Neuroscience 117 (2003) 779–783

LETTER TO NEUROSCIENCE

SIMILAR PLANNING STRATEGIES FOR WHOLE-BODY AND ARM MOVEMENTS PERFORMED IN THE SAGITTAL PLANE

C. PAPAXANTHIS,* V. DUBOST AND T. POZZO

INSERM/ERIT-M 0207 Motricité-Plasticité, Université de Bourgogne, U.F.R S.T.A.P.S, Campus Universitaire, B. P. 27877, 21078 Dijon, France

Abstract—The present paper looks for kinematic similarities between whole-body and arm movements executed in the sagittal plane. Eight subjects performed sit-to-stand (STS) and back-to-sit (BTS) movements at their preferred speed in the sagittal plane. Kinematics analysis focused on shoulder motion revealed that STS was composed of a straight, forward displacement followed by a curved, upward displacement while BTS was characterized by a curved, downward and straight, backward displacement. Curvature of the upward displacement was significantly greater than the downward one. Analysis of shoulder-velocity profiles showed that movement duration was significantly longer for BTS compared with STS and that the shape of the velocity profiles changed when subjects performed an STS compared with a BTS movement. Velocity profiles of the upward and downward displacements also differed; the relative acceleration duration (acceleration duration divided by movement duration during the vertical motion) was smaller for the upward compared with the downward displacement. The present results are in accordance with previous findings concerning the execution of vertical arm movements and suggest that the CNS uses similar motor plans for the performance of arm and whole-body movements in the sagittal plane.

Key words: kinematics, gravity, sit-to-stand, back-to-sit.

Previous investigations showed that asymmetric hand paths and velocity profiles characterize arm motion in the vertical plane (Atkeson and Hollerbach, 1985; Papaxanthis et al., 1998a,b,c; Pellegrini and Flanders, 1996). For instance, hand-path curvature is greater and hand velocity profiles have smaller relative acceleration duration (i.e. acceleration duration divided by movement duration) for an upward compared with a downward movement. This asymmetry in hand kinematics suggests different motor plans for the execution and the control of arm movements accomplished in a vertical plane. While such a motor plan has been well documented for the performance of arm movements, there are no investigations confirming the generalization of this asymmetric execution to movements of other parts of the body. If such a finding is confirmed, then it can be assumed that asymmetries in execution of vertical movements are not specific to the motion of a particular part of the body, but rather to a general motor plan related to movement performance in the vertical direction.

Sit-to-stand (STS) and back-to-sit (BTS) movements provide an interesting model for testing such a hypothesis (Mourey et al., 2000; Scholz et al., 2001; Kerr et al., 1997; Schenkman et al., 1990). These movements involve the motion of the whole body in the vertical plane, they do not necessitate the participation of the arm and they are performed under different mechanical constraints: STS is performed against gravity (upward movement), whereas BTS is performed with gravity (downward movement).

EXPERIMENTAL PROCEDURES

Subjects, motor task and measurement apparatus

Eight healthy male subjects (mean age 27 years±9 months) gave their written consent to participate in this study, which was approved by a local ethics committee. They were seated on an armless chair placed at knee height and they kept their arms folded across the chest. A back support on the chair was used to set their trunk in the vertical position while their feet were placed flat, 10 cm apart at the heels, with the shanks positioned in 10° flexion relative to the vertical. Subjects, with eyes open, were asked to stand up from the chair (STS), to maintain the upright standing position for approximately 4 s and to sit down again (BTS) without moving their arms during the whole action. They repeated five times this movement without any specific instructions about the speed or the trajectory of their whole-body motion. Before data collection all subjects performed three practice trials.

Body-segment kinematics was recorded using two cameras (sampling frequency 100 Hz, ELITE system, BTS Bioengineering, Italy). Reflective markers were placed on the head, the shoulder, the anterior–superior iliac spine, the upper femoral trochanter, the rotation point of the knee, the lateral malleolus, the heel and the fifth metatarsal. Visual inspection of recorded data showed that the marker placed on the shoulder was the first to move and the last to stop. We therefore focused the kinematics analysis on the motion of this marker.

