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MOTOR PLANNING OF ARM MOVEMENTS IS DIRECTION-DEPENDENT IN THE GRAVITY FIELD

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Abstract—In the present study we analyzed kinematic and dynamic features of arm movements in order to better elucidate how the motor system integrates environmental constraints (gravity) into motor planning and control processes. To reach this aim, we experimentally manipulated the mechanical effects of gravity on the arm while maintaining arm inertia constant (i.e. the distribution of the mass around the shoulder joint). Six subjects performed single-joint arm movements (rotation around the shoulder joint) in both sagittal (upward, U, versus downward, D) and horizontal (left, L, versus right, R) planes, at different amplitudes and from different initial positions. Under these conditions, shoulder gravitational torques (SGTs) significantly varied when arm movements were performed in the sagittal but not in the horizontal plane. Contrary to SGTs, arm inertia remained constant and similar for both horizontal and sagittal planes since subjects performed arm movements with only one degree of freedom. All subjects, whatever the movement direction, appropriately scaled shoulder joint kinematic parameters according to movement amplitude. Furthermore, peak velocity and movement duration were equivalent for both horizontal and sagittal planes. Interestingly, some kinematic parameters significantly differed according to U/D but not L/R directions. Specifically, acceleration duration was greater for D than U movements, while the opposite was true for peak acceleration. Consequently, although vertical and horizontal arm movements shared a general common strategy (i.e. scaling law), the kinematic asymmetries between U and D arm movements, especially those that reflect central planning process (i.e. peak acceleration), indicated different motor intentions regarding the direction of the upcoming movement. These findings indicate that the interaction of the arm with the dynamics of the environment is internally represented during the generation of arm trajectories.

Key words: arm kinematics, gravity force, inertial force, internal models, motor planning.

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Abbreviations: AD, acceleration duration; ANOVA, analysis of variance; Apeak, peak angular acceleration; D, downward; DD, deceleration duration; L, left; MD, movement duration; R, right; RMSE, root mean square error; SGT, shoulder gravitational torque; SIT, shoulder inertial torque; U, upward; Vmean, mean angular velocity; Vpeak, peak angular velocity.

The precise control of arm kinematics (i.e. hand and joint trajectories) and dynamics (i.e. muscle forces, joint torques), as well as the interaction of the arm with the external world (gravitoinertial or aquatic environments, object manipulation etc.), is an essential condition to perform skilful motor actions. Depending on the motor task, kinematic or dynamic criteria could influence the motor planning process in the CNS, that is, the elaboration of a specific motor pattern among the many ones which could allow performance of the task. Several studies using experimental and/or simulation approaches have suggested that dynamic criteria would be preponderant upon kinematic criteria in motor planning of arm movements in the sagittal plane (Soechting et al., 1995; Pellegrini and Flanders, 1996; Papaxanthis et al., 1998a,b,c, 2003a; Soechting and Flanders, 1998; Nakano et al., 1999; Nishikawa et al., 1999). The investigations have reported that hand kinematics in the sagittal plane do not remain invariant when the direction or the speed of the movement change; suggesting, that motion dynamics could influence the performance of vertical arm movements. In particular, for various motor tasks accomplished in the sagittal plane, hand (drawing and pointing task) or shoulder (sit–stand–sit task) acceleration duration (AD) is greater during a downward (D) compared with an upward (U) movement of equivalent duration and amplitude (Papaxanthis et al., 1998a,c, 2003a,b).

Mechanically, the dynamics of vertical arm movements are related to gravity and inertial constraints. Specifically, when arm movements with at least two degrees of freedom are performed in the sagittal plane, inertial torques are related to the amount of joint rotations, accelerations and velocities (i.e. net, interactions, coriolis and centripetal torques) whereas gravity torques are related to the position of the upper-arm and forearm with respect to the vertical axis. The respective contribution of gravity and inertia on the performance of arm movements was examined in previous investigations. Some have proposed that the selection of a particular arm trajectory is such that only the inertial forces are minimized (Soechting et al., 1995; Soechting and Flanders, 1998; Nishikawa et al., 1999), while others studies have suggested that not only inertia but also gravity may be relevant for the elaboration of the motor plan (Papaxanthis et al., 2003a, 2005). Without doubt, inertial forces influence the motion of the arm. A propos, several studies have demonstrated the predominant contribution of inertia on hand trajectory formation (Gordon et al., 1994b; Soechting et al., 1995; Sabes et al., 1998; Flanagan and Lolley, 2001; Gentili et al., 2004) and on control/learning process of arm pointing movements

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(Ebadzadeh et al., 2005). However, gravity may be equally or even more important than inertia when considering a specific class of arm movements, i.e. those performed in the sagittal plane. Notably, when vertical arm movements are performed at a natural speed, gravity torques exert a greater influence on movement dynamics than inertial torques (Papaxanthis et al., 2003a).

