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Neuroscience Letters 240 (1998) 159–162

Neuroscience Letters

Hand trajectory formation during whole body reaching movements in man

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Received 16 October 1997; received in revised form 4 December 1997; accepted 10 December 1997

Abstract

End-effector trajectory formation was studied during a reaching movement using the whole body. The movements of various parts of the body were measured with the optoelectronic ELITE system. Wrist reaching movement paths showed noticeable curvatures. The analysis of various marker onset latencies revealed that the wrist was the last to move, always after the head, knee or trunk, suggesting a subordinate role of the focal component with respect to the primary role of the equilibrium component. These results suggest that reaching wrist movements are subjected to whole-body equilibrium constraints in addition to constraints placed upon end-effector kinematics or the dynamic optimization of upper-limb movements. © 1998 Elsevier Science Ireland Ltd.

Keywords: Postural control; Kinematics; Body reaching; Trajectory formation

When a subject has to grasp and transport an object initially located on the ground, the central nervous system (CNS) has to solve two problems. A hand trajectory towards the extracorporal target has to be defined, while at the same time the centre of gravity of the entire body must remain inside the supporting foot area. These equilibrium and spatial components of the movement have classically been studied separately. Likewise, arm movements have often been investigated without considering equilibrium stabilization [10].

Kinematic invariances of arm reaching movements [13] have been studied in an attempt to understand in which coordinate frame(s) the brain represents the movement and what rules govern the selection of specific trajectories among an infinite number of possible ones [6,17]. Roughly straight hand paths with bell-shaped velocity profiles [1,5,7] been cited as evidence for a central representation of the motor command in terms of the end-effector spatial trajectory. Conversely, observations of curved end-effector trajectories have argued in favour of local and intrinsic movement planning [8].

In multijoint body movements, such as picking up an object located on the ground, arm movement control is much more complex because of joint and muscle redundancy and the difficulty of maintaining the centre of mass inside the supporting base. Until now, processes of arm movement control have been investigated during motor tasks which involved only the motion of the arm or simultaneous motions of the arm and trunk in sitting subjects [9]. The purpose of this study was to investigate end-effector trajectory formation during a task that possesses both equilibrium and spatial constraints. In this experiment, equilibrium constraints were tested as variables that determine the way in which hand movement can be organized and controlled. This raises an interesting and important question: are the control laws governing simple arm movements applicable for movements under equilibrium constraints, or must these constraints be added to the list of factors influencing wrist trajectory formation.

Eight voluntary subjects (23 ± 2 years) were tested during a whole body reaching task (consent forms were signed and all experiments were conducted in accordance with legal requirements and international norms). Subjects were instructed to grasp and lift a wooden bar (40 cm long, 7 cm in diameter and 1.8 kg in weight) oriented par-

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0304-3940/98/$19.00
PII S0304-3940(97)00943-9

allel to the frontal plane and mounted on two supports (15 cm high) located on the ground in front of them. Two cameras were both fixed on a vertical pole and located respectively at 1 and 2 m from the ground on the left side of the subject, at a distance of 3 m from the sagittal plane of the movement. Eleven markers, which defined eight links (Fig. 1), were fixed on the left hemi-body, on the head (on the external canthus of the eye and the auditory meatus); the upper limb (on the acromial process, the lateral condyle, the styloid process and 5th metacarpophalangeal); the trunk (at the level of the inferior angle of the omoplate and at the vertical of the axil); the lower limb (on the trochanter, the interstitial joint space of the knee, the external malleolus and the 5th metatarsophalangeal). Recording sessions included 12 trials (one task × four experimental conditions × three repetitions). Kinematic parameters in three dimensions were calculated from successive frames taken at 10 ms intervals. For each marker, the movement onset (t_0) was established using a tangential velocity profile. From their unimodal characteristics, t_0 were defined as the first 10 ms period where velocity profiles showed a sustained deflection above zero. In order to quantify postural component changes throughout the different experimental conditions, anterior-posterior displacement of the hip marker (located at the trochanter) were measured. Wrist path curvatures were estimated by considering the deviation from path straightness. This was achieved by interpolating a straight line between the initial and final end points (L) and measuring the maximum perpendicular distance (D_{max}) from the actual path to the straight line. The quantification of wrist curvatures was made using the ratio D_{max}/L. Forms of wrist velocity curves were also examined quantitatively using an evaluation of the ratio of maximum to average velocity ($C = V_{max}/(V_{avg})$) [11]. A 2 × 2 analysis of variance (ANOVA) was performed on the four experimental conditions (two velocities and two distances). Newman–Keuls post-hoc evaluations were used to test for significant differences between values. Any interaction effect has been mentioned only when it reached statistical significance at the 0.05 confidence level.

