

# EEG frequency analysis of cortical brain activities induced by effect of light touch

Tomoya Ishigaki<sup>1,2</sup> · Kozo Ueta<sup>3</sup> · Ryota Imai<sup>1</sup> · Shu Morioka<sup>1,3</sup>

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**Abstract** In human postural control, touching a fingertip to a stable object with a slight force (<1 N) reduces postural sway independent of mechanical support, which is referred to as the effect of light touch (LT effect). The LT effect is achieved by the spatial orientation according to haptic feedback acquired from an external spatial reference. However, the neural mechanism of the LT effect is incompletely understood. Therefore, the purpose of this study was to employ EEG frequency analysis to investigate the cortical brain activity associated with the LT effect when attentional focus was strictly controlled with the eyes closed during standing (i.e., control, fixed-point touch, sway-referenced touch, and only fingertip attention). We used EEG to measure low-alpha (about 8–10 Hz) and high-alpha rhythm (about 10–12 Hz) task-related power decrease/increase (TRPD/TRPI). The LT effect was apparent only when the subject acquired the stable external spatial reference (i.e., fixed-point touch). Furthermore, the LT-specific effect increased the high-alpha TRPD of two electrodes (C3, P3), which were mainly projected from cortical brain activities of the left primary sensorimotor cortex area and left posterior parietal cortex area. Furthermore, there was a negative correlation between the LT effect and increased TRPD of C3. In contrast, the LT effect correlated positively with

increased TRPD of P3. These results suggest that central and parietal high-alpha TRPD of the contralateral hemisphere reflects the sensorimotor information processing and sensory integration for the LT effect. These novel findings reveal a partial contribution of a cortical neural mechanism for the LT effect.

**Keywords** Postural control · Center of foot pressure (CoP) · Haptic feedback · EEG · Alpha rhythm · Task-related power decrease/increase (TRPD/TRPI)

## Introduction

Human postural control is a dynamic and complex skill based on sensory and motor interactions. Moreover, sensory feedback mechanisms (i.e., vision, somatosensory, and vestibular) are required for adapting postural orientation to an environment (Horak 2006). For example, subjects show greater postural sway when standing with their eyes closed compared with when their eyes are open (Edwards 1946). Similarly, greater postural sway occurs when afferent sensory feedback is attenuated by a foam rubber mat (Peterka and Black 1990–1991) or an ischemic block of the lower limb (Mauritz and Dietz 1980; Diener et al. 1984). Further in vestibular, galvanic vestibular stimulation induces postural displacement (Fitzpatrick et al. 1994).

The effect referred to as the effect of light touch (LT effect) is a postural orientation based on haptic feedback transmitted to the somatosensory system (Holden et al. 1994; Jeka 1997). This effect reduces postural sway by touching with a fingertip using slight force (i.e., <1 N) to a stable object. This effect is not achieved using mechanical support, but through afferent haptic feedback (Holden et al. 1994; Jeka and Lackner 1994; Kouzaki and Masani

✉ Tomoya Ishigaki  
p0611006@gmail.com

<sup>1</sup> Department of Neurorehabilitation, Graduate School of Health Sciences, Kio University, 4-2-2 Umaminaka, Koryo-cho, Kitakaturagi-gun, Nara 635-0832, Japan

<sup>2</sup> Department of Rehabilitation, Higashiikoma Hospital, 4-1, Tsuji, Ikoma-City, Nara, Japan

<sup>3</sup> Neuro Rehabilitation Research Center, Kio University, 4-2-2 Umaminaka, Koryo-cho, Kitakaturagi-gun, Nara 635-0832, Japan

2008), and this haptic feedback is used as a spatial reference for orientation (Jeka et al. 1998; Reginella et al. 1999; Krishnamoorthy et al. 2002). Furthermore, during the LT effect, illusory kinesthesia, which is induced using vibratory tendon stimulus on the biceps brachii of the touch side, displaces the center of foot pressure (CoP) to the touching side (Rabin et al. 2008). These findings indicate that the spatial reference provided by the stable object is a fundamental factor in achieving the LT effect.

Additionally, other studies suggest that supraspinal pathways (i.e., central nervous system; CNS) affording complex sensory processing contribute to the LT effect. Indeed, excitability of spinal anterior horn cells, which is evaluated by H-reflex of soleus muscle, is modulated during the LT effect (Huang et al. 2009). Furthermore, a long latency (approximately 300 ms) from haptic input until the adjusted postural sway is shown (Jeka and Lackner 1995). Additionally, previous studies focused on time series varying of postural sway employed the methods of intermittent light touch, and revealed that a few seconds (approximately 0.5–3 s) for the integrative process of haptic feedback are required before achieving sway stabilization by LT (Rabin et al. 2006; Sozzi et al. 2012). Thus, it suggests an involvement of sensory integration process in CNS, because changes in postural sway require a certain time from haptic input, which is much longer than reflexes or rapid voluntary responses. In a more closely designed study, in case of withdrawing after the 2-s touch, the level of postural sway increases and returns to baseline almost immediately. However, in case of a 5-s touch, reductions in postural sway persist for a few seconds, even after touch withdrawal (Johannsen et al. 2014). This after withdrawal effect also indicates that the integration of haptic feedback is likely to involve not only bottom-up sensory process but also top-down postural control and selective attention to the haptic information. In bottom-up sensory process, unperceivable vibratory noise to the fingertip enhances the LT effect (Magalhães and Kohn 2011; Kimura et al. 2012), and these findings indicate an involvement of unconscious mechanical sensory input intensity for the LT effect. On the other hand, when focusing on the involvement and influence of attention during the LT effect, the attentional demands are allocated (Vuillerme et al. 2006). Moreover, spatial orientation to the touched object is enhanced, even if it was unstable, such as a “curtain,” when the subject was instructed to focus on the relative position between the touch object and the body (Riley et al. 1999; McNevin and Wulf 2002). These findings also indicate that cerebral cortex, having function of sensory integration and attention, is involved in the LT effect.

