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Accurate digitization of EEG electrode locations by electromagnetic tracking system: The proposed head rotation method and comparison against optical system

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ABSTRACT

Electroencephalogram (EEG) electrode digitization is crucial for accurate EEG source estimation, and several commercial systems are available for this purpose. The present study aimed to evaluate the digitizing accuracy of electromagnetic and optical systems. Additionally, we introduced a novel rotation method for the electromagnetic system and compared its accuracy with the conventional method of electromagnetic and optical systems. In the conventional method, the operator moves around a stationary participant to digitize, while the participant does not move their head or body. In contrast, in our proposed rotation method with an electromagnetic system, the operator rotates the participant sitting on a swivel chair to digitize in a consistent position. We showed high localization accuracy in both the optical and electromagnetic systems, with an average localization error of less than 3.6 mm. Comparisons of the digitization methods revealed that the electromagnetic system demonstrates superior digitizing accuracy compared to the optical system. Notably, the proposed rotational method is the most accurate among the three methods, which can be attributed to the consistent positioning of EEG electrode digitization within the electromagnetic field. Considering the affordability of the electromagnetic system, our findings provide valuable insights for researchers aiming for precise EEG source estimation.

- The study compares the accuracy of electromagnetic and optical systems for EEG electrode digitization, introducing a novel rotation method for improved consistency and precision.
- The electromagnetic system, especially with the proposed rotation method, achieves superior digitizing accuracy over the optical system.
- Highlighting the cost-effectiveness and precision of the electromagnetic system with the rotation method, this research offers significant insights for achieving precise EEG source estimation.

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Background

Electroencephalography (EEG) is a non-invasive technique for measuring brain activity with high temporal resolution but limited spatial resolution. Tremendous efforts over the years have advanced EEG-based electrophysiological source imaging (ESI) that improves spatial resolution [1,2]. Precise ESI requires an individual head model obtained from structural magnetic resonance imaging (MRI), providing comprehensive spatiotemporal imaging of the brain. Recent studies employing ESI reported that EEG-based ESI can estimate brain activity that highly correlates with the signals recorded from deep brain regions [3,4]. One of the critical processes of ESI, the precise calculation of scalp potential distribution, requires EEG electrode digitization, that is, recording the position where the electrode is placed on the head. Thus, accurate registration of EEG electrodes is essential for ESI because inaccurate electrode digitization adversely affects the co-registration of the electrodes with the head model and the performance of EEG source reconstruction [5].

Several commercial systems are available for EEG electrode digitization. Three typical examples are electromagnetic (EM) systems used in *Polhemus*, photogrammetry systems used in *EGI Photogrammetry System*, and optical systems used in *Brainsight, Xensor Electrode Digitizer*, and *EEG PinPoint*. EM digitalization is a classical method widely used for digitalizing the EEG electrode position over the years and is the most affordable of the systems introduced above (e.g., approximately 3–5k USD for *Polhemus*'s PATRIOT system). Thus, if inexpensive EM systems can digitize the EEG electrode position with high accuracy, more researchers would have access to ESI, leading to advances in EEG research.

Although the use of conventional EM digitization seems simple, it has the problem that the accuracy of the EEG electrode digitization varies depending on the electrode position and is poorer than that of other digitization methods [5–7]. One possible reason for this problem is that the distance from the stylus receiver to the reference receiver and transmitter was too far, which reduced the signal-to-noise ratio and spatial resolution of the transmitted EM fields, resulting in poor digitization accuracy. Furthermore, insufficient preparation of the measurement environment and technique may cause the low accuracy of EM digitalization. Since an EM system is sensitive to environmental factors, the measurement environment must be arranged to avoid placing metals and other objects that distort the magnetic field generated by the transmitter. A recent study systematically investigated the factors affecting the accuracy of EM digitization and reported a recommended distance from the transmitter, measurement environment, and techniques for digitizing [8]. The previous study focused only on EM systems and did not compare the accuracy of EM digitization in the recommended environment and other digitization methods.

Therefore, the present study aims to compare the digitizing accuracy of EM digitization with that of commonly used optical digitization, considering the measurement environment and technique. In addition to comparing EM and optical systems (Fig. 1B and C), we propose a novel digitization method in EM system, the rotation method, in EM digitization (Fig. 1E) and compare these methods. Details of these methods are described in the Methods section.

