

Foot, face and hand representation in the human supplementary motor area

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The ability to localize the limb representation in the supplementary motor area (SMA) would be useful in planning surgical ablation of medial frontal lobe tumours. We investigated the relationship between the anatomy of the SMA and the functional representation of fingers, toes, and lips using fMRI in healthy volunteers. There was a significant difference between the location of the different body parts in the SMA, with a rostral-caudal location of the

face, hand and foot areas. Limb representation was located in an area spanning < 1 cm rostral and 1 cm caudal to the paracentral sulcus. These results support the somatotopic organization of the human SMA and suggest that the paracentral sulcus represents a landmark for body representation. *NeuroReport* 15:765–769 © 2004 Lippincott Williams & Wilkins.

Key words: fMRI; Motor system; Somatotopy; Supplementary motor area

INTRODUCTION

The supplementary motor area (SMA) is located in the medial part of the superior frontal gyrus (Brodmann area 6) [1,2]. Intracortical stimulation of the SMA in monkeys frequently produces movements of the head and limbs, which are organized somatotopically [3,4]. In humans, imaging studies have shown a rostral-caudal representation of the hand and foot territories in the SMA [2,5–10]. Even finer upper limb somatotopy has been reported in the SMA for shoulder, arm and fingers [11–13]. These results are in agreement with electrical stimulation data in patients with intractable seizures [8,14,15]. However, most of the studies on body representation reported in the SMA in the literature have involved groups and the precise location of limb representation in the SMA in individuals has not been fully defined. Such knowledge could be useful for functional imaging studies and also for patients requiring surgical ablation of lesion of the medial frontal lobe, since ablation of limb representation in the SMA would result in post-operative motor deficits [16]. Anatomical landmarks for functional areas are also valuable in neurosurgical procedures. Landmarks have been reported for the hand area in the motor cortex [17,18], and for the supplementary eye field in the medial frontal lobe [19], but whether there is a landmark for body representation in the SMA remains to be determined.

The aims of the present study were to examine the somatotopy in the SMA in normal individuals and to determine whether the paracentral sulcus (PCS) is a reliable

landmark for limb representation in the SMA. To this end, 11 healthy volunteers were examined using fMRI during performance of lip, hand and foot movements.

MATERIALS AND METHODS

Subjects: Eleven healthy right-handed volunteers were studied (six men, five women; age range 27–70 years; mean (\pm s.d.) age 39.8 ± 14.6 years). The Local Ethics Committee approved the study and all subjects gave written informed consent. Handedness was confirmed by a test of laterality.

Imaging: The MR protocol was carried out at 1.5T using blood oxygen level dependent (BOLD) contrast. The subject's head was immobilized using foam cushions and tape. The protocol included 20 axial gradient-echo echo-planar images (TR/TE/flip angle = 3 s/60 ms/90°, 5 mm no gap, in-plane resolution = 3.75×3.75 mm) and 110 axial contiguous inversion recovery 3D fast SPGR images for anatomical localization.

Tasks: Subjects performed five different tasks, including flexion/extension of the fingers of the right hand and left hand, of the toes of the right foot and left foot, and contraction of the lips. Movements of the left foot were examined in only five subjects. The order of the five tasks was randomized across all subjects to avoid an order effect. Movements were self-paced. Before scanning, the experimenter demonstrated the movements to the subjects at a

rate of about 1 Hz, without any explicit instruction concerning movement frequency. Subjects practised each movement for about 15–30 s. Task instructions were recorded on a digital audio device and presented using standard headphones customized for fMRI experiments and inserted in a noise-protecting helmet. During the scan, subjects lay in the dark with eyes closed. Echo planar images (124 volumes) were acquired over 6 min and 12 s for each of the five tasks. Tasks consisted of alternating 15 epochs of 24 s of motor task with rest. The first four volumes of each sequence were discarded to reach signal equilibrium. During the rest period, subjects lay quietly in a resting awake state. The frequency of the movements (about 1 Hz) was monitored by the experimenter.

Analysis: All data analyses were performed with statistical parametric mapping, version 99 (SPM 99, Wellcome Department of Cognitive Neurology, London). The functional scans, corrected for movement, were normalized to stereotaxic Talairach coordinates and smoothed with a 5 mm Gaussian kernel. Data were analyzed for each subject separately. Data from each run were modelled using the general linear model. A temporal cut-off of 120 s was applied to filter subject-specific low frequency drift. To test hypotheses about regionally specific condition effects, the estimates were compared using linear contrasts comparing each motor task and rest period. The statistical threshold was set at $p < 0.05$ ($T > 4.78$) corrected for multiple comparisons. Subsequent statistical analyses were performed on activation located at peak Z scores in the SMA.