To summarize the previous studies, although these studies establish that the LT effect is achieved by the spatial orientation through haptic feedback from the spatial reference

with attention focused on the touch point, they only evaluate behavioral indicators of motor output, such as postural sway, muscle activity, or fingertip contact force. Thus, the cortical brain activity which contributes to motor control is incompletely identified. However, in a study which focuses on cerebral brain activities, Bolton et al. (2011) measured somatosensory evoked potentials (SEP) to evaluate cortical brain activities and found that a peak amplitude of the P200 component during the stable touch condition (i.e., achieve the LT effect) show higher value than the no-touch and sway-referenced touch conditions. Moreover, Bolton et al. (2012) applied continuous  $\theta$ -burst transcranial magnetic stimulation (TMS), which inhibits cerebral activity, on the right dorsolateral prefrontal cortex and right primary motor cortex. As the results in both applied areas, the amplitude of the P200 component in the stable touch condition did not change. By contrast in the sway-referenced touch condition, the amplitude of the P200 component applied on the right dorsolateral prefrontal cortex showed relatively higher value than that of the right primary motor cortex. These findings suggest that the P200 component indicates the degree of a loss of “sensory gating” for the irrelevant haptic information to postural control and the right dorsolateral prefrontal cortex serve to this sensory gating function. However, they did not detect a correlation between the amplitude of the P200 component and decreased postural sway caused by the LT effect. Furthermore, the right dorsolateral prefrontal cortex is not related to the LT effect. Additionally, although Johannsen et al. (2014) reported that the disruption of left inferior parietal gyrus through 1-Hz repetitive TMS alters the time course of postural sway following an unpredictable contact removal, but the steady states of postural sway during the LT is not influenced. In consequence, the cortical brain activity which correlates with the LT effect as well as the neural mechanisms of the LT effect remains to be defined.

We believe that the two causes account for the lack of correlation between cortical brain activity and the LT effect reported by Bolton et al. (2011). First, attentional focus was not strictly controlled during standing. Although attentional focus to haptic input at the touch fingertip was controlled in the previous study (Bolton et al. 2011) using sway-referenced touch, which subjects were required to maintain fingertip contact on an object fixed about their wrist, the instruction for controlling attentional focus of the subjects was not followed. Actually, attentional focus on the touch point enhances and modulates the LT effect (Riley et al. 1999; McNevin and Wulf 2002). Moreover, previous studies document the influence of postural sway through controlling the subject’s attention on static standing (Wulf et al. 2004; Vuillerme and Nafati 2007; Reynolds 2010; Ueta et al. 2014), and these studies basically employed the emphasized instruction for controlling

attentional focus. Wulf et al. (2004) found that the external focus of attention reduces postural sway compared with internal focus of attention, and Vuillerme and Nafati (2007) found that the internal focus of attention on body sway promoted the use of less automatic control process compared with non-attentional condition. Specifically, in comparison with the automatic-controlled standing condition, Ueta found that the spatial variables of CoP are reduced by the internal focus of attention on the body sway, whereas the variables of CoP velocity are increased. Additionally, Reynolds (2010) found that the degree of voluntary control (i.e., effort to minimize postural sway) is increased according to the difficulty level of standing balance task. For these reasons, strict control of attentional focus is also required to compare the LT effects (postural sway) and to evaluate the LT effect on specific postural sway and cortical brain activity. Therefore, it is necessary to employ the controlled conditions such as spatial reference, haptic feedback, and attentional focus using the emphasized instruction to the subjects. Second, SEP evaluate cortical brain activity only during a few hundred milliseconds after the nerve stimulus induction. Thus, it might not be appropriate to investigate the relation between cortical brain activity measured using SEP and postural sway showing a periodic change during standing (i.e., ongoing task), since the time window for analysis differs greatly for each indicator. Besides, SEP require a nerve stimulus to evaluate cortical sensory processing, and this additional sensory input by nerve stimulus might contaminate natural sensory input obtained by touching. This instantaneous stimulus itself might induce a postural destabilizing. Thus, it is proper to employ a more precise electroencephalogram (EEG) measurement which is not contaminated with an additional sensory “jolt” to the sensory processing system. Therefore, we reasoned that a suitable approach might be provided by employing frequency analysis of the spontaneous EEG acquired when subjects are standing. Among studies employing EEG frequency analysis to investigate the cortical brain activity of an upright standing (Del Percio et al. 2007, 2009; Vecchio et al. 2008; Slobounov et al. 2009; Petrofsky et al. 2012; Tse et al. 2013; Petrofsky and Khowailed 2014), Del Percio et al. (2007) found a significant correlation between the changes in postural sway as well as the changes in cortical brain activity of subjects’ whose eyes were open compared with the those whose eyes were closed.

Therefore, to reveal the cortical neural mechanism of the LT effect, we employed EEG frequency analysis in the present study to investigate the cortical brain activity associated with the LT effect when attentional focus was more strictly controlled standing condition. Moreover, we hypothesized that only a standing condition which makes it possible to establish a stable spatial reference through haptic feedback reduces postural sway (i.e., the LT effect),

even if the other factors are controlled, and also hypothesized that EEG frequency analysis demonstrates a significant correlation between cortical brain activity and postural sway specific to the LT effect.

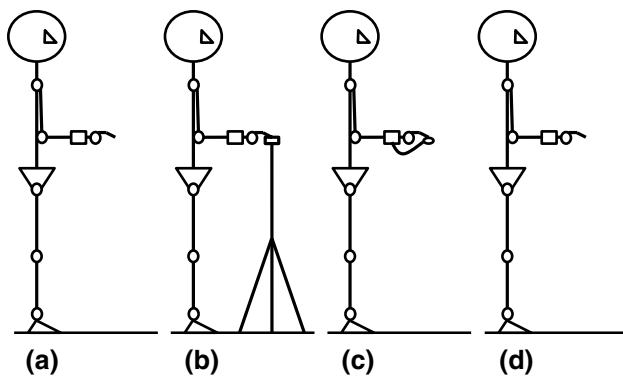
## Methods

### Subjects

Subjects included 15 healthy right-handed adults (age  $23.1 \pm 4.1$  years, weights  $56.5 \pm 9.3$  kg, height  $166.7 \pm 9.7$  cm, mean  $\pm$  standard deviation). Two subjects were excluded for excessive artifact, and one left-handed subject was excluded to avoid an influence by touching with non-dominant hand on the LT effect or cortical brain activity. The dominant hand was assessed using the Edinburgh Inventory (Oldfield 1971). The subjects claimed no history of neurological or musculoskeletal deficits. The study protocol conformed to the Declaration of Helsinki (1964), and all subjects were informed at the start of the study that they could discontinue participation at any time. We explained only the details of the experimental procedure to minimize biasing the results. Before participating, subjects granted written informed consent. The Ethics Committee of Kio University Health Science Graduate School approved this study (approval number H25-26).

