

MOLECULAR AND DEVELOPMENTAL NEUROSCIENCE

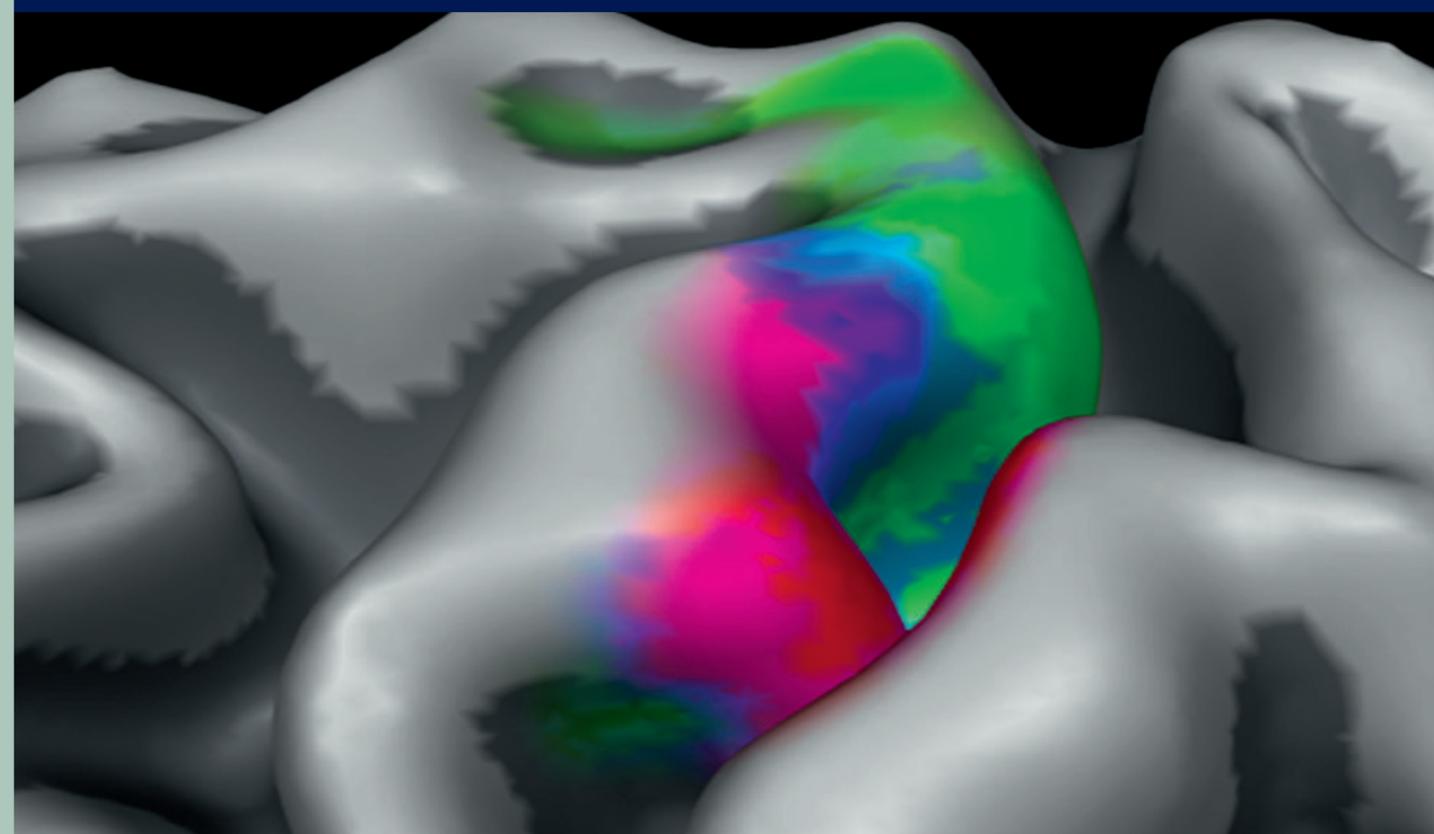
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NEUROSYSTEMS

Double representation of the wrist and elbow in human motor cortex

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Abstract

Movements of the fingers, hand and arm involve overlapping neural representations in primary motor cortex (M1). Monkey M1 exhibits a core–surround organisation in which cortical representation of the hand and fingers is surrounded by representations of the wrist, elbow and shoulder. A potentially homologous organisation in human M1 has only been observed in a single study, a functional MRI (fMRI) study by [J.D. Meier, T.N. Aflalo, S. Kastner & M.S. Graziano. (2008) *J Neurophysiol*, 100(4), 1800–1812]. The results of their study suggested a double representation of the wrist in human M1, an unprecedented finding. Our purpose was to document and simultaneously provide evidence that would extend the presence of double representation of the wrist to that of the elbow. Using fMRI, we observed somatotopic maps in M1 and the supplementary motor area (SMA), the only other cortical area that showed robust within-limb somatotopy during self-timed finger, wrist and elbow movements. We observed double wrist and elbow representation that bracketed finger fMRI responses in M1 and the SMA. Our results show that the cortical locations of these double representations are well predicted by local cortical anatomy. Double representation of the wrist and elbow is important because it violates the traditional somatotopic progression in M1 but it is consistent with the representation of synergistic movements involving adjacent effectors.

