the first dorsal interosseous muscle (FDI) during hand flexion–extension movements (black lines, raw EMG; white lines, rectified and smoothed EMG). The co-contraction index between FDS and ED is also given.

area bounding the trajectory during hand flexion–extension movements decreased following KINVIS, despite slight increases in range of motion of the MP and PIP joints. In par-

allel with these kinematic changes, increased hand muscle activity and temporal changes in co-contraction between finger flexor and extensor muscles were observed during

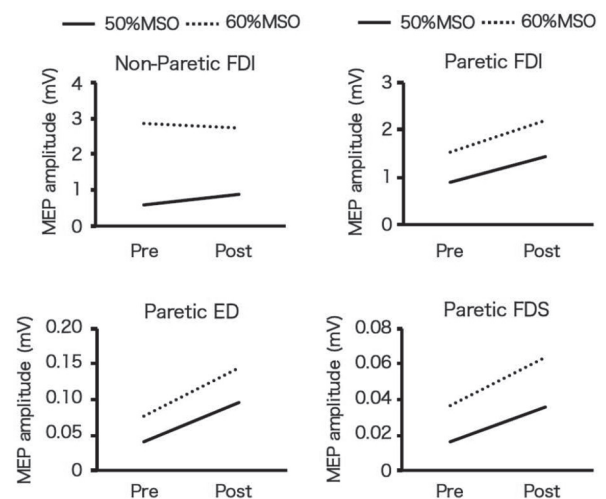
**Table 2.** Kinematic and EMG activity changes during hand flexion–extension movements before and after KINVIS intervention

		Pre	Post
Range of flexion–extension angle (°)	MP joint	34.9	40.2
	PIP joint	85.2	90.9
Total trajectory length (cm)		280.0	252.5
Rectangular area (cm <sup>2</sup> )		139.2	108.6
Maximum average EMG activity (μV)	Paretic FDI	40.0	61.7
	Paretic FDS	8.0	11.6
	Paretic ED	25.6	32.6
Co-contraction index	Flexion phase	36.1	78.4
	Extension phase	61.7	36.1

**Fig. 3.** The trajectory of the index fingertip during hand flexion–extension movements before and after KINVIS.

hand flexion–extension movements. These results suggested that KINVIS intervention may contribute to a reduction of ataxic symptoms associated with sensory loss, which may be related to changes in the level or coordination of muscle activity of the hand muscles.

Few effective treatments are available for sensory ataxia associated with loss of kinesthetic perception. Therapeutic interventions targeting sensory perception and balance were reported to improve dynamic balance in patients with chronic neuropathy or multiple sclerosis with sensory ataxia.<sup>7)</sup> Caronni et al.<sup>2)</sup> observed an effect of standard inpatient rehabilitation on sensory ataxia in patients with peripheral neuropathy, reporting significant improvements in walking ability and dynamic balance. Although no previous study has demonstrated improvements in sensory ataxia symptoms per se, the present results suggest that providing KINVIS instead of peripheral sensory input, which may be severely impaired, is a novel, potentially useful intervention for sensory ataxia. A previous study examining the effects

**Fig. 4.** Amplitude of the motor-evoked potential (MEP) at two stimulus intensities [50% and 60% of maximum stimulation output (MSO)] recorded for the paretic and non-paretic FDI muscles and the paretic ED and FDS muscles before and after KINVIS.

of KINVIS on paretic upper limb motor function in stroke patients indicated an increase in muscle activity during hand movement after the intervention.<sup>14)</sup> The results obtained here were consistent with those of this previous study. However, the previous study did not report the presence or absence of sensory impairment in stroke patients. Therefore, this is the first study to show that KINVIS intervention may be effective in improving motor function in patients with sensory deficits.

We speculated that changes in muscle coordination between hand muscles may be related to the mechanism underlying these kinematic changes in hand flexion–extension

sion movements. In the current study, we calculated the co-contraction index between FDS and ED, which are the agonist and antagonist muscles during hand flexion–extension movements, as a measure of hand muscle coordination. We found that the co-contraction index between FDS and ED was higher in the finger extension phase before the intervention, whereas it was higher in the flexion phase after the intervention. We were unable to determine whether the change in the temporal pattern of the co-contraction index after the intervention was the result of EMG activity approaching a normal pattern. However, because KINVIS intervention resulted in parallel changes in both the kinematics during finger flexion–extension movements and the temporal pattern of the co-contraction index of the agonist and antagonist muscles of these movements, the changes in temporal pattern of the co-contraction may have had some positive effect on the kinematic changes.