### Tasks

The subjects stood quietly on a stabilometer with their feet together and eyes closed. The left arm was positioned with the right elbow flexed  $90^\circ$ , and only the index finger was extended. To control for haptic feedback, spatial reference, and point of attentional focus that influence the LT effect, four conditions were set as follows (Fig. 1): In the control (C) condition (Fig. 1a), the subjects were instructed to concentrate full attention on their body movement to minimize it as far as possible (Reynolds 2010) to control attentional strength to the postural control compared with the other conditions. Second, in the fixed-point touch (FT) condition (Fig. 1b), subjects touched the stable top surface of a tripod with their right index fingertip with a slight force ( $<1$  N), and they were instructed to concentrate full attention on the touch-point movement to minimize it as much as possible (Riley et al. 1999; McNevin and Wulf 2002; Reynolds, 2010). This condition maintained a stable spatial reference (i.e., fixed point). Third, in the sway-referenced touch (ST) condition (Fig. 1c), subjects touched with a slight force a surface fixed to the right wrist with a wristband, and they were instructed to concentrate full attention on the touch-point movement to minimize it as much as possible (Riley et al. 1999; McNevin and Wulf



**Fig. 1** Subject positioning. The subjects stood on a stabilometer with their feet together, eyes closed, and the *left arm* positioned vertically with the *right elbow* flexed 90° with only the index finger extended. **a** Control condition. Subjects were instructed to concentrate full attention on their body movement and to try hard to minimize it as much as possible. **b** Fixed-point touch condition. Subjects touched the stable top surface of a tripod with their *right index fingertip* with a slight force (<1 N) and were instructed to concentrate full attention on the touch-point movement and try hard to minimize it as much as possible. **c** Sway-referenced touch condition. Subjects touched with a slight force the surface fixed to the right wrist with a band, and they were instructed to concentrate full attention on the touch-point movement and try hard to minimize it as much as possible. **d** Fingertip attention (FA). Subjects were instructed only to concentrate full attention on the movement of the right index fingertip and try hard to minimize it as much as possible

2002). This contact comprised a small plate-tipped wire (28.5 g solder wire, 1.2 mm dia.) secured to the right wrist and approximately 2 cm from the neutral-hanging index finger to serve as an unstable spatial frame reflecting postural sway (Bolton et al. 2011, 2012). This condition acquired only afferent haptic feedback but did not establish a stable external spatial reference. Fourth, in the fingertip attention (FA) condition (Fig. 1d), subjects were instructed only to concentrate full attention on the movement of the right index fingertip to minimize it as much as possible (Riley et al. 1999; McNevin and Wulf 2002). Except for the ST condition, to control for sensory input during the other conditions, subjects wore band on the right wrist that was adjusted to the same weight as wristband worn during the ST condition.

### Experimental protocol

The experiments were performed in a quiet and bright soundproof room. Before recording, subjects practiced light touching (<1 N) with feedback from a monitor. During the recording of each task, first, condition C was performed for 30 s, and conditions FT, ST, and FA were performed for 30 s in random order. To avoid fatigue, between each trial, the subjects rested with eyes open while seated. Two trials of each protocol were conducted.

### Fingertip contact force recording and data analysis

A force sensor (FlexiForce B201, Tekscan, South Boston, MA, USA) mounted on the horizontal top surface of tripod was used only for condition FT. A data recording system (ELF System, Tekscan, South Boston, MA, USA) was used to record the force in newtons generated by the fingertip contact. Contact force data were sampled at 20 Hz, the average fingertip contact force during 30 s was calculated for each trial, and the data are presented as the average of each trial.

### Center of foot pressure (CoP) recording and data analysis

A stabilometer (Twin Gravicorder G-6100, Anima, Tokyo, Japan) and G55smp software (Anima, Tokyo, Japan) were used to record CoP displacement. CoP data were sampled at 100 Hz, and offline data analysis software (G56dsp, Anima, Tokyo, Japan) was used to calculate the postural sway values. The amplitude of CoP of the frontal plane (CoPx) and sagittal plane (CoPy) was used. The CoP data acquired during 30 s were low-pass filtered at 6 Hz. Postural sway values are expressed as the root mean square area (RMS area) calculated using the equation as follows: root mean square (RMS) area

$$\text{RMS area} [\text{cm}^2] = \pi \left( \frac{1}{n} \sum_{i=1}^n \sqrt{(\text{CoPx}_i - \text{CoPx}_m)^2 + (\text{CoPy}_i - \text{CoPy}_m)^2} \right)^2$$

The data are presented as the average of the trials.

### EEG recording and preliminary data analysis

EEG was continuously recorded using Active Two system (BioSemi, Amsterdam, the Netherlands) and data recording software (ActiView, BioSemi, Amsterdam, the Netherlands). Active Ag–AgCl electrodes placed in an elastic head cap to record continuously EEG data from 32 scalp locations organized according to 10–20 system were used. The electrodes position were as follows: Fp1, Fp2, AF3, AF4, F7, F3, Fz, F4, F8, FC5, FC1, FC2, FC6, T7, C3, Cz, C4, T6, CP5, CP1, CP2, CP6, P7, P3, Pz, P4, P8, PO3, PO4, O1, Oz, and O2. The ground electrode used in conventional systems with two separate electrodes (the Common Mode Sense active electrode and the Driven Right Leg passive electrode). These electrodes form a feedback loop, driving the common mode potential of the subjects down and reducing the effective impedance of the ground. Data were digitized at 24-bit resolution and sampled at 1024 Hz. The EEG data were analyzed using multimodal EEG

analysis software (EMSE Suite 5.4, Source Signal Imaging, La Mesa, CA, USA). EEG data were band-pass filtered in the range of 1.0–80.0 Hz and applied to a common average reference montage. The removal of artifacts generated by eyes blinking, eyes movements, facial muscle activity, or body movement was performed using a specially designed spatial filter in EMSE Suite 5.4 (Source Signal Imaging, La Mesa, CA, USA) and visual inspection of frontal EEG trace (Fp1, Fp2).