Introduction

Human primary motor cortex (M1) represents both ‘intrinsic’ movement parameters such as muscle force, and ‘extrinsic’ parameters such as movement direction (Takei *et al.*, 1999). M1 is organised somatotopically with respect to major body divisions and shows clearly delineable representations of physically distant effectors, such as the head, arm, torso and leg. In contrast, within-limb representations in M1, such as those corresponding to movements of the fingers, wrist and elbow, are highly overlapping (Donoghue *et al.*, 1992; Sanes *et al.*, 1995; Hlustik *et al.*, 2001; Meier *et al.*, 2008); there is also evidence that the topography of within-limb representations is more complex than the progression of adjacent body part representations suggested by the traditional M1 homunculus. Seminal studies by Kwan *et al.* (1978) and Park *et al.* (2001) revealed a ‘core–surround’ organisation in monkey M1 within which neuronal populations representing arm movements surround those representing movements of the fingers.

Using high-resolution functional magnetic resonance imaging (fMRI), Meier *et al.* (2008) observed a double representation of the wrist and forearm that bracketed the representations of the fingers. Although these double representations did not fully surround those of

the fingers, the authors proposed that their findings were evidence of a putative homologue to the core–surround organisation observed in monkeys. Furthermore, Meier and colleagues argued that the observed double representations were related to the interaction of adjacent joints within the hand and arm (Graziano & Aflalo, 2007); this is plausible given that single M1 neurons in the monkey reflect the joint activity of multiple adjacent muscles (Cheney & Fetz, 1985). We tested whether or not the double representations predicted by the core–surround organisation of monkey M1 could be observed for elbow movements, a result that was not observed by Meier *et al.* (2008) even though they used elbow movements in their study.

Assuming we could successfully observe double representation of the wrist, and possibly the elbow, our second goal was to determine whether the cortical locations of these representations could be predicted in relation to the ‘hand knob’ (Yousry *et al.*, 1997), which we used as an anatomical landmark for an analysis of inter-subject variability in M1 somatotopy. This is important in assessing the reliability of these representations across subjects with respect to cortical anatomy. Additionally, we attempted to identify an analogous topography in the supplementary motor area (SMA). The SMA exhibits a primarily anterior–posterior somatotopic organisation (Mitz & Wise, 1987; Luppino *et al.*, 1991; Matsuzaka *et al.*, 1992; Fink *et al.*, 1997), with the representation of the arm anterior to that of the leg (Fried *et al.*, 1991), and face representation anterior to that of the arm (Picard & Strick, 1996). However, there are relatively few published somatotopic

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maps of the SMA relative to M1. The main reason to suspect that the SMA might contain a double arm representation similar to that purported for M1 is that the SMA is involved in both complex finger movements (Shibasaki *et al.*, 1993) and the coordination of hand and arm movements (Colebatch *et al.*, 1991). All of these entail the coordinated use of specific effectors, which Meier *et al.* (2008) proposed as an account of double within-limb representation in M1. The results reported here suggest that double representations of the wrist and elbow exist in both M1 and the SMA.

Materials and methods

Participants and task

We scanned 13 healthy right-handed volunteers (four female, nine male; 21–42 years of age). All participants gave written consent and all experiments were approved by the University of Western Ontario Ethics Review Board. Subjects were in good health with no history of neurological disorders. During the experiments, subjects were supine on a horizontal scanner bed. Subjects' heads were stabilised using foam pads to reduce head movements. Subjects performed repetitive flexes and extensions of one of the following: the metacarpophalangeal joint of the right index finger ('finger'); the pronated hand about the wrist ('wrist'); and the forearm ('elbow'). All movements were performed with forearm supported comfortably on foam and there was no externally applied resistance to the movements. Movements were performed in synchrony with a flashing word ('finger', 'wrist' or 'elbow') that indicated which effector to move and the frequency of movement (the word flashed at 0.5 Hz).

Subjects performed movements that resulted in equivalent movement of the finger tip between two remembered positions (i.e., the tip of the finger moved the same distance and direction regardless of which effector controlled the movement). These movements were always practiced prior to scanning. All subjects participated in three to seven scans. Scans lasted 6.6 min and consisted of blocked experimental conditions that involved either movement of the finger, hand (wrist) or forearm (elbow), or a rest period; the duration of each block was 16 s (during which the subject either performed a movement or rested). Each scan began with a rest block followed by three movement blocks, the order of which was pseudorandomised by effector. The number of blocks (conditions) was counterbalance within each scan.

fMRI data acquisition

We performed our experiments using a 3-Tesla Siemens Magnetom Tim Trio imaging system. Blood-oxygen-level-dependent (BOLD) data were collected using T2*-weighted interleaved, single segment, echo-planar imaging (EPI), PAT = 2, and a 32-channel head coil (Siemens, Erlangen, Germany). Functional data were aligned to high-resolution anatomical images obtained using a 3-D T1 MPRAGE sequence (TE, 2.98 ms; TR, 2300 ms; TI, 900 ms; flip angle, 9°; 192 contiguous 1-mm slices; FOV, 240 × 256 mm²). Scanning parameters for obtaining functional data were: TE, 30 ms; TR, 2 s (single shot); flip angle, 90°; FOV, 240 × 240 mm²; and an in-plane pixel size of 2 × 2 mm².

