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The role of the frontal aslant tract and premotor connections in visually guided hand movements

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ABSTRACT

Functional neuroimaging and brain lesion studies demonstrate that secondary motor areas of the frontal lobe play a crucial role in the cortical control of hand movements. However, no study so far has examined frontal white matter connections of the secondary motor network, namely the frontal aslant tract, connecting the supplementary motor complex and the posterior inferior frontal regions, and the U-shaped dorsal and ventral premotor fibers running through the middle frontal gyrus. The aim of the current study is to explore the involvement of the short frontal lobe connections in reaching and reach-to-grasp movements in 32 right-handed healthy subjects by correlating tractography data based on spherical deconvolution approach with kinematical data. We showed that individual differences in the microstructure of the bilateral frontal aslant tract, bilateral ventral and left dorsal premotor tracts were associated with kinematic features of hand actions. Furthermore, bilateral ventral premotor connections were also involved in the closing grip phase necessary for determining efficient and stable grasping of the target object. This work suggests for the first time that hand kinematics and visuomotor processing are associated with the anatomy of the short frontal lobe connections.

1. Introduction

Advances in our understanding of visuomotor processing showed that frontal lobe circuits are crucial for generating motor commands for simple hand movements such as reaching and reaching-to-grasp (Jeannerod et al., 1995; Castiello, 2005; Grafton, 2010). Reaching refers to a transport of the hand in space, whereas reach-to-grasp action consists of an additional grasping component, which implies hand shaping according to the target object's physical properties (Jeannerod, 1995).

In addition to the primary motor cortex (M1), secondary motor areas including supplementary motor complex and premotor regions are active during reaching and reach-to-grasp movements (Castiello, 2005; Filimon, 2010). Functional neuroimaging and lesion studies implicate these areas in a variety of motor-related processes, such as initiation, generation and control of voluntary hand movements (supplementary motor complex) (Picard and Strick, 1996; Nachev et al., 2008); visuomotor transformations and generation of finger and hand configurations (ventral premotor cortex, PMv) (Davare et al., 2006; Raos et al., 2006), and planning, control and online monitoring of hand actions (dorsal premotor cortex, PMd) (Begliomini et al., 2007, 2008; Glover et al., 2012).

A dual model of visuomotor processing suggested that PMd and PMv are part of two independent circuits, originating from the posterior parietal cortex, which control the reaching and the grasping components of prehensile movements, respectively (Jeannerod et al., 1995; Matelli and Luppino, 2001). However, this view has been challenged recently, when overlapping PMv and PMd activations were reported for both reaching and grasping actions (Grol et al., 2007; Begliomini et al., 2014, 2015; Fabbri et al., 2014; Tarantino et al., 2014). It was shown that PMv and PMd interact based on the motor planning and online control required, but not on the basis of movement type (Grol et al., 2007; Glover et al., 2012). The importance of the connections between PMv and PMd has been further corroborated by

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our previous work showing modulation of the PMv-PMd functional connectivity during precision grasping (i.e. index finger-thumb opposition; Begliomini et al., 2015). This is in line with the idea that the most appropriate grip type is selected in PMv (F5 in monkey), and then supplied to PMd (F2 in monkey), whose neurons keep a memory trace of the motor representation in order to continuously update hand configuration and orientation during target acquisition (Raos et al., 2004). This intra-hemispheric cross-talk between PMv and PMd is enabled by the underlying local white matter connections (Grafton, 2010).

Overall, research in monkeys and humans provided a comprehensive view on the cortical control of hand actions, but the underlying white matter received little attention. The likely contribution of the short frontal lobe connections mediating local connectivity is essentially unknown. Our study aims to fill this gap by investigating the hodology of white matter networks connecting secondary motor regions, and their role in reaching and reach-to-grasp movements. Specifically, the frontal aslant tract and the system of short U-shaped premotor fibers running superficially to the frontal aslant tract will be considered.