The reconstructed stick figure (Fig. 1) shows wrist reaching movements that involved large angular displacements of shoulder, hip, knee and ankle joints without displacement of the feet. All body marker trajectories were oriented in a forward direction, except for the hip which moved in the opposite direction (backwards). A similar postural synergy devoted to preventing large forward displacements of the centre of mass has previously been observed during forward trunk bending movements [3].

Fig. 2 depicts typical wrist paths in the sagittal plane for all four experimental conditions and eight subjects. Wrist paths presented noticeable curvatures, calculated values of which are presented in right part of Fig. 3 for each experimental condition.

At normal speeds and for both target distances, wrist paths incorporated three components. The initial part of the path was curvilinear and oriented forwards and upwards (i.e. in an opposite direction to that of target location). The transport phase involved a downward vertical movement. The end of the movement was slightly deviated backwards from the vertical, producing a ‘hooking’ type grasping path. This final curvature, due to the grasping movement, disappeared when three of the eight subjects tested were asked simply to point to the target (results not presented here). The maximum deviation (D_{max}) was located in the first half of the path.

Speed significantly affected the shape of wrist trajectories which became less curved during fast movements. An ANOVA analysis gave main effect differences of movement speed upon D_{max}/L values ($F(1,7) = 2.68$, $P < 0.05$). D_{max}/L decreased significantly with movement speed (on average 0.17 and 0.14 for normal and fast conditions, respectively; see Fig. 3). Initial path components, usually directed forwards and upwards, were absent at rapid speeds, wrist movements always being directed downwards. At the same time, the amplitude of the backward hip displacement, also plotted in Fig. 3, increased significantly at rapid speeds (main effect of speed ($F(1,7) = 21.1$, $P < 0.05$).

In contrast, target distance did not significantly

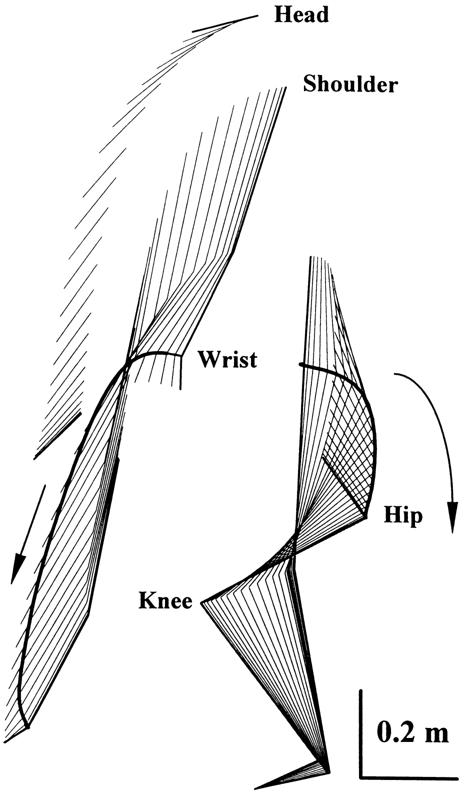

Fig. 1. Stick figure representation of a reaching movement to a target located on the ground at a height of 15 cm and a distance of 45 cm from the feet. Links between markers were reconstructed by computer. For clarity, only one stick every 50 ms has been plotted. The arrow indicates movement direction of the wrist marker. Curving wrist and hip trajectories are shown by a thick black line joining successive images.

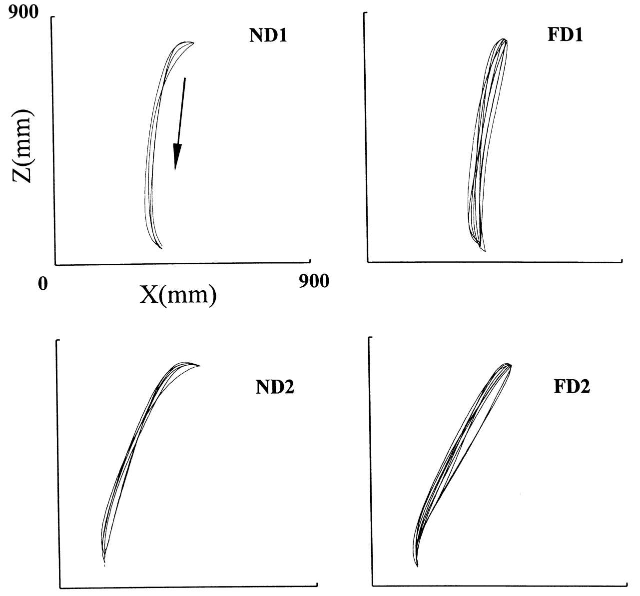

Fig. 2. Typical wrist paths in the sagittal plane of all subjects for the four experimental conditions. Paths are scaled and rotated so as to superimpose starting points. Arrows indicate movement direction. N, movement at normal speed; F, movement at rapid speed; D1, target at 5 cm from the feet; D2, target at 45 cm from the feet.