Data analysis

For both STS and BTS the shoulder marker moved in the sagittal plane with a clear forward–upward (STS) and downward–backward (BTS) displacement (see Fig. 1). In order to compare our results with previous findings obtained for upward–downward arm movements, apart from analyzing the kinematics of the total body

*Corresponding author. Tel: +33-3-8039-6748; fax: +33-3-8039-6702.
E-mail address: charalambos.papaxanthis@u-bourgogne.fr (C. Papaxanthis).
Abbreviations: BTS, back-to-sit; CoM, center of mass; MD, movement duration; STS, sit-to-stand.

0306-4522/03$30.00+0.00
doi:10.1016/S0306-4522(02)00964-8

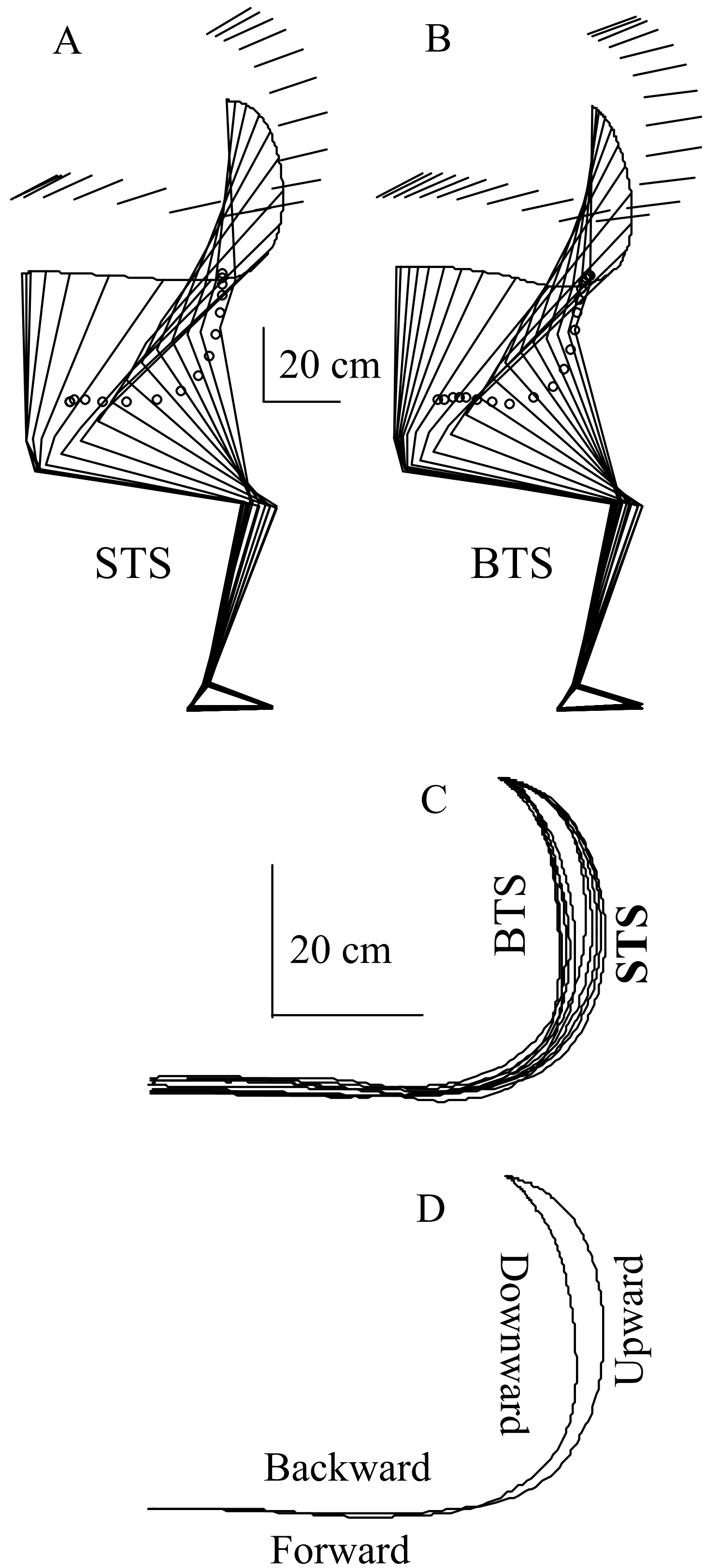

Fig. 1. Spatial features of sit-to-stand (STS) and back-to-sit (BTS) movements. Stick diagrams (drawn every 100 ms) from one subject represent the whole-body motion for a STS (A) and BTS (B) movement. Small circles indicate position and displacement of the center of mass. (C) Normalized and averaged shoulder paths from one subject for STS ($n=5$) and BTS ($n=5$). (D) Normalized and averaged shoulder paths for all subjects ($n=8$) for STS and BTS.

displacement for both STS and BTS, we also analyzed the upward (STS) and downward (BTS) components of the body motion.

After visual inspection of the shoulder motion we defined the total movement duration (MD) as the time interval between the moment at which shoulder tangential velocity exceeded 5% of its peak value and the moment at which the same velocity dropped below that value. For STS, MD for the upward component was defined as the duration between the first value of shoulder vertical velocity, which exceeded 5% of its maximum value and the end of the movement. For BTS, MD for the downward component corresponds to the duration between the onset of movement and the last moment in which the vertical component of the shoulder velocity dropped below 5% of its maximum value.

Shoulder paths during forward–backward motions (horizontal displacements) were both similar and straight. Therefore, we calculated shoulder-path curvature only for the upward–downward motions (vertical displacements) (see Fig. 1). Curvature was computed using the ratio D_{max}/L (L corresponds to a straight line passing between the initial and the final position of the shoulder vertical displacement and D_{max} refers to the maximal perpendicular distance measured from the actual path to the straight line). Shoulder tangential velocity profiles in the present study were bimodal and according to previous methods (Pai and Rogers, 1990) we distinguished three phases in the velocity profiles: (i) the acceleration phase, corresponding for STS (forward displacement) to the time interval between the onset of the