Functional cortical localization of the tongue using corticokinematic coherence with a deep learning-assisted motion capture system

Running title: Tongue CKC by motion capture

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Abbreviations: ACC, Accelerometer; CKC, Corticokinematic coherence; ECD, Equivalent current dipole; EMG, Electromyography; LED, light-emitting diode; MEG, Magnetoencephalography; MEF, Movement evoked field; MRI, Magnetic resonance image; SM1, primary sensorimotor cortex; SEM, Standard error of the mean.

29 **Acknowledgments**

30 We thank Dr. Takafumi Suzuki, Dr. Takeshi Nogai and Dr. Asuka Otsuka (Center for
31 Information and Neural Networks (CiNet), National Institute of Information and
32 Communications Technology, and Osaka University) for supporting our MEG
33 recording.

34

35 **Funding**

36 This work was supported by the Grants-in-Aid for Scientific Research from the Japan
37 Society for the Promotion of Science [grant numbers (A)18H04166 (MH),
38 (C)19K10218 (HM)].

39

40 **Conflict of interest disclosure**

41 The authors declare no competing financial interest.

42

43 **Data and Code Availability**

44 The movements of the tongue and fingers were analyzed with deep learning-assisted
45 motion capture using the open-source toolbox DeepLabCut
46 (<https://github.com/AlexEMG/DeepLabCut>). We also used custom-made MATLAB®
47 (MathWorks, Natick, MA, United States) scripts, created by Prof. Masao Matsushashi
48 (Kyoto university), for MEG data preprocessing. The custom MATLAB toolbox is
49 available from the corresponding authors upon reasonable request, subject to a formal
50 code sharing agreement with Prof. Masao Matsushashi. Data presented in this study will
51 be made available upon reasonable request and with permission of the study participants
52 and a formal data sharing agreement.

53

54 **Ethics approval statement**

55 The study was approved by the local ethics and safety committees at Osaka University
 56 Hospital (No. 16469-2) and the Center for Information and Neural Networks (CiNet) at
 57 the National Institute of Information and Communications Technology (No.
 58 1910280040). All the participants provided written informed consent in accordance
 59 with the ethical standards stated in the Declaration of Helsinki.

60

61

62 **Abstract**

63 Measuring the corticokinematic coherence (CKC) between magnetoencephalographic
 64 and movement signals using an accelerometer can evaluate the functional localization of
 65 the primary sensorimotor cortex (SM1) of the upper limbs. However, it is difficult to
 66 determine the tongue CKC because an accelerometer yields excessive magnetic artifacts.
 67 We introduce and validate a novel approach for measuring the tongue CKC using a deep
 68 learning-assisted motion capture system with videography, and compare it with an
 69 accelerometer in a control task measuring finger movement. Twelve healthy volunteers
 70 performed rhythmical side-to-side tongue movements in the whole-head
 71 magnetoencephalographic system, which were simultaneously recorded using a video
 72 camera and examined offline using a deep learning-assisted motion capture system. In
 73 the control task, right finger CKC measurements were simultaneously evaluated via
 74 motion capture and an accelerometer. The right finger CKC with motion capture was
 75 significant at the movement frequency peaks or its harmonics over the contralateral
 76 hemisphere; the motion-captured CKC was 84.9% similar to that with the accelerometer.
 77 The tongue CKC was significant at the movement frequency peaks or its harmonics
 78 over both hemispheres, with no difference between the left and right hemispheres. The
 79 CKC sources of the tongue were considerably lateral and inferior to those of the finger.
 80 Thus, the CKC based on deep learning-assisted motion capture can evaluate the
 81 functional localization of the tongue SM1. In this approach, because no devices are
 82 placed on the tongue, magnetic noise, disturbances due to tongue movements, risk of
 83 aspiration of the device, and risk of infection to the experimenter are eliminated.

84

85 Keywords: Magnetoencephalography, Motion tracking, Motor-evoked field, Lingual,

86 Oral function, Primary sensorimotor cortex.

87

88 **1. Introduction**

89 The tongue plays an important role in various critical human functions, including
 90 swallowing, mastication, and speech, and can perform sophisticated movements. The
 91 area of the primary sensorimotor cortex (SM1) representing the tongue occupies a wide
 92 distribution relative to its actual size in the body (Penfield and Boldrey, 1937),
 93 suggesting the functional importance of the SM1 of the tongue region. However, as it is
 94 difficult to measure electromagnetic cortical signals during tongue movements without
 95 artifact contamination because of the short distance between the tongue and brain, the
 96 cortical representation of the tongue regions has rarely been examined. Thus, it is
 97 important to establish robust methods for evaluating the functional localization of the
 98 tongue region to reveal the central mechanisms of fine tongue movements. Moreover, as
 99 the tongue is innervated by both hypoglossal nerves from the bilateral SM1 (Penfield
 100 and Boldrey, 1937). Therefore, neurosurgical operation of the target side of the tongue
 101 SM1 does not generally deteriorate the tongue motor functions compared with hand
 102 motor dysfunctions that frequently occur when operating on the hand SM1. However, it
 103 is essential to evaluate the presurgical localization of the SM1 of the tongue region to
 104 minimize the deterioration of tongue motor functions after surgery, which would
 105 significantly reduce the post-surgery quality of life, since dysfunctions in critical tongue
 106 motor functions can potentially cause dysphagia and silent aspiration (Meadows, 1973;
 107 Horner and Massey, 1988; Robbins et al., 1993). Thus, during neurosurgery, it is critical
 108 to evaluate the somatotopic source localization of the tongue region before the surgery.