Data analysis

Data were preprocessed and analysed using BrainVoyager QX 2.1 (BVQX; Brain Innovation, Maastricht, The Netherlands). We performed corrections for slice scan time, head motion (always < 2 mm) and low-frequency artifactual drift. Functional images were co-registered with the anatomical image for each subject and Talairach-

transformed using standard BVQX procedures (Goebel, 1996). The hemispheres were segmented at the grey–white matter boundary, and the resultant cortical sheet was then reconstructed, inflated and flattened for functional data analyses and visualisation. Functional data were analysed in individual subjects using standard general linear models. Each experimental condition was defined as a separate box-car predictor, convolved with a standard hemodynamic response function (Boynton *et al.*, 1996). For each subject, fMRI activation (per cent fMRI signal change) was calculated as the per cent signal change from an average baseline fMRI signal for the entire scan. Only clusters of ≥ 25 voxels at the significance level $P < 10^{-3}$ (uncorrected) were included in the activation maps. Additional details regarding our analyses are reported in the next section.

Results

Figure 1 shows graded somatotopic maps for the 13 subjects. In each map, all visible activation represents maximal whole-brain activity for each of the three movement types compared to the baseline (still) condition. The statistical significance of this activity scales with its transparency, with the most opaque activation being the most significant: all visible gradients are statistically significant in a movement > still contrast (P always < 10^{-3}). We then used this activation map to threshold with an effector-specific map indicating voxels with the strongest fMRI activation to a specific effector or pair of effectors during the externally-timed rhythmic movements of the finger, hand (wrist) and forearm (elbow). The different colours in Fig. 1 indicate contiguous voxels that showed maximal fMRI responses to a single effector (blue, wrist; green, elbow; red, finger). The intermediate colours in Fig. 1 (see legend) indicate equivalent maximal fMRI response magnitudes for adjacent effectors (finger,wrist > elbow or wrist,elbow > finger).

For all 13 subjects, somatotopic maps containing highly significant activation for all three effectors were observed along the anterior bank of the central sulcus in the vicinity of the hand knob (Yousry *et al.*, 1997). At a gross anatomical level, the cortical location and somatotopic progression of these maps was consistent with the results of many previous studies, including the study by Meier *et al.* (2008) and another fMRI study of the same effectors by (Alkadhi *et al.*, 2002). In addition to the observed somatotopic fMRI gradients in M1, we also observed graded somatotopic maps in the SMA. These were found in the most medial portion of the left hemisphere shown in Fig. 1, for all 13 subjects.

M1 somatotopy near the hand knob

We created cortical surface reconstructions of the left hemisphere for all 13 subjects in order to visualise the somatotopic progression in M1 along the anterior bank of the central sulcus. Figure 2 (upper left and right) shows an fMRI activation map on a reconstructed left hemisphere for a single subject. The surface map shows fMRI gradients on or near the hand knob and surrounding cortex. In order to further focus on fMRI activation along the anterior bank of the central sulcus in the vicinity of the hand knob we created rectangular activation 'strips' (Fig. 2, bottom) from a flattened cortical surface and the corresponding surface map of fMRI activation (Goebel, 2000). The strips show fMRI activation from a portion of the flattened surface map of each individual subject that corresponded to a section of the anterior bank of the central sulcus which fully encompassed the hand knob. The strips extended several millimetres beyond the length of the hand knob in both directions along central sulcus. In order to be sure