Method details

Description of EM system

An EM system operates on the principles of electromagnetism, particularly the interaction between magnetic fields and electric currents. It processes the EM signals to determine digitized positions. This system typically consists of a transmitter, a reference receiver, and a stylus receiver. The transmitter generates an EM field, serving as a geographical reference to ascertain the three-dimensional (3D) position and orientation of both the reference and stylus receivers. In an EM system, the reference receiver is attached to the temporal head of the participants, and operators digitize the electrode positions by touching the tip of the stylus receiver (a pen-shaped device with a built-in digitizing probe) to each electrode (see Fig. 1C). The system thus localizes EEG electrodes by identifying the digitized positions of the stylus receiver relative to the reference receiver. The strength of the transmitted EM field decreases with increasing distance from the source, following the inverse square law. This law states that the strength is inversely proportional to the square of the distance from the source. Therefore, the signal-to-noise ratio degrades when the sensors are further away from the generator, leading to reduced digitization accuracy. For this reason, it was recommended to digitize electrode locations near the generator in the EM system [8]. Conventionally, with this method, the operator moves around the participant to digitize, while the participant does not move their head or body. We here refer to this procedure as the EM system with the conventional method or the conventional EM digitization.

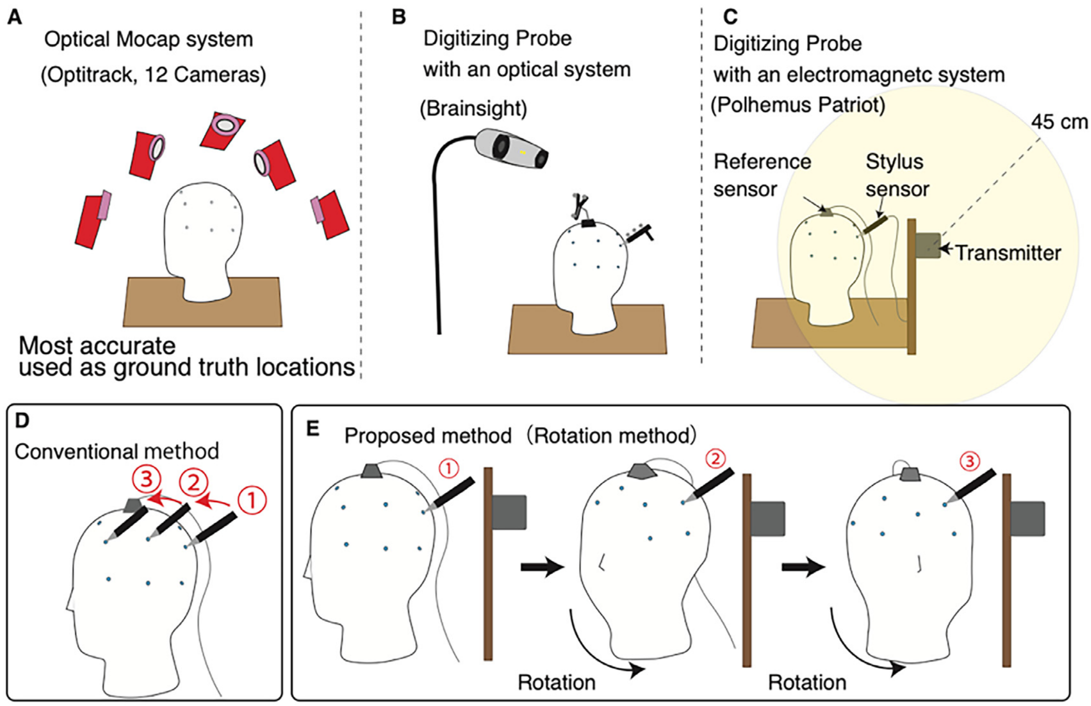

Fig. 1. Overview of the digitization methods used in the present study. (A) Motion capture system setup with 3-mm diameter markers to record the true locations of the 16 EEG electrodes and three fiducials. We compared the three digitization methods: (B) Optical system, (C) EM system with (D) the conventional method, and EM system with (E) the proposed rotation method. In (D) and (E), the numbers refer to the order of digitization of electrodes.

Proposal for a novel digitization method in EM system, namely the rotation method

In the proposed rotation method, the operator rotates the participant seated on a rotatory chair to digitize in the same position as much as possible, while the participant themselves does not move their head or body. Thus, in the conventional method, the operator moves around the stationary participant for digitization (Fig. 1D), whereas in the proposed method, the participant is moved (i.e., rotated) by the operator for digitization (Fig. 1E). In the conventional method, the distance between the stylus receiver and transmitter, as well as the strength of the EM field, varies depending on the electrode position to be digitized. However, the proposed rotation method allows for maintaining a short and constant distance from the stylus receiver to the transmitter, providing two potential advantages. First, the distance between the receivers and transmitter is always short, promising high digitizing accuracy. The second is that the EEG electrodes are digitized at almost the same position in the EM field. Therefore, even if there are effects of magnetic field distortion, the electrodes are digitized at a relative position from the reference receiver to the stylus receiver, which would leave scaling errors but reduce the effect of shape distortion of all electrodes in the proposed method, compared with the digitization in a broader area in the conventional method. The latter advantage would reduce the error due to an inaccuracy in the head coordinate system based on vectors obtained from the digitized three fiducial landmarks, which is the most common registration method of EEG electrodes and an MRI image.