109 Corticokinematic coherence (CKC) is a useful approach for identifying the SM1 of
 110 fingers in healthy adults (Bourguignon et al., 2011, 2019), newborns (Smeds et al.,
 111 2017), and patients with impaired spinocortical proprioceptive pathways in Friedreich

112 ataxia (Marty et al., 2019). Conventional CKC methods quantify the coupling between
113 magnetoencephalographic (MEG) signals and finger kinematics, which are measured
114 using an accelerometer (ACC) during repetitive, rhythmic, and voluntary finger
115 movements (Bourguignon et al., 2011; 2013). Previous studies have shown that the
116 CKC mainly reflects the proprioceptive input into the SM1 (Piitulainen et al., 2013a;
117 Bourguignon et al., 2015; 2017); this feature is comparable to the strongest deflections
118 observed in the cortical movement evoked fields (MEFs) associated with voluntary
119 finger movements (Cheyne et al., 1989; 1997; Gerloff et al., 1998). However, it is
120 difficult to apply this technique to regions of the tongue using an ACC because the ACC
121 produces excessive magnetic artifacts, which easily contaminate the cortical magnetic
122 activity due to the short distance between the tongue and MEG sensors. It is also
123 technically challenging to set an ACC on narrow and wet tongue regions. Moreover,
124 ACCs with cables have the disadvantage of sometimes disturbing the smooth
125 movements of the tongue.

126 Motion capture through videography is a useful approach for evaluating the motor
127 behaviors of humans and other species. Traditionally, motion capture has been
128 performed by placing tracking markers on the target regions of the subject (Bernstein,
129 1967; Winter, 2009; Vargas-Irwin et al., 2010; Wenger et al., 2014; Maghsoudi et al.,
130 2017). However, applying this approach to tongues present technical problems because
131 tracking markers set on wet tongue regions can easily be displaced during tasks
132 involving tongue movements. Moreover, using tracking markers pose risks in patients
133 with tongue sensorimotor impairment as they may accidentally swallow the tracking
134 markers. Regarding its clinical application, while setting objects on the tongue, it is

135 important to reduce the risk of infections such as COVID-19 to the experimenter via the
136 saliva.

137 Recently, Mathis et al. (2018) reported significant progress with the use of
138 “DeepLabCut.” They implemented a systematic method to estimate the tracks of
139 markerless movements. They successfully demonstrated that a small number of training
140 images (~200) was sufficient to train this network with human-level labeling accuracy.
141 This is possible because of transfer learning; the feature detectors are based on
142 extremely deep neural networks, which were pretrained on ImageNet (He et al., 2016).
143 Thus, this method involves the use of transfer learning techniques with deep neural
144 networks, and yields outstanding results with minimal training data. This deep
145 learning-assisted motion tracking system with DeepLabCut is useful for the application
146 of tongue CKC because it does not use any recording device or tracking marker on the
147 tongue, thereby eliminating the previously mentioned disadvantages of magnetic device
148 noise, marker displacement, and additional risks of accidental aspiration and infection.

149 Herein, we introduce a novel approach that utilizes the CKC between the MEG and
150 movement signals of the tongue during rhythmic tongue movements based on a deep
151 learning-assisted motion capture system. Our main hypothesis is that the source
152 locations for the tongue CKC differs from those of the finger CKC using the deep
153 learning-assisted motion tracking system. In addition, to confirm the hypothesis that the
154 CKC using the deep learning-assisted motion tracking system is reliable, we validate
155 this CKC approach by comparing the CKC of fingers using motion capture with the
156 CKC using ACC.

157

158 **2. Materials and Methods**

159 **2.1 Subjects**

160 Twelve healthy volunteers (10 men, 2 women; aged 21–35 y; mean age = 25.0 y)
161 were examined. The participants were right-handed, as determined by the Edinburgh
162 Handedness Inventory (Oldfield, 1971). None of the subjects had a history of
163 neurological or psychiatric disorders. All the participants provided written informed
164 consent in accordance with the ethical standards stated in the Declaration of Helsinki,
165 and the study was approved by the local ethics and safety committees at Osaka
166 University Hospital (No. 16469-2) and the Center for Information and Neural Networks
167 (CiNet) at the National Institute of Information and Communications Technology (No.
168 1910280040).