However, we cannot exclude the possibility that the kinematic changes in finger flexion–extension movements may have been caused not only by changes in muscle coordination but also by an increase in muscle activity itself. We found that the muscle activity in the paretic hand during hand flexion–extension movements increased after KINVIS, as reported previously.<sup>14)</sup> In parallel with these increases in muscle activity in the paretic hand muscles, we showed that MEP amplitudes in the paretic hand increased after the intervention, whereas there were no consistent changes in MEP amplitudes in the non-paretic hand. Therefore, KINVIS may have selectively increased corticomotor excitability in the damaged hemisphere, resulting in increased muscle activity during paretic hand movements. KINVIS-induced neurophysiological changes in normal individuals include increased frontoparietal network activity<sup>10)</sup> and increased corticomotor excitability as measured using TMS.<sup>12–14)</sup> However, it was unclear whether KINVIS increased corticomotor excitability in stroke patients. This is the first report showing that KINVIS could increase corticomotor excitability as well as muscle activity in a stroke patient. Further investigations are needed to determine whether the increases in corticomotor excitability and muscle activity are associated with improvements in hand kinematics in patients with sensory ataxia.

KINVIS has inherent advantages over other methods used to induce kinesthetic illusion, such as tendon vibration and mirror visual feedback (MVF). Tendon vibration induces a kinesthetic illusion by increasing Ia-afferent activity.<sup>25,26)</sup> This technique requires intact afferent transmission that activates the somatosensory cortex, which is not activated

during KINVIS.<sup>10)</sup> KINVIS does not require intact input from the paretic hand, making it more appropriate for use in cases of sensory ataxia associated with severe proprioceptive deficits.

MVF also induces a kinesthetic illusion and increases corticomotor excitability in healthy patients.<sup>27,28)</sup> Further, it reportedly increased excitability of the affected primary motor cortex (M1) in stroke patients after a single 30-min session.<sup>29)</sup> However, movement of the unaffected hand is required for MVF. Movement of the unaffected hand may increase M1 excitability in the unaffected hemisphere. In theory, this may inhibit increased M1 excitability in the affected hemisphere due to interhemispheric inhibition.<sup>30)</sup> The KINVIS system in the present study used a pre-recorded mirror image video of the non-paretic hand, allowing the generation of a kinesthetic illusion in the paretic hand without simultaneous movement of the non-paretic hand. Further, it selectively increased M1 excitability in the affected hemisphere. Therefore, KINVIS may circumvent potential issues arising from interhemispheric inhibition. Further studies are required to verify differences in neurophysiological effects between different kinesthetic illusion techniques, including comparison of the strength of interhemispheric inhibition between MVF and KINVIS.

The present case study had several limitations. First, although the patient in this study presented with sensory ataxia caused by a severe proprioceptive deficit, we cannot completely exclude a potential effect of cerebellar ataxia resulting from dentate–rubro–thalamic tract injuries. Second, we did not assess the changes in sensory function associated with the intervention. Indeed, previous studies examining the effects of KINVIS in stroke patients also did not investigate the changes in sensory function associated with the intervention.<sup>14,31)</sup> Consequently, we cannot exclude the possibility that improvement in hand movement was affected by changes in sensory function. This is an important issue that is closely related to the mechanisms underlying the effects of KINVIS, and further studies regarding this issue are required.

In this feasibility study, KINVIS therapy resulted in kinematic improvement of hand movements in a patient with sensory ataxia following stroke. Our results indicated that KINVIS is a new potentially useful intervention for sensory ataxia caused by severe kinesthetic deficits that currently have few effective treatment options. Future studies with larger sample sizes using not only kinematic data but also indexes of muscle coordination, brain activity, and sensory and motor function are needed to determine whether KIN-

VIS interventions are effective in ameliorating symptoms of sensory ataxia and to clarify the underlying mechanisms.