Overview of our methodology

We used a mannequin head taped to 16 EEG electrodes (actiCAP slim electrode, Brain Products GmbH, Germany) arranged in the international 10–10 system [9] to compare four methods for digitization. The electrodes were located at FPz, F3, F4, F7, F8, C3, C4, T7, T8, Pz, P3, P4, P7, P8, O1, and O2. Eight operators digitized the 16 EEG electrodes, right and left preauricular (RPA and LPA) and nasion (NAS) on the mannequin. We used actual EEG electrodes instead of simple pen-marked locations to consider the effects of distortion of EM fields by the electrodes. The electrodes and fiducial landmarks were pen-drawn circles approximately 3 mm in diameter to ensure that the same position was digitized for each method. First, we used a motion capture system with 3-mm diameter markers to record the true locations of the electrodes and fiducials (Fig. 1A). Second, participants digitized the electrodes and fiducials in the following three methods (Fig. 1B and C): (1) an optical system, (2) an EM system with the conventional method (Fig. 1D), and (3) an EM system with the proposed rotation method (Fig. 1E). For each method, participants performed the digitization twice, the first time as a practice and the second time as a test trial that was analyzed. The order of the digitization methods was randomized. Details of each method used in the present study are given below.

In addition to digitization using the mannequin head, digitization was also performed using a human head. We placed a cap with 16 EEG electrodes (actiCAP slim electrode, Brain Products GmbH, Germany) on a male. Six operators digitized the 16 EEG electrodes, RPA, LPA, and NAS on the male's head, following the same procedure as the digitization on the mannequin.

Optical motion capture system

We used an optical motion capture system composed of 12 cameras (OptiTrack system with Flex3 cameras, Natural Point, USA) with 3-mm diameter hemispherical reflective markers to digitize the electrodes and fiducials (Fig. 1A). The reflective markers were placed on the pen-drawn circles approximately 3 mm in diameter on electrodes and the fiducial landmarks of the mannequin. The pen-drawn circles were used for other digitization methods. We recorded the locations of 16 EEG channels and three fiducials for 2 s at 100 Hz. The locations recorded by the optical motion capture system are the most accurate of the methods (the average tracking error of the motion capture system was <0.1 mm based on calibration data) used in the present study and thus were used as the ground truth position for evaluation of digitizing accuracy as in a previous study [10].

Digitizing probe with an optical system

Participants digitized the electrodes and fiducials by using another optical system (Fig. 1B), a TMS neuronavigation system (Brain-Sight, Rogue Research, Canada) combined with a Polaris Spectra passive optical tracking system (Northern Digital, USA). The glasses-mounted markers were attached to the mannequin/human head. Location data was recorded when operators touched the tip of the digitizing probe to each channel and fiducial landmark. The operators listened to the sound generated during each digitization and re-digitized when they felt that the digitizing did not succeed (incorrect digitizing position or timing).

Digitizing probe with an EM system

Digitization with an EM system was performed using a Patriot system with a standard (TX2) transmitter (Polhemus Patriot, Polhemus, USA). This EM system consists of a transmitter, a reference receiver, and a stylus receiver (Fig. 1C). The transmitter generates an EM field attenuating over ~ 76 cm to determine the 3D position of the stylus receiver relative to the reference receiver. Thus, the receivers must be located within the EM field. Therefore, the mannequin/human head was placed in a position where all landmarks digitized by the stylus receiver were positioned within a 45 cm radius of the transmitter. The reference receiver was placed on the top of the mannequin's/human's head. Operators digitized the electrode positions relative to the reference receiver with 60 Hz using the EM system in the following two methods.

Conventional method. In the conventional method, operators digitized the electrodes and fiducials without moving the mannequin/human head (Fig. 1D). Location data was recorded when they touched the tip of the stylus receiver (a pen-shaped device with a built-in digitizing probe) to each channel and landmark and pressed a button on the receiver with their finger. The operators listened to the sound generated during each digitization and re-digitized when they felt that the digitizing did not succeed (incorrect digitizing position or timing). In this method, the distance from the receiver to the transmitter varies depending on the location of the electrode or fiducial to be digitized.