169

170 **2.2 Movement Tasks of Tongue and Fingers**

171 The subjects were asked to perform constant, rhythmic side-to-side tongue
172 movements with a slightly opened mouth for at least 3 min in two or three sessions
173 (60–90 s each), separated by 30-s rest periods. They were asked to avoid drastic tongue
174 movements to reduce the effects of touch sensations from the orofacial regions during
175 tongue movement. They were also requested to relax the other orofacial parts during
176 these tasks.

177 In the control task, the subjects were asked to make constant, rhythmic up-and-down
178 movements of the right index finger over a table for at least 3 min in two sessions (90 s
179 each), separated by a resting period of 30 s. During the resting periods, subjects were
180 permitted to relax their orofacial muscles and swallow the saliva.

181 We attempted to observe the rhythmic movements of the right index finger in all
182 twelve subjects (right finger condition). Four subjects (Subject 2, 3, 6, 12) performed

183 rhythmical movements for both conditions (right and bilateral finger conditions) in a
184 randomized order. The subjects were asked not to touch the table or other fingers during
185 the finger movement tasks.

186 During the tongue and finger movement tasks, the participants were directed to
187 fixate their gaze at a point on the wall in a magnetically shielded room to avoid any
188 effects of eye movement or visual perception.

189

190 **2.3 Recordings**

191 **2.3.1 MEG and ACC recording**

192 Cortical activity was recorded by CiNet using a whole-head MEG system with 360
193 channels (204 planar gradiometers, 102 magnetometers, and 54 axial gradiometers)
194 (Neuromag® 360, Elekta, Helsinki, Finland). Planar gradiometers with 204 channels
195 were used for the analysis. The position of the subject's head inside the MEG helmet
196 was continuously monitored by supplying a current to four coils fixed to the scalp for
197 tracking head movements. An electromagnetic tracker was used to fix the coils
198 according to the anatomical fiducials (Fastrak, Polhemus, Colchester, VT). The
199 participants were seated in an upright position in the magnetically shielded room. To
200 monitor the movements of the right index finger, a three-axis ACC (KXM52-1050,
201 Kionix, Ithaca, NY, USA) was attached to the nail of the right index finger. The ACC
202 cables were fixed to the hand and table using tape to prevent the generation of noise.
203 The MEG and ACC signals were recorded with a passband at 0.03–330 Hz, and the
204 signals were sampled at 1 kHz.

205

206 **2.3.2 Video and MRI recording**

207 The movements of each target region (the tongue and index fingers) were
208 video-recorded simultaneously throughout the MEG recording at 120 fps with a
209 resolution of 1280×720 pixels, using a camera (DMC-FZ200, Panasonic, Osaka,
210 Japan). To obtain a frontal view of each target region, the camera was positioned in
211 front of the MEG gantry at a distance of 1.5 m. To record the finger and tongue
212 movements, the zoom function of the camera was used to record the images of both
213 hands—including the index fingers—and the lower part of the orofacial region (from
214 neck to nasion). To match the onset time between the MEG and movement signals with
215 motion capture analysis, the MEG system included a light-emitting diode (LED) that
216 was strobed five times at 1 Hz before and after each movement task and was captured in
217 the video images. To determine the brain anatomy of each subject, three-dimensional T1
218 magnetic resonance images (MRIs) were acquired using a 3T MRI scanner (Siemens
219 MAGNETOM Trio or Vida, Siemens, Munich, Germany).

220

221 **2.4 Data Analysis**

222 **2.4.1 Movement signals with the motion capture system**

223 The movements of the tongue and fingers were analyzed offline via deep
224 learning-assisted motion capture with videography using the open-source toolbox,
225 DeepLabCut (Mathis et al., 2018) (<https://github.com/AlexEMG/DeepLabCut>). The
226 image resolution was changed to 960×540 pixels. For motion tracking, we extracted
227 100–150 random, distinct frames from the videos for each movement task. We cropped
228 the frames such that the target regions were clearly visible and manually labeled the tip
229 of the tongue/finger in each extracted frame. The system was then trained using a deep
230 neural network architecture to predict the target regions based on the corresponding

231 images. Different networks were trained for each target region in 100,000–200,000
232 iterations as the loss relatively flattened (Mathis et al., 2018; Nath et al., 2019). The
233 trained networks could track the locations of the target regions in the full sets of video
234 segments (Supplementary Videos 1 and 2). The labeled x -axis (i.e. left-right) and y -axis
235 (i.e. bottom-top) positions of the pixels in each frame were stored and exported in CSV
236 format for subsequent analysis using MATLAB (The MathWorks, Natick,
237 Massachusetts, USA). The Euclidian norm of the two orthogonal (x - and y -axes) signals
238 with baseline correction was used as the movement signal for motion capture.

