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Measurement of sensory deficiency in fine touch after stroke during textile fabric stimulation by electroencephalography (EEG)

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Abstract

Objective. Sensory deficiency of fine touch limits the restoration of motor functions after stroke, and its evaluation was seldom investigated from a neurological perspective. In this study, we investigated the cortical response measured by electroencephalography (EEG) on the fine touch sensory impairment during textile fabric stimulation after stroke.

Approach. Both participants with chronic stroke (n = 12, stroke group) and those unimpaired (n = 15, control group) were recruited. To investigate fine touch during textile fabric stimulations, full brain EEG recordings (64-channel) were used, as well as the touch sensation questionnaires based on the American Association of Textile Chemists and Colorists (AATCC) Evaluation Procedure 5. During the EEG measurement, relative spectral power (RSP) and EEG topography were used to evaluate the neural responses toward the fabric stimuli. In the subjective questionnaire, the fine touch for fabric stimuli was rated and represented by 13 different sensation parameters. The correlation between the fine touch evaluated by the EEG and the questionnaire was also investigated.

Main results. The neural responses of individuals with fine touch impairments after stroke were characterized by a shifted power spectrum to a higher frequency band, enlarged sensory cortical areas and higher RSP intensity (P < 0.05). Asymmetric neural responses were obtained when stimulating different upper limbs for both unimpaired participants and stroke participants (P < 0.05). The fine touch sensation of the stroke participants was impaired even in the unaffected limb. However, as a result of different neural processes, the correlation between the EEG and the questionnaire was weak (r < 0.2). Significance. EEG RSP was able to capture the varied cortical responses induced by textile fabric fine touch stimulations related to the fine touch sensory impairment after stroke.

1. Introduction

Approximately 85% of stroke survivors experience sensory deficiency. This deficiency is typically characterized by a reduced tactile perception of pain, temperature, touch, and proprioception [1, 2]. Insufficient or impeded sensation affects the accuracy and coordination of movements [3, 4], and further limits the restoration of motor functions, which may inhibit participation in the activities of daily living [1]. In a longitudinal study on stroke survivors, a significantly higher prevalence of severe motor deficiency was found among individuals who experienced sensory deficiency following a stroke. More specifically, sensory deficiency in fine touch, i.e. tactile stimulation with light intensities, was found to be related to a detailed discrimination in the sensory nervous system [5]. Sim et al [6] reported the immediate training effects of hand function following stroke with several types of somatosensory stimulation. They found that the hand function could be significantly improved after the stimulation of fine touch. Some clinical evidence suggested that the stimulation of fine touch could also facilitate postural stability, and this might be due to an increased sensory feedback to active body movements during the postural control [7, 8]. Although fine touch is known to affect motor recovery in individuals after stroke, its evaluation and the associated rehabilitation effects are usually underestimated and overlooked in traditional stroke
rehabilitation programs, which are mainly emphasizing on motor treatments.

To investigate fine touch after stroke, it is important to use valid and reliable evaluation methods. In the current clinical practice in stroke rehabilitation, the traditional assessments for sensory deficiency are fewer than those for evaluating motor impairments [9]. Clinically, the current sensory assessments related to fine touch mainly include the evaluations on the responses to the different stimulation intensities and discrimination of minimum physical distance [1]. For example, the traditional approaches measuring fine touch on intensity variation include the Semmes-Weinstein monofilament test [10] and the sensation part of light touch in the Fugl-Meyer Assessment (FMA) [11]; while the assessment for distance discrimination is the two-point discrimination tests [12]. These assessments are graded with a numeric ordinal scale with low resolutions [12]. Particularly, the measured scores are based on subjective judgements of the assessors, which could be affected by different professional experiences, and the personal cognitive responses of patients (e.g. in questionnaire). It has been found that the fine touch sensation to a stimulation evaluated by questionnaires could vary because of individual discrepancies, including cognition, race, psychology, or even cultural background [13–15]. Using FMA as an example, there are only 3 grades for fine touch answered by patients when stimulated by professionals, including normal, hypesthesia and anesthesia. In the early stage after stroke, most of stroke patients could be categorized into anesthesia or hypesthesia because of the gradual sensorimotor return in spontaneous recovery after stroke [16]; In the chronic stage after stroke, the poststroke neuroplasticity for spontaneous recovery tends to be stable [16], and most of the patients could be rated as hypesthesia without further discrimination on the detailed sensory impairments by FMA [12]. Another evaluation method that has the ability to measure somatosensory performance systematically from different aspects of tactile perception covering fine touch is the Rivermead assessment of somatosensory performance [17]. However, the evaluation section for fine touch is just the combination of Semmes-Weinstein monofilament test and the two-point discrimination test. In addition to the above, the tactile discrimination test [18] which uses plastic gratings with different surface spatial intervals can be used to assess touch sensibility. However, this method is limited in the texture variations it could provide such as bumpiness and hardness. Another limitation of the evaluation methods mentioned above is that they require the patients’ participation and as such, only participants without severe cognitive deficits following stroke can be used [1]. Furthermore, the current clinical assessments lack direct evaluation of neural response in the central nervous system to a specified stimulus. The neuronal activity in the sensory recovery of tactile perception after stroke could be measured via magnetoencephalography (MEG), electroencephalography (EEG) and functional magnetic resonance imaging (fMRI) [19–22]. MEG has been used in investigations that have found that an increased somatosensory performance evoked magnetic fields from the primary somatosensory cortex (SI) after stroke over time [20]. In addition to this, fMRI has been used to reveal the long-term rehabilitative effects related to the post-stroke neural plasticity in resting-state [20–23]. However, fMRI is hard to reveal the transient neural response to tactile stimulation, because the temporal resolution of current fMRI is around 2 to 5 s [24]. Furthermore, the transient sensory neural response will attenuate quickly during tonic tactile stimulation (in milliseconds), because of sensory adaptation [25]. Techniques with higher temporal resolution is desired for sensory impairment evaluation after stroke. EEG, as a non-invasive and cost-effective technology, has been applied in the investigations of neural activities of sensorimotor impairments in the upper limb after stroke, for the potential wide clinical applications [26]. However, most of the current EEG studies mainly focused on the motor functions [27]. Only limited studies were reported on the neural responses to tactile stimulation for both unimpaired and stroke patients. For example, EEG rhythmic activity around 20 Hz has been proposed to be a representative feature in response to temporal light touch stimulation in unimpaired adults [28]. The EEG feature demonstrated transient and multi-phasic variations within 900 ms to the stimulation [28], which could not be captured by the current fMRI technique due to its low temporal resolution. However, the feasibility of this method has not been investigated in stroke survivors. Another study conducted by Ahn et al [29] compared the relative power in EEG during active and passive tactile abrasion/exploration by hand on a paper board for stroke survivors. The sensory responses captured by the EEG power in the prefrontal lobe and parietal lobe showed higher intensities during active exploration than the passive motion [29]. These studies suggested the possibility of using EEG as a measurement to investigate sensory impairment of fine touch after stroke objectively, compared to the traditional subjective assessments. However, the stimulation adopted in the fine touch assessments should be more related to the daily contacts for a better representation of the sensory function, as the daily tasks adopted in most of the motor assessments clinically (e.g. in Action Research Arm Test [30]).

In recent years, tactile stimulation by textile fabrics has been proposed as a way in which to investigate fine touch. This is because, the main external stimulation that comes into contact with the skin in everyday life is textile fabrics [29, 31]. Fine touch introduced by textile fabrics are associated with their physical properties, and different fabric materials
could provide wide variations in texture such as differences in smoothness, thickness and softness [32]. In some studies, fabric stimulation has been adopted to investigate the sensory physiology of fine touch in unimpaired individuals via fMRI and EEG [33, 34]. Wang et al [33] reported that the use of fMRI was a promising method to quantitatively investigate brain responses during tactile stimulation by fabrics, with the representative cortical regions in the SI and the secondary somatosensory cortex (SII). In one EEG study, Hoefer et al [34] attempted to use event-related potential (ERP) in the time domain to investigate touch discrimination in three different fabric samples. The results of this study showed that the ERP amplitudes could be affected by different textile stimulations. However, the ERP amplitudes in the time domain did not provide a high enough resolution to distinguish the different textiles in the study. Another study by Singh et al [35] investigated the beta (β) band in the EEG frequency domain and suggested that the energy changes in β could differentiate pleasant stimuli from unpleasant stimuli with different textile fabrics on a single trial basis. These studies support the feasibility of using textile fabric stimulation to investigate the neural response of fine touch in unimpaired populations. Despite this, studies regarding individuals who have experienced stroke are limited. Therefore, the purpose of this study was to investigate the cortical response measured by EEG during textile fabric stimulation as an objective detection of fine touch sensory impairment after stroke.