Proposed rotation method. In the present study, we proposed the rotation method that maintains a short distance from the receiver to the transmitter. The procedure is identical to the conventional method, except for the rotation of the mannequin/human head. In the proposed rotation method, operators digitized the electrodes and fiducials after rotating the mannequin/human head to a position where the distance from the receiver to the transmitter was shortened (Fig. 1E). Therefore, the distance in the proposed rotation method was shorter, with less variance than that in the conventional method.

Data analysis

We compared the accuracy among three methods (the optical system and the EM system with both the conventional and proposed rotation methods). The data were analyzed offline using custom-written codes on MATLAB 2022b (Mathworks, MA, USA). The distance metrics and the transformation method used throughout the present study are the Euclidean distance and the Euclidean transformation, respectively.

Transformation to head coordinates. In this study, we used three different coordinate systems: global co-ordinate system, reference receiver coordinate system (1st Head coordinate system), and three fiducial landmarks-based coordinate system (2nd Head coordinate system). We first digitized the position and orientation of the reference receiver, placed on the vertex, and the position of the EEG electrode in the global coordinate system. In this system, the origin is set at a vertex of the square-shaped EM field generator, with X, Y, and Z axes set in forward, right, and upward directions, respectively. Digitization of the reference receiver and target electrode was performed on each electrode. The positions of the electrodes, recorded in the global coordinate system, were then transformed into the reference receiver coordinate system based on the reference receiver's location and orientation, which was recorded simultaneously with each electrode and head landmark digitization. After transforming all the electrodes and head landmarks into the reference receiver's coordinate system, they were further transformed into the head coordinate system with respect to three landmarks for comparison with other digitization methods. We used a coordinate transformation method based on the three fiducial landmarks (LPA, RPA, and NAS), commonly used for the co-registration of EEG electrodes and MRI data in ESI studies [1]. In this coordinate system, the X-axis is defined as the vector from LPA to RPA, and the origin is the projection of the NAS to the X-axis. Therefore, the Y-axis is defined as the vector from the origin to the NAS, and the Z-axis is the cross-product of the X and Y unit vectors.

Variability and accuracy of digitized locations. We qualified the variability of the digitization by the variance of digitized locations across operators at each location in each digitization method. The variance was calculated based on the Euclidean distance of all digitized locations from the centroid. This analysis was performed only for data in the fiducial landmark-based coordinate system as this method is widely used in EEG-based ESI research. Then, we qualified digitizing accuracy based on the Euclidean distance between the digitized location and the ground truth location at each location in each digitization method. The accuracy was calculated using the fiducial landmark-based method. To compare our current results with a previous study, which investigated digitization accuracy of ultrasound, structured-light 3D scan, infrared 3D scan methods using the digitized locations by the optical system as the true value, we calculated the location differences between the optical and EM systems using the Euclidean distance.

Statistical analyses

Differences in the variance of digitization locations among the three digitization methods were compared using one-way repeated measures analysis of variance (rmANOVA) with a post hoc Holm test. Then, the accuracy of digitization locations among the three digitization methods was compared using a non-parametric comparison method with 1000 random permutations [11], as normality was not observed in all cases. For the variance, 19 samples were included in a single method because the variance was calculated at each electrode location. Conversely, for the accuracy, 152 (19 locations × 8 operators) and 114 samples (19 locations × 6 operators) were included in a single method for the mannequin head and human data, respectively. We then compared the location differences from the optical systems between the EM methods using a paired *t*-test. Before the analyses, we used the Kolmogorov-Smirnov Test to check the normality. P-values were corrected using the Holm method, and Cohen's d values were calculated as the effect size for comparison between digitization methods. For all statistical tests, the significance level was set at $p < 0.05$. Thresholds for interpreting Cohen's d values were set to 0.2, 0.5, and 0.8 for small, medium, and large effect sizes, respectively [12].

Method validation

Mannequin head

We first show results obtained from the mannequin head. Fig. 2 (A and B) shows the mean deviation across operators of the digitized positions of EEG electrodes and fiducial landmarks in each digitization method. The mean deviations in the EM system with the proposed rotation and conventional methods were 0.56 mm and 0.52 mm, respectively. The mean deviation in the optical system was 1.56 mm. One-way rmANOVA revealed a significant main effect of digitization methods ($F_{2, 54} = 84.1$, $p < 0.0001$). Post hoc *t*-tests with Holm correction showed no significant differences between the conventional and rotation EM system methods ($t_{18} = 1.20$, $p = 0.24$, Cohen's $d = 0.26$). The deviation in the optical system methods was significantly higher than the EM systems (rotation method: $t_{18} = 12.4$, $p < 0.0001$, Cohen's $d = 3.01$; conventional method: $t_{18} = 12.2$, $p < 0.0001$, Cohen's $d = 3.07$).