239

240 **2.4.2 Coherence between MEG and movement signals**

241 The raw MEG signals were spatially filtered offline with the temporal extension of
242 the signal space separation method (Taulu and Simola, 2006; Taulu and Hari, 2009)
243 using MaxFilter (version 2.2.12, Elekta Neuromag, Finland). The MEG and ACC
244 signals were adjusted by down-sampling to 500 Hz. The movement signals were
245 adjusted by up-sampling with the motion capture system to match the MEG signals at
246 500 Hz. LED flashes were applied to the images for correction between the MEG and
247 movement signals with motion capture.

248 The coherence spectra between the MEG and rectified movement signals with
249 motion capture were calculated using the method proposed by Welch (1967) for the
250 estimation of spectral density, where half-overlapping samples, a frequency resolution
251 of 0.5 Hz, and a Hanning window were used. The following equation was used to
252 determine the coherence (Coh_{xy}).

$$\text{Coh}_{xy}(\lambda) = \frac{|R_{xy}(\lambda)|^2}{f_{xx}(\lambda) \cdot f_{yy}(\lambda)},$$

253 where $f_{xx}(\lambda)$ and $f_{yy}(\lambda)$ respectively denote the values of the auto-spectra of the MEG
254 signals and rectified movement signals with motion capture for a given frequency, λ ,
255 and $f_{xy}(\lambda)$ represents the cross-spectrum between $f_{xx}(\lambda)$ and $f_{yy}(\lambda)$. We used the position
256 data as movement signals for the CKC analysis with capture motion since the mean
257 CKC value is within 5% error among approaches using position, velocity, and
258 acceleration (Supplementary Table). The coherence spectra between the MEG and
259 Euclidian norm of the three orthogonal ACC signals (x -axis (i.e. left-right), y -axis (i.e.
260 bottom-top), z -axis (i.e. near-far)) from right index finger were also calculated.

261 We checked the epochs comprising artifacts related to unintended orofacial muscle
262 movements such as coughing, which were distinguished through visual inspection.
263 96.83 ± 1.79 (mean $\pm$ standard error of the mean (SEM)) (ranging from 88 to 107 ($n =$
264 12)) samples were obtained for the tongue CKC. The epochs for the finger CKC
265 included 96.42 ± 1.52 (ranging from 87 to 106 ($n = 12$)) samples for the right finger
266 condition and 105.00 ± 3.24 (ranging from 98 to 111 ($n = 4$)) samples for the bilateral
267 finger condition. According to the method proposed by Rosenberg et al. (1989), all
268 coherence values above Z were considered to be significant at $p < 0.01$, where $Z =$
269 $1 - 0.01^{(1/L-1)}$ and L denotes the total number of samples for the auto- and cross-spectrum
270 analyses.

271 The cross-correlogram in the time domain was calculated by applying an inverse
272 Fourier transformation to the averaged cross-spectra for the tongue CKC and right
273 finger CKC with motion capture. The cross-correlogram underwent bandpass filtering at
274 1–45 Hz. Isocontour maps were constructed at the time points at which the peaks of the
275 cross-correlogram were observed. The sources of the oscillatory MEG signals were
276 modeled as equivalent current dipoles (ECDs). To estimate the ECD locations, the

spherical head model was adopted; the center of this model was consistent with the local curvature of the brain surface of an individual, as determined by the MRI (Sarvas, 1987). Only the ECDs with a goodness-of-fit value of at least 85% were accepted. One subject (Subject 11) was excluded from the ECD analysis of the tongue CKC due to an insufficient goodness-of-fit criterion.

2.5 Statistical analysis

The data are expressed as the mean $\pm$ SEM. An arc hyperbolic tangent transformation was used to normalize the values of the coherence to ensure that the variance was stabilized (Halliday et al., 1995). The values of the CKC of the tongue were analyzed between the left and right hemispheres using paired *t*-tests. The statistical significance level was set to $p < 0.05$. The ECD locations over the left hemisphere along each axis (*x*-, *y*-, and *z*-axes) were analyzed between the tongue CKC and right finger CKC using paired *t*-tests with Bonferroni correction. The corrected *p* value with Bonferroni correction was set to $p < 0.0167$ ($0.05/3$). The *x*-axis intersected the preauricular points from left to right; the *y*-axis intersected the nasion; the *z*-axis was perpendicular to the plane determined by the *x*- and *y*-axes.

3. Results

Figures 1A and B depict representative raw data and power spectra of the movement signals with motion capture and the ACC, respectively, for the right finger condition of Subject 2. Cyclic rhythms were observed at a specific frequency band of the finger movements for both motion capture and the ACC (Fig. 1A). The peak of the power spectra of movement signals with both motion capture and the ACC exhibited the same

frequency band of movement rhythms, at 3.3 Hz (indicated by arrows) (Fig. 1B). The peak CKC of the right finger was observed over the contralateral hemisphere at 7.0 Hz with both motion capture (CKC value = 0.61) and the ACC (CKC value = 0.60), around the harmonic frequency band of finger movements (Fig. 1C). The peak CKC of the tongue was observed over the left hemisphere (CKC value: 0.43) and right hemisphere (CKC value: 0.46) at 3.3 Hz, around the harmonic frequency band of tongue movements (Fig. 2A[1,2]).

