**Special issue: Research report**

# A new method to record and control for 2D-movement kinematics during functional magnetic resonance imaging (fMRI)

*Bjoern Hauptmann[a,d,*], Ronen Sosnik[a,b], Oded Smikt[b], Eli Okon[b], David Manor[c], Tammar Kushnir[e], Tamar Flash[b] and Avi Karni[a,c]*

[a]Department of Neurobiology, Brain Research, The Weizmann Institute of Science, Rehovot, Israel
[b]Department of Applied Mathematics and Computer Science, The Weizmann Institute of Science, Rehovot, Israel
[c]The Brain–Behavior Research Center, Haifa University, Israel
[d]Department of Neurology, Charité, University Medicine Berlin, Berlin, Germany
[e]Department of Clinical Imaging, MRI Unit, Chaim Sheba Medical Center, Tel Hashomer, Israel

### ARTICLE INFO

### ABSTRACT

The recording of movement kinematics during functional magnetic resonance imaging (fMRI) experiments is complicated due to technical constraints of the imaging environment. Nevertheless, to study the functions of brain areas related to motor control, reliable and accurate records of movement trajectories and speed profiles are needed. We present a method designed to record and characterize the kinematic properties of drawing- and handwriting-like forearm movements during fMRI studies by recording pen stroke trajectories. The recording system consists of a translucent plastic board, a plastic pen containing fiber optics and a halogen light power source, a CCD camera, a video monitor and a PC with a video grabber card. Control experiments using a commercially available digitizer tablet have demonstrated the reliability of the data recorded during fMRI. Since the movement tracking signal is purely optical, there is no interaction with the MR (echoplanar) images. Thus, the method allows to obtain movement records with high spatial and temporal resolution which are suitable for the kinematic analysis of hand movements in fMRI studies.

## 1. Introduction

There is a clear need for detailed, accurate and robust measurements of complex motor actions in biomedical research on motor control and motor learning mechanisms. The need for objective quantification of complex movements, e.g., point-to-point movements or drawing- and writing-like

movements, has resulted in the development of systems for objective 2D- and 3D-digital recordings (e.g., Ferrigno and Pedotti, 1985; Flash, 1987; Inzelberg et al., 1995, for a comprehensive overview, see Medved, 2001 or Fischer, 2000). These optoelectronic or electronic devices allow recording of movement kinematics with high temporal and spatial accuracy for behavioural studies of motor control and/or for motor

---

* *Corresponding author.* Present address: Neurological Centre, Segeberger Kliniken, 23795 Bad Segeberg, Germany.
  E-mail address: bjoern.hauptmann@segebergerkliniken.de (B. Hauptmann).

the vertical retrace of the video starts, the data are transferred to the computer memory, thereafter the grabber card is released to collect the next field. The program is set to cluster pixels based on their locations. Ideally, there would be only one such 'spot', or cluster, in the field, consisting of 10–50 pixels. The center of gravity of this cluster is then calculated, weighting the intensities of the pixels. The result is given in terms of pixel coordinates, up to the precision of .1 pixel, and is stored in memory until the end of the trial. Storage is economical, only one pair of coordinates per video field. The trajectory data are then recorded to disk as a text file.

## Appendix B.

Initially, in the workspace pad's plane, the coordinates of the four targets (A, B, C, D) were measured in millimetres with respect to one of the corners of the transparency. The center of gravity of the targets was calculated and arbitrarily chosen to be the new origin of coordinates, and the targets' coordinates were translated to it. This calculation was done once, since all the subjects used the same transparency.

For each session: first, all data y-values were multiplied by the pixel aspect ratio ($\sim$1.35) to obtain square pixel coordinates. In this coordinate system, the center of gravity of the reference targets was re-calculated, and was assigned to be the new origin. The targets were translated to the new origin. Second, given that the two sets of targets, actual workspace pad targets and reference targets, have their origin in the center of gravity, we virtually overlay the two centers of gravity, and then calculate two coefficients, one for rotation and the other for scaling. Such that, after the transform to the millimetre plane the reference targets fit over the actual target locations as closely as possible. These new locations of the reference targets are thereafter used to evaluate the subject's performance throughout the session, transforming the data of all trials using the two coefficients and the translation values of the session.

## REFERENCES

Bauswein E, Fromm C, Werner W, and Ziemann U. Phasic and tonic responses of premotor and primary motor cortex neurons to torque changes. *Experimental Brain Research*, 86: 303–310, 1991.

Burbaud P, Doegle C, Gross C, and Bioulac B. A quantitative study of neuronal discharge in areas 5, 2, and 4 of the monkey during fast arm movements. *Journal of Neurophysiology*, 66: 429–443, 1991.

Diedrichsen J and Shadmehr R. Detecting and adjusting for artifacts in fMRI time series data. *NeuroImage*, 27: 624–634, 2005.

Doyon J, Song AW, Karni A, Lalonde F, Adams MM, and Ungerleider LG. Experience-dependent changes in cerebellar contributions to motor sequence learning. *Proceedings of the National Academy of Sciences of the United States of America*, 99: 1017–1022, 2002.

Ferrigno G and Pedotti A. ELITE: a digital dedicated hardware system for movement analysis via real-time TV signal processing. *IEEE Transactions on Biomedical Engineering*, 32: 943–950, 1985.

Fischer R. Motion capture process and systems. In Jung M, Fischer R, Gleicher R, Thingvold JA, and Bevan M (Eds), *Motion Capture and Editing: Bridging Principle and Practice*. AK Peters, 2000 [chapter 2].

Flament D and Hore J. Relations of motor cortex neural discharge to kinematics of passive and active elbow movements in the monkey. *Journal of Neurophysiology*, 60: 1268–1284, 1988.

Flash T. The control of hand equilibrium trajectories in multi-joint arm movements. *Biological Cybernetics*, 57: 257–274, 1987.

Floyer-Lea A and Matthews PM. Changing brain networks for visuomotor control with increased movement automaticity. *Journal of Neurophysiology*, 92: 2405–2412, 2004.

Ganesh G, Franklin DW, Gassert R, Imamizu H, and Kawato M. Accurate real-time feedback of surface EMG during fMRI. *Journal of Neurophysiology*, 97: 912–920, 2007.

Georgopoulos AP, Ashe J, Smyrnis N, and Taira M. The motor cortex and the coding of force. *Science*, 256: 1692–1695, 1992.

Georgopoulos AP, Caminiti R, and Kalaska JF. Static spatial effects in motor cortex and area 5: quantitative relations in a two-dimensional space. *Experimental Brain Research*, 54: 446–454, 1984.