The frontal aslant tract is among the newly described intralobar frontal tracts that links the cortical nodes of the secondary motor network, possibly enabling PMv-PMd cross-talk. It connects the supplementary motor complex in the dorso-medial frontal regions of the superior frontal gyrus (SFg), and the most posterior part of the Broca's territory (pars opercularis, BA44, pars triangularis, BA45, but also precentral regions, BA6) (Ford et al., 2010; Catani et al., 2012; Thiebaut de Schotten et al., 2012; Vergani et al., 2014). The supplementary motor complex consists of two areas (Nachev et al., 2008), namely the supplementary motor area (SMA) supporting online control, and the pre-SMA responsible for movement planning during reach-to-grasp movements (Glover et al., 2012). The SMA, unlike the pre-SMA, has direct connections to M1 and the spinal cord, and it is thus considered as a premotor area (Dum and Strick, 1991). The frontal aslant tract's ventral terminations lie within PMv, which includes precentral BA6 and Broca's area BA44 (Vogt and Vogt, 1919; Binkofski and Buccino, 2004). Cytoarchitectonically, BA44 represents the most likely human homologue of monkey's F5, crucially involved in hand movements (for reviews see Rizzolatti et al., 2002; Binkofski and Buccino, 2004; Fadiga and Craighero, 2006), such as grasping and other manipulative actions (Binkofski et al., 1999a, 1999b, 2000; Gerardin et al., 2000; Nishitani and Hari, 2000; Grèzes et al., 2003; Hamzei et al., 2003). To date, the frontal aslant tract has been associated with different aspects of speech and language (Catani et al., 2013; Kinoshita et al., 2014; Kronfeld-Duenias et al., 2014; Mandelli et al., 2014; Vassal et al., 2014; Fujii et al., 2015; Kemerdere et al., 2015; Sierpowska et al., 2015) and orofacial movement control in Foix-Chavany-Marie syndrome (Martino et al., 2012), but its contribution to voluntary hand movements remains unknown. In addition, a system of short U-shaped fibers running superficially to the frontal aslant tract has been described, interconnecting SFg and inferior frontal gyrus (IFg) to the posterior portion of the middle frontal gyrus (MFg) (Catani et al., 2012). We use the terms dorsal (MFg-SFg) and ventral (MFg-IFg) premotor connections, having in mind the proposed PMv-PMd border at the level between the superior and inferior frontal sulci in humans (Tomassini et al., 2007). The functions of these premotor U-shaped fibers are unknown. Nevertheless, based on their cortical topography, it was suggested that the dorsal connections might play a role in initiating and coordinating complex eye, hand and arm movements for reaching actions, while the ventral connections may support the 'grasping' network (Catani et al., 2012).

Here we used diffusion imaging tractography, based on the spherical deconvolution approach, to dissociate the role of the short frontal connections underlying secondary motor areas in visually guided hand movements. Spherical deconvolution has the advantage, over the classical diffusion tensor model, to resolve the crossing fibers problem and improve tractography reconstructions of short intralobar tracts by reducing the presence of false negatives (Tournier et al., 2004; Dell'Acqua et al., 2010, 2013). We dissected the frontal aslant tract and the premotor U-shaped connections in 32 right-handed healthy participants, whose hand kinematics was separately recorded for reaching and reach-to-grasp movements. The hindrance modulated orientational anisotropy (HMOA) was used as a measure of white matter microstructure, being a true tract-specific index, and better reflecting the microstructural organization (e.g. myelination, axonal density, axon diameter, and fiber dispersion) than the traditional voxel-specific diffusion indices (e.g. fractional anisotropy) (Dell'Acqua et al., 2013). We hypothesized that individual differences in the microstructure of the short frontal lobe connections linking secondary motor areas would be associated with the kinematic markers of reach and reach-to-grasp movements. Furthermore, according to previous literature outlining the evidence of a crucial involvement of the bilateral PMv in hand shaping and grip formation, we expected to find a higher involvement of the ventral premotor connections in the grasp-specific components of reach-to-grasp actions, compared to the dorsal premotor fibers, expected to be more involved in reaching.

2. Materials and methods

2.1. Participants

A sex and age-balanced sample of 32 healthy participants (14 males, 18 females; mean age 24.6 ± 2.7, age range: 20–31 years) was recruited. All participants were right-handed according to the Edinburgh Handedness Inventory (Oldfield, 1971), which ranges from -100 for purely left handed to +100 for purely right-handed participant. No history of neurological and psychiatric disorders was present in the study sample. All participants gave informed written consent in accordance with the ethics approval by the Institutional Review Board at the University of Padova, in accordance with the Declaration of Helsinki (Sixth revision, 2008).

2.2. Behavioral experiment

2.2.1. Task and stimulus

Participants were requested to perform two tasks: a reach-to-grasp task, in which they were asked to reach toward and grasp the stimulus with a precision grip, and a reaching task in which they were asked to perform a movement toward the stimulus and touch the stimulus frontal surface with their knuckles, maintaining the hand in a closed fist (Fig. 1). The fist's posture was chosen as to minimize distal involvement. Participants fixated the target object during both the reaching and the reach-to-grasp actions. The stimulus consisted of a spherical object (2 cm diameter) that would normally be grasped with a precision grip (PG; using the index finger and thumb). All participants were explicitly asked to use a PG for grasping the object. Participants were informed as to which task to perform by an auditory cue (high-pitch: reach-to-grasp; low-pitch: reaching). The sound also had a 'go-signal' function in the sense that participants were asked to start their actions toward the stimulus only after the sound was delivered. Trials in which the participants did not comply with the task or did not fixate the stimulus were not included in the analysis.

2.2.2. Procedure

Each participant sat on a height-adjustable chair in front of a table (900×900 mm) with the elbow and wrist resting on the table surface and the right hand in the designated start position (Fig. 1). The hand was pronated with the palm resting on a pad (60×70 mm), which was shaped to allow for a comfortable and repeatable posture of all digits, i.e., slightly flexed at the metacarpal and proximal interphalangeal joints. The starting pad was attached 90 mm away from the edge of the table surface. The object was placed on a platform located at a distance