For the right finger condition, the peak frequencies of the power spectrum of the movement signals were the same, at 1.8–3.8 Hz for both motion capture and the ACC (Table 1). The coherence spectra exhibited significant peaks ($p < 0.01$) over the contralateral hemisphere at 2.0–7.0 Hz and 2.0–7.0 Hz with motion capture and the ACC, respectively, corresponding to the frequencies of finger movements or their harmonics in all 12 subjects (Table 1). The CKC value with motion capture (mean, 0.433) was compared with that of CKC with the ACC (mean, 0.510), achieving a similarity of 84.9% (Table 1). For the bilateral finger condition, the CKC also exhibited peaks for each side of the finger in all 4 subjects (Table 2).

For the tongue movements, the peak frequencies of the power spectrum of the movement signals were detected at 1.3–3.3 Hz (Table 3). The CKC spectra for the tongue showed significant peaks ($p < 0.01$) at 2.5–5.3 Hz over the left hemisphere and at 2.5–6.0 Hz over the right hemisphere in all subjects, corresponding to the frequency of tongue movements or their harmonics (Table 3). The CKC values were not significantly different between the left (mean, 0.203) and right (mean, 0.188) hemispheres ($p = 0.499$) (Table 3).

324 The spatial distributions of the cross-correlogram of the finger and tongue CKC
325 showed peaks over the contralateral and bilateral hemispheres (Fig. 2A[3–5]),
326 respectively. Dipolar field patterns, which were centered on the Rolandic sensors, were
327 observed at the principal peaks of the cross-correlogram (Fig. 2B[1]). The sources for
328 the tongue CKC were estimated to be over the left and right SM1 in 11 subjects,
329 respectively (Fig. 2B[2]). The sources for the right finger CKC were located in the SM1
330 over the contralateral hemisphere in all of the 12 subjects (Fig. 2C[2]). The results of
331 the paired *t*-test implied that the locations of the ECDs of the tongue were considerably
332 lateral (mean = 13.99 mm; $p < 0.001$; paired *t*-test with Bonferroni correction) and
333 inferior (mean = 20.78 mm; $p < 0.001$), but not anterior (mean = 5.15 mm; $p = 0.029$) to
334 those of the finger (Fig. 3).

335

336 4. Discussion

337 Significant coherence between MEG and tongue movement signals was detected
338 over the bilateral hemispheres using deep learning-assisted motion capture with
339 videography. The sources of the coherence activity were detected in the bilateral SM1 of
340 the tongue region, which were found to be considerably lateral and inferior to the finger
341 SM1, corresponding to the classical homunculus. These results suggest that the use of
342 deep learning-assisted motion capture in CKC is a robust and useful approach for
343 evaluating the functional localization of the tongue SM1.

344 The reliability of measuring CKC using motion capture is comparable to that of the
345 conventional ACC-based CKC method (Bourguignon et al., 2011; 2012), as evidenced
346 by the fact that the finger CKC value obtained using motion capture achieved a
347 similarity of 84.9% when compared with the CKC value obtained using the ACC and

the finger CKC value obtained using ACC. In addition, as the power spectrum of movement signals and CKC showed the same peak frequency bands between the motion capture and ACC for all subjects during the finger movement tasks, determining the CKC with deep learning-assisted motion capture was found to be reliable.

Previous studies involving non-human primates have revealed that several movement parameters, such as position, rotation, direction, and movement velocity, are encoded in the SM1, as determined using the recordings of a single neuron, local field potential, and multi-unit activity (Ashe and Georgopoulos, 1994; Caminiti et al., 1990; Carmena et al., 2003; Mehring et al., 2003; Moran and Schwartz, 1999; Reina et al., 2001). MEG studies involving humans have also revealed the significance of the SM1 cortex oscillations for encoding the parameters of voluntary movements, such as velocity (Jerbi et al., 2007) and acceleration (Bourguignon et al., 2011; 2012). When studying CKC with motion capture, we evaluated the movement parameters of the target positions of pixels in each image with videography by using a deep learning-assisted motion capture system, since the CKC value with motion capture is not significantly different among approaches using position, velocity, and acceleration (Supplementary Table).