Georgopoulos AP and Massey JT. Static versus dynamic effects in motor cortex and area 5: comparison during movement time. *Behavioural Brain Research*, 18: 159–166, 1985.

Gowen E and Miall RC. Differentiation between external and internal cuing: an fMRI study comparing tracing with drawing. *NeuroImage*, 36: 396–410, 2007.

Harrington GS, Farias D, Davis CH, and Buonocore MH. Comparison of the neural basis for imagined writing and drawing. *Human Brain Mapping*, 28: 450–459, 2007.

Ino T, Asada T, Ito J, Kimura T, and Fukuyama H. Parieto-frontal networks for clock drawing revealed with fMRI. *Neuroscience Research*, 45: 71–77, 2003.

Inzelberg R, Flash T, Schechtman E, and Korczyn AD. Kinematic properties of upper limb trajectories in idiopathic torsion dystonia. *Journal of Neurology, Neurosurgery, and Psychiatry*, 58: 312–319, 1995.

Kalaska JF, Cohen DA, Hyde ML, and Prud'homme M. A comparison of movement direction-related versus load direction-related activity in primate motor cortex, using a two-dimensional reaching task. *Journal of Neuroscience*, 9: 2080–2102, 1989.

Karni A, Meyer G, Jezzard P, Adams MM, Turner R, and Ungerleider LG. Functional MRI evidence for adult motor cortex plasticity during motor skill learning. *Nature*, 377: 155–158, 1995.

Liu JZ, Dai TH, Elster TH, Sahgal V, Brown RW, and Yue GH. Simultaneous measurement of human joint force, surface electromyograms, and functional MRI-measured brain activation. *Journal of Neuroscience Methods*, 101: 49–57, 2000.

Matsuo K, Nakai T, Kato C, Moriya T, Isoda H, Takehara Y, et al. Dissociation of writing processes: functional magnetic resonance imaging during writing of Japanese ideographic characters. *Brain Research. Cognitive Brain Research*, 9: 281–286, 2000.

Medved V. *Measurement of Human Locomotion*. Boca Raton: CRC Press LLC, 2001.

Oreja-Guevara C, Kleiser R, Paulus W, Kruse W, Seitz R, and Hoffmann KP. The role of V5 (hMT+) in visually guided hand movements: an fMRI study. *European Journal of Neuroscience*, 19: 3113–3120, 2005.

Sosnik R, Hauptmann B, Karni A, and Flash T. When practice leads to co-articulation: the evolution of geometrically defined movement primitives. *Experimental Brain Research*, 156: 422–438, 2004.

Sosnik R, Hauptmann B, Karni A, and Flash T. The acquisition and implementation of the smoothness maximization strategy is dependent on spatial accuracy demands. *Experimental Brain Research*, 176: 311–331, 2006.

Todorov E. Direct cortical control of muscle activation in voluntary arm movements: a model. *Nature Neuroscience*, 3: 391–398, 2000a.

Todorov E. Reply to 'One motor cortex, two different views'. *Nature Neuroscience*, 3: 964, 2000b.

Todorov E and Jordan MI. Optimal feedback control as a theory of motor coordination. *Nature Neuroscience*, 5: 1226–1235, 2002.

Van Duinen H, Zijdewind I, Hoogduin H, and Maurits N. Surface EMG measurements during fMRI at 3 T: accurate EMG recordings after artifact correction. *NeuroImage*, 27: 240–246, 2005.

learning experiments. Whereas optoelectronic devices are regarded as the method of choice for 2D- as well as 3D-movements, digitizer tablets represent a much cheaper alternative if the experimental paradigm is restricted to the recording of writing and drawing movements. However, while these two methods work well within standard settings for behavioural testing, the implementation of these systems into a functional brain imaging environment using functional magnetic resonance imaging (fMRI) is, due to technical constraints, rather difficult if not impossible. Thus, while an ever increasing number of fMRI experiments are devoted to the study of the neuronal bases of cognitive processes only a relatively small number of neuroimaging studies investigate writing and drawing tasks; in part, this paucity reflects technical limitations in movement recordings and analysis in a high magnetic field.

The primary difficulty in recording movement kinematics in fMRI experiments results from the need to place electrical equipment or devices that contain metal elements, inside or in close proximity to the MRI scanner. Electronic equipment and metallic devices can disrupt the homogeneity of the MRI magnetic fields leading to poor image quality, or the strong magnetic field might render unusable the movement recording system (e.g., digitizer tablet or a motion tracking system using active markers). Nevertheless, MRI compatible force sensors (Floyer-Lea and Matthews, 2004) and joystick systems (Oreja-Guevara et al., 2005) are available and are used for measuring isometric motor performance or for recording visually guided hand tracking movements of small amplitude. However, these MRI compatible systems are not appropriate for the recording of fast movements or large amplitude movements, e.g., drawing- or handwriting-like movements. Thus, most fMRI experiments on motor control and motor learning are restricted to sequential finger tapping paradigms where movement timing is recorded by simple keyboards or response boxes that are MRI compatible (Doyon et al., 2002). Even with these devices the imaging data quality can be markedly reduced (J. Doyon, personal communication). Moreover, while the pace of sequential movements may be controlled via earphones by an external acoustic trigger, the amplitudes, direction and accuracy of these types of movements can only poorly be controlled with a video camera, which does not afford on-line tracking and analysis of movement kinematics (Karni et al., 1995).

We describe a system for high-resolution 2D-movement recording that allows one to record, and subsequently analyse, complex handwriting-like movements during fMRI experiments.

## 2. Methods

In the following we will describe two different set-ups: first, the behavioural set-up for the control experiments, and second, the experimental set-up for fMRI recording. Both set-ups differed with respect to the used drawing systems as well as the movement recording systems. However, the positioning of the participants, the field of view (FOV), the surface and size of the workspace as well as the configuration of the drawing movements were the same.

Five right-handed subjects who practiced outside the magnet were also tested inside the magnet at three different time points throughout training: at the beginning, middle and end of the experiment. Subjects trained by producing 200 movements/day for 10 days. Subjects trained on different target configurations of spatially co-aligned segments ($\overline{AB}$; $\overline{BC}$ and $\overline{CD}$; $\overline{DA}$). For each target configuration, functional brain images were acquired while subjects performed the trained sequence – SEQ (ABCDA), the trained sequence but in a reverse direction – REV (ADCBA), and the four sequence components – COMP (AB–BC–CD–DA) (the data of the imaging experiment will be presented elsewhere, for behavioural data see Sosnik et al., 2004, 2006). Subjects were given the same instructions as outside the magnet ('move as rapidly and as accurately as possible'). In either experimental set-up participants were placed at a convenient, individually adjusted distance from the work area for drawing-like movements. The FOV enabled the subject a clear view of the whole work area without moving or lifting up the head. The subject was instructed to avoid lifting the tip of the pen from the workspace surface. The subjects placed the pen on the starting point A until a computer generated an auditory 'start' signal that triggered the respective trial.