movement and the maximal horizontal velocity or for BTS (downward displacement) to the time interval between the onset of the movement and the maximal vertical velocity, (ii) the transition phase, corresponding for STS to the time interval between the maximal horizontal velocity and the maximal vertical velocity of the shoulder or for BTS to the time interval between the maximal vertical velocity and the maximal horizontal velocity of the shoulder, (iii) the deceleration phase, corresponding for STS (upward displacement) to the time interval between the maximal vertical velocity and the end of the movement or for BTS (backward displacement) to the time interval between the maximal horizontal velocity and the end of the movement). In order to compare differences in velocity profiles between the STS and BTS movements we calculated the relative durations of acceleration, transition and deceleration phases. These relative durations were defined as the ratio of the duration of each phase to the total MD.

We also examined the differences on the shoulder tangential velocity profiles between STS and BTS during only the vertical displacement of the body. To do this we compared the relative acceleration duration (ratio of acceleration duration to vertical MD) along the vertical axis between STS and BTS. Center of mass (CoM) motion was calculated using the equations described by Stapley et al. (2000).

Statistical analysis

All the analyzed data showed normal distribution (Kolmogorov-Smirnov test) and had equivalent variance (Levene test). Differences between STS and BTS movements were tested by paired *t*-tests (level of significance $P<0.05$).

RESULTS

Fig. 1 (A and B) shows typical stick diagrams of whole-body motion from one subject. During STS (A), motion of the shoulder and the CoM indicates a forward displacement of the body followed by an upward one. The forward displacement corresponds essentially to trunk and thigh motions, which, before the beginning of the upward displacement, move the CoM inside the base of stance (delimited by the feet) and the shoulder over the knee. An inverse pattern is observed during BTS (B), namely, a downward displacement, during which, the CoM remains above the feet, inside the base of stance, the shoulder over the knee, and a backward displacement to come back to the sitting position. It can be further noted that shoulder paths were almost straight during the forward–backward displacements and noticeably curved during the upward–downward displacements. However, curvature was more pronounced for the upward (STS) compared with downward (BTS) displacement. This result is further illustrated in Fig. 1C, which depicts all shoulder paths, five for STS