### Determination of individual alpha sub-bands

The EEG data were divided into 2-s segments. The segmented data were subjected to power spectral analysis, which was performed using a standard FFT algorithm using Welch technique and Hanning window (50 % overlap) function. All individual power density of EEG spectra sharply declined before and after at the alpha-band (about 8–12 Hz) peak frequencies (around 10 Hz). In contrast, some of the subjects (6 out of 15) did not show clear beta-band (about 16–30 Hz) peak frequencies. Therefore, we used only alpha band for further EEG analysis.

For the determination of the alpha sub-bands, individual alpha frequency (IAF) peak was identified according to the same procedure of previous studies (Del Percio et al. 2007, 2009), which complied on the literature guidelines (Klimesch 1996, 1999; Klimesch et al. 1998). Practically, IAF was defined as the frequency showing the higher power density at 6- to 12-Hz range of the individual EEGs. With reference to IAF, the alpha sub-bands of interest were as follows: low-frequency alpha band as IAF – 2 Hz to IAF and high-frequency alpha band as IAF to IAF + 2 Hz. Mean IAF values were 10.5 Hz ( $\pm 0.9$ ;  $\pm$ standard deviation) for the C condition, 10.5 Hz ( $\pm 0.7$ ;  $\pm$ standard deviation) for the FT condition, 10.4 Hz ( $\pm 0.8$ ;  $\pm$ standard deviation) for the ST condition, and 10.4 Hz ( $\pm 0.8$ ;  $\pm$ standard deviation) for the FA condition.

### Computation of alpha task-related power decrease/increase (TRPD/TRPI)

Changes of the low-alpha and high-alpha band power density during each condition (FT, ST, and FA) compared with the C condition were calculated using the same line of reasoning widely used for the computation of event-related desynchronization/synchronization (ERD/ERS) (Pfurtscheller and Lopes da Silva 1999).

The equation used was Task-related power decrease/increase (TRPD/TRPI)

$$\frac{\text{TRPD}}{\text{TRPI}} [\%] = \left( \frac{E - C}{C} \right) \times 100$$

where  $E$  indicates the alpha power density during the experimental conditions (FT, ST, and FA) and  $C$  indicates the alpha power density during the C condition. The same procedure was repeated for low-alpha and high-alpha sub-bands. Percent negative values (i.e., lower alpha power density during the experimental condition than the C condition) represent the alpha TRPD (Gerloff et al. 1998; Manganotti et al. 1998). On the contrary, percent positive values (i.e., higher alpha power density during the experimental condition than the C condition) represent the alpha TRPI (Gerloff et al. 1998; Manganotti et al. 1998). This equation is also used in other EEG study of standing balance (Del Percio et al. 2009). Note that we did not use ERD/ERS index but TRPD/TRPI index, since we investigated steady-state changes associated with different conditions rather than phasic changes associated with a single discrete “event.”

In addition, two-dimensional (2D) scalp topography consisted of the TRPD/TRPI value for each condition, and sub-band was generated using EMSE Suite 5.4 (Source Signal Imaging, La Mesa, CA, USA) with spline interpolation.

### Statistical analysis

One-way analysis of variance (ANOVA) was used to test hypotheses by comparing the RMS area and the ERD/ERS among the touch conditions. A post hoc test using the Bonferroni correction was used to compare the FT condition and the other conditions (C, ST, and FA) in the RMS area ( $P$  values at  $P < 0.05$  corrected). Likewise, in comparisons of TRPD/TRPI, the Bonferroni correction was used for comparing the FT condition with the other conditions (ST and FA). In addition, we employed interest electrodes (C3, C4, P3, and C4) for statistical analysis. These electrodes are roughly located on the scalp area which are mainly projected from the cortical brain activity of primary sensorimotor cortex (PSMC: C3, C4) area and posterior parietal cortex (PPC: P3, P4) area (Okamoto et al. 2004; Koessler et al. 2009; Giacometti et al. 2014), and these areas relate to the processing of afferent somatosensory information, efferent motor command, and integration of somatosensory information in humans (Iwamura 1998; Dijkerman and de Haan 2007). Therefore, we considered not only the number of condition combinations, but also the number of interest electrodes, when Bonferroni correction is applied in comparison of TRPD/TRPI ( $P$  values at  $P < 0.05$  corrected).

The Pearson’s product–moment correlation coefficient was used to examine the relation between the change in the ratio of the RMS area compared with the C condition (i.e., degree of the LT effect) and the value of TRPD/TRPI. This



change in the ratio of the RMS area was used to evaluate the magnitude of the LT effect and was calculated using the equation as follows:

Change in the ratio of the RMS area (%)

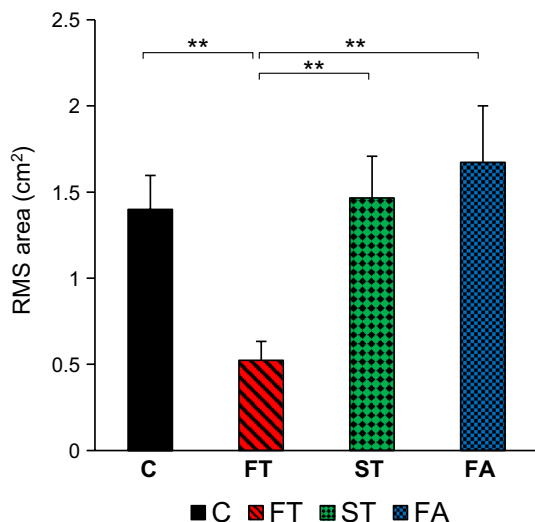
$$= \left( \frac{\text{Value of the LT effect specific condition} - \text{Value of the C condition}}{\text{Value of the C condition}} \right) \times 100$$

The correlation analysis was performed for each standing condition, and low-alpha and high-alpha sub-bands on the electrodes of interest (C3, C4, P3, and P4) show statistically significant differences at the above ANOVA of TRPD/TRPI. Bonferroni correction was applied for the multiple repetition of the correlation analysis. Statistical analysis software SPSS version 20 for Windows (IBM, Armonk, NY, USA) was used for the statistical calculations.  $P$  values of  $<0.05$  were considered statistically significant.

## Results

### Fingertip contact force

In all trials of the FT condition, the contact forces were  $<1$  N. The average of the contact force was  $0.43 \pm 0.18$  N (mean  $\pm$  standard deviation).