### 2.1. Behavioural set-up: drawing system and movement recording system

The experimental apparatus for the control experiments consisted of an adjustable metal scaffold attached to a narrow bed simulating the MRI scanner bed (Fig. 1). In order to achieve a comparable body position during behavioural testing and during the imaging session, the participants were placed in a supine position on the bed. A commercially available digitizer table was used for the behavioural control experiments conducted outside the magnetic resonance scanner. The digitizer tablet (WACOM INTUOS, $616 \times 446 \times 37$ mm, max. data rate 200 pps, accuracy $\pm.25$ mm) was mounted on the scaffold vertically, above the participant's hips and at a convenient distance for the hand to reach the tablet with a pen (cordless, 13 g weight). The position (distance from head) and height of the digitizer tablet was adjusted
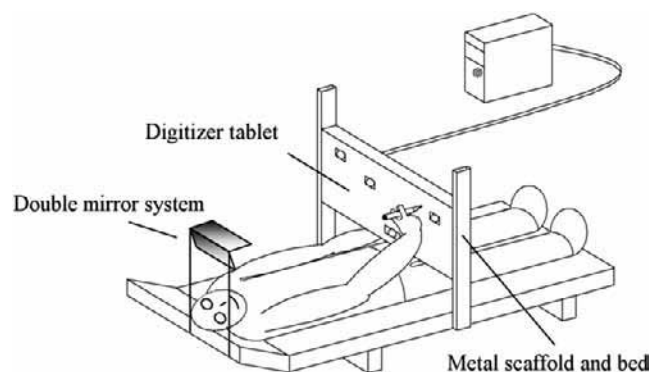


**Fig. 1 – Behavioural set-up. The recording system for the control experiments consists of a digitizer tablet fixed to a metal scaffold and a bed. Subjects look at the working area through a double mirror system.**

individually for each subject. To minimize shoulder movements, prevent any head movements and guarantee an fMRI-like head position, the head was restrained by a plastic head-holder (frame) and foam pads. Participants viewed the digitizing tablet (i.e., the workspace) through a double mirror system (Fig. 1). To minimize friction, the targets for the stylus movements (black crosses of $10 \times 10$ mm) were drawn on commercial transparencies (A4 size) that were attached to the surface of the digitizer tablet. Feedback for accuracy, e.g., crossing the target zones ($10 \times 10$ mm), was given immediately after each movement sequence was completed. Inaccurate trials and trials in which the subjects lifted the pen from the tablet's surface were discarded. The FOV, head position and body position as well as the drawing distance during the behavioural training were comparable to those in use during the fMRI session.

## 2.2. fMRI set-up

We tested the movement recording system on both a 2 T and a 3 T MRI system. The 2 T MRI system used was an Elscint scanner, equipped with echo-planar imaging (EPI) capabilities using the standard head coil for radio-frequency (RF) transmission and signal reception. Using a mid-sagittal scout image, 12 axial slice positions (no gap) were oriented parallel to the bi-commissural plane with the uppermost slice aligned 5 mm below the vertex, thus approximately covering most of the brain (specifically, covering the primary motor cortex, hand area, and the lateral and medial pre-motor areas). Another six slices (1 mm inter-slice gap) covering the cerebellum were acquired. T1-weighted images (TR = 11.4 msec, TE = 4.4 msec, $15°$ flip angle, FOV = $256 \times 256$ mm$^2$, matrix size = $200 \times 256$, 128 sagittal slices with 1.33 mm thickness) were also acquired to determine the anatomical landmarks.

In each experiment a time series of 132 scans was acquired. In each scan, a set of 44 axial T2*-weighted gradient-echo echo-planar images [repetition time (TR) = 3 sec, echo time (TE) = 48 msec, FOV = $220 \times 220$ mm$^2$, matrix size = $64 \times 64$, voxel size = $3.43 \times 3.43 \times 5$ mm$^3$] were collected. We used a single event design in which a baseline phase (30 sec) was followed by four alternating movement (two scans of 3 sec each) and rest (six scans of 3 sec each) periods. The imaging data were acquired for 6 sec while performing (active images), and for 18 sec while resting (rest images) with the eyes looking at the target screen. Three seconds before the end of the respective resting conditions subjects were instructed to lift the arm upon a computer generated acoustic 'get ready' signal, and each movement sequence was triggered by an acoustic 'go' signal. Timing and accuracy of each movement sequence was controlled visually on a video monitor outside the scanning room. At the end of each imaging session the movement recording system was calibrated again.

The same MRI compatible movement kinematic recording system was installed on a 3 T GE scanner. We compared images of the brain acquired either with the recording system on or with the recording system off to test that no reduction in image quality is induced by the movement recording system at 3 T, a magnet field strength available to many laboratories. Imaging parameters on the 3 T scanner were: EPI – TR/TE/FA

3000/25/90, in plane resolution $3.4 \times 3.4$ mm$^2$, slice width 3 mm with a .4 gap. Anatomy 3D-FLAIR.

In the magnet, subjects wore either prism glasses or used a mirror device that guaranteed the same FOV and a comparable workspace as in the behavioural experiments (Fig. 2). Headphones were used for the auditory signal input. Similar to the behavioural set-up, the subject's head was stabilized with rubber foam pads on both sides. After positioning the subject in a supine position inside the MRI scanner bore, the workspace pad was clamped to the inner wall of the bore within a convenient distance for drawing (handwriting like) movements, in similarity to the set-up for the behavioural control experiment. From that stage on, the subject was instructed to remain 'as still as possible'. The fiber-optic cable (feeding into the stylus) was strapped to the wrist, and prism glasses were adjusted such that the FOV covered the whole target area. The procedures described above take approximately 3–5 min and are accomplished very easily.

## 2.3. fMRI set-up: drawing system

The fMRI compatible movement recording system consists of a translucent plastic board (workspace pad), a stylus (i.e., a plastic pen with a fiber-optic core, connected through fiber optics to a halogen light power source), a CCD camera, a video monitor and a PC with a special video processor for light detection (grabber card).