2. Methodology

In this study, the poststroke fine touch during the textile fabric stimulation was investigated by using both objective EEG measurement and subjective questionnaire with an ordinal sensory scale. Three different fabrics were used to evaluate the fine touch for both stroke survivors and individuals who were unimpaired. During the EEG measurement, signal spectral power and EEG topography were used to describe the neural responses toward the fabric stimuli. In the subjective questionnaire, the fine touch for fabric stimuli was rated and represented by 13 distinct sensation parameters. The results obtained from EEG measurement and fine touch questionnaire were then correlated.

2.1. Participants

Before conducting the study, approval was obtained by the Human Subjects Ethics Sub-Committee of the Hong Kong Polytechnic University. Twelve participants who had experienced chronic stroke were recruited to the ‘stroke group’. Additionally, fifteen unimpaired adults were recruited to the ‘control group’. Participants in the stroke group were recruited from local districts based on the following inclusion criteria: (1) individuals must be at least six months post-onset of a singular and unilateral brain lesion due to stroke; (2) the lesions occurring due to stroke were experienced in the subcortex area; (3) individuals had no visual, cognitive or attention deficits that would prevent them from following instructions or performing the experimental procedures (assessed by the Mini-Mental State Examination (MMSE) score > 21) [36]; (4) the spasticity during extension of wrist and elbow joints was lower than or equal to 2 as measured by the Modified Ashworth Scale (MAS) [37]; (5) individuals had moderate to severe sensory impairment on their affected forearm with a score of 1 as measured by the sensation part of light touch in the Fugl-Meyer Assessment (FMA) [11]. In this study, chronic stroke patients were recruited because their sensorimotor functions were relatively stable and representative for the large population of most stroke survivors. Meanwhile, in order to ensure the accessibility of EEG generated from the cortex, particularly the sensorimotor cortex, stroke subjects with lesions in subcortical areas were recruited, since their cerebral cortex were not directly damaged due to stroke. Participants in the control group were also recruited from local districts. It was required that individuals in the control group did not have any history of neurological, psychiatric, cognitive and/or cardiovascular diseases. All recruited participants gave written consent before the start of the experiment. The demographic characteristics of the participants are presented in table 1. In this study, the recruited participants were mainly in middle age (45–65 years old [38]), with a mean value of 55.13 for the stroke group and 46.40 for the control group without statistical significance (p > 0.05, independent t-test).

2.2. EEG measurement of cortical response during fabric fine touch simulation

2.2.1. EEG experimental setup

The experiment was conducted in a lab which was temperature and humidity controlled. The room temperature was fixed at 24 ± 2 °C and the relative humidity was fixed at 60% ± 5%. Each participant was comfortably seated in front of a table. This experimental setup is shown in figure 1(A). A 64-channel EEG system (BP-01830, Brain Products Inc.) was mounted on the scalp of each participant based on the standard 10–20 system which is used to record the whole brain EEG with the skin impedance of each channel under 5 KΩ [39]. The decision to use a 64-channel EEG to record the entire brain was made as a result of the possibility that sensory stimulation could activate multiple cortical regions, not just within the primary somatosensory cortex [35].

In this study, three different fabric samples of (1) cotton, (2) nylon, and (3) wool were used. The textile composition and representative physical properties of these three fabric samples as evaluated by Fabric Touch Tester (FTT) [40] are shown in table 2. The first fabric used in the experiment
Table 1. Demographic characteristics of the participants.

| Characteristics                                      | Stroke group (n = 12) | Control group (n = 15) |
|------------------------------------------------------|-----------------------|------------------------|
| Age in years (mean ± SD)                             | 55.13 ± 16.04         | 46.40 ± 17.39          |
| Gender (male/female)                                 | 11/1                  | 5/10                   |
| Affected side (right/left)                           | 6/6                   | Nil                    |
| Type of stroke (ischemic/hemorrhagic)                | 10/2                  | Nil                    |
| Times since stroke in years (mean ± SD)              | 14.92 ± 5.79          | Nil                    |
| MAS elbow (mean ± SD)                                | 1.08 ± 0.69           | Nil                    |
| FMA full score for upper extremity (mean ± SD)       | 42.5 ± 15.17          | Nil                    |
| FMA for light touch on forearm (mean ± SD)           | 1 ± 0                 | Nil                    |

Figure 1. The experimental setup for the EEG evaluation during the fabric stimulation: (A) participants with the recording position; (B) demonstration of the fabric stimulation.

was cotton, and it was 100% cotton with a plain weave. The second fabric used in the experiment was nylon which was comprised of 87% nylon and 13% elastane. This combination results in a cool feeling on the skin due to a relatively high thermal conductivity [41]. The third fabric used in the experiment was wool which was composed of 60% polyester and 40% wool. This combination was used as it provides a feeling of warmth similar to that of pure wool [41]. The distances in the fabrics physics among the three fabrics were quantified by the normalized physical properties in table 2 with respect to the cotton, i.e. each property was divided by the value of that of the cotton, using following equation:

\[
d(\vec{u}, \vec{v}) = \left\| \vec{u} - \vec{v} \right\|
\]

\[
= \sqrt{(u_1 - v_1)^2 + (u_2 - v_2)^2 + \cdots + (u_n - v_n)^2}
\]

where, \(d(\vec{u}, \vec{v})\) is the distance between two fabrics; and \(\vec{u}\) and \(\vec{v}\) are the vectors of physical properties for each fabric sample. The distances between cotton and nylon, cotton and wool, and nylon and wool were calculated as 3.56, 4.75, and 6.73, respectively. Cotton was selected as the baseline stimulation, since it has been recognized as the most comfortable and widely adopted fabric in our daily living [41]. The other two textile fabrics, i.e. wool and nylon, were selected according to their textile physical properties (e.g. smoothness, thickness, etc) measured by the FTT, which are located in the opposite directions with equivalent distances with respect to the cotton for a balanced comparison. All the fabric samples were tailored into 20 cm × 10 cm pieces for the experiment in this work.

2.2.2. EEG experimental protocol

The experimental protocol presented with the timeline is summarized in figure 2. Each single trial consisted a 30 s baseline test, three 13 s fabric stimuli and three 60 s resting times between two consecutive fabric stimuli. During the EEG recording, participants were asked to perform the recording position (figure 1(A)). This consisted of participants keeping their eyes closed, placing their two forearms on the
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Table 2. Textile composition and representative physical properties of the three fabric samples evaluated by fabric touch tester (FTT).

| Fabric Name   | Fabric Description | Component | Weight (g m⁻²) | Thickness (mm) | SRA | BAR | Qmax | CW | Fabric Image |
|---------------|--------------------|-----------|---------------|----------------|-----|-----|------|----|--------------|
| Cotton        | 100% Cotton        | Plain     | 127.7         | 0.39           | 16.7| 188.1| 1467.8| 345.4 |              |
| Nylon         | 87% Nylon/13% Elasthan | Jacquard | 113.3         | 0.77           | 8.3 | 152.4| 1745.0| 117.9 |              |
| Wool          | 60% Polyster/40% Wool | Woven   | 340.8         | 1.29           | 40.0| 349.5| 633.1 | 1339.0|              |

SRA: Surface Roughness Amplitude (µm); Qmax: Maximum Thermal Flux (W m⁻²); BAR: Bending Average Rigidity (gf mm⁻²); CW: Compression Work (gf mm).}

Table whilst remaining relaxed and still. Disturbances from visual and audio stimuli from the surroundings were further minimized by wearing an eye mask and ear plugs. In this study, forearms were selected as the stimulation area because they have high contacts with the textile fabrics in the daily living. Several studies also selected forearm to investigate the textile fabric stimulations in unimpaired subjects [34, 35]. During the baseline test, the participants were asked to maintain the recording position and remain awake without mental activity. No stimulation was applied to the participants during this baseline test. During the fabric stimulation, each fabric sample was statically loaded (i.e. without striking) onto the skin surface of the ventral side of the either left or right forearm (figure 1(B)) for 13 s with a randomized sequence. The participants were asked not to perform active cognition toward the fabric stimulations. In contrast to the evaluation by questionnaire which would be mentioned later, no forced choice was required during the EEG test. The cycle of the fine touch evaluation was repeated three times for each side of the forearm.