### ACKNOWLEDGMENTS

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### CONFLICTS OF INTEREST

FK is the founding scientist of Connect Inc., a commercial company set up in October 2018 for the development of rehabilitation devices. This company does not have any relationship with the device or setup used in the present study. FK received license fees from Inter Reha Co., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

### REFERENCES

- Rothwell JC, Traub MM, Day BL, Obeso JA, Thomas PK, Marsden CD: Manual motor performance in a deafferented man. *Brain* 1982;105:515–542. DOI:10.1093/brain/105.3.515, PMID:6286035
- Caronni A, Picardi M, Pintavalle G, Aristidou E, Redaelli V, Antoniotti P, Sterpi I, Tropea P, Corbo M: Responsiveness to rehabilitation of balance and gait impairment in elderly with peripheral neuropathy. *J Biomech* 2019;94:31–38. DOI:10.1016/j.jbiomech.2019.07.007, PMID:31327524
- Dobato JL, Villanueva JA, Giménez-Roldán S: Sensory ataxic hemiparesis in thalamic hemorrhage. *Stroke* 1990;21:1749–1753. DOI:10.1161/01.STR.21.12.1749, PMID:2264084
- Yekutieli M, Guttman E: A controlled trial of the retraining of the sensory function of the hand in stroke patients. *J Neurol Neurosurg Psychiatry* 1993;56:241–244. DOI:10.1136/jnnp.56.3.241, PMID:8459238
- Lynch EA, Hillier SL, Stiller K, Campanella RR, Fisher PH: Sensory retraining of the lower limb after acute stroke: a randomized controlled pilot trial. *Arch Phys Med Rehabil* 2007;88:1101–1107. DOI:10.1016/j.apmr.2007.06.010, PMID:17826453
- Doyle S, Bennett S, Fasoli SE, McKenna KT: Interventions for sensory impairment in the upper limb after stroke. *Cochrane Database Syst Rev* 2010;CD006331. DOI:10.1002/14651858.CD006331.pub2, PMID:20556766
- Missaoui B, Thoumie P: How far do patients with sensory ataxia benefit from so-called “proprioceptive rehabilitation”? *Neurophysiol Clin* 2009;39:229–233. DOI:10.1016/j.neucli.2009.07.002, PMID:19853794
- Desmurget M, Reilly KT, Richard N, Szathmari A, Mottolese C, Sirigu A: Movement intention after parietal cortex stimulation in humans. *Science* 2009;324:811–813. DOI:10.1126/science.1169896, PMID:19423830
- Shibata E, Kaneko F: Event-related desynchronization possibly discriminates the kinesthetic illusion induced by visual stimulation from movement observation. *Exp Brain Res* 2019;237:3233–3240. DOI:10.1007/s00221-019-05665-1, PMID:31630226
- Kaneko F, Blanchard C, Lebar N, Nazarian B, Kavounoudias A, Romaiuguère P: Brain regions associated to a kinesthetic illusion evoked by watching a video of one’s own moving hand. *PLoS One* 2015;10:e0131970. DOI:10.1371/journal.pone.0131970, PMID:26287488
- Kaneko F, Shibata E, Hayami T, Nagahata K, Aoyama T: The association of motor imagery and kinesthetic illusion prolongs the effect of transcranial direct current stimulation on corticospinal tract excitability. *J Neuroeng Rehabil* 2016;13:36. DOI:10.1186/s12984-016-0143-8, PMID:27079199
- Aoyama T, Kaneko F, Hayami T, Shibata E: The effects of kinesthetic illusory sensation induced by a visual stimulus on the corticomotor excitability of the leg muscles. *Neurosci Lett* 2012;514:106–109. DOI:10.1016/j.neulet.2012.02.069, PMID:22402187
- Kaneko F, Yasojima T, Kizuka T: Kinesthetic illusory feeling induced by a finger movement movie effects on corticomotor excitability. *Neuroscience* 2007;149:976–984. DOI:10.1016/j.neuroscience.2007.07.028, PMID:17935897
- Kaneko F, Inada T, Matsuda N, Shibata E, Koyama S: Acute effect of visually induced kinesthetic illusion in patients with stroke: a preliminary report. *Int J Neuro-rehabil* 2016;3:212. DOI:10.4172/2376-0281.1000212
- Sakamoto T, Arissian K, Asanuma H: Functional role of the sensory cortex in learning motor skills in cats. *Brain Res* 1989;503:258–264. DOI:10.1016/0006-8993(89)91672-7, PMID:2605518