The workspace pad on which the sequential point-to-point movements were performed during the functional imaging sessions consisted of a translucent semicircular plastic board (width 415 mm, length 430 mm). The targets for the movements were drawn on the same kind of transparency as was used during the behavioural control experiments, which was then attached to the pad surface. The anchoring of the pad had to be fixed in a stable position to prevent any displacement of the targets during task performance. To eliminate motion artefacts resulting from breathing and other intentional and unintentional movements, no contact of the pad with the subject's body was allowed. As the pad had to resist
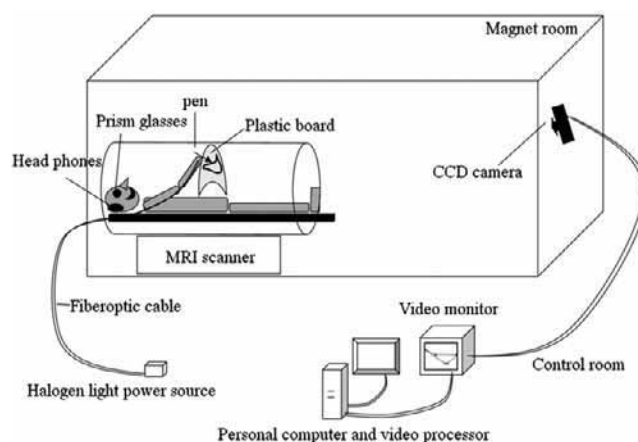


Fig. 2 – fMRI set-up. The recording system consists of a translucent plastic board, a plastic pen containing fiber optics and a halogen light power source, a CCD camera, a video monitor and a PC with a video grabber card.

considerable forces during the performed movement sequences, its anchoring was to the magnet itself. However, the workspace pad could not be permanently fixed to the magnet's inner bore (the tunnel wall) as such fixation would (a) prevent individual positioning of the subjects during the scanning sessions, (b) constitute an obstacle to standard scanning, and (c) constitute an impediment for rapid evacuation from the scanner. In accordance with these constraints, the workspace pad was clamped to the inside surface of the magnet's bore by means of two strong adhesive plastic strips (SCOTCH™) and, on the pad's side, via rubber stoppers with flexible joints. This enabled (a) the rapid dismounting of the pad at any time, including by the participant, by applying a vertical downward force; (b) individualized setting of the pad's distance from the participant's head (along the long axis of the magnet bore) thus affording a convenient drawing distance for each subject which was comparable to the one afforded during the behavioural control experiments.

Movements during the imaging experiments were performed with a stylus of comparable size and weight to the one provided with the commercial digitizer tablet. The only difference was that a fiber-optic cable was inserted into the stylus for light transmission. A standard fiber-optic jacketed bundle was used, 2.2 mm thick and ~15 m long, consisting of 16 acrylic polymer fibers with 240 μm core diameter each. The fiber-optic cable was strapped to the subject's wrist to prevent the generation of torque around the wrist during the performed movements. The fiber-optic cable was used to guide halogen light to the tip of the pen resulting in a small bright dot (stylus tip). The bright stylus tip resulted in a very clear and focused spot of light. The bright tip was easily picked up by the camera which faced the other (far) surface of the translucent pad (see below) as it constituted the brightest, and the only light-emitting, point in the camera's FOV. The light-emitting source that fed into the fiber-optic cable was placed outside the scanning room (Fig. 2). Preliminary measurements on water phantoms indicated that the cables had no effect on the homogeneity of the magnetic field and exhibited no interaction with the magnetic gradients.

### 2.4. fMRI set-up: movement recording system

A commercially available video camera (Pulnix TM-300, 1/2 in. CCD sensor, nominal resolution 752H × 582V, video format analog CCIR) was mounted on the wall at a distance of 5.5 m from the scanner's bore center and at an angle of 10° above its axis. Hence, the line of sight of the camera was not strictly perpendicular to the screen. There was, however, only a negligible distortion of the image geometry. The video signal was transferred out of the magnet room and into the control room (Fig. 2), where a video monitor and the computer system were placed, using the standard magnet room safety and surveillance camera cable installation.

The lens optics used with the camera had a focal length of 140–150 mm adjusted so that the drawing area, defined by the location of the movement targets, occupied the whole FOV. The aperture was f/2.8–f/4. In order to avoid amplifying camera noise and background light the fixed video gain (no AGC) option was used. During the experiment the lights in the magnet room were dimmed.

A personal computer with a proprietary video-grabbing card was used for data recording under DOS operating system. The grabber card collects only those data points whose intensity exceeds a given threshold. The threshold can be adjusted to obtain a compromise setting between background illumination and the stylus tip's light spot. The electronic circuits of the camera were manipulated to maintain the spatial resolution capacity with a sampling rate of 50 Hz, and to reduce the amount of data transmitted to the host computer (Appendix A).

### 2.5. fMRI set-up: calibration and data processing

The goal of the calibration procedure is to transform the recorded data from pixel coordinates in the camera image plane back to millimetre coordinates in the pad targets' plane. Thereafter the data analysis routines that were used for the standard digitizing tablet data could be applied.

Calibration of the system was as follows. The participant was instructed to maintain the lighted stylus tip on target, for each target, for several seconds. Several iterations of measurements from both beginning and the end of the session were averaged to determine the accurate pixel coordinates of each target. The process was repeated at the end of the session as the system might have slightly drifted or moved. Note that any number of sets of target locations can be obtained and may be given different weights in calculating the final average reference target positions in the pixel plane. Nevertheless, we found only slight differences between target localisations and, if at all, not greater than a couple of pixels in our set-up.

The different steps (calculations) adopted in order to make the transformation from the captured images to the targets' pad plane are presented in Appendix B.

## 3. Results

Typical representative movement trajectories, as performed by a single representative participant, before and after extensive training on the target movement sequence are shown in Figs. 3 and 4. Details of the behavioural study, including data from a number of individuals, can be found in Sosnik et al. (2004, 2006). At the beginning of training, the movement sequences consisted of a series of straight trajectories with distinctive bell-shaped velocity profiles (Fig. 3A). With continuous practice, the trajectories for the first and second segment pairs ($\overline{AB}$; $\overline{BC}$ and $\overline{CD}$; $\overline{DA}$, respectively) became partially curvilinear with double-peaked velocity profiles (Fig. 3B). Following multi-session training, the prototypical straight movement paths disappeared and two curved paths emerged, the first with a bell-shaped velocity profile and the second with a double-peaked velocity profile (Fig. 3C).