2.2.3. EEG data processing

During the real-time EEG recording, the sampling frequency was set at 1000 Hz. After acquiring the targeted EEG data, the EEG signals were processed offline with a band-pass filter from 0.1 Hz to 100 Hz and a notch filter from 49 Hz to 51 Hz to eliminate the 50 Hz noise from the environment. Following this, the EEG signals were divided into individual segments containing the baseline and fabric stimulation periods. Then, the relative power of each EEG frequency bands, i.e. Delta (δ, 0.1 ~ 4 Hz), Theta (θ, 4 ~ 8 Hz), Alpha (α, 8 ~ 13 Hz), Beta (β, 13 ~ 30 Hz) and Gamma (γ, 30 ~ 100 Hz) [42, 43], were calculated based on the following equation:

\[ P_{\text{Relative/band}} = \frac{\int_{0}^{100} P(f) \, df}{\int_{0}^{100} P_{\text{Baseline}}(f) \, df} - \frac{\int_{0}^{100} P_{\text{Baseline}}(f) \, df}{\int_{0}^{100} P_{\text{Baseline}}(f) \, df} \]

where, \( P_{\text{Relative/band}} \) is the relative spectral power (RSP) of a frequency band; \( P(f) \) is the power spectral density of an EEG segment for a fabric stimulating event, estimated by Fast Fourier Transform; \( F_1 \) and \( F_2 \) are the cutoff frequencies of a EEG frequency band, as stated above; and \( P_{\text{Baseline}}(f) \) is the power spectral density of the EEG segments in the baseline tests of each trial.

2.3. Fine touch perception evaluated by questionnaire

After the EEG recording, the fine touch perceptions of the three fabric samples were evaluated by a subjective questionnaire [32] designed according to the American Association of Textile Chemists and Colorists (AATCC) Evaluation Procedure 5 [44]. The AATCC questionnaire details the sensations evoked by textile fabric stimulation adopted in studies on neurophysiological mechanisms of touch perceptions [45]. The questionnaire was divided into thirteen sensory properties, including warmth, dryness, itchiness, scratchiness, prickliness, smoothness, adhesiveness, pliability, thickness, softness, elasticity, fullness and the overall comfort. For each property, a numeric rating scale [41] from 1 to 7 was provided so that participants were able to indicate the extent of each sensation perceived according to each of the thirteen sensory properties. During the subjective questionnaire evaluation, each participant was seated with the same configuration as in the EEG recording with their forearms placed on the table, wearing an eye mask. However, ear plugs were not used in this evaluation stage. Each fabric was statically loaded onto the skin surface of the participant’s forearm. The participant was then asked by an experimental operator to rate each item according to the fine touch perception questionnaire. The sequence of the stimulation by different fabrics was also randomized. For the stroke group, the subjective questionnaire was conducted on both sides of the forearm, whereas for the control group, only the dominant side of their forearm was evaluated as it was commonly performed as such in the literature for the unimpaired persons [32]. In this study, all unimpaired participants and stroke survivors before their stroke onset were right-handed.

2.4. Statistical analysis

During statistical analysis, the stroke group were further divided into a stroke affected group and a
stroke unaffected group based on the affected side of stroke participants. To provide a more comprehensive exploration of neural response during the fine touch stimulation, a total of 62 EEG channels to measure the entire brain of each participant were used for the statistical analysis. The total amount of samples taken from the control group was 16,740 (15 participants’3 trials’62 EEG channels’2 stimulation sides’3 fabric samples). The total amount of samples taken from the stroke affected group and stroke unaffected group were 6,696 (12 participants’3 trials’62 EEG channels’3 fabric samples). Figure 3 shows the flow diagram for the statistical analysis. The normality tests on the EEG data and questionnaire scores were evaluated via the Lilliefors method with insignificant probabilities (P > 0.05), and they all obeyed normal distribution [46].

To begin, intragroup comparisons of the RSP were conducted for each group. In the literature, variations of neural responses during both sensory and motor tasks were observed between the left and right hands due to different handedness [47, 48]. Therefore, the independent factor of stimulation side (i.e. left forearm and right forearm) was considered into the statistical analysis. This would be discussed further in the discussion section. For each group, a two-way Analysis of Variance (ANOVA) was used to evaluate the differences with respect to the independent factors of the stimulation side and fabric sample (i.e. cotton, nylon and wool) on the RSP of each EEG frequency band. Then, an independent t-test was used to evaluate the RSP differences with respect to the independent factor of stimulation side. In addition to the above, a one-way ANOVA was conducted to investigate the RSP difference for varying fabric samples with either the Bonferroni post hoc test or the Dunnett’s T3 post hoc test. In this study, a correlation pair was found by linking the RSP from an EEG channel with the score of a sensory property in the questionnaire during the same fabric stimulation. For example, for the stroke affected group, in the 62-channel EEG recording of the 3 different fabric stimulations on 12 participants with 3 repetitions, there were a total of 6,696 pairs of data in the correlation on each sensory property. Similar correlation analyses were conducted by Wang et al and Singh et al whereby the relationship between electrophysical signals (multi-channel EMG and EEG) versus subjective sensations (by questionnaire), in addition to the fabrics’ physical properties during textile stimulation [35, 50]. In this work, the level of statistical significance was 0.05, and the significance at levels 0.01, 0.001 were also indicated.

3. Results

3.1. Cortical response to fine touch stimulation induced by textile fabric

Figure 4 shows the EEG RSP in response to the fabric stimuli for each group at the different EEG frequency bands. Table 3 presents the two-way ANOVA probabilities and predicted effect sizes (EFs) with respect to the independent factors of the stimulation side and fabric sample. Table 4 provides a summary of the detailed values, means and 95% confidence intervals of each RSP, in addition to the one-way ANOVA.
and independent t-test probabilities and the estimated effect sizes (EFs). In the control group (figure 4(A)), significant RSP differences with respect to the fabric samples were detected at the theta (P < 0.001, two-way ANOVA, table 3) and beta (P = 0.002, two-way ANOVA, table 3) bands. In terms of the stimulation sides, significant differences were observed at the alpha band (P = 0.001, two-way ANOVA, table 3). Furthermore, significant interactions between the fabric samples and the stimulation sides were captured at the theta (P = 0.001, two-way ANOVA, table 3) and alpha (P = 0.006, two-way ANOVA, table 3) bands. The theta RSP in response to the wool fabric was significantly higher than the theta RSP in response to the cotton and nylon fabrics on both stimulation sides (P < 0.01, one-way ANOVA, table 4).

When stimulating the right forearm, the theta RSP for nylon was also significantly higher than that for cotton (P < 0.001, one-way ANOVA, table 4). In terms of the RSP for the beta band in the control group, significant intragroup differences were only observed between cotton and nylon when the left forearm was stimulated (P = 0.034, one-way ANOVA, table 4). Meanwhile, significant RSP differences with respect to the independent factor of stimulation side were observed by independent t-test in the delta, theta and alpha bands (P < 0.05, table 4). The RSP of the right forearm were significantly lower than the left forearm in the delta band (P = 0.024, independent t-test, table 4), while the RSP of the right forearm were significantly higher than the left forearm in the theta (P < 0.05, independent t-test, table 4) and alpha (P < 0.01, independent t-test, table 4) bands.

In the stroke unaffected group (figure 4(B)), significant RSP differences with respect to the fabric samples were observed in the results of the two-way ANOVA at the theta (P = 0.002, table 3), alpha (P = 0.003, table 3) and beta (P = 0.007, table 3) bands. In addition to this, significant differences with respect to the stimulation side were detected in all the frequency bands (P ≤ 0.001, two-way ANOVA, table 3). In terms of the interactions between the fabric sample factors and stimulation sides, significance was found at the alpha (P = 0.045, two-way ANOVA, table 3), beta (P = 0.018, two-way ANOVA, table 3) and gamma (P = 0.007, two-way ANOVA, table 3) bands.