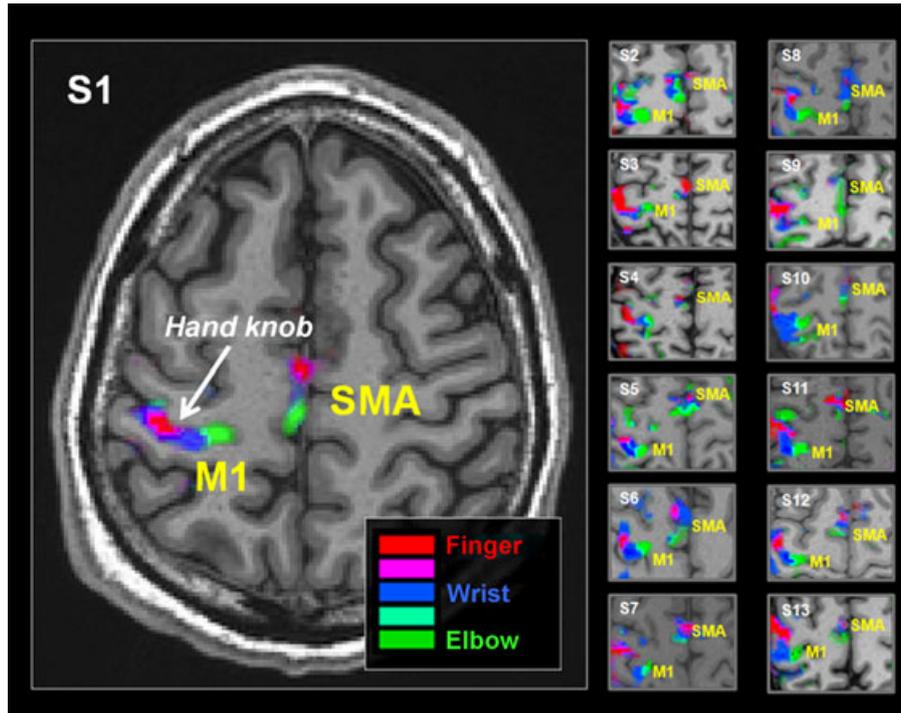


FIG. 1. Somatotopic fMRI gradients for movements of the right index finger, wrist and elbow for 13 subjects (cortex displayed using neurological convention). The greatest activation for all movements was observed in M1 and the SMA. The different colours represent maximal fMRI response for a given effector. Intermediate colours indicate equal fMRI response for the two adjacent effectors. Secondary wrist and elbow representation in M1 can be seen in the lateral-most fMRI activation in subject 1 (S1, left).

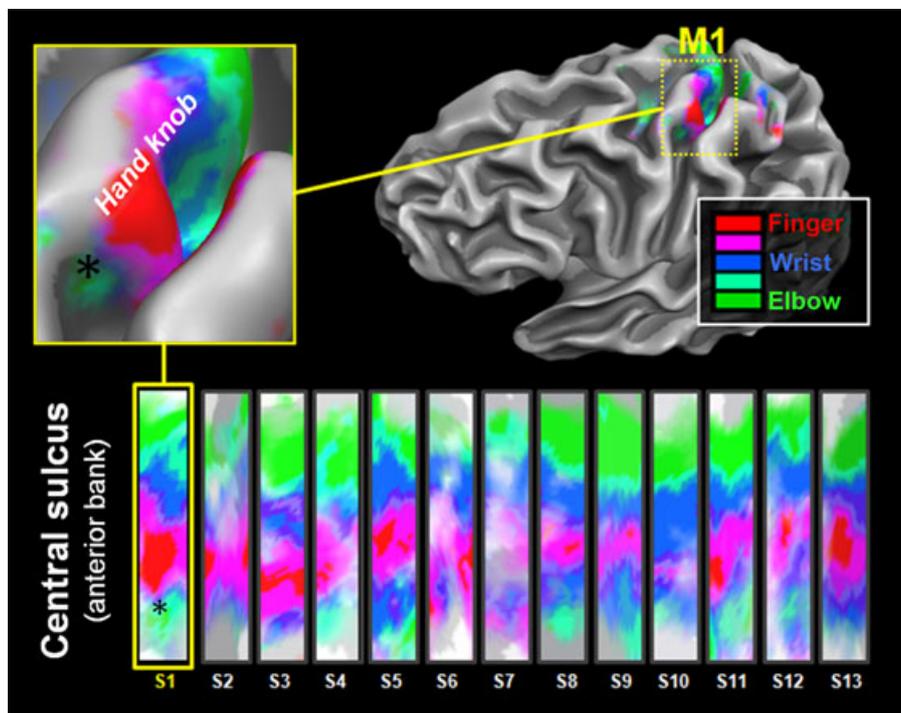


FIG. 2. The upper left figure shows a close up view of an M1 fMRI gradient displayed on a reconstructed cortical surface for a single subject (upper right). For each subject, gradients were transformed into a dorsal-to-ventral rectangular strip showing activation along the anterior wall of the central sulcus. Wrist and elbow fMRI responses were consistently observed in two portions of central sulcus: in the dorsomedial portion of the hand knob and in a second location adjacent to the hand knob. The maximal secondary wrist/elbow fMRI responses are apparent in the reversal of fMRI activation (i.e., transition from red to blue) ventral and medial to the maximal finger fMRI responses (asterisk).