**Fig. 2** Average RMS areas ( $\text{cm}^2$ ) ( $\pm$ standard error) of all subjects. C (black), control condition; FT (red oblique line), fixed-point touch condition; ST (green rhomboid), sway-referenced touch condition; FA (blue shade), fingertip attention condition. \*\*Only the average RMS area of the FT condition was significantly lower compared with that of any other condition ( $P < 0.01$ )

### Postural sway—RMS area

We hypothesized that the FT condition would only reduce postural sway compared with the other conditions, and this

reduced RMS area in the FT condition would indicate the LT effect. To test this hypothesis, we used the computational and statistical analyses described in Methods. As the result, there was significant difference between the RMS areas of each condition ( $F_{3,14} = 16.84$ ,  $P < 0.001$ ). Post hoc tests of comparing the FT condition with the other conditions revealed that only the RMS area of the FT condition (RMS area  $0.52 \pm 0.11$   $\text{cm}^2$ , mean  $\pm$  standard error) was significantly lower (RMS area; C:  $1.40 \pm 0.20$   $\text{cm}^2$ , ST:  $1.46 \pm 0.24$   $\text{cm}^2$ , FA:  $1.67 \pm 0.33$   $\text{cm}^2$ , mean  $\pm$  standard error) (all comparisons,  $P < 0.001$ ) (Fig. 2).

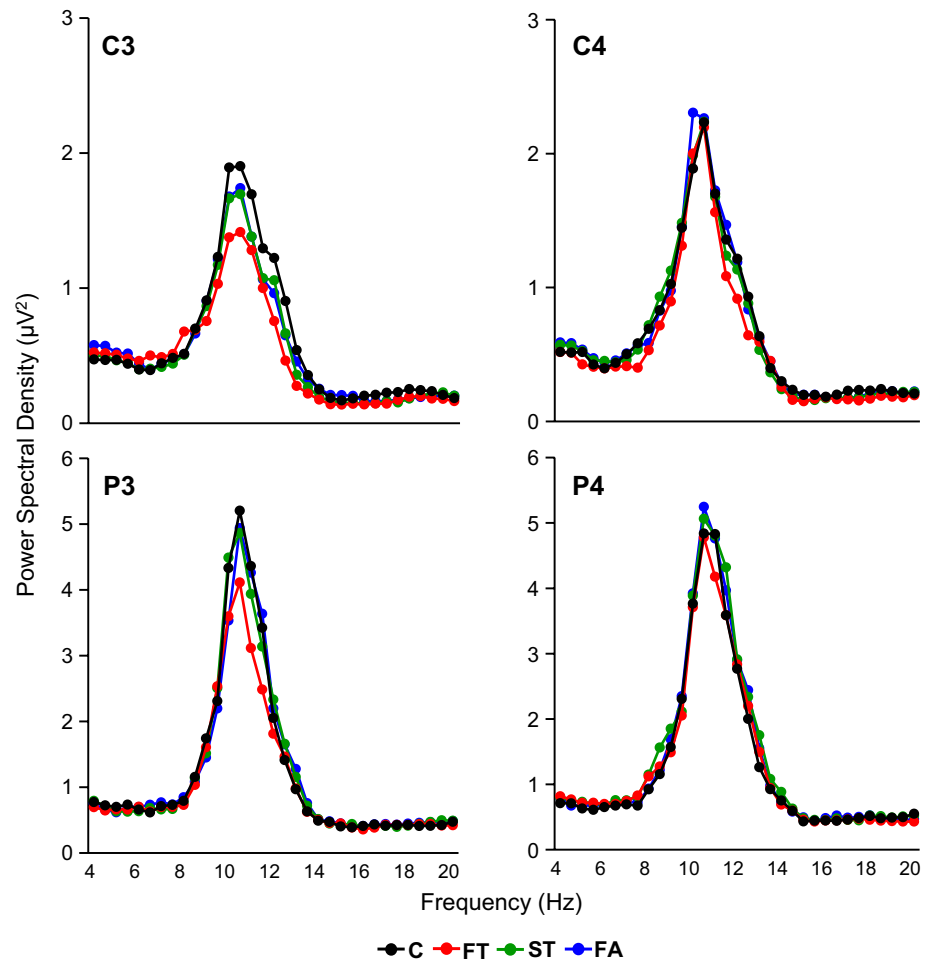
### EEG analysis of TRPD/TRPI

The power spectral density (grand average) data are shown in Fig. 3 for the each condition and four electrodes interest (C3, C4, P3, and P4). The figure represents the power density around the alpha range in the C, FT, ST, and FA conditions. In all conditions, there was an evident IAF around 10 Hz greater in parietal area electrodes (P3 and P4). Particularly, in the C3 and P3 channels, there were certain attenuation of the alpha power density (i.e., alpha TRPD) in the FT condition compared with the C and the other conditions.

Grand-averaged low-alpha and high-alpha TRPD/TRPI value of all channels for the FT, ST, and FA conditions (C condition as a baseline) are displayed as the 2D scalp topography (Fig. 4). Around the C3 and P3 electrodes, TRPD was observed clearly in the FT condition compared with the ST and FA conditions. It was more strongly and widely observed in the high-alpha band than low-alpha band.

To reveal the cortical brain activity specific to the LT effect, we employed the computational and statistical analyses described in Methods. As the result, the ANOVA for the low-alpha TRPD/TRPI showed no significant difference (all electrodes;  $P > 0.1$ ) (Fig. 5) and was not further considered. On the other hand, the ANOVA for the high-alpha TRPD/TRPI showed significant differences in the C3 ( $F_{2,14} = 5.79$ ,  $P = 0.008$ ) and P3 electrode ( $F_{2,14} = 6.76$ ,  $P = 0.004$ ). There were no significant differences in the other interested electrodes of high-alpha TRPD/TRPI (all channels;  $P > 0.1$ ) (Fig. 6). Post hoc tests between the high-alpha TRPD/TRPI of the FT and other conditions in the

**Fig. 3** Power spectral density (grand average) of EEG data for the electrodes of interest C3, C4, P3, P4. The graphs represent the power spectral density around the alpha range (4–20 Hz) in each electrode. C (black line), control condition; FT (red line), fixed-point touch condition; ST (green line), sway-referenced touch condition; FA (blue line), fingertip attention condition



C3 channel revealed that only the TRPD value of the FT condition (TRPD/TRPI— $19.41 \pm 5.91$  %, mean  $\pm$  standard error) was significantly higher as compared with any other conditions (TRPD/TRPI; ST,  $-4.63 \pm 5.55$  %; FA,  $-4.63 \pm 6.31$  %; mean  $\pm$  standard error) (FT vs. ST;  $P = 0.042$ , FT vs. FA;  $P = 0.038$ ) (Fig. 6), and in the P3 channel revealed that only the TRPD value of the FT condition (TRPD/TRPI— $17.66 \pm 2.56$  %, mean  $\pm$  standard error) was significantly higher as compared with any other conditions (TRPD/TRPI; ST,  $0.18 \pm 4.34$  %; FA,  $3.62 \pm 6.93$  %; mean  $\pm$  standard error) (FT vs. ST;  $P = 0.046$ , FT vs. FA;  $P = 0.011$ ) (Fig. 6).