Recently, Bourguignon et al. (2019) reported that using two different approaches showed interactions between central and peripheral body parts during motor executions; i.e. CKC and cortico-muscular coherence (CMC) occurs by different mechanisms. CKC, which is coherent with the movement frequency and its harmonics, is mainly related to proprioceptive afferent signals. CMC, which mainly occurs at beta frequency bands during weak muscle contraction, is mainly driven by mu-rhythm-specific neural modulations in efferent signals. Bourguignon et al. (2019) also reported that the values

of CKC during rhythmic finger movements were substantially higher and easier to detect than those of CMC during isometric finger movements (Brown et al., 1998; Conway et al., 1995; Farmer et al., 1993; Gross et al., 2000; Halliday et al., 1998; Kilner et al., 1999, 2004; Mima et al., 1999; Salenius et al., 1997). Because a recording time of at least 10 min was required for the CMC of the tongue in previous studies (Maezawa et al., 2014; 2016), the proposed motion capture approach offers the advantage of a short recording time—approximately 3 min for the CKC of the tongue. The CKC of the tongue with motion capture also has a technical advantage of enabling free movement because no objects, such as an ACC, electromyography (EMG) electrodes, or tracking markers, are placed on the tongue. When objects are placed on the tongue, they disturb the execution of smooth movement tasks. For example, for the tongue CMC recording, it is sometimes technically challenging to set the EMG electrodes on narrow and wet tongue regions because placing electrodes on the tongue can induce uncomfortable feelings in subjects, resulting in a vomiting reflex. Moreover, because no objects are used on the tongue in this CKC method, the risk of an object being swallowed during a tongue movement task is eliminated. In clinical applications for patients with sensorimotor disorders of the tongue, patients sometimes face difficulties performing smooth tongue movements and are easily fatigued by movement tasks. Therefore, the short recording time of the tongue CKC technique provides an advantage over the conventional CKC and CMC methods that use ACC devices or EMG electrodes. In a recent clinical setting, Marty et al. (2019) reported that utilization of the finger CKC is a useful approach for patients with impairment of spinocortical proprioceptive pathways in Friedreich ataxia. As oropharyngeal dysphagia and/or speech disorders are also commonly present in individuals with Friedreich ataxia and

396 worsens with disease duration and severity (Keage et al., 2017), the CKC approach of
397 the tongue might provide electrophysiological evidence for proprioceptive impairment
398 of corticobulbar proprioceptive pathways.

399 Damage to the cortical areas representing sensorimotor function of the extremities
400 and language function causes severe dysfunction and seriously decreases the quality of
401 life. Thus, cortical localization of these functions has received much attention for the
402 presurgical evaluation of neurosurgical procedures. In contrast, cortical localization of
403 functions relating to the tongue and other orofacial regions has been relatively
404 undervalued. This is because the cortical representation of orofacial motor function is
405 bilateral, and thus damage to the orofacial SM1 does not apparently induce severe
406 dysfunctions unless the damage is bilateral as well (Cukiert et al., 2001; Lehman et al.,
407 1994). However, dysfunctions in critical orofacial motor functions may still result from
408 damage to the orofacial SM1, severely reducing the quality of life. For example,
409 dysfunctions in critical tongue motor functions can cause dysphagia and silent
410 aspiration (Meadows, 1973; Horner and Massey, 1988; Robbins et al., 1993). In
411 addition, damage to the orofacial SM1 may cause a cosmetically conspicuous imbalance
412 of facial expression between the left and right sides of the face (Lehman et al., 1994).
413 Because this unbalanced facial expression is easily recognized in daily communication,
414 the problem should be considered as a target for improvement. Thus, more attention
415 should be paid to preserving motor functions of the tongue and other orofacial regions
416 during neurosurgical operations. Here, the CKC technique may be helpful in evaluating
417 SM1 localization of the orofacial regions in patients with brain lesions observed around
418 the central sulcus.

419 Previous studies have shown that the finger CKC mainly reflects the proprioceptive
420 input into the contralateral SM1 (Piitulainen et al., 2013; Bourguignon et al., 2015),
421 which corresponds to the timing of the strongest deflection of the cortical MEFs
422 associated with self-paced finger movements (Cheyne et al., 1997). Thus, it is likely that
423 the cortical mechanisms of the CKC and MEFs are closely related; therefore, it is
424 reasonable that the tongue CKC was detected over both SM1s without hemispheric
425 dominance—similar to the MEF results obtained in the bilateral SM1 associated with
426 self-paced tongue protrusion tasks with intervals of approximately 10 s (Maezawa et al.,
427 2017).

428 Previous studies have reported that the CMC for the tongue was detected at 2–10 Hz,
429 which may have been driven by proprioceptive afferents from the tongue muscles to the
430 cortex—as well as the beta frequency band—during sustained tongue protrusion tasks
431 (Maezawa et al., 2014; 2016). Because human tongue muscles are rich in muscle
432 spindles (Cooper, 1953), it is reasonable that the tongue CKC may be related to the
433 proprioceptive afferents from the tongue muscles associated with rhythmic tongue
434 movements.

435 Ruspantini et al. (2012) reported that low oscillatory frequency, which is related to
436 the proprioceptive afferent feedback obtained from the mouth muscles, might be
437 necessary to generate the fine oral movements required to produce speech. Therefore,
438 sensory feedback obtained by muscle spindles of the orofacial regions may contribute to
439 excellent oral motor functions, including swallowing, speech, and mastication. CKC
440 with motion capture has the advantage of being able to track the motions of multiple
441 body parts, as the finger CKC for bilateral finger movements can be evaluated
442 simultaneously. Thus, in the future, CKC with motion capture might be useful for

Maezawa et al.