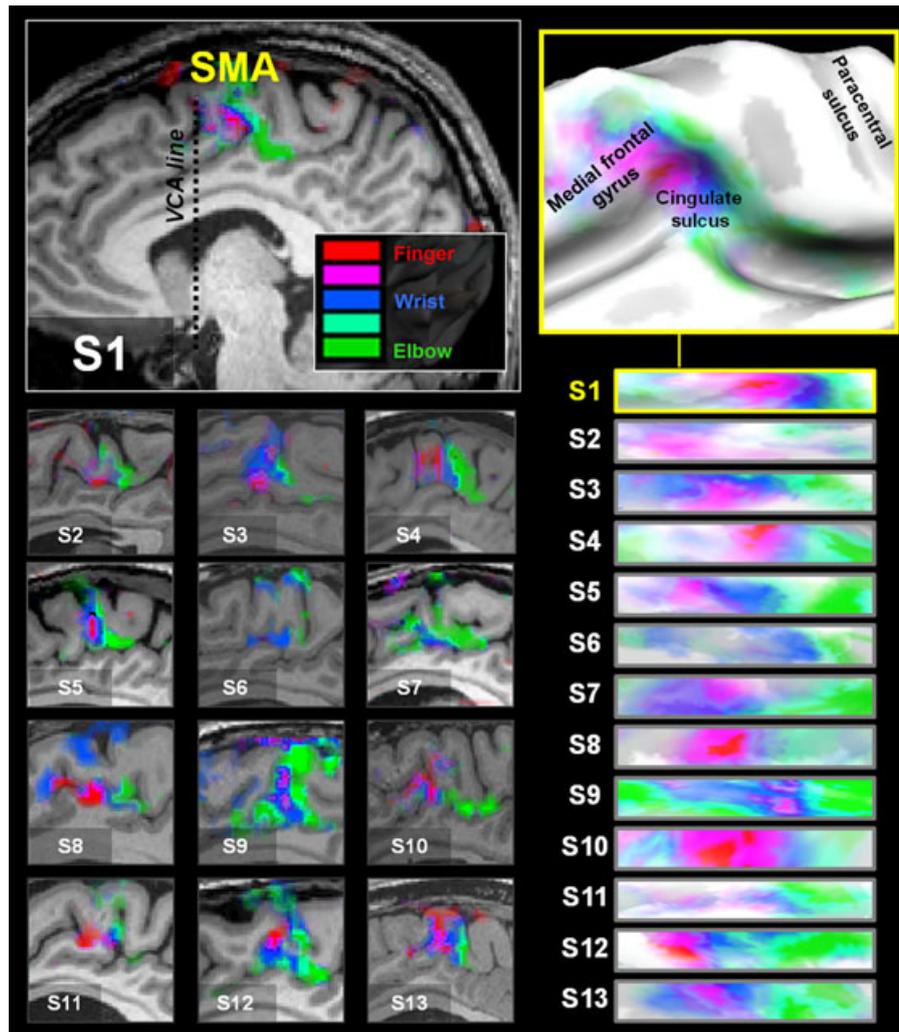


FIG. 3. Sagittal view of somatotopic gradients in the SMA. Maximal fMRI activation during elbow movements was always posterior to that observed during wrist and finger movements. Elbow and finger activation typically bracketed the wrist activation. SMA activation was always found within a portion of the superior bank of cingulate sulcus and the medial frontal gyrus, and maximal elbow-related activation was always anterior the paracentral sulcus. Maximal fMRI activation was always posterior to the VCA line.

that we were sampling from M1, these strips were always bounded by the deepest portion of the central sulcus and the apex of the anterior central gyrus, a distance of ~ 2 cm (Kiernan & Barr, 2009). These M1 strips are shown in Fig. 2 (bottom) and are oriented such that the elbow (arm movement) activation is at the top-most portion of each strip, which corresponds to the most medial (and slightly dorsal) portion of each sample.

The M1 strips in Fig. 2 (bottom) showed similar somatotopic progressions in all subjects. This progression was a predominantly medial-to-lateral transition of elbow (green), wrist (blue) and finger (red) fMRI activation, with intermediate colours representing roughly equivalent activation for adjacent effectors. Maximal activation for each effector (green, blue or red) was typically separated by that for the adjacent effector by at least 2 mm of relatively graded activation. The cortical locations of the points of maximal effector-specific activation varied along both medial–lateral and dorsal–ventral dimensions. In addition to the overall similarity of somatotopic progression across subjects, all subjects also showed striking evidence of additional wrist activation (blue) slightly ventral to the maximal finger movement activation (red), similar that of Meier *et al.* (2008); in over half of our subjects (S1, S2, S4, S5 and S8–S12) we also

observed additional elbow activation (green) that graded into the wrist activation in the same cortical vicinity. Whereas the study by Meier and colleagues did not report the precise anatomical location of their secondary wrist activation, we consistently observed this activation (and the secondary elbow activation) in a portion of the central sulcus adjacent to the underside of the hand knob. We revisit this in a later analysis of inter-subject consistency.

Somatotopy in the SMA

In addition to the somatotopic activation in M1, we observed significant ($P < 10^{-3}$) somatotopic activation in the SMA in all of our subjects. The SMA activation was of interest because, although it was not always as strong as that observed in M1, it was the only other consistent site of significant somatotopic mapping of the arm in the frontal lobe (posterior parietal cortex showed consistent movement-related fMRI activation, but this area showed no somatotopy (Heed *et al.*, 2011)). Somatotopic maps in the SMA are shown in Figs 1 and 3 for all subjects. In both figures, the SMA maps are visible in a medial portion of the left hemisphere near the midline, adjacent to the cingulate sulcus. The SMA maps were always anterior to the