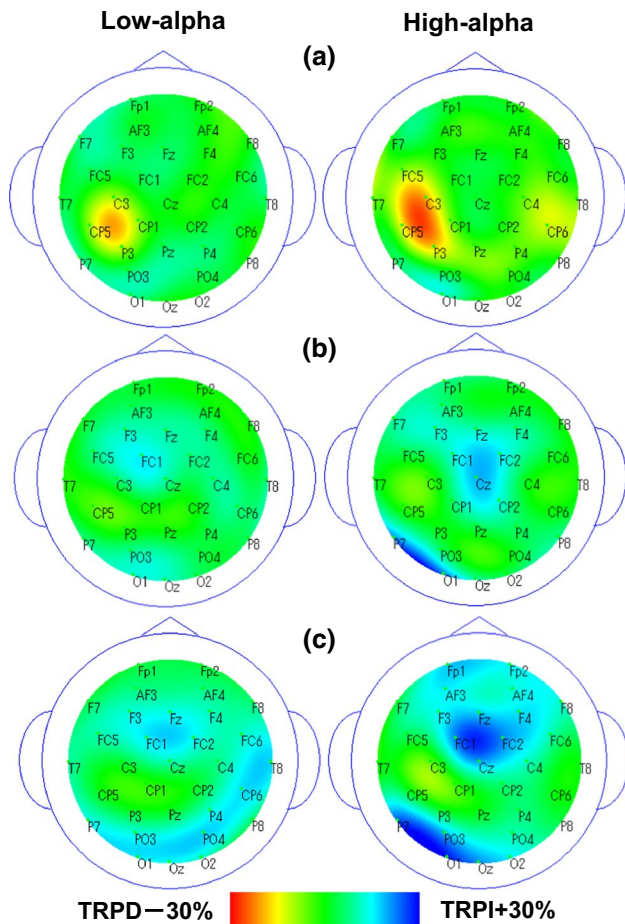
#### Correlation between the change in the RMS area ratio and TRPD/TRPI

According to the above ANOVA results of RMS area and TRPD/TRPI, the correlation analysis was performed in the FT condition between the high-alpha TRPD and change in RMS area ratio compared with the C condition. For two repetitions of correlation analysis at the C3 and P3, Bonferroni correction was applied at  $P$  value as  $P < 0.025$

(in result  $P$  values at  $P < 0.05$  corrected). As results, the change in the RMS area ratio compared with the C condition and the TRPD/TRPI value of C3 channel in the FT condition showed a significant negative correlation ( $r = -0.78$ ,  $P = 0.001$ ) (Fig. 7), and on the other hand, P3 channel showed a significant positive correlation ( $r = 0.65$ ,  $P = 0.017$ ) (Fig. 7).

#### Discussion

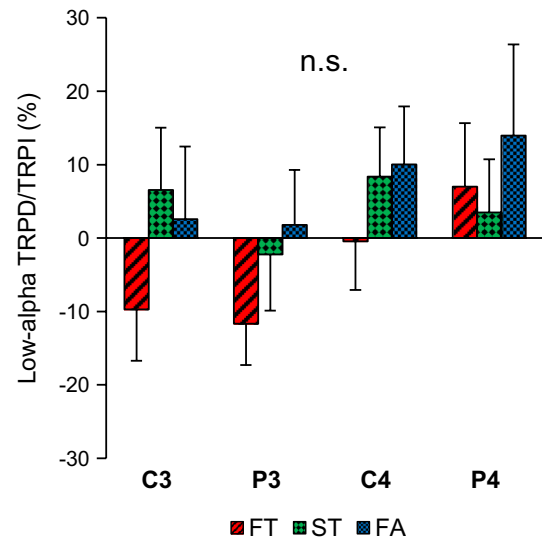
In order to reveal the cortical brain activity associated with the LT effect, we performed the experiments using EEG frequency analysis under the strictly controlled standing conditions, which were spatial reference, haptic feedback, and attentional focus controlled. The hypothesis was verified as we expected that when EEG frequency analysis and the more strictly controlled standing conditions were employed, the LT effect-specific cortical activities and significant correlations between the reductions in postural sway caused by the LT effect would be shown. These results certify that the task (each standing condition) and



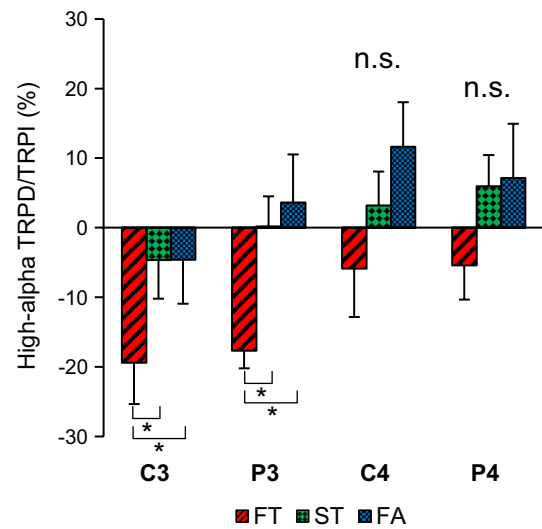
**Fig. 4** Two-dimensional depiction of scalp topography based on the grand average value of low-alpha and high-alpha TRPD/TRPI in each condition. **a** Fixed-point touch condition. **b** Sway-referenced touch condition. **c** Fingertip attention condition. Both of the low and high-alpha TRPD were higher (red) around the C3 and P3 area in the fixed-point touch condition **a**

methods (EEG frequency analysis) employed in the present study are appropriate for examining the association between the cortical brain activity and the postural sway caused by the LT effect. Moreover, we believe that those results advocate the Del Percio et al. (2009) study which investigated the association between cortical brain activity and steady-state postural sway under the ongoing task.