As subjects performed the same target movement sequences in daily training sessions (using the behavioural set-up described above) and at different points in time while being scanned (fMRI), we were able to compare the kinematics of the movements as recorded in the magnet with those acquired at a corresponding point in time outside the magnet, using the standard digitizer tablet, in the same individual.
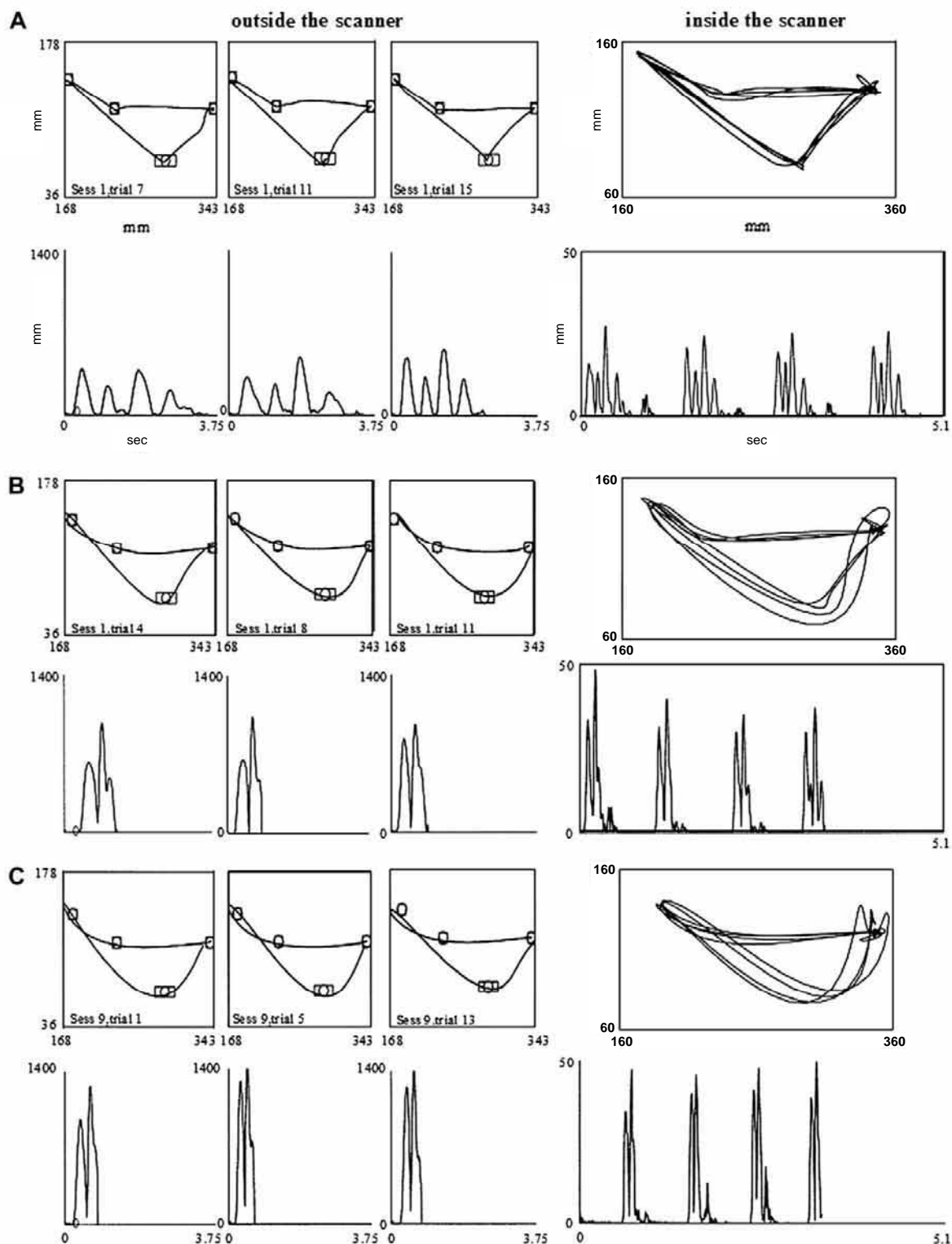
Fig. 3 – Training of movement sequences. (A) Movement kinematics of the first training session. Representative movement sequences recorded with the optic system (right-hand graph) and three movement sequences recorded with the digitizer tablet (left-hand graph), respectively. *Upper graphs* depict the path of the movement, *lower graphs* show the respective velocity profiles. (B) Recordings on Day 6 and (C) Day 9, respectively.
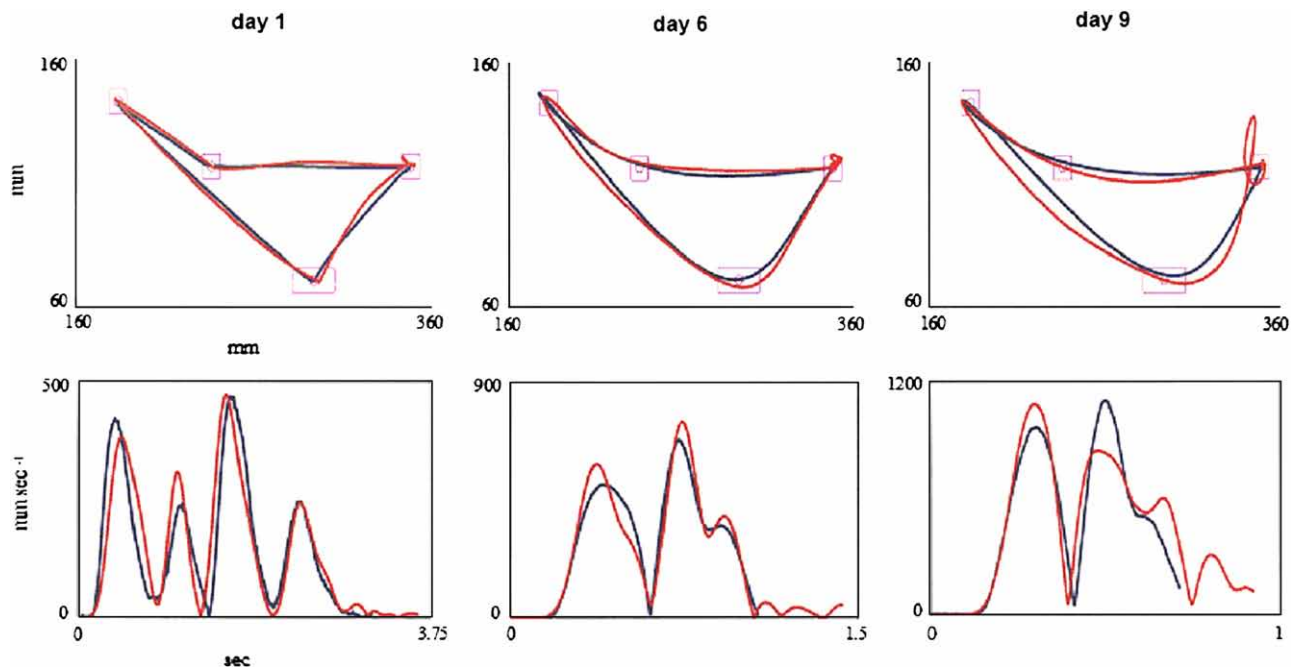
**Fig. 4 – Superimpositions of average path and velocity profiles. Data taken with the optic system inside the MR scanner (red) reveal movement kinematics comparable to control data recorded with a digitizer tablet outside the MRI environment (blue) at different time points.**