Anatomical localization of the SMA: The SMA extended from the brain vertex to the cingulate sulcus, and from the precentral sulcus, posteriorly (Talairach coordinate $y = -24$, separating SMA from primary motor cortex activation), to the VAC line, anteriorly (a vertical line passing at the level of the anterior commissure and perpendicular to the anterior commissure–posterior commissure plane, Talairach coordinate $y = 0$).

RESULTS

General activation pattern: For all movements, the areas activated by the motor tasks included the primary sensorimotor cortex (contralateral to the moving limb or bilaterally for lip movements) and the premotor cortex, the SMA, the inferior frontal area (BA44/45), the secondary somatosensory area (SII), the basal ganglia, the thalamus, and the cerebellum bilaterally.

Supplementary motor area: According to Ono's classification [20], there are four types of PCS. In 13 of the 22 hemispheres in our study, the PCS corresponded to either type A, type B or type C (Fig. 1, Table 1). Type D was not found. In four other hemispheres, classification of the PCS was ambiguous, and in the five remaining hemispheres the PCS did not correspond to any of the forms described in Ono's classification. In the latter five hemispheres, the PCS was continuous from the brain vertex to the cingulate sulcus (Fig. 1, subject 9, right hemisphere). In all 22 hemispheres, the PCS was located rostral to the central sulcus (26.5 ± 6.2 mm and 24.4 ± 8.3 mm in the right and left hemispheres, respectively).

The location of peak Z scores relative to the PCS is presented in Fig. 1 and Table 1. For lip movements, activation was bilateral in 70% and unilateral in 30% of the hemispheres. For hand movements, activation was bilateral in 47% of the hemispheres, predominated in the hemisphere contralateral to the moving limb in 21%, and was exclusively contralateral to the moving limb in 32%. For foot movements, activation was bilateral in 46% of the

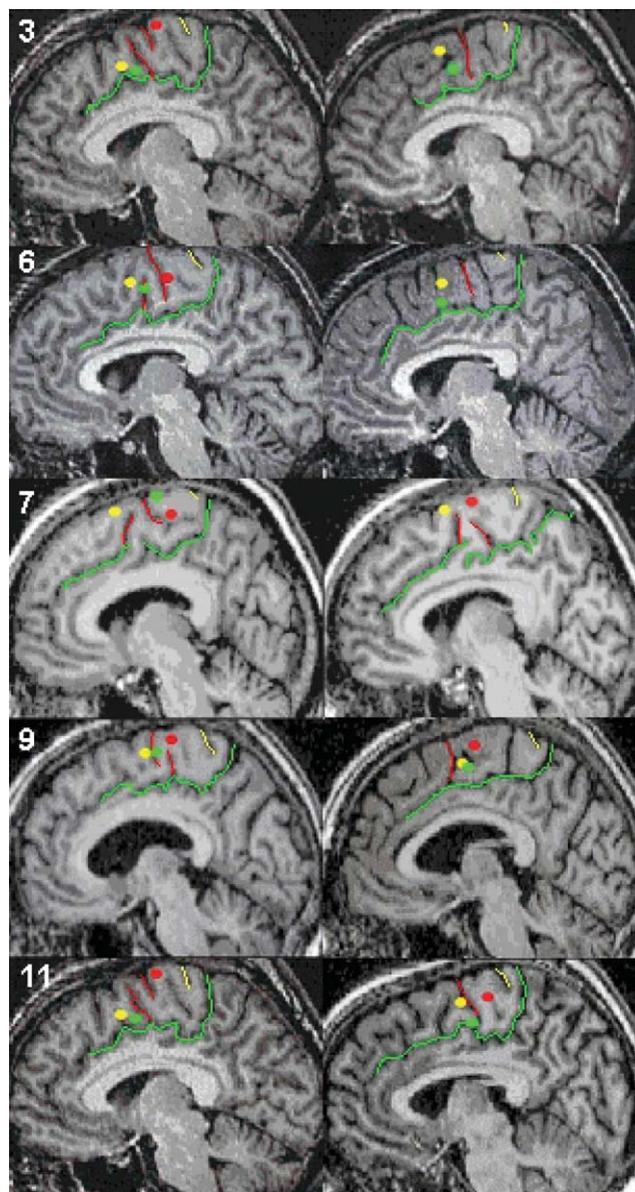


Fig. 1. Localization of peak activation for body movements in five subjects. Activation peaks are indicated by yellow (lip), green (hand) and red (foot) dots and are superimposed on sagittal T1-weighted MR images of the left (left) and right (right) hemispheres. The central sulcus, cingulate sulcus and paracentral sulcus (PCS) are traced in yellow, green and red, respectively. Activation for the three body parts was located in the area of the PCS following a pattern common to most of the 11 subjects, with the lip and hand areas located rostral and the foot area caudal to the PCS. Subjects 7 (left hemisphere) and 9 (right hemisphere) presented a different pattern relative to the PCS. PCS types were: A (subject 7, right hemisphere), B (subjects 3, 6 and 11, right hemisphere), and C (all subjects, left hemisphere).