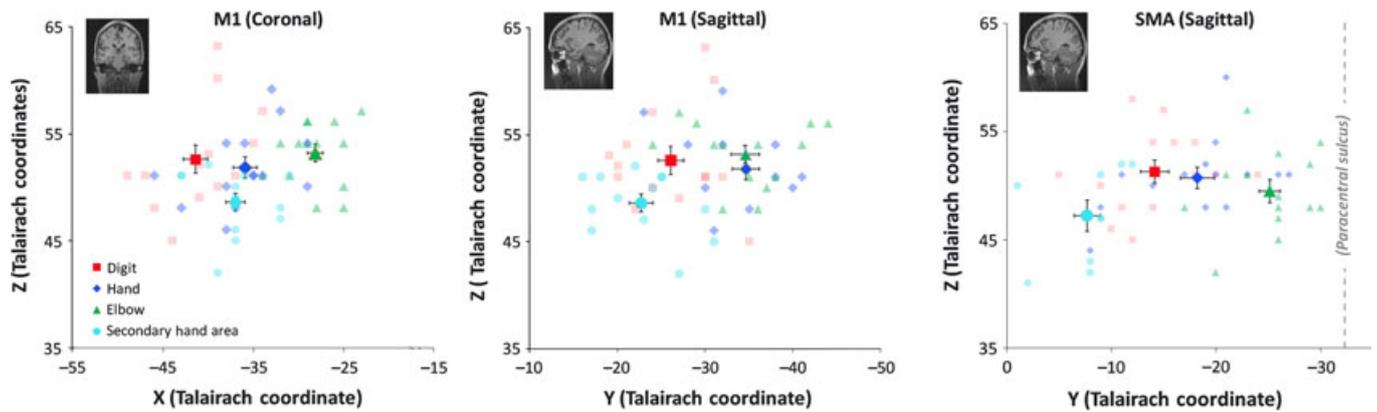


FIG. 4. Mean Talairach coordinates indicated maximal fMRI responses for each effector in M1 (left two graphs) and the SMA (rightmost graph). Coloured symbols refer to the three effectors (red, finger; blue, wrist; green, elbow) or their combination for the secondary wrist activation (turquoise). Intersubject variability is indicated by error bars on mean values (large symbols); individual Talairach coordinates are indicated by smaller symbols. A medial–lateral somatotopic progression was observed in M1 (left two graphs) and a predominantly or wholly anterior–posterior progression in the SMA (rightmost graph). In the SMA, all activation was between the VCA ($y = 0$) and the paracentral sulcus ($y = 32 \pm 2$; dashed grey line).

paracentral sulcus and posterior to a vertical line through the anterior commissure (the VCA line; Fig. 3, perpendicular to the AC–PC line; Talairach & Tournoux, 1988), thus confirming that the gradients were not in the pre-SMA (Picard & Strick, 2001).

Somatotopic gradients were observed in the SMA in all subjects but the somatotopic progression was not as straightforward as it was in M1. We nevertheless observed a primarily anterior–posterior progression of effector boundaries. On the basis of this general observation and its consistency with anterior–posterior SMA somatotopy reported elsewhere (e.g., Chainay *et al.*, 2004), we created fMRI activation strips for the SMA using the same procedure as outlined for M1. These strips are shown in Fig. 3, and were taken from a portion of the cortical surface between the medial frontal gyrus and the superior bank of the cingulate sulcus. The strips were always roughly parallel to the cingulate sulcus, i.e. were predominantly anterior–posterior in orientation, and spanned several millimetres beyond the entire length of significant fMRI activation in both directions.

It is apparent from the SMA strips in Fig. 3 that the overall fMRI activation in the SMA was not consistently as strong as that in M1 (Fig. 2), that is, there was less activation (opaque colour) and less clearly delineated boundaries for some subjects (i.e., the transitions between colours were more difficult to ascertain than in M1). Nevertheless, maximal elbow (green) activation was consistently posterior to that of the wrist and fingers. The main purpose of the strips was, however, to ascertain possible evidence of a double representation of the wrist and elbow in the SMA, as in M1. While the evidence is not as strong as that observed in M1, over half of the subjects' activation maps (S1, S3, S4, S6, S7, S9–S11 and S13) showed > 25 contiguous wrist- and/or elbow-preferring voxels (blue/green) at the anterior-most part of the strips. While this result is not as strong as the observed double representation in M1, it is consistent with the somatotopic reversal in M1 in that it occurred in a portion of the SMA anterior to the finger representation and, importantly, in a direction opposite to that of the maximal elbow activation.

Somatotopic consistency and local cortical anatomy

The fMRI activation maps in Figs 1–3 suggested considerable inter-subject consistency in somatotopy for M1 and the SMA. We conducted a final analysis of the precise cortical locations of maximal

fMRI activation in M1 and the SMA for each effector, for all subjects. Figure 4 shows the results of this analysis of inter-subject consistency in which we examined the locations and variability of Talairach coordinates corresponding to maximal effector-specific fMRI responses (green, elbow > wrist, finger; blue, wrist > elbow, finger; red, finger > wrist, elbow); coordinates corresponding to the maximal secondary wrist/elbow activation (wrist, elbow > fingers) are also included (turquoise). The graphs in Fig. 4 show mean Talairach coordinates and standard errors for all 13 subjects. Paired-sample *t*-tests confirmed that all of these differed significantly along at least one Talairach dimension (P always < 0.01, two-tailed), that is, each occupied different cortical locations. It is worth noting that we did not restrict this analysis to the strips in Figs 2 and 3, which could have artificially reduced the variability in Fig. 4 by restricting the possible ranges of Talairach values within each subject.