Fig. 4 depicts superimpositions of average paths and velocity profiles (four trials) as recorded in the MR scanner and the average paths and velocity profiles as recorded in the behavioural set-up (20 trials) with the digitizer tablet on the same day. As can be clearly seen, there was no difference between trials recorded with the digitizer tablet and trials recorded with the optical recording system inside the scanner during the fMRI data acquisition. Fig. 5 shows the corresponding activation maps for Day 1, Day 6 and Day 9.

Fig. 6 depicts a representative fMRI acquired on a 3 T scanner showing that there was no interference of the optical system with EPI images. This analysis however highlights the (lack of) static effects of the optical system on the brain image. To test the effect of dynamic motion of the arm itself on head movements and the magnetic field, respectively, the following analysis was run. Fig. 7A depicts a representative fMRI image showing the pattern of brain regions' activation during the performance of drawing movements (a figure of eight) with the optical movement recording system on. During the movement periods, only minor head movements were observed (Fig. 7B). Head movements similar in range and variance in terms of position ($x$, $y$, $z$: $.24 \pm .41$, $.31 \pm .67$, $.07 \pm .01$ mm) and rotation (roll, pitch, yaw: $.16 \pm .09$, $.23 \pm .41$, $.05 \pm .008$ mm) were observed while the subject performed the movement sequences shown in Fig. 3. Even without any movement of the head, image noise may result from local distortions of the magnetic field when a mass (e.g., the forearm) moves through the magnetic field (Diedrichsen and Shadmehr, 2005). In order to quantitatively assess the amount of image noise when participants perform overt arm movements in the scanner we inspected the residuals of the fMRI time series that contrasted movements versus rest. Fig. 7C shows that a similar amount of noise, expressed as standard deviation over scans relative to mean intensity of the realigned brain images, occurred during task performance and during rest.

## 4. Discussion

We describe a robust, and easy to operate system for recording digital 2D-hand movement kinematics during fMRI brain mapping studies. This system enables investigators (a) to correlate cortical activation with movement kinematics; (b) to control, in various kinds of motor experiments, for the actual movements performed, with high accuracy; (c) to implement new, more sophisticated experimental designs involving the generation of complex movement sequences. The system has been successfully implemented for use on 2 T Elscint and 3 T GE magnet systems. Furthermore, this optic-based recording system can be modified for other applications in a high magnetic field environment and is open for further extensions, e.g., combination with an EMG measuring system (Liu et al., 2000).

By employing an active light source placed outside of the magnet room and using a fiber-optic cable ending at the stylus tip we were able to acquire kinematic data in parallel with brain imaging data in a typical fMRI environment. The hitherto available movement tracking system requires the use of either active markers, usually light-emitting diodes (LEDs), or passive markers, reflecting external light, that are incompatible with work in a high magnetic field environment. This incompatibility stems from the considerable electrical interference that occurs between active markers and the magnetic field, causing either malfunctioning of the markers or
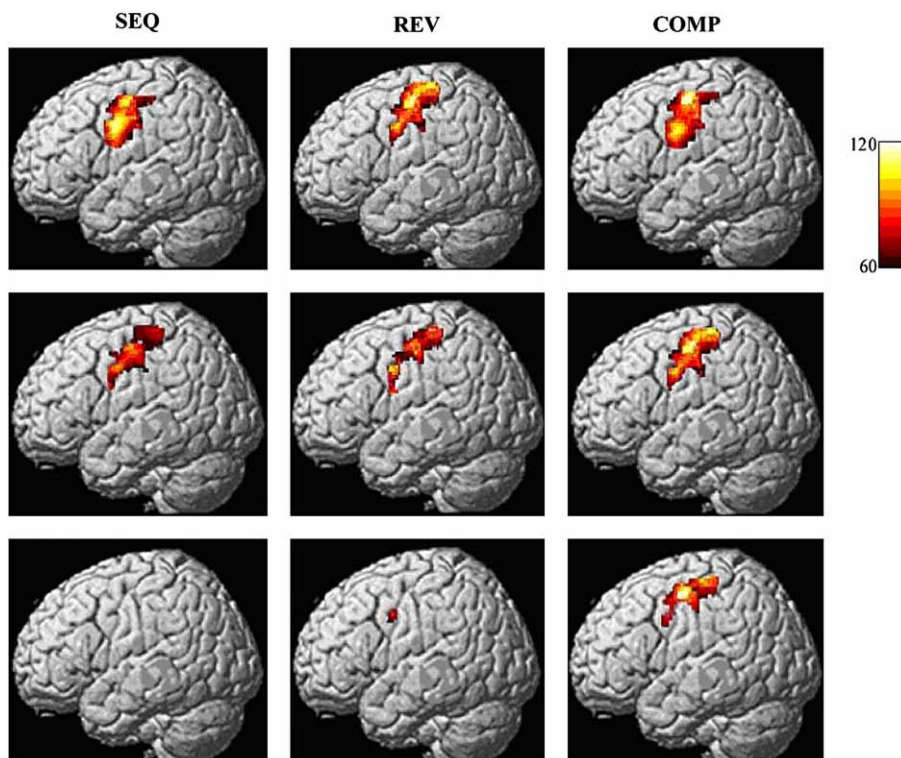
**Fig. 5 – Activation in M1 in different scanning days and training conditions. Upper line shows activation maps for sequence (SEQ = ABCDA) movements, reverse (REV = ADCBA) movements and component (COMP, e.g., AB) movements on Day 1. Middle line shows activation maps for Day 6 and bottom line for Day 9, respectively. To attain significance the voxels were thresholded at $p < .05$ two-tailed and corrected for false discovery rate (FDR\*). The colour bar depicts T values. \*FDR controls the expected *proportion* of false positives among suprathreshold voxels. An FDR threshold is determined from the observed $p$-value distribution, and hence is adaptive to the amount of signal in the data.**

a reduction in MR image quality (increased image noise) secondary to induced electrical currents. Furthermore, as we were interested in the recording of point-to-point movements performed with a pen the critical element of interest was the tip of the stylus, where it would be difficult to place passive markers. Using our method, we were able to achieve on-line tracking of movements via simple light detection with a conventional CCD camera and a special video processor for light detection without any interference with the magnetic field or the RF system (see Figs. 6 and 7).