Fig. 2 (C and D) shows the mean digitizing accuracy based on the error in the Euclidean distance between the digitized and ground truth locations in each digitization method. The mean errors using the fiducial-based transformation in the EM system with the proposed and conventional rotation methods and in the optical system were 1.29 mm, 1.78 mm, and 2.49 mm. The permutation test with Holm correction showed the error in the EM system with the proposed rotation method was lower than that in the EM system with the conventional method ($p < 0.0001$ Cohen's $d = 1.21$) and that in the optical system ($p < 0.0001$, Cohen's $d = 1.23$). Furthermore, the error in the EM system with the conventional method was lower than that in the optical system ($p < 0.0001$, Cohen's $d = 0.65$).

Human head

Then, we show results obtained from the human head. Fig. 3 (A and B) shows the mean deviation across operators of the digitized positions of EEG electrodes and fiducial landmarks in each digitization method. The mean deviations in the EM system with the proposed rotation and conventional methods were 0.82 mm and 1.1 mm, respectively. The mean deviation in the optical system was 2.9 mm. One-way rmANOVA revealed a significant main effect of digitization methods ($F_{2, 54} = 52.3$, $p < 0.0001$). Post hoc *t*-tests with Holm correction showed that the deviation in the EM system with the rotation method was lower than that in the EM system with the conventional method ($t_{18} = 4.94$, $p = 0.00010$, Cohen's $\boldsymbol{d} = 1.00$) and that in the optical system ($t_{18} = 9.15$, $p < 0.0001$, Cohen's $\boldsymbol{d} = 2.57$). Furthermore, the deviation in the EM system with the conventional method was lower than that in the optical system ($t_{18} = 9.48$, $p < 0.0001$, Cohen's $\boldsymbol{d} = 2.13$).

Fig. 3 (C and D) shows the mean digitizing accuracy. The mean errors using the fiducial-based transformation in the EM system with the proposed rotation and conventional methods and in the optical system were 2.64 mm, 3.56 mm, and 3.25 mm, respectively. The error in the EM system with the proposed rotation method was significantly lower than that in the EM system with the conventional method ($p < 0.0001$, Cohen's $d = 1.10$) and that in the optical system ($p = 0.0012$, Cohen's $d = 0.44$). The error in the EM system with the conventional method was significantly larger than in the optical system ($p = 0.035$, Cohen's $d = 0.27$).

Fig. 4 shows the location differences between the optical and EM systems. For the mannequin head, the mean differences using the fiducial-based transformation in the EM system with the proposed rotation and conventional methods were 2.28 mm and 2.47 mm, respectively. The mean difference in the EM system with the proposed rotation method was significantly lower than that with the