In addition to the Talairach coordinates indicating maximal fMRI activation for each effector, we also catalogued the coordinates of a specific location in the central sulcus in the vicinity of the hand knob to determine whether or not effector-specific fMRI activation could be predicted via local anatomy, the secondary wrist activation in particular. We chose a location in the central sulcus adjacent to the point of maximal curvature along the inverted 'omega' of the precentral gyrus, which was directed posterolaterally and protruded into the central sulcus (Yousry *et al.*, 1997); the average \pm SE Talairach coordinates for this location were $x = -36 \pm 1$ mm, $y = -31 \pm 1$ mm, $z = 49 \pm 1$ mm. We first tested whether or not taking into account the Talairach location of each individual's landmark reduced between-subject variability in the location of the secondary wrist activation. When we took into account the Talairach coordinates of each subject's hand knob landmark by subtracting it from those indicating the maximal secondary wrist activation we observed a reduction $\geq 35\%$ in the between-subject variability in the location of maximal secondary wrist activation (46% for x , 47% for y and 37% for z), that is, the landmark was predictive of the location of the maximal secondary wrist activation, which was consistently anterior to our landmark (9 ± 1 mm along the y dimension). The predictive validity of our landmark also applied to the other locations of maximal effector-specific fMRI activation, which consistently varied with respect to the landmark along one or more x , y and z dimensions.

In addition to the observed double representation in M1, we observe preliminary evidence of a double wrist/elbow representation in SMA.

We identified ≥ 25 wrist/elbow-preferring voxels in an anterior portion of the SMA in nine of our thirteen subjects. The corresponding Talairach coordinates are shown in the rightmost graph of Fig. 4 (turquoise points). The results in Fig. 4 clearly confirm the anterior–posterior progression of finger, wrist and elbow representations in the SMA, with a putative secondary swath of wrist/elbow activation at the most anterior portion of the SMA. In all subjects, the posterior-most elbow activation was always anterior to the individual subject's paracentral sulcus ($y = 32 \pm 2$ mm). The secondary wrist/elbow activation was always found within a portion of the superior bank of the cingulate sulcus and sometimes spilling over on to the medial frontal gyrus (and always posterior to the VCA line, defined earlier and shown in Fig. 3).

Discussion

We used fMRI to create somatotopic maps of finger, wrist and elbow movements in human motor cortex. Our primary goal was to identify the putative double representation of the wrist in M1 reported by Meier *et al.* (2008), and also to determine whether a similar organisation exists for the elbow. The latter was not observed by Meier and colleagues but is predicted by results from studies of core-surround hand and forearm representation in monkey M1 (Kwan *et al.*, 1978; Park *et al.*, 2001), which Meier and colleagues proposed as a putative homologue. The failure of Meier and colleagues to observe double representation of the elbow is also noteworthy because such a double representation would be expected if the current theory that the motor cortex maps movements rather than muscles (Graziano & Aflalo, 2007) is correct. This motivated our focus on elbow movements in addition to finger movements and wrist movements in the present study. In addition to replicating the study of Meier *et al.* (2008), we also hoped to identify the precise location of these representations in relation to the hand knob (Yousry *et al.*, 1997), and to assess the degree to which the double wrist representation is predicted by an individual's cortical anatomy. Finally, we sought evidence of analogous double representation in the SMA, which we also attempted to characterise in relation to local cortical anatomy.

Within-limb somatotopy in M1

M1 represents both intrinsic and extrinsic movement parameters (Kakei *et al.*, 1999). Because we kept the end path (of the finger tip) constant for all movements our results do not speak directly to the representation of extrinsic movement properties, which has been shown at both single-neuron and population levels in monkey and human M1 (Georgopoulos *et al.*, 1982, 1986; Eisenberg *et al.*, 2010; Fabbri *et al.*, 2010), but may nevertheless have eventual implications for the representation of both types of movement parameters. Our results clearly showed a within-limb progression of within-limb body part representations in M1, and although these representations overlapped, representations of the finger, wrist, forearm and elbow were clearly distinguishable.

Our graded fMRI activation maps showed a clear medial-to-lateral and dorsal-to-ventral progression of elbow, wrist and finger activation along the anterior bank of the central sulcus. As expected, all of this activation was in the vicinity of the hand knob, an omega-shaped protrusion of the precentral gyrus toward the central sulcus when viewed in the axial plane. The hand knob is posterior to the intersection of the superior frontal sulcus with the precentral sulcus and it projects to the middle genu of the central sulcus (Salamon *et al.*, 1991; Yousry *et al.*, 1997). Maximal fMRI activation during finger

movements was inferior to maximal activation during wrist movements, which was inferior to the maximal elbow activation. The most medial and dorsal activation in M1 always corresponded to elbow movements, as in previous fMRI studies (e.g., Alkadhi *et al.*, 2002). Maximal effector-specific fMRI activation (greater response to one effector than all others) always graded into an adjacent effector. As elbow-specific activation transitioned into wrist-specific activation, equal fMRI activation was observed for the two effectors, and this activation was significantly higher than that for finger movements.