443 elucidating the cortical mechanisms that enable swallowing and speech through
444 evaluation of the synchronization of signals between the MEG and movements of
445 multiple orofacial regions.

446 The occurrence of synchronous head movements corresponding to rhythmic tongue
447 movements may yield coherent artifacts in the cross-correlogram. This feature
448 represents a potential limitation of the tongue CKC during repetitive tongue movements,
449 similar to the limitations related to the finger CKC mentioned in previous studies
450 (Bourguignon et al., 2011; 2019). In clinical applications of the tongue CKC, the
451 appearance of artifacts related to head movements must be addressed in patients who
452 struggle to perform repetitive movements. Another potential limitation is the effect of
453 touch sensations from the tongue and other orofacial regions, such as the buccal and lip,
454 during tongue movement tasks. Because CKC appears to be primarily driven by
455 proprioceptive feedback with no significant evidence of any effect due to cutaneous
456 input (Piitulainen et al., 2013; 2015), touch sensations might not have been a severe
457 problem in the present study. Further studies are required to analyze the effects of touch
458 sensations from orofacial regions on the tongue CKC during tongue movement tasks.
459 We applied single dipole fitting analysis for the source localization for clinical
460 application, as dipole fitting is useful for evaluating the somatotopic localization in a
461 pre-neurosurgical situation. However, it is also useful to reveal the distribution of
462 cortical activity based on the distributed source modelling from the systematic and
463 physiological point of view. Further studies are needed to reveal the cortical
464 mechanisms of tongue movements using distributed source modelling analysis.

465 In conclusion, the use of CKC together with deep learning-assisted motion capture
466 is a robust and useful approach for evaluating the functional localization of the SM1 of

467 the tongue; it is a magnetic, noise-free, movement-free, and risk-free approach because

468 no recording devices are placed on the tongue.

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Table 1. Peak frequency and values of CKC of the fingers—right finger conditions

Sub	Peak frequency (Hz)				CKC value	
	Movement signal		CKC		ACC	Motion capture
	ACC	Motion capture	ACC	Motion capture		
1	1.8	1.8	3.3	3.3	0.80	0.69
2	3.3	3.3	7.0	7.0	0.60	0.61
3	2.0	2.0	4.0	4.0	0.47	0.44
4	3.8	3.8	3.3	3.3	0.41	0.32
5	2.0	2.0	4.0	3.5	0.44	0.55
6	1.8	1.8	3.3	3.3	0.65	0.49
7	1.8	1.8	3.8	3.8	0.35	0.32
8	2.8	2.8	3.0	5.5	0.33	0.34
9	2.0	2.0	4.0	3.8	0.56	0.47
10	2.0	2.0	2.0	2.0	0.66	0.55
11	2.5	2.5	5.0	5.3	0.55	0.26
12	2	2	2	2	0.29	0.19
Ave	2.32	2.32	3.56	3.49	0.510	0.433
Min	1.8	1.8	2.0	2.0	0.29	0.19
Max	3.8	3.8	7.0	7.0	0.80	0.69
SEM	0.19	0.19	0.41	0.43	0.044	0.043

ACC: accelerometer; Ave: average; CKC: corticokinematic coherence; Max: maximum; Min: minimum; Movement signal: power spectrum of the movement signal; SEM: standard error of the mean; Sub: subject number.

Table 2. Peak frequency and values of CKC of the fingers—bilateral finger conditions

Sub	Peak frequency (Hz)						CKC value		
	Movement signal			CKC					
	ACC	Motion capture		ACC	Motion capture		ACC	Motion capture	
	Rt	Rt	Lt	Rt	Rt	Lt	Rt	Rt	Lt
2	3.0	3.0	3.0	6.0	6.0	3.3	0.48	0.22	0.22
3	2.3	2.3	2.3	2.3	2.3	2.3	0.69	0.49	0.38
6	2.0	2.0	2.0	2.0	2.0	4.3	0.36	0.26	0.20
12	2.5	2.5	2.5	5.0	2.5	2.8	0.36	0.24	0.22

ACC: accelerometer; CKC: corticokinematic coherence; Lt: left finger; Movement signal: power spectrum of the movement signal; Rt: right finger; Sub: subject number.