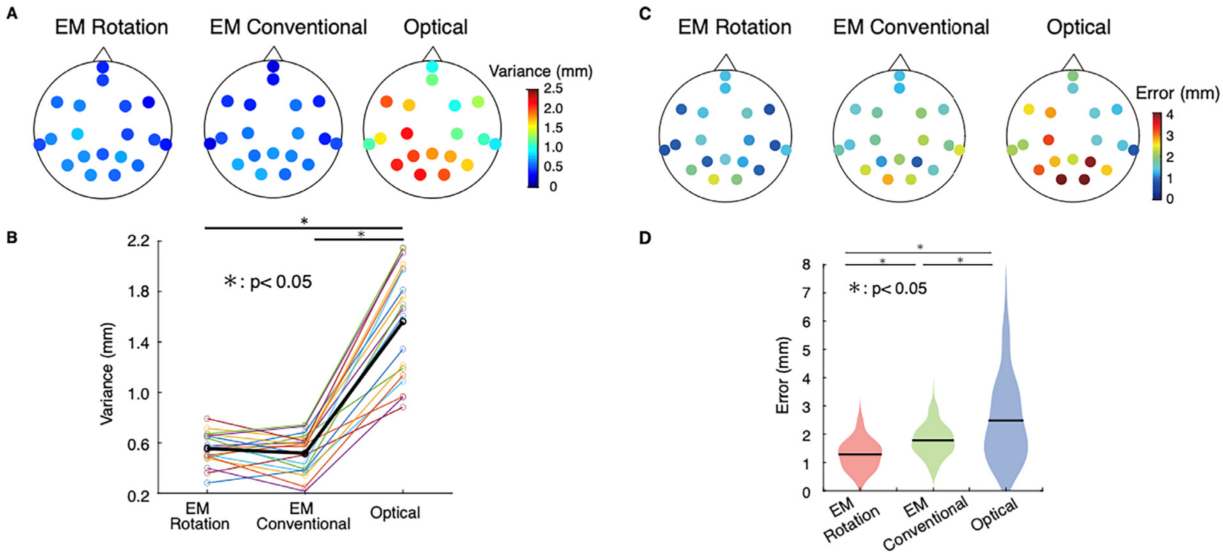

Fig. 2. Results obtained from the mannequin head. (A) Mean deviation across operators of digitized positions of each EEG electrode and fiducial landmark in EM (EM) system with the proposed rotation and conventional methods and optical system. The color bar represents the valence (mm). (B) Comparison of the deviations for all digitized positions across three digitization methods. Each colored plot represents the mean deviation across operators for each electrode. The black plots indicate averages in mean deviation across all electrodes. Asterisks significantly indicate significant differences in deviations among the methods. Statistical analysis revealed that the conventional EM method showed the least deviation compared to both the EM system with the proposed rotation method and the optical system. The right-side shows mean digitizing accuracy based on the error in the Euclidean distance between the digitized and ground truth locations in the EM system with the proposed rotation and conventional methods and optical system. The errors were calculated using the fiducial-based transformation (C). The color bars represent the valence (mm). Comparison of the errors for all digitized positions across three digitization methods with the fiducial-based transformation (D). Violin plots represent the distribution of errors. The black bar indicates the mean value. Asterisks significantly indicate significant differences in errors between the digitizing methods. Statistical analysis revealed that the error in the EM system with the proposed rotation method was lower than that in the EM system with the conventional method and that in the optical system and, the error in the EM system with the conventional method was lower than that in the optical system.

conventional method ($t_{151} = 3.33$, $p = 0.0011$, Cohen's $\boldsymbol{d} = 0.27$). For the human head, the mean differences using the fiducial-based transformation in the EM system with the proposed rotation and conventional methods were 3.34 mm and 3.92 mm, respectively. The mean difference in the EM system with the proposed rotation method was significantly lower than that with the conventional method ($t_{113} = 4.43$, $p < 0.0001$, Cohen's $\boldsymbol{d} = 0.41$).

Explanation of validation

The present study aimed to assess the digitizing accuracy among EM digitization with the conventional method and the newly proposed rotation method and optical digitization. Our results obtained from both the mannequin and human heads revealed that the EM digitization had less deviation than the optical digitization (Fig. 2). In the human head experiment, the EM digitization with the proposed rotation method showed the least deviation among the three methods (Fig. 3). Furthermore, for the fiducial-based transformations, the proposed rotation method in the EM system demonstrated the lowest error, thus ensuring the highest accuracy in both heads (Figs. 2 and 3). Our findings indicate that both the optical and EM digitization have a sufficient accuracy (error less than 2.5 mm with the ground truth position for the mannequin head; error less than 3.6 mm for the human head) for EEG-based ESI research [10]. Notably, among the methods compared in this study, EM digitization with the rotation proposed method exhibits superior accuracy.

The EM system with the conventional and proposed methods demonstrated less variation among operators for digitized positions than the optical system (Fig. 2A and B). These results indicate that, in the recommended environment [8], the EM system can digitize with lower variation than the optical system. Within the EM system, our results in the human head showed that the proposed rotation method had less variation than the conventional method (Fig. 3A and B). For digitizing accuracy, the EM system with the proposed rotation method demonstrated the lowest errors compared to the conventional EM system and then the optical system (Figs. 2C, 2D, 3C, and 3D). Thus, when performed in the recommended environment [8], the EM system with the proposed rotation method exhibited higher accuracy than the optical method. Although it takes time and effort to build the recommended environment, the EM system is more affordable for many researchers compared to optical systems. Combined with our results indicating low variation and high accuracy, EM digitization is highly suitable for EEG-based ESI research.

Our results also found superior digitizing accuracy in the EM system with the proposed rotation method (Figs. 2C, 2D, 3C, 3D, and 4), supporting our hypothesis. As explained in the introduction, the proposed rotation method maintains a short and consistent