The contact force of the FT condition was >1 N in the present study, and only the RMS value of the FT condition was the lowest among all conditions. These results are consistent with those of similar studies showing that the LT contact is >1 N (Holden et al. 1994; Jeka and Lackner 1994). Furthermore, the LT effect was not achieved here through mechanical support (Holden et al. 1994; Jeka and Lackner 1994; Kouzaki and Masani 2008), but through spatial orientation to the external contact object based on afferent haptic feedback (Jeka et al. 1998; Reginella et al. 1999;



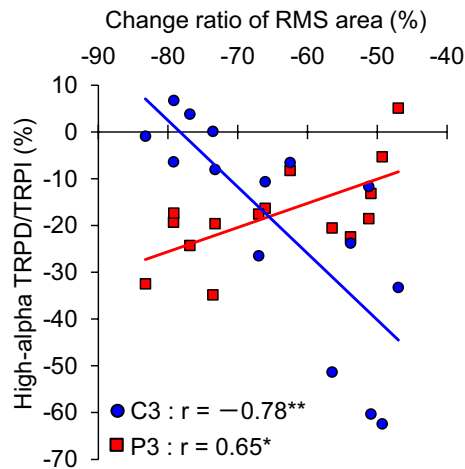
**Fig. 5** Average low-alpha TRPD/TRPI values (±standard error) in each electrode of all subjects. FT (red oblique line), fixed-point touch condition; ST (green rhomboid), sway-referenced touch condition; FA (blue shade), fingertip attention condition. *n.s.* not significant (in ANOVA)



**Fig. 6** Average high-alpha TRPD/TRPI values (±standard error) in each electrode of all subjects. FT (red oblique line), fixed-point touch condition; ST (green rhomboid), sway-referenced touch condition; FA (blue shade), fingertip attention condition. \*Only the average TRPD value of the FT condition was significantly higher compared with that of any other conditions in C3 and P3 electrodes ( $P < 0.05$ ). *n.s.* not significant (in ANOVA)

Krishnamoorthy et al. 2002; Rabin et al. 2008). Therefore, we conclude that the results of the analyses of the FT condition confirm the LT contact and its effect in accordance with the studies of others cited above. Moreover, not only the value of the RMS areas of the C condition but also that





**Fig. 7** Correlation between the change in the ratio of the RMS area with the high-alpha TRPD/TRPI values of the C3 and P3 electrodes in the fixed-point touch condition. \*\*Significant correlation (C3: blue round scatter plot:  $r = -0.78$ ,  $P < 0.01$ ). \*Significant correlation (P3: red square scatter plot:  $r = 0.65$ ,  $P < 0.05$ )

of the ST and FA conditions were higher compared with that of the FT condition. In regard to this result, Reginella et al. (1999) reported that the postural sway-referenced touch did not achieve the LT effect. The other, Riley et al. (1999) reported that even though the touch object is such as unstable curtain, the attentional focus on the external touch point (i.e., attention to the relative positional relationship between own body and reference point) achieve postural stabilization, only when being able to obtain the spatial reference frame from touch object (e.g., the curtain contacts on the floor). In contrast, under the condition where the touch object is an unstable curtain that does not contact the floor, which prevented acquiring a stable spatial reference, the LT effect is not achieved even when the attentional focus is set to the external touch point (McNevin and Wulf 2002). Considering these findings together with those in the present study, we conclude that even when the attentional focus is set to the external contact point (ST condition) or fingertip (FA condition), it does not reveal the reduction in postural sway if haptic information regarding the spatial orientation (i.e., fixed point) is not obtained. This finding emphasizes that the influence of attentional focus on the LT effect is limited to the condition that can acquire a stable spatial reference.

In the EEG frequency analysis, contrary to not showing clear peak power frequency of the beta band in some of the subjects, only the alpha band showed clear peak power frequency (around 10 Hz). This result advocates the study of Del Percio et al. (2009) which did not show clear beta-band peak frequency in some of the subjects and denoted as “beta (when present).” Certainly, beta-band peak frequency

would be shown in a single discrete “event” (e.g., simple self-paced movements; Neuper and Pfurtscheller 1996), but it would not been shown in the case of “ongoing task,” such as steady state of standing (e.g., present study and Del Percio et al. 2009). For the results of the present and previous studies, subjecting only the alpha band for EEG analysis is appropriate in case of ongoing standing task.

Alpha rhythms dominate EEG oscillations in subjects posed at relaxed resting state and reflect the functional modes of basal forebrain, thalamus, and cortical loops that facilitate/inhibit the transmission and retrieval of both sensorimotor and cognitive information into the brain (Pfurtscheller and Lopes da Silva 1999; Neuper and Pfurtscheller 2001). In this framework, the low-alpha (about 8–10 Hz) band would be related to global brain alertness, whereas the high-alpha (about 10–12 Hz) would be related to the task-related oscillation of selective neural systems involved in the expectancy of event or task specific sensorimotor information (Klimesch 1996, 1999; Klimesch et al. 1998). Indeed, the alpha ERD has been repeatedly associated with cortical sensorimotor information processing in humans, and the features of the alpha TRPD are quite similar to those reported in the ERD during sensorimotor demands (motor execution, motor imagery, action observations, sensory input, and sensory motor interaction); studies (Pfurtscheller and Aranibar 1979; Pfurtscheller and Neuper 1994, 1997; Babiloni et al. 1999, 2014; Pfurtscheller et al. 1997, 2006; Muthukumaraswamy and Johnson 2004a, b; Muthukumaraswamy et al. 2004; Bastiaansen and Brunia 2001; Stancák 2006; Neuper et al. 2006) provide the percentage of negative values representing the alpha ERD, and it indicates the enhancement of cortical sensorimotor information processing in each related event or task. In contrast, the ERS (percentage of positive values) indicates the attenuation of cortical sensorimotor information processing.