Drawing and writing are subserved by complex processes that draw on linguistic, cognitive and motor skills. Numerous electrophysiological and stimulation studies have attempted to unravel the role that different cortical and sub-cortical motor areas play in the planning and execution of various upper limb movements. The activity level in different motor areas was suggested to be correlated with various temporal and spatial characteristics of the hand trajectories, e.g., velocity (Bauswein et al., 1991; Burbaud et al., 1991; Flament and Hore, 1988), force (Georgopoulos et al., 1992; Kalaska et al., 1989), muscle activation (Todorov, 2000a; Todorov, 2000b; Todorov and Jordan, 2002), hand position (Georgopoulos et al., 1984; Georgopoulos and Massey, 1985) and movement direction (Georgopoulos et al., 1992). Elaborate study designs aimed at controlling the underlying cognitive processes of drawing and writing movements by means of fMRI. Unfortunately, the

cognitive processes usually could not be matched by detailed recordings and analysis of the actual motor product. Furthermore, since neural activities in the different brain areas code for different motion parameters, even fine differences in the kinematic or dynamic features of a movement may have a substantial effect on the neural activity levels. Thus, poor experimental control of motor actions during functional neuroimaging studies may lead to erroneous interpretations of the role that specific brain areas play in tasks such as writing or drawing and may lead to inconsistent, sometimes contradicting findings. For example, in two recent fMRI studies when subjects were asked to write or draw on a pad of paper placed on their lap (Harrington et al., 2007) or to write with the index finger onto the surface of the MRI stretcher (Matsuo et al., 2000) there was almost no control of the motion parameters during the performance of the tasks. Others have used an experimental set-up with an L-shaped transparent plastic board placed on the subject's abdomen with movements recorded by a video camera (Ino et al., 2003). However, abdominal breathing movements are a concern in such a set-up. Parameters such as the size of the figural forms that are drawn (e.g., a circle, a square) are also as important (Gowen and Miall, 2007).

The solution adopted in the design of the current system, which involved clamping the workspace to the magnet bore in an adjustable and easily retractable manner, provides a highly
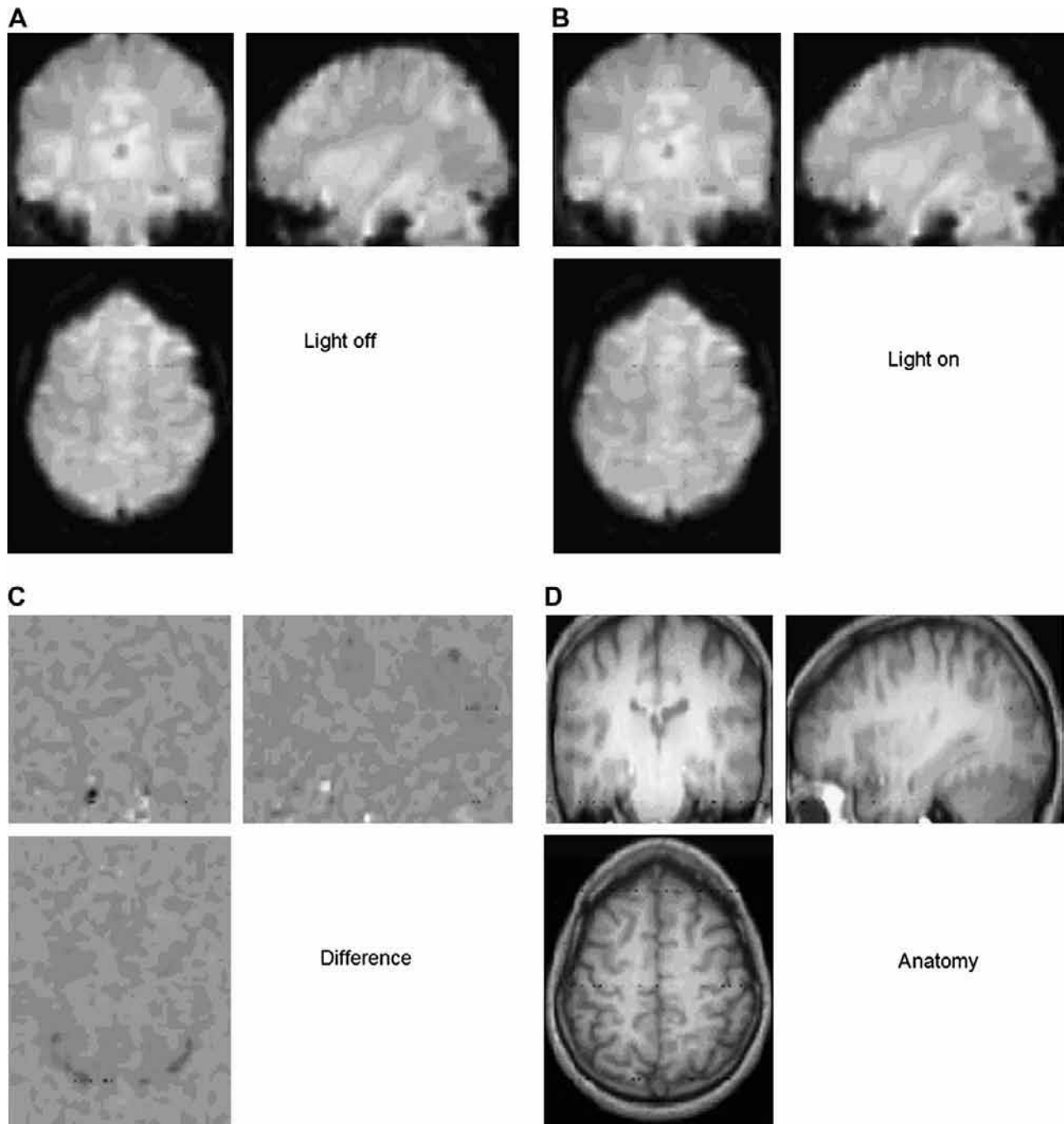
**Fig. 6 – No interference of the light-pen with EPI images. (A) Orthogonal sections through the motor cortex of EPI images with the light-pen off, (B) light-pen on and (C) showing the difference image. There were no pen-related imaging artefacts. (D) The anatomical details are shown on the T1 images. All images were normalized into a standard space using SPM2 toolbox for MATLAB.**