16. Bernardi NF, Darainy M, Ostry DJ: Somatosensory contribution to the initial stages of human motor learning. *J Neurosci* 2015;35:14316–14326. DOI:10.1523/JNEUROSCI.1344-15.2015, PMID:26490869
17. Lazzaro VD, Oliviero A, Saturno E, Pilato F, Insola A, Mazzone P, Profice P, Tonali P, Rothwell J: The effect on corticospinal volleys of reversing the direction of current induced in the motor cortex by transcranial magnetic stimulation. *Exp Brain Res* 2001;138:268–273. DOI:10.1007/s002210100722, PMID:11417469
18. Kaneko K, Kawai S, Fuchigami Y, Morita H, Ofuji A: The effect of current direction induced by transcranial magnetic stimulation on the corticospinal excitability in human brain. *Electroencephalogr Clin Neurophysiol* 1996;101:478–482. DOI:10.1016/S0013-4694(96)96021-X, PMID:9020819
19. Stinear CM, Barber PA, Coxon JP, Fleming MK, Byblow WD: Priming the motor system enhances the effects of upper limb therapy in chronic stroke. *Brain* 2008;131:1381–1390. DOI:10.1093/brain/awn051, PMID:18356189
20. Day B, Thompson PD, Harding AE, Marsden CD: Influence of vision on upper limb reaching movements in patients with cerebellar ataxia. *Brain* 1998;121:357–372. DOI:10.1093/brain/121.2.357, PMID:9549511
21. Gera G, Fling BW, Horak FB: Cerebellar white matter damage is associated with postural sway deficits in people with multiple sclerosis. *Arch Phys Med Rehabil* 2020;101:258–264. DOI:10.1016/j.apmr.2019.07.011, PMID:31465761
22. Menegoni F, Milano E, Trotti C, Galli M, Bigoni M, Baudo S, Mauro A: Quantitative evaluation of functional limitation of upper limb movements in subjects affected by ataxia. *Eur J Neurol* 2009;16:232–239. DOI:10.1111/j.1468-1331.2008.02396.x, PMID:19146643
23. Nakamura K, Yoshida K, Miyazaki D, Morita H, Ikeda S: Spinocerebellar ataxia type 6 (SCA6): clinical pilot trial with gabapentin. *J Neurol Sci* 2009;278:107–111. DOI:10.1016/j.jns.2008.12.017, PMID:19157422
24. Rudolph KS, Axe MJ, Buchanan TS, Scholz JP, Snyder-Mackler L: Dynamic stability in the anterior cruciate ligament deficient knee. *Knee Surg Sports Traumatol Arthrosc* 2001;9:62–71. DOI:10.1007/s001670000166, PMID:11354855
25. Roll JP, Vedel JP: Kinaesthetic role of muscle afferents in man, studied by tendon vibration and microneurography. *Exp Brain Res* 1982;47:177–190. DOI:10.1007/BF00239377, PMID:6214420
26. Albert F, Bergenheim M, Ribot-Ciscar E, Roll JP: The Ia afferent feedback of a given movement evokes the illusion of the same movement when returned to the subject via muscle tendon vibration. *Exp Brain Res* 2006;172:163–174. DOI:10.1007/s00221-005-0325-2, PMID:16421730
27. Garry MI, Loftus A, Summers JJ: Mirror, mirror on the wall: viewing a mirror reflection of unilateral hand movements facilitates ipsilateral M1 excitability. *Exp Brain Res* 2005;163:118–122. DOI:10.1007/s00221-005-2226-9, PMID:15754176
28. Jegatheeswaran G, Vesia M, Isayama R, Gunraj C, Chen R: Increases in motor cortical excitability during mirror visual feedback of a precision grasp is influenced by vision and movement of the opposite limb. *Neurosci Lett* 2018;681:31–36. DOI:10.1016/j.neulet.2018.05.026, PMID:29787788
29. Novaes MM, Palhano-Fontes F, Peres A, Mazzetto-Betti K, Pelicioni M, Andrade KC, dos Santos AC, Pontes-Neto O, Araujo D: Neurofunctional changes after a single mirror therapy intervention in chronic ischemic stroke. *Int J Neurosci* 2018;128:966–974. DOI:10.1080/00207454.2018.1447571, PMID:29490535
30. Ferbert A, Priori A, Rothwell JC, Day BL, Colebatch JG, Marsden CD: Interhemispheric inhibition of the human motor cortex. *J Physiol* 1992;453:525–546. DOI:10.1113/jphysiol.1992.sp019243, PMID:1464843
31. Kaneko F, Shindo K, Yoneta M, Okawada M, Akaboshi K, Liu M: A case series clinical trial of a novel approach using augmented reality that inspires self-body cognition in patients with stroke: effects on motor function and resting-state brain functional connectivity. *Front Syst Neurosci* 2019;13:76. DOI:10.3389/fnsys.2019.00076, PMID:31920571