Table 1. Types of paracentral sulcus (PCS) and location of peak activation relative to the PCS.

Subject	Left hemisphere						Right hemisphere									
	Type of sulcus					Location/PCS			Type of sulcus					Location/PCS		
	A	B	C	D	E	Foot	Hand	Lip	A	B	C	D	E	Foot	Hand	Lip
1			+			Interm.	—	Rostral		+				—	—	Between
2		+				Caudal	Between	—		+				—	Rostral	Rostral
3			+			Caudal	Rostral	Rostral			+			—	Rostral	Rostral
4	+					Caudal	Interm.	—					+	—	Rostral	Rostral
5			+			Interm.	Rostral	—		+				—	Rostral	—
6		+				Caudal	Interm.	Rostral			+			—	Rostral	Rostral
7		+				Caudal	Between	Rostral	+					Caudal	—	Rostral
8			+			Interm.	Rostral	Rostral			+			Caudal	Rostral	—
9		+				Caudal	Interm.	Rostral					+	Caudal	Caudal	Caudal
10					+	Interm.	Interm.	Interm.					+	—	Rostral	Interm.
11		+				Caudal	Caudal	Bostral					+	Caudal	Rostral	Rostral
Total	1	6	3	0	1				1	3	3	0	4			

Types of PCS (types A-D as defined by Ono *et al.* [20]). A: a side branch of the cingulate sulcus; B: a sulcus from the lateral surface; C: both a side branch of the cingulate sulcus and a sulcus from the lateral surface; D: an anterior extension of the posterior segment of the cingulate sulcus; E: a branch linking the lateral surface and the cingulate sulcus. Location of peak activation. Caudal: caudal to the PCS, between: between 2 branches of the PCS; interm.: on the PCS; rostral: rostral to the PCS.

hemispheres, predominated in the hemisphere contralateral to the moving limb in 26%, and was exclusively contralateral to the moving limb in 28%. Mean activation peaks were located 7.0 ± 7.7 mm rostral to the PCS for lip movements, 6.5 ± 5.4 mm rostral to the PCS for hand movements, 5.7 ± 5.4 mm caudal to the PCS for foot movements (Fig. 2). For lip and hand movements, activation peaks were located rostral to the PCS in 60% of the hemispheres (Table 1). For foot movements, activation peaks were located caudal to the PCS in 70% of the hemispheres. In the remaining hemispheres, activation was located at the level of the PCS (9% for lip, 18% for hand, and 25% for foot movements) or there was no activation. In a few hemispheres, activation was in a different rostro-caudal order, rostral to the PCS for foot movements (6%) and caudal to the PCS for hand (9%) and lip (4%) movements. Activation was observed in the SMA for all three body parts in nine of 22 hemispheres (Table 1). Six of these nine hemispheres (66%) presented a somatotopic organization. SMA activation was observed for only two of the body parts in 11 hemispheres. Nine of these 11 hemispheres (82%) presented a somatotopic organization. Activation was observed for only one of the body parts in one hemisphere.

Statistical analysis: Non-parametric Friedman repeated measures ANOVA on ranks with body parts (lip, hand, foot) as a factor were conducted. Statistical analyses were performed on the y and z values of peak Z scores of activation contralateral to the moving limb and of lip movements in the same hemisphere. The first analysis was performed for the y coordinate of both hemispheres together. There was a global effect of body part for y values ($\chi^2 = 13.5$, $p < 0.001$). Pairwise multiple comparisons (Tukey test) showed significant differences ($p < 0.05$) for the location of peak Z scores between lips and foot, and between lips and hand. The difference between hand and foot was not significant.

Analyses were also performed for the right and the left hemisphere, separately (Table 2). These analyses confirmed

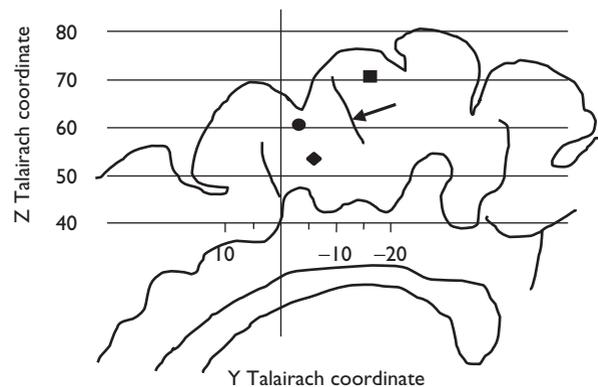


Fig. 2. Schematic representation in Talairach space of mean peak activation for the three body parts (lateral view). Coordinates are in mm relative to the anterior commissure. Lip (circle) and hand (diamond) representation was located rostral to the PCS, and foot representation (square) was located caudal to the sulcus. Anterior is left. Abbreviations: CC, corpus callosum; CiG, cingulate gyrus; CiS, cingulate sulcus; CS, central sulcus; PCS, paracentral sulcus; V, ventricle.