Meier *et al.* (2008) argued against the idea of complete overlap between within-limb representations of different body parts. Furthermore, they proposed that a possible reason for representational overlap is that within-limb effectors (e.g., finger, wrist, forearm and elbow) are normally used in conjunction (e.g., finger, wrist, forearm and elbow), or synergy, and should thus be represented together. This perspective has been offered by others as well (Donoghue *et al.*, 1992; Schieber & Hibbard, 1993; Sanes *et al.*, 1995; Nudo *et al.*, 1996) and proposes that body parts that are correlated in an animal's behavioural repertoire develop overlapping cortical representations (Aflalo & Graziano, 2006, 2007). The primary evidence in favour of this view from the fMRI study by Meier and colleagues was the observation of multiple arm representations that, together, bracketed a unified hand/finger representation but were nevertheless graded. The authors concluded that their findings of graded somatotopy reflected the maximisation of cortical proximity and overlap of representations of effectors that are frequently used in synergy. As in Meier *et al.* (2008), we also observed graded somatotopic representation and evidence of a bracketing double representation in human M1, which we discuss next.

Double representation in M1

Maximal wrist activation was observed in a portion of the hand knob that was medial and dorsal to that of maximal finger activation. Nevertheless, we consistently observed what Meier *et al.* (2008) described as a 'non-somatotopic reversal' in the forearm representational progression in M1 (Fig. 2). That is, we observed a double representation of the wrist and elbow in M1 that followed a reversal in the graded somatotopic transition between representations of elbow to wrist to finger to wrist to elbow along the anterior bank of the central sulcus near the hand knob (Figs 1 and 2). The additional ('secondary') wrist activation was observed in a more ventral and anterior cortical location than the maximal activation to the same effectors adjacent to the hand knob (Fig. 4), which is consistent with the secondary wrist activation in the figures of Meier *et al.* (2008); they did not describe the location of this activation in detail. Importantly, this secondary activation was not spatially contiguous with the maximal wrist activation observed medial and dorsal to the maximal finger activation. Moreover, we found that this secondary wrist activation occurred in a similar cortical location in all of our subjects: it was consistently located in a deep part of the central sulcus adjacent, ~ 8 mm anterior to the hand knob. Between-subject variability was ~ 1 mm, which was similar to that of the locations of the expected maximal fMRI responses in the hand knob itself and is consistent with the results of an fMRI study of the reproducibility of M1 somatotopy for the same effectors (Alkadhi *et al.*, 2002).

Within-limb somatotopy in the SMA

In addition to the graded somatotopic fMRI maps in M1 we observed graded maps in the SMA that were arranged along a primarily anterior–posterior axis, as in a study of foot, face and hand

representation by Chainay *et al.* (2004). To our knowledge, there has not yet been a systematic within-limb fMRI study of the somatotopic representation of finger, wrist and elbow movements in the SMA with the purpose of identifying a secondary wrist/elbow area of activation (Meier and colleagues did not report any SMA results). Although our evidence of a double wrist/elbow representation in the SMA was not as strong as that observed in M1, we did observe evidence of secondary wrist/elbow activation in some of our subjects. This activation was always more anterior than the maximal finger activation and was not contiguous with the more posterior wrist/elbow activation. It is therefore plausible that double representation of the wrist/elbow is not limited to M1 but also exists in the SMA. This is a novel and tantalising result given the relative paucity of published somatotopic maps for the SMA. Future studies might identify more robust secondary wrist/elbow representations by using more complex movements in accordance with known SMA function (Picard & Strick, 1996) or by using different fMRI techniques, as in a recent study by Cauda *et al.* (2011).

Conclusion

We report evidence of a double representation of the wrist and elbow which brackets that of the finger. This was especially evident in M1, but it was also observed, to a lesser degree, in the SMA. Our findings replicate and extend findings from a previous fMRI study by Meier *et al.* (2008), and are consistent the core-surround organisation of monkey M1 (Kwan *et al.*, 1978; Park *et al.*, 2001). Our results are also consistent with alternative M1 organisational principles (Huntley & Jones, 1991; Donoghue *et al.*, 1992; Capaday *et al.*, 1998; Schneider *et al.*, 2002), as well as known subdivisions of M1 (Geyer *et al.*, 1996). A notable difference between our M1 results and the core-surround organisation in monkey M1 is that the wrist/elbow representations along the hand knob observed in our study were not contiguous with the secondary representations; the latter were always separated by the finger representation. It is unclear whether this indicates a difference in topology between human and monkey M1 or a potential lack of homology. Additional studies are necessary to explore the double wrist/elbow representation in human M1 and the SMA in more detail.

Our findings demonstrate the feasibility of anatomy-based predictions of within-limb representations in human M1 and the SMA, including secondary representations of the wrist and elbow in M1. We characterised the anatomical location of the observed effector-specific fMRI responses in detail by showing that its location is in a deep (medial) part of central sulcus that is consistently anterior and slightly ventral to the hand knob, along which the traditional M1 representation of the index finger is typically observed. Our findings complicate the traditional homuncular view of human somatotopy and, along with the results of Meier *et al.* (2008), suggest a somatotopic organisation of human M1 homologous to that observed in monkeys. This organisation is consistent with the representation of synergistic movements involving adjacent effectors and appears to apply to both M1 and the SMA.

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Abbreviations

fMRI, functional magnetic resonance imaging; M1, primary motor cortex; SMA, supplementary motor area; VCA line, vertical line through the anterior commissure.

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