stable writing and drawing surface. It also provides an option for a rapid evacuation of the subject from the magnet bore which is an important safety requirement. The video-based image capture set-up provides for sampling and resolution parameters comparable to those afforded by commercially available digitizer tablets that are used as the method of choice for recording 2D-movement kinematics in studies of writing and drawing movements outside the MR scanner's environment. The current system can be improved with respect to on-line data analysis. In the current version of the system, the data analysis is performed off-line after the termination of the brain imaging session. However, with additional software, immediate feedback about accuracy and velocity of the performed movement is feasible. Furthermore, our system may be coupled with on-line EMG recording (Ganesh et al., 2007; Van Duinen et al., 2005) to disclose the
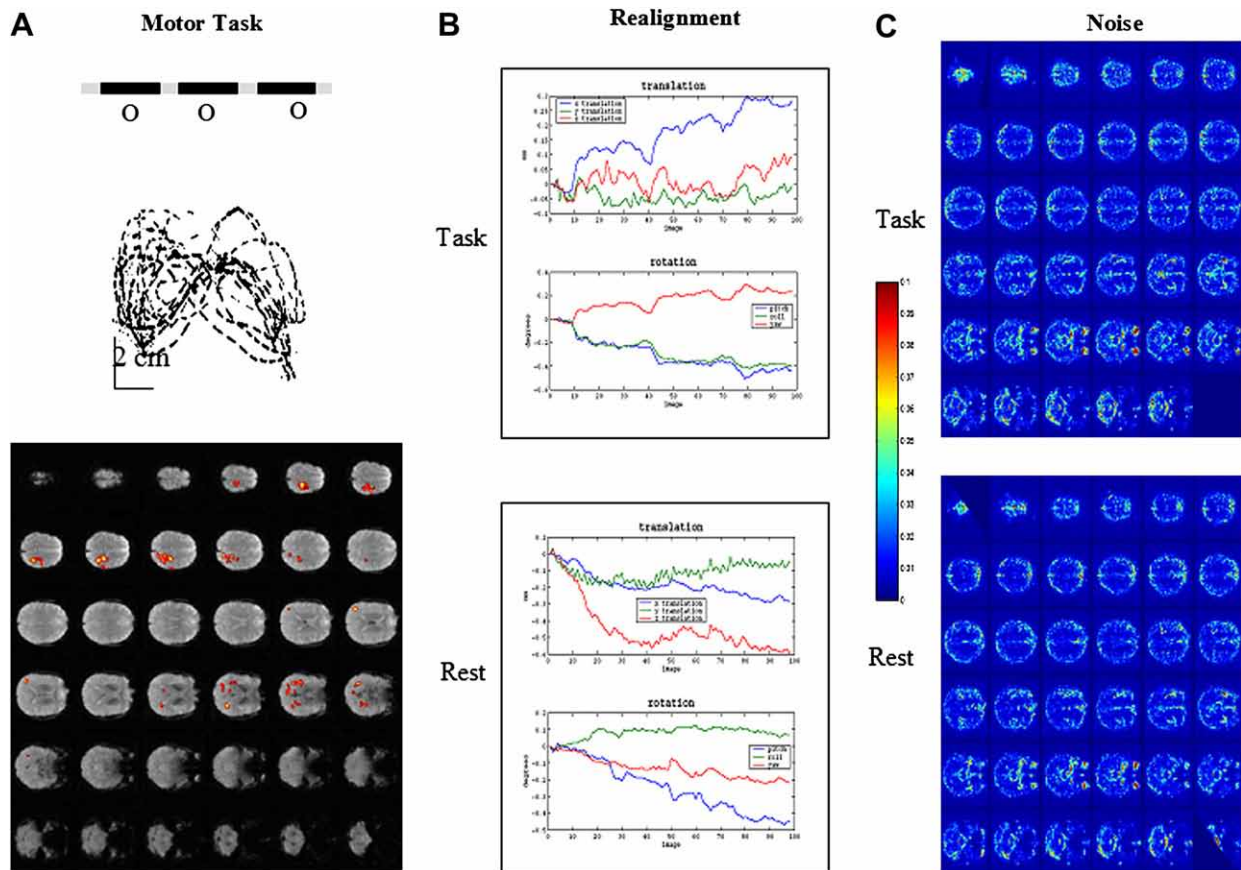
Fig. 7 – Head and arm movement related noise. The motor task (A) consisted of interleaved periods of 24 sec rest and 72 sec of free drawing ('On') (top) of the depicted trace (middle) at a rate of about one cycle per 2 sec. The resulting activation map overlaid on the EPI images (bottom). The realignment plots (B) demonstrate movements of similar extents during performing of the motor task and during control acquisition with subject resting with eyes closed and the light-pen off. Similar noise (C), expressed as standard deviation over scans relative to mean intensity of the realigned brain images, was measured during task performance and during rest.

muscle activity pattern involved in the performed movements.

The availability of kinematic data acquired in parallel to the brain activation data during functional MRI studies may improve our ability to understand brain activity associated with the planning and execution of complex writing and drawing tasks.

# Appendices.

## Appendix A.

The camera was switch-set to 'field mode', wherein data are recorded during 20 msec of field time and then retrieved (sampling rate 50 Hz). Because there was motion in the scene we used the electronic shutter available in the camera to limit the exposure time to a fraction of the field time in order to lessen the smearing of the image of the light spot (field time = 10 msec). The camera sends continuously alternate odd and even fields of a standard video signal, each field contains 291 sequential lines of the scene plus 21.5 invisible TV scan lines. In 'field mode', one line represents data collected by two adjacent horizontal rows of photosensitive cells in the CCD sensor, namely the data from two vertically neighboring cells are summed up. This arrangement doubles the sensitivity of the sensor, but it also doubles pixel height, virtually halving the vertical resolution. In alternate fields the summation of charges also alternates, e.g., if row 25 adds to row 26 and row 27 adds to 28, etc., in one field, then in the next field 26 adds to 27 and 28 adds to 29, etc. As a result, the location observed in an even field must be shifted vertically by one-half pixel with respect to location of the same spot as observed in an odd field. In contrast to the vertical dimension of the pixel, its horizontal size is determined by the rate of the sampling clock in the grabber card (10 MHz). Thus, in the grabbed field there are ∼290 pixels vertically and ∼520 pixels horizontally, and each pixel's height is ∼1.35 times its width (aspect ratio).

In the video grabber card, while the analog-to-digital converter is sampling the video signal, those pixels that traversed the threshold values for luminance are stored for both location and intensity. At the end of the field time when