The high-alpha TRPD values of C3 and P3 electrodes measured in the FT condition, which achieved the LT effect, were higher compared with those of the other conditions. Since the variables of the ST and FA conditions differed from those of the FT condition, the differences suggest that in the increased high-alpha TRPD values can be attributed to the unique aspects of the FT condition. Therefore, we regard that these specific change of increased TRPD reflects cortical brain activities associate with the LT effect. Moreover, as mentioned in previous paragraph, the high-alpha TRPD represents the enhancement of task-related cortical sensorimotor information processing, and the C3 and P3 electrodes roughly located on scalp areas which were mainly projected from each cortical brain activity (C3: left PSMC area, P3: left PPC area) (Okamoto et al. 2004; Koessler et al. 2009; Giacometti et al. 2014). In regard to the involvement of left PSMC area (C3) in the LT effect, we infer that the enhancement of cortical brain

activity can be attributed to the left PSMC area because the right index fingertip was used for touching in the present study. Moreover, we presume that it does not reflect mere haptic input itself because TRPD value of the FT condition was significant higher than that of the ST condition. In other words, it may reflect not mere haptic input but higher sensory processing of sensorimotor interaction. Considering this, the time series variations of fingertip contact force and postural sway (i.e., CoP or head movement) showed similar variation in each variable during the LT contact (Jeka and Lackner 1994, 1995). Additionally, contrary to the stable touch condition, postural sway was increased related to the external driving signal in case of the moving touch object (Jeka et al. 1997, 1998; Wing et al. 2011), and this effect of spontaneous postural entrainment to moving touch object is used for closed-loop driving postural sway of an individual (Vérité et al. 2014). For these findings, we can presume the relation that the subjects who exhibit an increased LT effect perform fewer variations of fingertip contact force. Actually, the present study shows here a negative correlation between the LT effect (i.e., change in the ratio of RMS area with the FT compared with the C condition) and the values of high-alpha TRPD at the C3 during the FT condition. This result indicates that the greater LT effect associates with lower cortical brain activity of the left PSMC area. This relation is similar to that of the previous studies by (Jeka and Lackner 1994, 1995; Jeka et al. 1997, 1998; Wing et al. 2011; Vérité et al. 2014); thus we determine that negative correlation was shown in the present study. That is, we conclude that the alpha TRPD of C3 represents delivery of centrifugal motor commands and processing of somatosensory afferents information from periphery (fingertip touch) at the left PSMC.

On the other hand, with regard to the involvement of left PPC area (P3) in the LT effect, the values of high-alpha TRPD recorded in the P3 electrode were positively correlated with the LT effect during the FT condition, in contrast to the inverse correlation of C3 (left PSMC). The results indicate that the greater LT effect is also associated with greater cortical brain activity of the left PPC area. Similar to the involvement of left PSMC, we infer that cortical activity of left PPC area was shown in the contralateral hemisphere of touch side, since the subjects touched with right fingertip. Regarding the afferent haptic information processing in cortical brain, first processing is performed at the contralateral primary sensory cortex, and then haptic information is transmitted to the posterior parietal cortex, in order to perform higher-order sensory processing being referred to as “sensory integration” (Iwamura 1998; Dijkerman and de Haan 2007). Besides, Del Percio et al. (2007) study showed correlation of high-alpha ERD of ventral centro-parietal electrode and reduction in postural sway when visual input was available indicating sensory integration for

the stabilizing of postural sway. Therefore, we considered that the high-alpha TRPD of P3 during the FT condition is cortical activity of left PPC related to sensory integration of haptic information through the LT contact and it contributes to motor command for postural stabilizing (i.e., top-down postural control; the LT effect).

Based on these observations, we infer that the sensory integration at the left PPC would be required to achieve the LT effect because of the positive correlation with the LT effect, and the task-related sensorimotor interaction at the left PSMC would be a task specific cortical activity generated from the LT effect because of the negative correlation. However, note that although all subjects show LT effect (at least more than 40 %), some subjects show very low TPRD/TPRI values (Fig. 7). Even subjects with TPRI (cortical inhibition) show greater stabilization of postural sway. We presume that these unexpected results are attributed to a hypothesis in which there is different neural mechanism of the LT effect, i.e., all mechanism of LT effects rather than not being achieved by the cortical brain activity, it hypothesized that a part of the mechanisms is constituted by the lower level of the nervous system (e.g., spinal cord or brainstem et al.). Actually, the mechanism of passive aspect (bottom-up) for the LT effect has been shown (Rogers et al. 2001; Menz et al. 2006; Magalhães and Kohn 2011; Kimura et al. 2012). Contrary to our present study focused on the effect of active “top-down” postural control in the LT contact, these studies focused on the effect of passive “bottom-up” postural control, which is achieved by passive sensory input. Considering the possibility of passive mechanism for the LT effect, the results of the present study indicate the active aspect of neural mechanisms for the LT effect. For this reason, the present study suggests that although all subjects show clear LT effect, some subjects do not show very low or inhibited cortical brain activity. On the other hand, the influence on steady state of postural sway not observed during the LT condition in the study of Johannsen et al. (2015), which was applied inhibit stimulus by rTMS on contralateral inferior parietal cortex (a part of PPC) may be explained through the difference in active and passive mechanism for the LT effect. They did not employ the “active light touch” but the “intermittent passive light touch.” Therefore, we consider that there was no influence on steady-state postural sway during the LT condition.

As for the limitations of the present study, even though the present study reveals the cortical brain activities associated with the LT effect, but the area of the brain that mediates the LT effect remains to be determined with certainty and requires further research in consideration of the active and passive mechanism of the LT effect. Moreover, it is unclear whether the cerebral lateralization for the LT effect is there or not, since the right fingertip was only used for touch in the present study. In future research, we

should consider also whether the touch with left fingertip or right.

In conclusion, compared with previous studies that demonstrate that the LT effect is achieved by spatial orientation based on haptic feedback, the present study is the first, to our knowledge, which used a neurophysiological indicator, to reveal the association between the LT effect and cortical brain activity. We believe that these findings were acquired by setting strict limits of the standing condition that included attentional focus and were acquired using frequency analysis of spontaneous EEG instead of SEP. Finally, for the data feature of scatter plot (Fig. 7) described the correlations between the LT effect and cortical activities, a further hypothesis, which not only cortical activities but also the lower level of the nervous system might being contribute to the LT effect, is arisen. In other words, although a partial contribution of a cortical neural mechanism associated with active aspect of the LT effect has been revealed in the present study, the neural mechanism associated with passive aspect of the LT effect remains to be clarified.

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#### Compliance with ethical standards

**Conflict of interest** The authors declare that they have no conflict of interest.

**Ethical approval** All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the Declaration of Helsinki (1964) and its later amendments or comparable ethical standards.

**Informed consent** Informed consent was obtained from all individual participants included in the study.

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