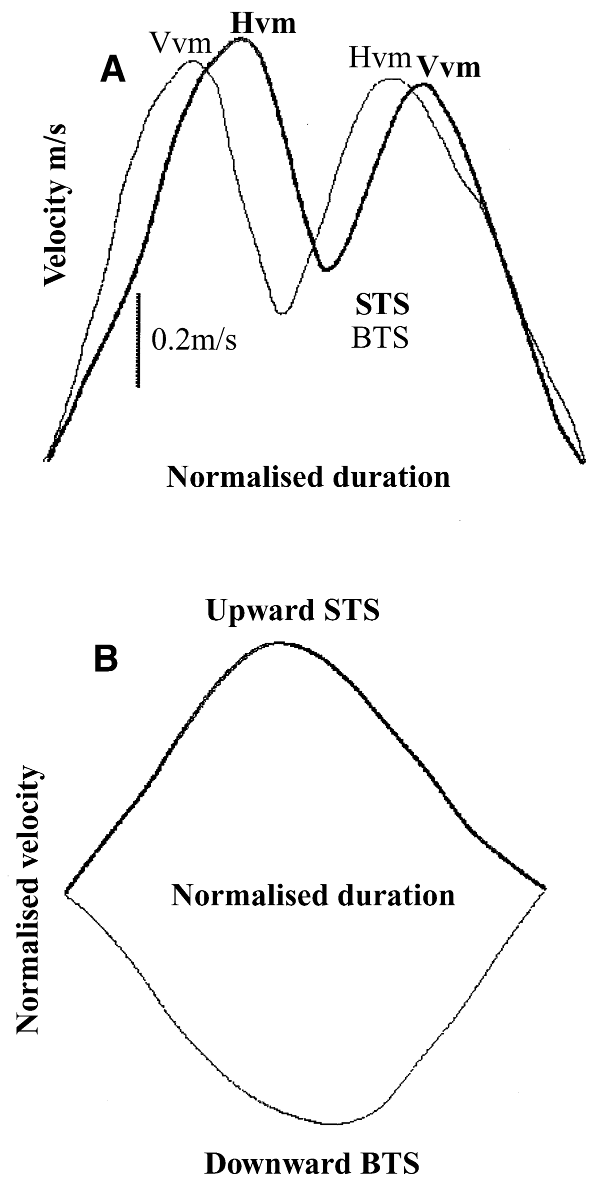

Fig. 2. Temporal features of sit-to-stand (STS) and back-to-sit (BTS) movements. (A) Typical shoulder tangential velocity profiles from one subject representing a STS and a BTS movement. (B) Average and normalized shoulder velocity profiles for all subjects (n=8) representing upward (positive velocities) and downward (negative velocities) displacements during STS and BTS movements, respectively. Hvm: horizontal maximum velocity, Vvm: vertical maximum velocity.

and five for BTS, for a different subject. Statistical analysis performed on the curvature values of upward and downward displacements showed that path curvature was significantly greater ($P<0.001$) for STS (on average: 0.267 ± 0.021) compared with BTS (on average: 0.216 ± 0.029). This is qualitatively illustrated in Fig. 1D, which depicts shoulder paths for STS and BTS averaged and normalized for all subjects ($n=8$).

MD was significantly longer ($P<0.01$) for BTS (on average: 1.98 ± 0.20 s) compared with STS (on average: 1.74 ± 0.21 s). A more detailed analysis, however, showed that the duration of upward (on average: 1.04 ± 0.11 s) and downward (on average: 1.03 ± 0.10 s) displacements was similar ($P>0.5$), and consequently, that temporal differences between STS and BTS were due to the forward–backward displacements (on average: 0.71 ± 0.11 s and 0.94 ± 0.15 s for forward and backward, respectively, $P<0.01$).

Average maximum velocity during STS was 0.99 ± 0.07 m/s for the forward and 0.95 ± 0.10 m/s for the upward displacement. During BTS it was 0.86 ± 0.09 m/s for the downward and 0.85 ± 0.08 m/s for the backward displacement. Average minimal velocity was 0.60 ± 0.07 m/s (transition from forwards to upwards) and 0.52 ± 0.08 (transition from downwards to backwards). Statistical analysis showed that all the maximal and minimal values were significantly lower for BTS compared with STS ($P<0.01$).