When conducting a one-way ANOVA, when the right forearm was stimulated, significant differences between the RSP of wool and cotton could be observed in all EEG frequency bands (P < 0.05, table 4), while the significant differences between the RSP of wool and nylon were only found in the high frequency bands (i.e. beta and gamma bands, P < 0.001, one-way ANOVA, table 4). When the left forearm was stimulated, significant variations between the RSP of cotton and nylon were observed on the theta (P = 0.031, one-way ANOVA, table 4) and gamma (P = 0.008, one-way ANOVA, table 4) bands. Furthermore, the significant differences in respect to the factor of stimulation side were widely noticed in all EEG frequency bands for the stroke unaffected group (P < 0.05, independent t-test, table 4). Meanwhile, when compared with the left forearm, during stimulation from the fabrics, the right forearm achieved significantly lower RSP in the delta band (P < 0.05, independent t-test, table 4), and higher RSP in theta, alpha, beta and gamma bands (P < 0.05, independent t-test, table 4).

In the stroke affected group (figure 4(C)), significant differences with respect to the stimulation sides were detected at the delta, beta and gamma bands (P < 0.001, two-way ANOVA, table 3). Despite this, there were no significant differences in RSP in terms of the fabric sample factors and the interactions between stimulation sides and fabric samples. However, significant intragroup differences of RSP with respect to the factor of fabric sample were found from the conduction of a one-way ANOVA test in the delta, theta and beta bands when the left forearm was stimulated (P < 0.05, table 4). The RSP of theta bands in response to the wool were significantly higher than those induced by cotton (P = 0.029, one-way ANOVA, table 4), and the beta RSP for both nylon and wool were significantly higher than the cotton (P = 0.034, one-way ANOVA, table 4). However, no significant intragroup variations could...
be found within the stroke affected group when the right forearm was stimulated in any EEG frequency band \((P > 0.05,\) one-way ANOVA, table 4). However, within the stroke affected group, it was found that the right forearm had a higher RSP than the left forearm \((P < 0.05,\) independent t-test, table 4), which is similar to results in the other groups.

Figure 5 demonstrates the whole brain EEG topography of the mean RSP in all EEG frequency bands for each group with respect to the factor of fabric sample and stimulation side. The hotspots related to the significant RSP in all EEG frequency bands were mainly captured in the parietal and frontal regions bilaterally for both stroke and unimpaired participants. In the theta band (figure 5(B)), the amount of power in the brain was increased in the frontal and parietal regions for unimpaired participants on both stimulation sides. For stroke participants who had experienced right-side brain lesions, increased theta activity was typically obtained in the paramedian central area. In contrast, for stroke participants who had experienced left-side brain lesions, theta activity decreased in the left hemisphere. In contrast, for stroke participants who have experienced left-side brain lesions, brain activity of both affected and unaffected side increased significantly over the frontal and parietal areas.

Figure 6 compares the group differences of overall RSP in response to the fabric stimuli at each EEG frequency band. Table 5 displays the values of statistical results including probabilities and EFs of the two-way ANOVA and one-way ANOVA. Significant differences between the groups were found when conducting the two-way ANOVA in all the EEG frequency bands \((P < 0.001,\) table 5). In the low frequency bands (i.e. delta, theta and alpha), differences between fabric samples were found to be significant \((P < 0.05,\) two-way ANOVA, table 5). Significant interaction between the fabric sample factors and groups was only found at the beta band \((P = 0.013,\) two-way ANOVA, table 5). In comparison to the control group, the overall RSP of the stroke affected group in response to fabric stimulations were significantly lower at the delta band \((P < 0.05,\) one-way ANOVA, table 5), and higher in the alpha, beta and gamma bands \((P < 0.01,\) one-way ANOVA, table 5). Furthermore, significant differences of the overall RSP in response to different fabric samples could also be observed between the stroke affected group and the stroke unaffected group in the theta, alpha, beta, and gamma bands \((P < 0.01,\) one-way ANOVA, table 5). The overall RSP of the stroke affected group in the theta band were significantly lower than that of the unaffected group when stimulated by cotton \((P = 0.007,\) one-way ANOVA, table 5) and nylon \((P < 0.001,\) one-way ANOVA, table 5). For the high frequency band (i.e. beta and gamma bands), the overall RSP of the stroke affected group were significantly higher than the unaffected group in response to all three

| Bands | Groups | Fabric P (Partial \(\eta^2\)) | Stimulation side P (Partial \(\eta^2\)) | Fabric* Stimulation side P (Partial \(\eta^2\)) |
|-------|--------|---------------------------|-----------------------------------|-----------------------------------------------|
| Delta | Control Group | 0.131 (0.001) | 0.209 (0.000) | 0.112 (0.001) |
| Stroke Group-affected side | 0.143 (0.002) | 0.000 \(\bullet\bullet\) (0.037) | 0.260 (0.001) |
| Stroke Group-unaffected side | 0.059 (0.003) | 0.000 \(\bullet\bullet\) (0.016) | 0.077 (0.002) |
| Theta | Control Group | 0.000 \(\bullet\bullet\bullet\) (0.009) | 0.412 (0.000) | 0.000 \(\bullet\bullet\) (0.003) |
| Stroke Group-affected side | 0.053 (0.003) | 0.167 (0.001) | 0.116 (0.002) |
| Stroke Group-unaffected side | 0.002 \(\bullet\bullet\) (0.006) | 0.000 \(\bullet\bullet\bullet\) (0.019) | 0.240 (0.001) |
| Alpha | Control Group | 0.052 (0.001) | 0.001 \(\bullet\bullet\) (0.002) | 0.006 \(\bullet\bullet\) (0.002) |
| Stroke Group-affected side | 0.795 (0.000) | 0.622 (0.000) | 0.159 (0.002) |
| Stroke Group-unaffected side | 0.003 \(\bullet\bullet\) (0.005) | 0.000 \(\bullet\bullet\bullet\) (0.017) | 0.045 \(\bullet\bullet\) (0.003) |
| Beta | Control Group | 0.002 \(\bullet\bullet\) (0.002) | 0.067 (0.001) | 0.709 (0.000) |
| Stroke Group-affected side | 0.112 (0.002) | 0.000 \(\bullet\bullet\bullet\) (0.039) | 0.712 (0.000) |
| Stroke Group-unaffected side | 0.237 (0.001) | 0.000 \(\bullet\bullet\bullet\) (0.008) | 0.018 \(\bullet\bullet\) (0.004) |
| Gamma | Control Group | 0.521 (0.000) | 0.312 (0.000) | 0.237 (0.001) |
| Stroke Group-affected side | 0.274 (0.001) | 0.000 \(\bullet\bullet\bullet\) (0.042) | 0.225 (0.001) |
| Stroke Group-unaffected side | 0.007 \(\bullet\bullet\) (0.004) | 0.001 \(\bullet\bullet\) (0.005) | 0.007 \(\bullet\bullet\) (0.004) |

Differences with statistical significance are marked with \('\bullet\) (\(p < 0.05,\) two-way ANOVA intra-group tests on the fabric and stimulation side effects). Significant levels are indicated as, 1 superscript for \(p < 0.05,\) 2 superscripts for \(p < 0.01,\) 3 superscripts for \(p < 0.001.\)
Table 4. The relative spectral power with respect to the independent factors of the stimulation side and fabric sample on each EEG frequency band.