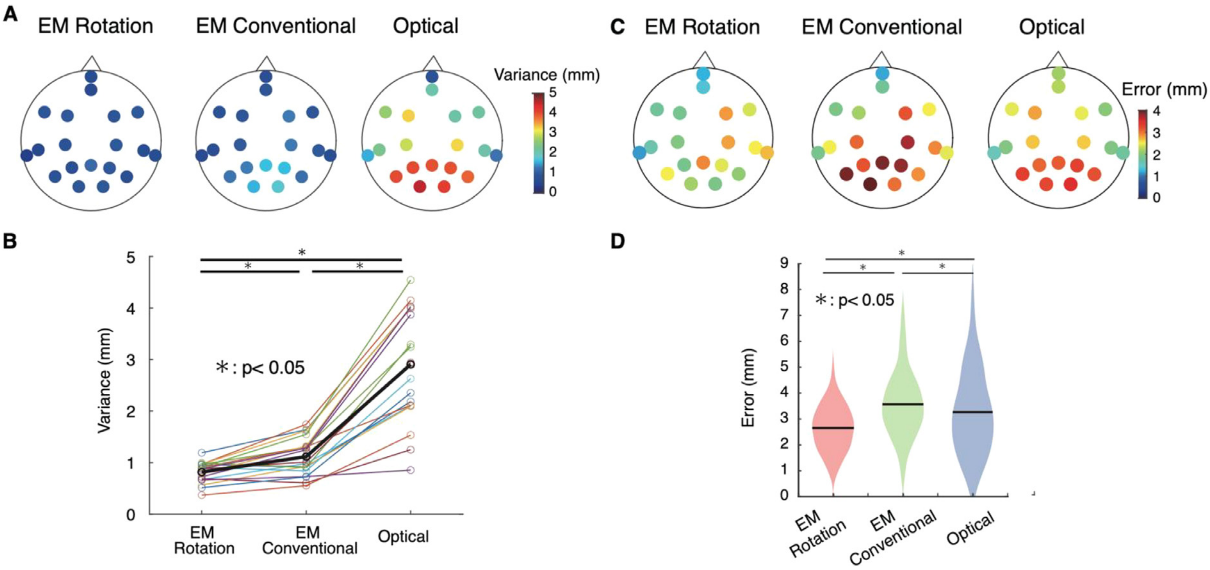

Fig. 3. Results obtained from the human head. (A) Mean deviation across operators of digitized positions of each EEG electrode and fiducial landmark in EM (EM) system with the proposed rotation and conventional methods and optical system. The color bar represents the valence (mm). (B) Comparison of the deviations for all digitized positions across three digitization methods. Each colored plot represents the mean deviation across operators for each electrode. The black plots indicate averages in mean deviation across all electrodes. Asterisks significantly indicate significant differences in deviations among the methods. Statistical analysis revealed that the EM system with the proposed rotation method showed the least deviation compared to both the conventional EM method and the optical system. The right-side shows mean digitizing accuracy based on the error in the Euclidean distance between the digitized and ground truth locations in the EM system with the proposed rotation and conventional methods and optical system. The errors were calculated using the fiducial-based transformation (C). The color bars represent the valence (mm). Comparison of the errors for all digitized positions across three digitization methods with the fiducial-based transformation (D). Violin plots represent the distribution of errors. The black bar indicates the mean value. Asterisks significantly indicate significant differences in errors between the digitizing methods. Statistical analysis revealed that the error in the EM system with the proposed rotation method was lower than that in the EM system with the conventional method and that in the optical system and, the error in the EM system with the conventional method was lower than that in the optical system.

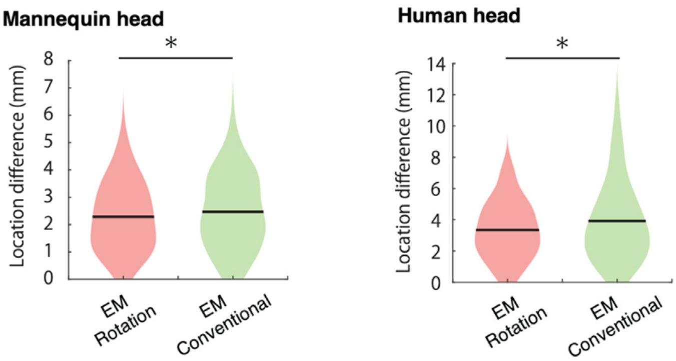

Fig. 4. Results obtained from the mannequin (left) and human (right) heads: Mean value of location differences between the optical and EM systems. Violin plots represent the distribution of the location differences. The black bar indicates the mean value. Asterisks significantly indicate significant differences between the proposed and conventional methods.

distance between the receivers and the transmitter, allowing EEG electrodes to be digitized at nearly uniform positions within the EM field. These combined advantages resulted in the rotation method achieving higher accuracy compared to the conventional method. Furthermore, the low variance and high accuracy of the proposed method may be associated with the fiducial-based transformation. In this transformation, the digitizing accuracy of the three landmarks is critical; any misalignment of fiducial landmarks adversely affects the digitizing accuracy of all electrodes. The proposed rotation method, where the fiducial landmarks are digitized at nearly identical positions in the EM field, leads to highly similar misalignments of the fiducial landmarks in the global coordinate system. Considering the misalignments in a spherical coordinate system after the reference sensor-based transformation, the scale (r) and angular (θ, φ) misalignment would be similar for all three landmarks. Consequently, the proposed rotation method can reduce angular misalignment more effectively than the conventional method, owing to the accurate relative positions of the three points, although the scaling effect remains. Thus, the rotation method can create a highly accurate head coordinate system.