Fig. 2A illustrates averaged tangential velocity profiles (normalized in duration) for all subjects. It is noticeable that subjects performed STS and BTS with different velocity profiles. More precisely, the relative duration of acceleration phase was significantly longer ($P<0.001$) for STS compared with BTS (on average, 0.39 and 0.31, respectively), while the relative transition and deceleration phases were significantly shorter ($P<0.01$) for STS compared with BTS (on average, 0.25 and 0.28 for the transition phase and 0.34 and 0.39 for the deceleration phase). Differences in velocity profiles between STS and BTS were also observed when we considered only the upward–downward displacement of the body. Fig. 2B shows average tangential velocity profiles averaged and normalized for all subjects. It appears that relative acceleration duration was greater ($P<0.05$) for downward (0.55 ± 0.05) compared with upward (0.44 ± 0.06) movements.

DISCUSSION

The main results of the present study revealed that STS and BTS movements differed both in their spatial (shoulder path) and temporal (shoulder velocity profile) characteristics. These findings extend previous data obtained for arm reaching and writing (Papaxanthis et al., 1998a,b,c) and indicate that arm and whole-body movements performed in the sagittal plane share common features at the kinematic level. For instance, upward movements (for both arm and whole-body motions) showed greater curvature and shorter relative acceleration duration compared with downward movements. In addition, for both arm and whole-body movements, duration is equal between a downward and an upward motion while maximum velocity is greater for an upward compared with a downward movement. The common kinematic features mentioned above suggest that similar motor plans underlie the performance of arm and whole-body movements in the sagittal plane. According to this plan, asymmetric execution characterizes upward and downward movements in the sagittal plan for various motor tasks with diverse goals (i.e. reaching, writing, body transfer) and motion dynamics (i.e. body segments involved in motion, inertia, gravity torques).

The global similarities between arm and whole-body movements do not mean, however, that both kinds of movements share each and every facet of motor execution. Path curvatures of both upward and downward movements are greater for whole-body compared with arm movements (see Atkeson and Hollerbach, 1985; Papaxanthis et al., 1998b; Pellegrini and Flanders, 1996). Furthermore, relative acceleration durations of upward and downward movements are respectively smaller and greater for whole-body compared with arm movements (see Papaxanthis et al., 1998a,c). These variations in movement execution may be provided by a different motor program that takes into account differences in body-segment inertia, gravitational torques and equilibrium constraints between a whole-body and an arm movement.

These results corroborate previous studies, which showed that the CNS integrates gravity in motor programming during arm and whole-body reaching movements (Papaxanthis et al., 1998a,b,c; Pozzo et al., 1998; McIntyre et al., 1998, 2001; Stapley et al., 2000) and during rapid changes of posture (Cheron et al., 1997, 1998).

On the other hand, the different kinematic patterns between STS and BTS movements, instead of being the consequence of the integration of gravito-inertial forces into the neural command, could be simply attributed to postural and/or equilibrium constraints. For instance, the transition between different postures, that is, from the standing to the sitting position (STS) and the inverse (BTS), and the possible loss of balance during this transition could influence the execution of the upward (STS) and downward (BTS) movements.

However, kinematic differences between upward and downward motions could be hardly explained by postural or equilibrium constraints only. It is of interest that findings from the present and previous studies (Cheron et al., 1997, 1998) showed different kinematic patterns for the execution of upward and downward motions for whole-body movements with different levels of postural and equilibrium constraints (number of segments involved in the motion, contact or not contact with a stable support before and after the movement).

Furthermore, in the present study, equivalent MDs between upward (STS) and downward (BTS) movements, argues against the hypothesis of an inappropriate motor command, which could produce the kinematic asymmetries between the two vertical displacements. In addition, the higher peak velocities observed for the forward (STS) compared with the backward displacement (BTS), indicated that the CNS optimizes the forward displacement and takes advantage from it for the execution of the subsequent upward displacement (against gravity). The higher peak velocities and smaller acceleration durations observed for the upward compared with downward displacement seem to support such a motor strategy. Therefore this asymmetric execution of upward and downward movements, could be more attributed to the integration of gravito-inertial forces into the motor command rather to other factors such as postural and equilibrium constraints or multiple segment coordination.