| Bands  | Groups               | Stimulation side | Control Group | Nylon                        | Wool                          | One-way ANOVA |
|--------|----------------------|------------------|---------------|------------------------------|------------------------------|---------------|
|        |                      | Stimulation side |                | Mean (95% confidence interval, E-03) |                              | P (Partial η²) |
| Delta  | Control Group        | Left forearm     | −3.52 (~6.49 ~ −0.55) | −3.94 (~6.92 ~ −0.97) | −3.34 (~6.32 ~ −0.37) | 0.959 (0.001) |
|        |                      | Right forearm    | −1.92 (~4.82 ~ 0.98) | −5.48 (~8.38 ~ −2.59) | −8.01 (~10.91 ~ −5.12) | 0.014* (0.003) |
|        | Independent t-test   | P (Cohen’s d)    | 0.42 (~ −0.037)   | 0.499 (~0.031)           | 0.024* (~0.105)             |               |
|        | Stroke Group-affected side | Left forearm | −2.03 (~7.49 ~ 3.43) | −6.88 (~12.34 ~ −1.42) | −12.15 (~17.60 ~ −6.69) | 0.037* (0.006) |
|        |                      | Right forearm    | −14.60 (~ −21.38 ~ −7.82) | −19.62 (~26.40 ~ −12.84) | −15.89 (~22.67 ~ −9.11) | 0.566 (0.001) |
|        | Independent t-test   | P (Cohen’s d)    | 0.001 (~0.256) | 0.005* (~0.206) | 0.457 (~0.055) |               |
|        | Stroke Group-unaffected side | Left forearm | 0.59 (~5.53 ~ 6.72) | −0.12 (~6.25 ~ 6.01) | 0.22 (~5.91 ~ 6.34) | 0.987 (0.000) |
|        |                      | Right forearm    | −7.65 (~12.81 ~ −2.50) | −13.47 (~18.62 ~ −8.31) | −21.02 (~26.17 ~ −15.86) | 0.002** (~0.12) |
|        | Independent t-test   | P (Cohen’s d)    | 0.036* (~0.154) | 0.001** (~0.248) | 0.000*** (~0.358) |               |
| Theta  | Control Group        | Left forearm     | 1.58 (~1.13 ~ 2.02) | 1.58 (~1.14 ~ 2.02) | 2.50 (~2.05 ~ 2.94) | 0.004* (~0.004) |
|        |                      | Right forearm    | 0.71 (~0.23 ~ 1.18) | 2.23 (~1.76 ~ 2.71) | 3.18 (~2.71 ~ 3.66) | 0.000*** (~0.019) |
|        | Independent t-test   | P (Cohen’s d)    | 0.003* (~0.139) | 0.049* (~0.091) | 0.063 (~0.086) |               |
|        | Stroke Group-affected side | Left forearm | −0.45 (~3.26 ~ 2.37) | 1.53 (~1.28 ~ 4.35) | 4.90 (~2.08 ~ 7.72) | 0.029* (~0.006) |
|        |                      | Right forearm    | −0.01 (~1.94 ~ 1.92) | 1.24 (~0.69 ~ 3.17) | 0.59 (~1.34 ~ 2.52) | 0.669 (0.001) |
|        | Independent t-test   | P (Cohen’s d)    | 0.789 (~ −0.020) | 0.872 (~0.012) | 0.013* (~0.184) |               |
|        | Stroke Group-unaffected side | Left forearm | −0.08 (~1.85 ~ 1.70) | 3.29 (~1.52 ~ 5.07) | 1.37 (~0.40 ~ 3.15) | 0.301* (~0.06) |
|        |                      | Right forearm    | 4.47 (~2.00 ~ 6.95) | 8.27 (~5.80 ~ 10.75) | 9.33 (~6.85 ~ 11.80) | 0.017* (~0.007) |
|        | Independent t-test   | P (Cohen’s d)    | 0.002 (~0.225) | 0.002* (~0.226) | 0.000*** (~0.376) |               |
| Alpha  | Control Group        | Left forearm     | 0.64 (~1.25 ~ 2.54) | −3.26 (~5.15 ~ −1.37) | −0.39 (~2.28 ~ 1.50) | 0.012* (~0.003) |
|        |                      | Right forearm    | −0.19 (~1.98 ~ 1.60) | 1.57 (~0.22 ~ 3.36) | 3.27 (~1.48 ~ 5.06) | 0.028* (~0.003) |
|        | Independent t-test   | P (Cohen’s d)    | 0.539 (~0.028) | 0.000* (~0.177) | 0.000* (~0.126) |               |
|        | Stroke Group-affected side | Left forearm | 2.98 (~0.09 ~ 5.88) | 4.05 (~1.15 ~ 6.94) | 5.82 (~2.93 ~ 8.71) | 0.389 (0.002) |
|        |                      | Right forearm    | 5.26 (~2.47 ~ 8.05) | 6.15 (~3.35 ~ 8.94) | 3.20 (~0.40 ~ 5.99) | 0.323 (0.002) |
|        | Independent t-test   | P (Cohen’s d)    | 0.174 (~ −0.100) | 0.304 (~0.076) | 0.269 (~0.081) |               |
|        | Stroke Group-unaffected side | Left forearm | −0.86 (~3.35 ~ 1.64) | 0.49 (~2.00 ~ 2.99) | 0.44 (~2.06 ~ 2.93) | 0.697 (0.001) |
|        |                      | Right forearm    | 3.20 (~ −0.10 ~ 6.50) | 7.69 (~4.39 ~ 10.98) | 11.89 (~8.60 ~ 15.19) | 0.001** (~0.012) |
|        | Independent t-test   | P (Cohen’s d)    | 0.012* (~0.185) | 0.001** (~0.251) | 0.000*** (~0.335) |               |

(Continued)
Table 4. (Continued).

| Bands        | Groups                      | Stimulation side | Cotton       | Nylon        | Wool        | One-way ANOVA |
|--------------|-----------------------------|------------------|--------------|--------------|-------------|---------------|
|              |                             |                  | Mean (95% confidence interval, E-03) | P (Partial $\eta^2$) |             |               |
| Beta         | Control Group               | Left forearm     | 0.82 (0.17 ~ 1.46) | 2.10 (1.46 ~ 2.75) | 1.34 (0.70 ~ 1.99) | 0.021* (0.003) |
|              |                             | Right forearm    | 1.34 (0.75 ~ 1.93) | 2.29 (1.70 ~ 2.89) | 2.05 (1.46 ~ 2.64) | 0.069 (0.002)  |
|              | Independent t-test          |                  | 0.000*** (−0.510) | 0.000** (−0.438)  | 0.000* (−0.340)  |               |
| Stroke Group-affected side | Left forearm |                  | 7.02 (4.40 ~ 9.64) | 9.62 (7.00 ~ 12.24) | 9.28 (6.66 ~ 11.90) | 0.326 (0.002)  |
|              | Independent t-test          |                  | 0.000*** (−0.510) | 0.000** (−0.438)  | 0.000* (−0.340)  |               |
| Gamma        | Control Group               | Left forearm     | 1.19 (−1.09 ~ 3.47) | −2.01 (−4.29 ~ 0.28) | −1.47 (−3.76 ~ 0.81) | 0.115 (0.004)  |
|              |                             | Right forearm    | 1.34 (0.60 ~ 2.08) | 1.74 (1.00 ~ 2.48) | 3.38 (2.64 ~ 4.12) | 0.000*** (0.015) |
| Stroke Group-affected side | Left forearm |                  | 0.913 (−0.008) | 0.001** (−0.249)  | 0.000** (−0.293)  |               |
|              | Independent t-test          |                  | 0.000*** (−0.510) | 0.000** (−0.438)  | 0.000* (−0.340)  |               |
| Stroke Group-unaffected side | Left forearm |                  | 0.72 (0.13 ~ 1.30) | 0.74 (0.15 ~ 1.33) | 0.04 (−0.55 ~ 0.63) | 0.177 (0.001)  |
|              | Independent t-test          |                  | 0.000*** (−0.510) | 0.000** (−0.438)  | 0.000* (−0.340)  |               |
| Gamma        | Control Group               | Right forearm    | 0.67 (0.17 ~ 1.17) | 0.70 (0.20 ~ 1.20) | 0.82 (0.32 ~ 1.32) | 0.908 (0.000)  |
|              |                             | Right forearm    | 0.895 (0.006) | 0.924 (0.004) | 0.058 (0.088) |               |
| Stroke Group-affected side | Left forearm |                  | 0.14 (0.03 ~ 0.25) | 0.08 (−0.04 ~ 0.19) | −0.02 (−0.14 ~ 0.09) | 0.120 (0.004)  |
|              | Independent t-test          |                  | 0.000*** (−0.464) | 0.000** (−0.449) | 0.000* (−0.382) |               |
| Stroke Group-unaffected side | Left forearm |                  | 2.54 (1.49 ~ 3.59) | 3.79 (2.74 ~ 4.84) | 3.03 (1.98 ~ 4.08) | 0.251 (0.002)  |
|              | Independent t-test          |                  | 0.000*** (−0.464) | 0.000** (−0.449) | 0.000* (−0.382) |               |

Differences with statistical significance are marked with superscripts beside the P values ("*" for one-way ANOVA intra-group tests with Bonferroni post hoc tests or Dunnett's T3 post hoc tests, "#" for independent t-test). Significant levels are indicated as, 1 superscript for <0.05, 2 superscripts for <0.01, and 3 superscripts for <0.001.
The EEG relative spectral power in response to the fabric stimuli on the left and right forearms for (A) control group, (B) stroke group-unaffected side and (C) stroke group-affected side on the whole brain at the delta, theta, alpha, beta and gamma band presented as mean value with SE (error bar). The significant intragroup differences are indicated by ‘∗’ (p < 0.05, one-way analysis of variance with Bonferroni post hoc tests or Dunnett’s T3 post hoc tests), and the significant inter-group difference is indicated by ‘#’ (p < 0.05, independent t-test).