We also considered the effect of rotation methods on the three coordinate systems, focusing on digitization accuracy as it is essential for accurate ESI. In the fiducial-based transformation, the digitizing accuracy of the three landmarks is critical because any misalignment of fiducial landmarks in the coordinate system adversely affects the digitizing accuracy of all electrodes. The rotation method digitizes the fiducial landmarks at almost the same positions in the global coordinate system, which indicates that they are digitized at almost the same positions in the EM field. This results in almost similar misalignment in all landmarks. Considering these misalignments in a spherical coordinate system after the reference sensor-based transformation, the scale (r) and angular (θ, φ) misalignment would be similar for all three landmarks. This constant angular (θ, φ) misalignment for all the fiducial landmarks can retain the relative position information required for making a head coordinate system; thus, the rotation method can create a highly precise head coordinate system. On the other hand, in the conventional method, fiducial landmarks are digitized at different positions in the EM field, leading to potential variations in the magnitude and direction of misalignment. The advantage of the rotation method in creating the head coordinate system probably contributes to more accurate digitization. Indeed, the results obtained from both the mannequin and human heads demonstrated that the rotation method achieves better digitizing accuracy than the conventional method.

In addition to the digitizing accuracy, the efficiency of the proposed method should be higher than the conventional method in noisy environments. In noisy environments with large magnetic field distortion, the effect of this distortion on digitization varies depending on the digitizing location. In the proposed rotation method, the distance between the sensors and the EM field generator is kept short; thus, the signal-noise ratio is high, and the effect of noise can be reduced. Furthermore, the EEG electrodes are digitized at almost the same position within the EM field. Therefore, even in noisy environments, the proposed method would provide relatively more stable digitization than the conventional method because digitizing in a narrow area minimizes the effect of magnetic field distortion. Additionally, the proposed method requires less area for noise checking and would provide stable digitizing even in noisy environments, provided there is a small space with minimal magnetic field distortion.

Finally, we calculated the location differences between the optical and EM systems (Fig. 4) because previous studies have often calculated the Euclidean distance between the location for an optical system and the location for other digitizing methods (e.g., [10]). We compared the digitizing accuracy of the EM system in the current study with that of other well-known digitization techniques in a previous study [10]. The previous study used the mannequin head and the fiducial-based transformation. The previous results showed that the mean differences in the ultrasound, structured-light 3D scan, and infrared 3D scan systems were 4.3 mm, 6.3 mm, and 4.1 mm, respectively. Our results from the mannequin experiment showed that the mean differences using the fiducial-based transformation in the EM system with the conventional and proposed rotation methods were 2.47 mm and 2.28 mm, respectively. Therefore, the EM system, especially with the proposed method, may exhibit more accurate digitizing than the ultrasound, structured-light 3D scan, and infrared 3D scan systems. However, the comparison between our current result and the previous result [10] may not directly reflect the actual difference in error between the EM system and other well-known digitization systems. This is because digitized positions for the optical system, which are used as true values in this comparison, showed an error with the true locations determined by a motion capture system greater than the EM system (Figs. 2C, 2D, 3C, and 3D). Thus, we should be cautious when comparing digitizing accuracy across studies. Further studies are needed to compare the EM system with the ultrasound, structured-light 3D scan, and infrared 3D scan systems by using digitized positions in a motion capture system as true values.

In summary, we evaluated the accuracy of both the EM and optical systems under the recommended environment and introduced a new method for the EM system. Both the optical and EM systems showed good localization accuracy (mean localization error less than 3.6 mm). Comparisons of the systems and digitization methods revealed that the EM system offers superior digitizing accuracy compared to the optical system, and the proposed rotational method is the most accurate among the three methods. Given the affordability of the EM system, our results could pave the way for more researchers to engage in EEG source estimation, promoting a broader application of ESI analysis.

Limitations

None.

Ethics statements

The Ethics Committee of the University of Tokyo approved all experimental procedures (approval number: 701–4). An individual participated in the present study after providing written informed consent according to the Declaration of Helsinki (1964).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Naotsugu Kaneko: Methodology, Validation, Investigation, Writing – original draft, Visualization, Funding acquisition. **Moeka Yokoyama:** Software, Formal analysis, Writing – review & editing. **Kimitaka Nakazawa:** Writing – review & editing, Funding acquisition. **Hikaru Yokoyama:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition.

Data availability

Data will be made available on request.

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