Table 3. Peak frequency and values of CKC of the tongue

692

Sub	Movement signal	Peak frequency (Hz)		CKC value	
		CKC			
		Lt hemis.	Rt hemis.	Lt hemis.	Rt hemis.
1	1.8	3.3	3.3	0.43	0.46
2	2.5	5.3	5.3	0.26	0.25
3	2.5	3.5	3.3	0.34	0.16
4	2.8	5.0	6.0	0.19	0.21
5	1.5	2.8	3.0	0.14	0.09
6	2.3	4.3	4.3	0.17	0.10
7	1.5	2.8	2.5	0.14	0.11
8	3.0	3.0	2.5	0.14	0.19
9	1.3	2.5	2.5	0.18	0.29
10	1.5	3.0	3.3	0.13	0.17
11	3.3	3.3	3.3	0.14	0.12
12	1.8	4.0	4.0	0.18	0.11
Ave	2.15	3.57	3.61	0.203	0.188
Min	1.3	2.5	2.5	0.13	0.09
Max	3.3	5.3	6.0	0.43	0.46
SEM	0.19	0.26	0.32	0.027	0.031

693 Ave: average; CKC: corticokinematic coherence; Lt hemis: left hemisphere; Max:

694 maximum; Min: minimum; Movement signal: power spectrum of the movement signal;

695 Rt hemis: right hemisphere; SEM: standard error of the mean; Sub: subject number.

696 **Figure legends**

697 **Fig. 1.**

698 A. Raw data of movement signals obtained through motion capture and an
699 accelerometer (ACC), and magnetoencephalographic (MEG) signal from the
700 contralateral (left) Rolandic sensor for the right finger movement condition of a single
701 participant (Subject 2). Cyclical rhythms are observed at a specific frequency band of
702 finger movements using both the motion capture and ACC. B. Power spectra of
703 movement signals obtained through motion capture and the ACC for the right finger
704 movement condition of a single participant (Subject 2). The scale of the *x*-axis is 10 Hz.
705 Note that the peak frequency occurs in the same frequency band of finger movement,
706 i.e., at 3.3 Hz, in both the motion capture and ACC results (indicated by arrows). C.
707 Corticokinematic coherence (CKC) waveform from a representative channel over the
708 contralateral hemisphere for the right finger movement condition of a single participant
709 (Subject 2) using motion capture and the ACC. The scale of the *x*-axis is 10 Hz. The
710 horizontal dashed line indicates a significance level of 99%. The CKC peak is observed
711 at 7.0 Hz in the motion capture (CKC value: 0.61) and ACC (CKC value: 0.60) results
712 around the harmonic frequency band of the finger movements.

713

714 **Fig. 2.**

715 A. [1, 2] Corticokinematic coherence (CKC) waveform for the tongue from a
716 representative channel over the left [1] and right [2] hemispheres of a single participant
717 (subject 1). The scale of the *x*-axis is 10 Hz. The horizontal dashed line indicates a
718 significance level of 99%. The CKC peak is observed at 3.3 Hz in the left hemisphere
719 (CKC value: 0.43) and right hemisphere (CKC value: 0.46). [3-5] Spatial distribution of

720 the 1-s-long cross-correlogram for the tongue of a single participant (subject 1). The
 721 largest peaks of the cross-correlogram occurred in the Rolandic sensors of the left [4]
 722 and right [5] hemispheres for the tongue CKC. B. Isocontour maps and dipole locations
 723 for the tongue (B) and finger (C) of Subject 1. The time points that showed the
 724 cross-correlation peaks were used to obtain the contour map. The incoming and
 725 outgoing magnetic fluxes are denoted by the blue and red lines, respectively (B[1],
 726 C[1]). The green arrows denote the directions and locations of the equivalent current
 727 dipoles (ECDs), which were projected onto the surface of the skull. The arrowheads
 728 indicate the negative poles of the ECDs. The ECDs (blue dots) of the tongue (B[2]) and
 729 finger (C[2]) are superimposed on magnetic resonance image slices of the participant.
 730 The directions of the blue lines represent the negative poles of the ECDs. Both ECDs
 731 are located at the central sulcus (B[2], C[2]). The locations of the ECDs of the tongue
 732 are estimated to be more lateral, anterior, and inferior to those of the finger. Lt: Left
 733 side.

734

735 **Fig. 3.**

736 Average locations of the ECDs of the tongue and finger CKCs on the x -, y -, and z -axes,
 737 considering all participants. The data points represent the means $\pm$ SEM values. The
 738 locations of the ECDs of the tongue are considerably lateral and inferior to those of the
 739 finger. The x -axis intersects the preauricular points from left to right; the y -axis passes
 740 through the nasion; the z -axis is perpendicular to the plane determined by the x - and
 741 y -axes. Asterisks indicate statistically significant differences ($p < 0.0167$).

742

743 **Supplementary Video 1.**

744 Sample video of pose estimation of the tongue during the tongue movement task. The
745 solid blue circles were identified using the learning program with DeepLabCut. The
746 movie is slowed to a quarter of the real-time speed.

747

748 **Supplementary Video 2.**

749 Movement task of the fingers in the bilateral finger condition. The solid blue (right
750 finger) and red (left finger) circles were identified using the learning program with
751 DeepLabCut. The movie is slowed to a quarter of the real-time speed.

A.

Motion capture signal

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B.

Motion capture

ACC

C.

A. Coherence and cross-correlogram for the tongue

B. Isocontour map [1] and dipole location [2] for the tongue

C. Isocontour map [1] and dipole location [2] for the finger

x-axis

y-axis

z-axis