When comparing the overall RSP values of the control group and the stroke unaffected group, significant differences could be observed in the theta and alpha bands in response to the nylon and wool (P ≤ 0.001, one-way ANOVA, table 5), and a significant difference could be found in the beta and gamma bands (P < 0.01, one-way ANOVA, table 5) in response to the nylon.

3.2. Fine touch perception by questionnaire
Figure 7 shows the results of the questionnaire regarding the sensory properties of the three fabric samples as indicated by the participants in each group. Table 6
Figure 5. The whole brain EEG topography on the mean relative spectral power of (A) delta, (B) theta, (C) alpha, (D) beta, (E) gamma in response to the fabric stimuli in respect to the stimulation side.

displays the values, means and 95% confidence intervals of each sensory property, in addition to the one-way ANOVA probabilities and the EFs. In the control group (figure 7(A)), significant differences between cotton and the other two fabrics could be found in all sensory properties ($P < 0.001$, one-way ANOVA, table 6). For nylon and wool, in every sensory property except fullness, significant differences were found ($P < 0.001$, one-way ANOVA, table 6).

In the stroke unaffected side group (figure 6(B)), all ratings for the sensory properties showed significant differences between cotton and nylon, and nylon and wool ($P < 0.001$, one-way ANOVA, table 6). When comparing cotton and wool, significant differences could be found in all sensory properties ($P < 0.001$, one-way ANOVA, table 6) except softness. For the stroke affected side group (figure 7(C)), significant differences between cotton and nylon could be found.
Table 5. Comparisons on the overall relative spectral power with respect to the independent factors of the group and fabric sample on each EEG frequency band.

| Bands | Fabric | One-way ANOVA | Fabric | Two-way ANOVA |
|-------|--------|---------------|--------|---------------|
|       | P (Partial $\eta^2$) | Group | Fabric | P (Partial $\eta^2$) | Group | Fabric |
| Delta | 0.022 ($0.002$) | 0.001 ($0.001$) | 0.000 ($0.000$) | 0.678 ($0.000$) |
|       | 0.001 ($0.004$) | 0.000 ($0.001$) | 0.000 ($0.005$) | 0.053 ($0.001$) |
|       | 0.001 ($0.004$) | 0.000 ($0.004$) | 0.000 ($0.004$) | 0.053 ($0.001$) |
| Theta | 0.000 ($0.003$) | 0.000 ($0.004$) | 0.000 ($0.004$) | 0.000 ($0.005$) |
|       | 0.000 ($0.010$) | 0.000 ($0.004$) | 0.000 ($0.005$) | 0.050 ($0.001$) |
|       | 0.001 ($0.004$) | 0.000 ($0.003$) | 0.000 ($0.005$) | 0.013 ($0.001$) |
|       | 0.000 ($0.007$) | 0.172 ($0.000$) | 0.000 ($0.011$) | 0.071 ($0.001$) |
|       | 0.000 ($0.009$) | 0.000 ($0.018$) | 0.000 ($0.011$) | 0.013 ($0.001$) |
|       | 0.000 ($0.011$) | 0.000 ($0.012$) | 0.000 ($0.005$) | 0.071 ($0.001$) |

Differences with statistical significance are marked with superscripts beside the P values ('#' for one-way ANOVA inter-group tests with Bonferroni post hoc tests or Dunnett’s T3 post hoc tests, '△' for two-way ANOVA inter-group tests on the fabric and group effects). Significant levels are indicated as, 1 superscript for $< 0.05$, 2 superscripts for $< 0.01$, 3 superscripts for $< 0.001$.

Figure 6. The EEG overall relative spectral power in response to the fabric stimuli for each group on the whole brain at the delta, theta, alpha, beta and gamma band respectively, presented as mean value with SE (error bar). The significant inter-group differences are indicated by '# (P < 0.05, one-way analysis of variance with Bonferroni post hoc tests or Dunnett’s T3 post hoc tests).

...in almost all the sensory properties ($P < 0.001$, one-way ANOVA, table 6), except regarding itchiness, scratchiness and prickliness. Significant differences between cotton and wool were observed in all the sensory properties ($P < 0.001$, one-way ANOVA, table 6) except dryness, elasticity and comfort, while the significant differences between nylon and wool were found in all sensory properties ($P < 0.001$, one-way ANOVA, table 6) except fullness.

3.3. Correlation between EEG and questionnaire
The correlation analysis between the EEG RSP of representative frequency bands and the questionnaire scores is summarized in table 7. For unimpaired participants, the RSP of the theta and beta bands showed significant correlations with the subjective sensory properties ($P < 0.05$, Bivariate Correlation Analysis, table 7). The RSP of the theta band was significantly correlated with all subjective sensory properties ($P < 0.05$, Bivariate Correlation Analysis, table 7) except warmness and pliability, while the RSP of the beta band had significant correlations with all subjective sensory properties ($P < 0.05$, Bivariate Correlation Analysis, table 7) except dryness, smoothness, adhesiveness and thickness. In terms of the unaffected stroke group, the RSP of the alpha and beta bands had certain significant correlations with the subjective sensory properties ($P < 0.05$, Bivariate Correlation Analysis, table 7). The alpha RSP was significantly correlated with all subjective sensory properties ($P < 0.001$, Bivariate Correlation Analysis, table 7) except dryness, scratchiness and pliability, while the RSP of the beta band was only significantly correlated with a few sensory properties ($P < 0.05$, Bivariate Correlation Analysis, table 7): dryness, scratchiness and pliability. In terms of the affected stroke group, the RSP of alpha and beta bands were significantly correlated with the subjective sensory properties ($P < 0.05$, Bivariate Correlation Analysis, table 7). The RSP of the alpha band was significantly correlated with all subjective sensory properties ($P < 0.05$, Bivariate Correlation Analysis, table 7).
Participants.

However, only weak correlations (r < 0.2, table 7) except the scratchiness. The RSP of the beta band showed significant correlations with all subjective sensory properties (P < 0.05, Bivariate Correlation Analysis, table 7) except the scratchiness. However, only weak correlations (r < 0.2, table 7) [51] could be obtained between the EEG and questionnaire scores for both unimpaired and stroke participants.

### 4. Discussion

In this study, textile fabric stimulation was conducted to investigate post-stroke fine touch. It was measured using both EEG relative spectral power and an AATCC sensation questionnaire. The EEG RSP responses to the fine touch stimulation by different fabrics was examined in participants who had experienced chronic stroke and participants who had not. This study also explored the possibility of using EEG to detect the fine touch impairment after stroke. Responses to fabric stimuli applied to different upper limbs were investigated for both groups, and the relationship between the EEG and questionnaire was analyzed and explored.