Up to now, earlier studies, without being controversial, left open the question of the involvement of gravity into the planning process of vertical arm movements. Specifically, does the integration of gravity into the motor plan contribute to U versus D differences in arm kinematics? Besides, while acceleration of gravity is constant (direction and magnitude) in space, its mechanical effects on the moving limbs (gravity torques) depend on body segment configuration and movement amplitude. Accordingly, does the brain adapt kinematic features of U and D arm movements according to the variation of gravity torques? Desiring to elucidate how the human brain integrates gravity force, we asked subjects to perform U and D arm pointing movements in the sagittal plane under various conditions of movement amplitude and arm initial position. In addition, subjects performed similar movements in the horizontal plane (in both left, L, and right, R, directions). In order to emphasize the effects of gravity during arm movement execution, we simplified motion dynamics by imposing arm movements with one mechanical degree of freedom (rotation around the shoulder joint). During single-joint arm movement, inertia (i.e. the distribution of the arm mass around the shoulder joint in a body fixed coordinate system with origin the shoulder joint location) remains constant and thus inertial torques are related only to joint acceleration. On the contrary, gravity torques in the sagittal plane significantly change according to movement direction, arm initial position and movement amplitude, while they remain constant during arm movements in the horizontal plane. We consider that a kinematic analysis, based on a detailed experimental manipulation of gravity torques while simplifying as much as possible the effects of inertia, could elucidate on the role of gravity in the motion planning of vertical arm movements.

EXPERIMENTAL PROCEDURES

Subjects and experimental device

Six male adults, healthy, R-handed and with normal or corrected-to-normal vision (mean age=25±3 years, mean weight=78±2.51 kg and mean height=1.75±0.02 m), participated voluntarily in the current study. The experimental protocol was carried out in accordance with legal requirements and international norms.

Subjects, sitting on an adjustable chair, performed single-joint arm movements (rotation around the shoulder joint) in both sagittal and horizontal planes (Fig. 1). For the execution of arm movements in the sagittal plane, 11 targets (LEDs, diameter of 5 mm, fixed on a steel semicircular bar) were placed in front of the subjects in a polar frame of reference. The targets were centered on the subjects' R shoulder joint and positioned at a distance equal to the length of their fully extended arm. The middle of the 11 targets was aligned with the horizontal axis. In this polar frame of reference, the elevation angle of the shoulder when the index fingertip pointed toward the targets was from U to D: 25°, 40°, 50°, 65°, 75°, 90° (middle target, arm aligned with the horizontal axis), 105°, 115°, 130°, 140°, 155°. For the execution of arm movements in the horizontal plane, we simply rotated (90° clockwise) the experimental device. In this way, we conserved its center of rotation around the shoulder joint and consequently the azimuth angle of the shoulder when the index fingertip pointed toward the targets were from L to R: 25°, 40°, 50°, 65°, 75°, 90° (middle target), 105°, 115°, 130°, 140°, 155°.

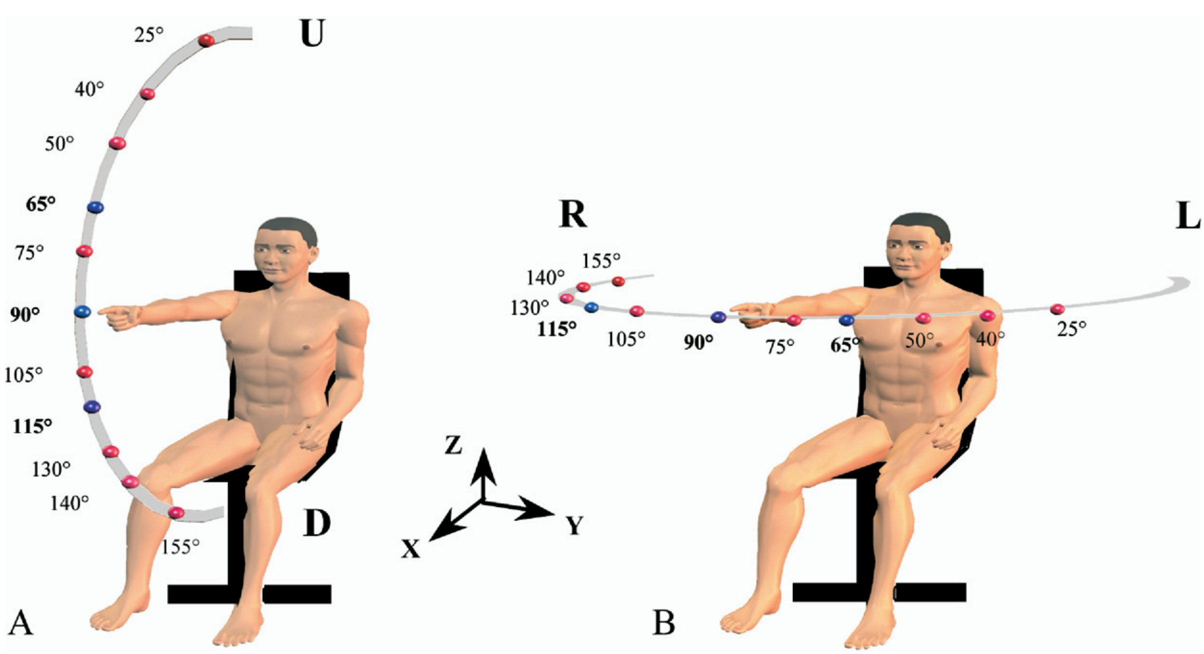

Fig. 1. Experimental device and subjects' postures during arm movements performed in the sagittal (A) and horizontal (B) planes. Targets (n=11), centered on the R shoulder of the subjects, are illustrated by small spheres and the numbers near to them indicate shoulder elevation (vertical movements) or azimuth (horizontal movements) angles (°) when the index fingertip was located in front of them.