($P > 0.05$) affect D_{max}/L values (on average 0.11 for normal and fast conditions) and wrist reaching paths remained approximately the same shape for the two distances of target placement. The distant target induced significantly less marked backward hip displacements with respect to hip trajectories produced at the closer target distance ($F(1,7) = 19.6$, $P < 0.05$).

Despite inter-subjects variations, out of the four markers considered (head, hip, knee and wrist), averages for all subjects showed that, throughout all experimental conditions, the head was the first to move, followed by the knee, the hip and lastly, the wrist. On average, latencies of knee, hip and wrist markers relative to the onset of head marker movement were 57, 91 and 172 ms, respectively at normal speed, and 4, 58 and 117 ms at rapid speed. ANOVA analysis (two velocities, two distances and three markers) reveal a main effect of movement speed ($F(1,7) = 10.5$, $P < 0.05$) and marker ($F(1,7) = 16.34$, $P < 0.05$) upon latencies without significant interaction between the three variables.

C values decreased significantly in fast speed conditions ($F(1,7) = 33$, $P < 0.001$) but not with distance ($P > 0.05$) (on average 1.79 and 1.84 at normal and distant target, respectively), indicating that tangential velocity profiles were not invariant with respect to overall movement speed (on average 1.88 and 1.75 at normal and rapid speeds, respectively).

In the present study, we have found that wrist paths during whole body reaching movements showed noticeable curvatures. This result is in contrast to relatively straight wrist paths [1,5,7,11] and partially in accordance with curved paths previously obtained during arm movements in the absence of major postural constraints [2,12]. Indeed, at normal velocities and for both target distances, we found that the initial part of the path was directed in an opposite direction to that of target location. This is in contrast to the slight curvature obtained in the above mentioned studies. This suggests that spatial trajectories of the wrist do not represent the primary planned variable for such a motor task. Additionally, the analysis of various marker onset latencies revealed that the wrist moved last, always after the head, knee or trunk. The fact that the limbs usually involved in postural control are mobilised early during task execution suggests (1) that equilibrium components are integrated early into motor programming and (2) a subordinate role of the spatial components which adapt to demands of equilibrium.

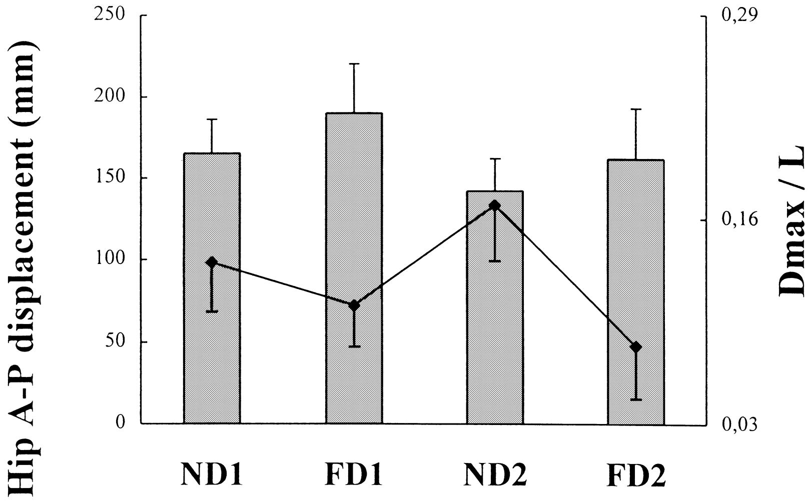

Fig. 3. Histogram showing the mean ± SD of hip backward displacements amplitudes in the four experimental conditions. Filled triangles superimposed on each of the bars represent mean values of wrist path curvatures quantified through the ratio of D_{max}/L (see text for the definition of this index).

Differing *C* values observed for different speed conditions indicates that velocity profiles were not an invariant of the movement and that they could be modified with respect to task demands. This finding also illustrates the dependence of wrist path on equilibrium constraints.

Straightness of path has been used to propose that limb trajectories are explicitly planned in a Cartesian frame of reference [8]. Nevertheless, extrinsic planning schemes, coupled with inaccuracies in visual perception [18] or execution [5] might explain the present curved paths of the end-point of the arm. We can present two arguments against these interpretations. Firstly, the initial part of the reaching path was oriented at an angle of approximately 90° with respect to the line connecting initial and final positions. It seems difficult therefore to accept the idea that the CNS would settle for such a large difference between the actual trajectory and a programmed straight line. Secondly, if subjects planned a straight path but were not able to achieve them due to inaccuracies in movement execution, fast speeds that provoke stronger modifications to movement dynamics, should more greatly affect path curvatures. Surprisingly however, in the present study, subjects produced straighter paths at high speeds, while the time available to regulate the movement decreased. These results seem to indicate the adoption of different movement strategies as a function of increasing speed, rather than simple inefficiencies in programming and execution.