#### 4.1. Cortical responses to textile fabric fine touch stimulation

The EEG results of the unimpaired participants (figure 4(A)) highlighted that different fabric stimulations could induce a varied RSP across the target frequency bands (i.e. theta and beta bands). It was observed that both theta and beta bands were

| Sensory properties | Control Group | Unimpaired side | Mean (95% confidence interval) | P (Partial $\eta^2$) |
|--------------------|---------------|-----------------|------------------------------|---------------------|
| Warmness | 4.13 (4.05 – 4.21) | 5.00 (4.90 – 5.10) | 0.000*** (0.508) |
| Stroke Group-affected side | 3.92 (3.79 – 4.05) | 4.42 (4.29 – 4.55) | 0.000*** (0.093) |
| Stroke Group-unaffected side | 4.75 (4.62 – 4.88) | 4.42 (4.29 – 4.55) | 0.000*** (0.148) |

**Table 6.** Fine touch perception during the textile fabric stimulation evaluated by the questionnaire.

| Sensory properties | Control Group | Unimpaired side | Mean (95% confidence interval) | P (Partial $\eta^2$) |
|--------------------|---------------|-----------------|------------------------------|---------------------|
| Dryness | 6.00 (5.93 – 6.07) | 5.79 (5.72 – 5.86) | 0.137 (0.055) |
| Stroke Group-affected side | 5.92 (5.82 – 6.01) | 6.25 (6.16 – 6.35) | 0.080 (0.148) |
| Stroke Group-unaffected side | 5.50 (5.41 – 5.59) | 6.71 (6.62 – 6.81) | 0.000*** (0.222) |

| Sensory properties | Control Group | Unimpaired side | Mean (95% confidence interval) | P (Partial $\eta^2$) |
|--------------------|---------------|-----------------|------------------------------|---------------------|
| Itchiness | 6.47 (6.38 – 6.50) | 7.00 (6.91 – 7.09) | 0.000*** (0.085) |
| Stroke Group-affected side | 6.50 (6.45 – 6.61) | 6.50 (6.40 – 6.61) | 0.000*** (0.095) |
| Stroke Group-unaffected side | 6.42 (6.33 – 6.51) | 7.00 (6.91 – 7.09) | 0.000*** (0.085) |

| Sensory properties | Control Group | Unimpaired side | Mean (95% confidence interval) | P (Partial $\eta^2$) |
|--------------------|---------------|-----------------|------------------------------|---------------------|
| Scratchiness | 5.33 (5.19 – 5.47) | 6.93 (6.82 – 7.03) | 0.000*** (0.103) |
| Stroke Group-affected side | 5.68 (5.60 – 6.67) | 7.00 (6.91 – 7.09) | 0.000*** (0.074) |
| Stroke Group-unaffected side | 5.50 (5.45 – 5.62) | 6.79 (6.70 – 6.87) | 0.000*** (0.213) |

| Sensory properties | Control Group | Unimpaired side | Mean (95% confidence interval) | P (Partial $\eta^2$) |
|--------------------|---------------|-----------------|------------------------------|---------------------|
| Comfort | 5.58 (5.46 – 5.71) | 6.42 (6.29 – 6.54) | 0.000*** (0.103) |
| Stroke Group-affected side | 5.50 (5.47 – 5.63) | 6.50 (6.37 – 6.63) | 0.000*** (0.213) |
| Stroke Group-unaffected side | 5.50 (5.45 – 5.59) | 6.79 (6.70 – 6.87) | 0.000*** (0.317) |

Differences with statistical significance are marked with superscripts beside the P values (‘∗’ for one-way ANOVA intra-group tests with Bonferroni post hoc tests). Significant levels are indicated as, 1 superscript for <0.05, 2 superscripts for <0.01, and 3 superscripts for <0.001.
Table 7. Summary of correlations between the fine touch during the textile fabric stimulation evaluated by EEG relative spectral power and questionnaire.

| Groups                  | Bands | Statistic | Warmness | Dryness | Scratchiness | Smoothness | Adhesiveness | Pliability | Thickness | Softness | Elasticity | Fullness | Comfort |
|-------------------------|-------|-----------|----------|---------|-------------|------------|--------------|------------|-----------|----------|------------|----------|---------|
| Control group           | Theta | Correlation coefficient | —        | —       | —           | —          | —            | —          | —         | —        | —          | —        | —       |
|                         |       | P value    | 0.003    | 0.039   | 0.000       | 0.000      | —            | 0.000      | 0.000     | 0.000    | 0.000      | 0.000    | 0.006   |
| Stroke Group-unaffected side | Theta | Correlation coefficient | 0.091**  | —       | 0.068**     | —          | —            | —          | —         | 0.085**  | 0.12**     | 0.16**   | 0.101** |
|                         |       | P value    | 0.000    | —       | 0.001       | —          | —            | —          | —         | 0.000    | 0.000      | 0.000    | 0.000   |
| Stroke Group-affected side | Theta | Correlation coefficient | —        | —       | —           | —          | 0.112**      | —          | —         | —        | —          | 0.061**  | —       |
|                         |       | P value    | 0.000    | 0.001   | 0.013       | 0.000      | 0.000        | —          | —         | —        | —          | 0.004    | —       |

Note: only correlation coefficients with p < 0.05 are presented in the table (** for Bivariate Correlation Analysis). Significant levels are indicated as, 1 superscript for <0.05, 2 superscripts for <0.01.
positively activated with increased power during the stimulation by the fabric samples. This is supported by the work of Michail et al on touch stimuli [52]. Theta activity is typically aroused during focused attention and information uptake, processing, and learning [53, 54]. Higher theta oscillations have been reported to reflect involuntary attention [55, 56], i.e. the processes of attending that are not elicited by intentions but by certain outside events [57]. When receiving external sensory stimulations, sensory and frontal cortices become activated [58], which is in line with the topography results of this study (figure 5(B)). One possible explanation for the arousal of theta activity is the iterative connections between sensory and attentional regions via competitive receptive-field interactions [58]. It was also suggested that the power of the theta band increases as the exogenous involuntary attention becomes more difficult [59, 60]. Chen et al [60] found that the intensity of attention oscillation was relatively low when processing an easy task, whereas, in order to obtain more information, the attention oscillation was maintained for a larger period of time with a higher intensity when the task was difficult. In this study, the participants’ involuntary attention was passively drawn by the different fabric stimulations during the EEG recording, and it was observed that the wool and nylon could arouse higher intensity of theta RSP than the cotton (figure 4(A)). Cotton was one of the most familiar fabrics in our daily living and was used as a reference fabric in the textile clothing industry [41], which might reflect an easy task, e.g. highly familiarity to the cotton touch, during the involuntary attention. Furthermore, nylon and wool provide distinctly different sensory experiences according to their physical properties as shown in table 2. This may unconsciously increase the difficulty of the involuntary attention. Beta oscillation plays a fundamental role in both the motor and somatosensory system [52, 61], and was reported to show an onset during the touch stimulations [52]. It had been suggested that beta oscillation had a specific pathway in binding processes within somatosensory cortical areas [62, 63]. Ede et al [64] proposed that the understanding of touch perception was related to a large-scale somatomotor beta network. Adhikari et al [65]

**Figure 7.** The fine touch perception during the textile fabric stimulation measured by questionnaire for (A) control group, (B) stroke group-affected side and (C) stroke group-affected side presented as mean value with SE (error bar). The significant intra-group differences are indicated by ">" (P < 0.05, one-way analysis of variance with Bonferroni post hoc tests).
further explained that the beta network was established by a feed-forward loop, which connect somatosensory regions to parietal and frontal brain regions. Meanwhile, Singh et al [35] found that the beta band was able to reflect affective mental states and distinguish pleasant fabric stimuli from unpleasant stimuli. This was not observed in the results of the current study which instead found an increased beta oscillation during the fabric stimulation in the unimpaired participants. Additionally, the touch discrimination between the cotton and nylon was only obtained in the left forearm. The limited sensitivity of touch discrimination and absence of reflecting affective mental states in the beta RSP was possibly due to the dominance of the theta band during involuntary attention evoked by the sensory stimulation as designed in this work.

In this study, it was observed that neural performance was asymmetric when the fabric stimuli were applied to different upper limbs in the control group, with significance largely captured in the low EEG frequency bands (figures 4(A) and 5). The results showed that the right forearm achieved higher RSP and exhibited a better touch discrimination to the different fabrics than the left forearm. For example, the theta RSP was able to distinguish the three fabrics in the right forearm, whereas in the left forearm, this distinction was not observed. This imbalance of the neural response toward fine touch stimulation could be related to the effect of handedness. In this study, all unimpaired participants were right-handed. The asymmetry between the dominant right hand and the non-dominant left hand were also observed during individuals’ manual performance, hand preferences and pain sensation [47, 48, 66, 67]. In addition to this, the dominant right hand typically displayed a higher performance level when performing single-handed tasks in comparison to the non-dominant left hand. The non-dominant left hand showed an earlier onset of negativity due to its lower dexterity, which could also lead to a lateralization of the sensory neural pathway and functions [68–70].