The results of the present study emphasize and generalize recent approaches for the study of whole-body movement in the field of motor disorder for which shoulder kinematics in the sagittal plane have been described as a pertinent criterion for the distinction between different types of cerebral palsies (Dan et al., 2001).

The finding that the CNS executes in a similar manner various motor tasks in the sagittal plane indicates that the vertical direction and therefore gravitational forces, play a particular role in motor planning and control. Indeed, gravity force which provides an invariant reference (vertical direction), can be integrated by the CNS at different levels of the sensorimotor process and therefore, can facilitate the interaction between the motor system and the physical world for various motor tasks performed in the sagittal plane.

Acknowledgements—This work was supported by C.N.E.S. (Centre National d'Etudes Spatiales) and the C.R.B. (Conseil Regional de Bourgogne).

REFERENCES

Atkeson CG, Hollerbach JM (1985) Kinematic features of unrestrained vertical arm movements. J Neurosci 5:2318–2330.

Cheron G, Bengoetxea A, Pozzo T, Bourgeois M, Draye JP (1997) Evidence of a preprogrammed deactivation of the hamstring muscles for triggering rapid changes of posture in humans. Clin Neurophysiol 105:58–71.

Cheron G, Bengoetxea A, Bouillot E, Lacquaniti F, Dan B (1998) Early emergence of temporal co-ordination of lower limb segments elevation angles in human locomotion. Neurosci Lett 308:123–127.

Dan B, Bouillot E, Bengoetxea A, Boyd SG (2001) Distinct multi-joint control strategies in spastic diplegia associated with prematurity or Angelman syndrome. Clin Neurophysiol 112:1618–1625.

Kerr KM, White JA, Barr DA, Mollan RA (1997) Analysis of the sit-stand-sit movement cycle in normal subjects. Clin Biomech 12: 236–245.

McIntyre J, Zago M, Berthoz A, Lacquaniti F (2001) Does the brain model Newton's laws? Nat Neurosci 4:693–694.

McIntyre J, Berthoz A, Lacquaniti F (1998) Reference frames and internal models for visuo-manual coordination: what can we learn from microgravity experiments? Brain Res Brain Res Rev 28:143–154.

Mourey F, Grishin A, d'Athis P, Pozzo T, Stapley P (2000) Standing up from a chair as a dynamic equilibrium task: a comparison between young and elderly subjects. J Gerontol A Biol Sci Med Sci 55:425–431.

Pai YC, Rogers MW (1990) Control of body mass transfer as a function of speed of ascent in sit-to-stand. Med Sci Sports Exerc 22:378–384.

Papaxanthis C, Pozzo T, Stapley P (1998a) Effects of movement direction upon kinematic characteristics of vertical arm pointing movements in man. Neurosci Lett 253:103–106.

Papaxanthis C, Pozzo T, Popov K, McIntyre J (1998b) Hand trajectories of vertical arm movements in one-G and zero-G environments: evidence for a central representation of gravitational force. Exp Brain Res 120:496–502.

Papaxanthis C, Pozzo T, Vinter A, Grishin A (1998c) The representation of gravitational force during drawing movements of the arm. Exp Brain Res 120:233–242.

Pellegrini JJ, Flanders M (1996) Force path curvature and conserved features of muscle activation. Exp Brain Res 110:80–90.

Pozzo T, Papaxanthis C, Stapley P, Berthoz A (1998) The sensorimotor and cognitive integration of gravity. Brain Res Brain Res Rev 28:92–101.

Schenkman M, Berger RA, Riley PO, Mann RW, Hodge WA (1990) Whole-body movements during rising to stand from sitting. Phys Ther 70:638–648.

Scholz JP, Reisman D, Schöner G (2001) Effects of varying task constraints on solutions to joint coodination in a sit-to-stand task. Exp Brain Res 141:485–500.

Stapley P, Pozzo T, Grishin A, Papaxanthis C (2000) Investigating centre of mass stabilisation as the goal of posture and movement coordination during human whole body reaching. Biol Cybern 82:161–172.

(Accepted 8 November 2002)