The observed curvilinear paths may also have reflected the presence of intrinsic constraints such as joint coordination, which could strongly determine spatial end-effector trajectories. Nevertheless, the modification of the shape of wrist trajectories during fast movements, implying the use of different joint configurations for the same task, suggests that joint variables did not represent the primary planned variable. If joint variables were planned, very similar paths should have been observed for all conditions regardless of speed. However, due to the multijoint nature of the task, the possibility of local joint coupling between upper or lower parts of the body must not be neglected.

A stronger hypothesis would be that whole-body equilibrium constraints determine hand paths for a given movement speed. At higher speeds, the more important initial backward thrust at the hip and the straight hand path (see Fig. 3) may be necessary to conserve equilibrium because of conflicting dynamic balance and performance constraints. This is supported by recent studies which have demonstrated that CM displacements decreased with increasing whole body reaching speed [15,16]. Thus from our results, it can be proposed that whole-body equilibrium requirements be added to the list of factors, including accuracy constraints [14] or mechanical interactions with the environment [4], that affect hand path and tangential velocity profiles.

This work was supported by the Institut National de la Santé et de la Recherche Médicale (INSERM/CRE, grant no. 92107) and the Centre National d'Etudes Spatiales.

[1] Abend, W., Bizzi, E. and Morasso, P., Human arm trajectory formation, Brain, 105 (1982) 331–348.
[2] Atkeson, C.G. and Hollerbach, J.M., Kinematic features of unrestrained vertical arm movements, J. Neurosci., 5 (1985) 2318–2330.
[3] Crenna, P., Frigo, C., Massion, J. and Pedotti, A., Forward and backward axial synergies in man, Exp. Brain Res., 65 (1987) 538–548.
[4] Desmurget, M., Jordan, M., Prablanc, C. and Jeannerod, M., Constrained and unconstrained movements involve different control strategies, J. Neurophysiol., 77 (1997) 1644–1650.
[5] Flash, T., The control of hand equilibrium trajectories in multi-joint arm movement, Biol. Cybern., 57 (1987) 257–274.
[6] Flash, T. and Hogan, N., The coordination of movements: an experimentally confirmed mathematical model, J. Neurosci., 7 (1985) 1688–1703.
[7] Gordon, J., Ghiraldi, M.F. and Ghez, C., Accuracy of planar reaching movements. I. Independence of direction and extent variability, Exp. Brain Res., 99 (1994) 97–111.
[8] Hollerbach, J.M. and Atkeson, C.G., Deducing planning variables from experimental arm trajectories: pitfalls and possibilities, Biol. Cybern., 56 (1987) 279–292.
[9] Ma, S. and Feldman, G., Two functionally different synergies during arm reaching movement involving the trunk, J. Neurophysiol., 73 (1995) 2120–2122.
[10] Morasso, P., Spatial control of arm movements, Exp. Brain Res., 42 (1981) 223–227.
[11] Ostry, D.J., Cooke, J.D. and Munhall, K.G., Velocity curves of human arm and speech movements, Exp. Brain Res., 68 (1987) 37–46.
[12] Osu, R., Yasuharu, K., Uno, Y. and Kawato, M., Possible explanations for trajectory curvature in multijoiny arm movements, J. Exp. Psychol., 23 (1997) 890–913.
[13] Soechting, J.F. and Lacquanti, F., Invariant characteristics of a pointing movement in man, J. Neurosci., 1 (1981) 710–720.
[14] Soechting, J.F., Effect of target size on spatial and temporal characteristics of a pointing movement in man, Exp. Brain Res., 54 (1984) 121–132.
[15] Stapley, P., Pozzo, T. and Grishin, A., The role of anticipatory postural adjustments during whole body forward reaching movements, NeuroReport, (1997) in press.
[16] Toussaint, H.M., Commissaris, D.A.C.M., Dieën, J.H., van Reijnen, J.S., Praet, S.F.E. and Beek, P.J., Controlling ground reaction force during lifting, J. Mot. Behav., 27 (1995) 225–234.
[17] Uno, Y., Kawato, M. and Suzuki, R., Formation and control of optimal trajectory in multijoint arm movement: minimum torque-change model, Biol. Cybern., 61 (1989) 89–101.
[18] Wolpert, D.M., Ghahramani, Z. and Jordan, M.I., Are arm trajectories planned in kinematics or dynamic coordinates? An adaptation study, Exp. Brain Res., 103 (1995) 460–470.