In this study, the neural responses of post-stroke fine touch by textile fabric stimulation were investigated. It was observed that the representative power spectrum toward fine touch stimulation after stroke shifted to higher frequency bands. The sensitive EEG spectra which were able to distinguish between the three fabrics of cotton, nylon and wool (figure 4(A)) were predominantly in the theta, alpha and beta bands in the control group. However, the gamma band (figures 4(B) and (C)) was involved in the fine touch for stroke participants in both affected and unaffected groups. Chen et al [71] reported that the changes of beta and gamma oscillation were a representation of impaired afferent proprioception and efferent control in sensorimotor system after stroke. Bannister et al [72] further discovered that stroke patients unconsciously employed higher-level attention and behavioral processes to compensate for the impaired somatosensory perceptual functions in contrast to the unimpaired control group. In the literature, activation of gamma oscillation after stroke was reported to not only contribute to the cognitive motor tasks [73, 74], but also to act as a coding feature for functional prevalence in hand sensory areas [75, 76]. The current study's results regarding shifts in the power spectra implied that the high frequency bands were of utmost importance during fine touch stimulation following stroke even in the involuntary attention process.

Significant differences between the neural responses to the stimulation to the affected limb of the stroke participants were also observed in this study. RSP differences among the different fabrics on the delta, theta and beta oscillations were obtained for stroke participants with left hemiplegia (figure 4(C)) when the stimulation applied to the affected side. However, there was no statistical difference in RSP in any frequency band toward the fabric stimuli for those with right hemiplegia (figure 4(C)). These results suggested that the brain lesion in different hemispheres might result in variations in fine touch impairments, and the neural response measured by EEG RSP was more sensitive in touch discrimination for stroke participants with left hemiplegia than those with right hemiplegia. Despite a lack of existing literature regarding the effects of brain lesions on sensory impairments [77–81], slower motor restoration in gait functions of right hemiplegia than the left had been previously reported [80, 81]. This particular finding could be related to the lateralization of brain function mentioned above, since the left hemisphere is superior in controlling complex motor movements [82]. However, the differences in sensory impairment after left/right hemisphere lesion have been seldom reported, and Goodin et al [83] argued that further investigations on the hemisphere lateralization of sensory functions are necessary.

Another finding of this study was that the neural response toward fine touch stimulation on the unaffected side of stroke group differed from the pattern exhibited by the unimpaired control group. Significant RSP variations toward the three different fabric stimuli could be observed in all frequency bands (figure 4(B)). Meanwhile, the RSP of the unaffected side also shifted to a higher frequency band, which was similar to the affected side. In a systematic review by Kitsos et al [84] on the function of ipsilesional upper limb following stroke, it suggested that certain sensorimotor deficits occurred in the ipsilesional upper limb following a stroke, including impaired fine and gross manual dexterity, weakened grip strength, decreased sensory discrimination and reduced speed of movement [84–86]. These deficiencies were related to the transcallosal interactions of interhemispheric [87].

Whole brain RSP topography was used to investigate the sensory cortical centers in response to fine
touch textile fabric stimulation (figure 5). The cortical locations of the significant RSP in all EEG frequency bands were mainly in the frontal and central brain, covering the premotor cortex, primary motor cortex (MI), and SI for unimpaired participants. This finding further provided evidence for the associative relationship between the MI and SI during somatosensory processing [88]. For the stroke participants, the relevant activated cortex in response to the fabric stimulation was located not only in the MI and SI, but also in the posterior area of the somatosensory association cortex. The somatosensory association cortex is involved in tactile perception, typically integrating sensory information from the SI to comprehend the stimulation being experienced [89]. The activation of the somatosensory association cortex in stroke participants might imply that it is necessary for stroke participants with sensory impairments to combine multiple neural inputs in order to process external stimulation.

The results of the study showed that the overall RSP intensity for the stroke affected group were significantly higher than that of the control group, particular in the alpha, beta and gamma bands (figure 6). This suggested that additional neural efforts and cortical resources, represented by increased EEG overall RSP intensity, were aroused to process the information on tactile sensory input from the affected side. Similar findings were observed by Thibaut et al [90] who studied motor performance after stroke and discovered that poor motor performance was related to an increased high-frequency EEG oscillation in the beta band. These power spectral deviations detected during the motor and sensory tasks might occur for the following reasons: (1) the increased activity in higher frequency bands is associated with excessive cortical effort after stroke, implying that stroke survivors find it challenging to complete desired tasks relating to pathological reorganization during the recovery period [90]. (2) The weaker interhemispheric connectivity following a stroke could lead to impaired tactile processing, as activity in both hemispheres plays an important role during sensory processing [72, 91, 92]. The disrupted interhemispheric connectivity has been indicated to have a negative effect on the attention and movement functions [93–96].

4.2. Correlation between EEG and subjective questionnaire

In this study, the fine touch perception during the textile fabric stimulation was also evaluated by the subjective questionnaire. Significant differences were found regarding the sensation properties of the three distinct fabric samples in both unimpaired and stroke participants (figure 7). The major difference between the fine touch evaluated by the EEG RSP and questionnaire was the participation of voluntary cognition. For the questionnaire evaluation, participants were asked to rate each fabric according to the sensation properties described in the questionnaire. This involved the cognitive processes including four primary elements of comprehension, retrieval, judgment and response [97, 98]. On the contrary, the cortical response captured by EEG RSP in the fine touch stimulation was the direct cortical response associated with involuntary attention drawn by the fabric fine touch stimulation. During the EEG recording, to minimize the bias caused from the participants’ active thinking, individuals were requested to remain awake yet mentally inactive. Therefore, the cortical responses captured by EEG RSP were much more preliminary than the cognitive processes during the questionnaire rating. It also implied that the questionnaire results on the measurement of sensory impairments could be compensated by the voluntary cognition based on individual experiences, which led to the higher discrimination rates on different fabrics in questionnaire evaluation than the EEG RSP detection (shown in figures 4 and 7).

From the correlation analysis, overall weak correlations (R < 0.2) between the EEG RSP results and the questionnaire properties were observed, associated with significant positive correlations (P < 0.05) in most subscales of the subjective questionnaire for the unimpaired participants and stroke participants on their unaffected sides, and with statistically significant negative correlations (P < 0.05) in the affected side of the stroke participants (table 7). This suggested that the relationships between EEG RSP and questionnaire scores were not directly linear, mainly because of the different processing stages in the perception of external fine touch stimulation, i.e. involuntary attention in EEG detection versus voluntary cognition in questionnaire response. In this work, EEG RSP provided a more direct measurement on the sensory impairments during the fine touch stimulation than the questionnaire, by minimizing the disturbance of the compensatory effects from the voluntary cognition which widely occurred in the traditional subjective assessments.

One of the limitations of this study is the small sample size for chronic stroke, while the significant EEG RSP differences had been obtained in both unimpaired and chronic stroke populations even with the current small sample size. In the future work, more stroke participants in different recovery stages, different age groups and lesion sites will be investigated for a more comprehensive understanding. This work is the first study that applied the AATCC questionnaire to stroke population for the assessment on fine touch impairment. Based on the results, it demonstrated significant differences in fabric discrimination for both unimpaired and stroke populations. The repeatability and reliability of the questionnaire on sensory impairments after stroke will be investigated further with large scale populations.
5. Conclusion

In this study, the cortical response, as measured by EEG, on fine touch impairments following a stroke was investigated using textile fabric stimulation. In comparison with the EEG RSP features of the unimpaired control, deviated patterns in the stroke group were (1) representative power spectrum shifted to higher frequency bands, (2) enlarged sensory cortical areas in somatosensory association cortex, (3) higher RSP intensity in high frequency bands. Meanwhile, asymmetric neural responses were obtained when stimulating different upper limbs, and the stroke participants with left hemiplegia showed a potential higher touch discrimination to the fabric stimulations on their affected forearms. In addition to this, this study found that the fine touch sensation of stroke participants was impaired even in the unaffected limb. These EEG RSP patterns could be adopted as more direct measures on the sensory impairments in neural responses to fine touch after stroke compared to the traditional questionnaires by subjective evaluation. Furthermore, as a result of differing neural processes, the correlation between the EEG and questionnaire was weak. In future assessments, the EEG RSP analysis could be a complementary evaluation to the traditional questionnaires for the fine touch impairment after stroke.

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