the global effect of body parts in the left hemisphere ($p < 0.007$) with all multiple comparisons significant at $p < 0.05$. The effect of body parts in the right hemisphere was calculated for lips and hand (there were not enough data for foot), and the difference did not reach significance. There was no difference in the location of peak Z scores between hemispheres. Within subjects, the y coordinates were similar in both hemispheres ($p = 0.25$). The global effect of body part was also observed for the z coordinate ($\chi^2 = 14.6$, $p < 0.001$). Pairwise multiple comparisons showed a significant difference ($p < 0.05$) for the location of peak Z scores between foot and hand. Differences between hand and lips, and between lips and foot did not reach significance. This global effect was also found in each hemisphere separately (left $p < 0.005$, right $p < 0.03$). Post-hoc analyses showed that the difference between the location of peak Z scores for hand and foot movements was significant in the left hemisphere only ($p < 0.05$).

Table 2. Talairach coordinates of peak activation in the SMA for lip, hand and foot movements (in mm).

	Body part								
	Lips			Left hand			Left foot		
	x	y	z	x	y	z	x	y	z
Right hemisphere									
Mean	8	-1.3	62.7	6.7	-4.2	54	6.8	-14.8	69.8
s.d.	2.6	6.8	4.1	3.6	6.6	3.4	3.8	6.4	5.1
Left hemisphere									
Mean	-4.1	-3.4	61.1	-4.2	-5.8	55.4	-5.5	-15.6	71.5
s.d.	2.7	8.2	6.8	3.5	6.5	5.4	3.8	6.2	4.6

DISCUSSION

A somatotopic organisation of the SMA was observed along the rostro-caudal axis for all three body parts and along the supero-inferior axis for hand and foot representations. This somatotopic organisation was observed in all but two hemispheres among the 11 subjects. These results are in line with previous studies in monkeys. The rostro-caudal organization of orofacial and limb representations within the SMA was originally observed by Woolsey *et al.* [21] and was later supported by intracranial microstimulation studies [3,4,22]. In humans, the rostro-caudal distribution of hand and foot representation has been reported based on the results of functional imaging [6–10] and electrical stimulation [8,14] and on surgical observations [23]. The somatotopy of the SMA would appear to lend additional support to the reported similarity between this region and executive motor areas [2].

The PCS may represent a landmark for body representation in the SMA. This landmark appears to be less reliable than the hand motor area, however [17,18]. In our study the PCS was variable in length and morphology. The PCS could be classified according to Ono's classification [20] in only 59% of the hemispheres. Although activation peaks for lip, hand and foot movements were located in the area of the PCS, the spatial relationship between this sulcus and the activation site was not always the same. Lip and hand representation was located either rostral to or at the level of the PCS, and foot representation was located caudal to or at the level of the PCS. However, the spatial extent of limb representation in respect to the PCS was relatively small, extending from 1 cm rostral to 1 cm caudal to this sulcus.

Surgical ablation of medial frontal lobe tumours may result in immediate postoperative motor and speech deficits, which recover within several weeks or months [16,23]. The deficit reportedly occurred when the area in the SMA that was activated during preoperative fMRI of hand movements was resected [16]. In contrast, no postoperative motor deficit occurred in any of the patients in whom the area activated in the SMA was preserved during surgery. The present results suggest that the PCS may help localize limb representation within the SMA and predict postoperative deficit. There was considerable variability in the rostro-caudal location (y coordinate) of peak activation between subjects. The y coordinates for hand representation were located between 1 and -17 in the left hemisphere, and between 6 and -16 in the right hemisphere. This inter-individual variability in our study suggests that Talairach coordinates obtained from group studies may be less reliable than the PCS as a means of localizing body

representations in the SMA in individual subjects. It may also partly explain the variability in Talairach coordinates reported in the literature [2]. In contrast, there was no difference in Talairach coordinates between hemispheres.

CONCLUSION

The present results detail the somatotopy of the human SMA with a rostro-caudal location of the face, hand and foot areas and show the spatial relationship between limb representation and the PCS. They suggest that the PCS is a useful landmark to localize limb representation within the SMA, and may help neurosurgical planning in patients with medial frontal lobe tumours.

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