Effects of kinematics constraints on hand trajectory during whole-body lifting tasks

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Abstract

Trajectories of the hands and whole-body center of mass were studied during whole-body lifting tasks. The movements of different parts of the body were monitored with the ELITE system. Subjects were instructed to lift to shoulder height an object placed at one of two distances (5–45 cm) before them on the floor. The lifts were performed both with and without kinematics constraints (i.e. to produce a straight hand trajectory while lifting, and to lift without any instructions, respectively). Hand trajectories were roughly straight when performed under the constrained condition, but curved when performed without instruction. Hand velocity curves showed bell-shaped profiles. In both groups, body centers of mass (whole-body, upper and lower part) were calculated and their trajectories showed invariant sagittal displacements. These results support the idea that movement contributes to postural control and, reciprocally, that whole-body center of mass is a robust and controlled variable which plays an important role in hand trajectory formation. © 1999 Elsevier Science Ireland Ltd. All rights reserved.

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Some early eighties studies have demonstrated that in pointing or reaching movements, hand trajectories are essentially straight [1,8,12] with bell-shaped velocity profiles. In contrast, more recent experiments [2,7,14] focusing on more natural movements, reported that trajectories are curved or relatively straight, depending upon the workspace region in which the movement was performed. When comparing hand trajectory models, the perceptual process by which trajectories were evaluated must be taken into account [7,14], as well as whether both the kinematics and dynamics of movement were considered.

Kinematics invariances of pointing movements in man have been studied in order to determine in what frame of references the movement was planned [12]. Invariant straight hand trajectory performance suggests that the trajectory is planned at the end effector-level [1,4,5,8]. By end-effector, we mean the distal segment (here the hand) of the effector system involved in the performance of the task.

In contrast, a curved path suggests that the trajectory is planned at the joint level [2]. It has been proposed that curved path could result from an extrinsic planning of a straight trajectory altered by a perceptual distortion which makes the movement appear to be straighter than it really is [14]. In this case, the subject is unable to produce a straight trajectory. Another possibility is that trajectory formation is under postural constraints [11] (e.g. center of mass displacement inside of base of support, or joints coupling). Curved hand movements have been found in whole-body reaching tasks, suggesting that whole-body equilibrium constraints determine hand paths for a given movement speed [11]. The purpose of this study is to verify these issues by revealing the types of trajectories during lifting movements. In addition, assuming that curved trajectories are found, we will determine if subjects are able to produce a straight trajectory, when so instructed.

Hand trajectory formation has been investigated during whole-body lifting tasks performed with and without kinematics constraints. The following questions were asked. Are hand trajectories curved or straight? If curved trajectories are found, are they the result of postural constraints? Can

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Table 1
Centers of mass sagittal displacements for each condition (free or instructed) and each distance (D1 = 5 cm, D2 = 45 cm)[a]

	Sagittal displacements (mm)		
	CoM_b	CoM_l	CoM_u
F condition, distance 1	74.65 ± 16.34	87.39 ± 11.85	78.50 ± 19.28
F condition, distance 2	86.72 ± 14.51	87.05 ± 11.30	86.89 ± 17.96
I condition, distance 1	65.53 ± 12.33	61.84 ± 6.78	71.29 ± 17.43
I condition, distance 2	70.59 ± 15.36	77.90 ± 14.10	69.55 ± 18.16

[a] Average values and SDs for the center of mass of the body (CoM_b), the center of mass of the lower limbs (CoM_l) and the center of mass of the upper body (i.e. head plus trunk), CoM_u.

freely standing subjects performing lifts move their hands along straight trajectories when so instructed? What is really planned and controlled in trajectory formation?

Eight healthy and consenting male subjects (22.5 ± 2.5 years) were tested during this experiment. The subjects were asked to start by standing with their hands clasped together in front of the pelvis. An object which was a wooden bar (40 cm long, 7 cm in diameter and 1.8 kg in weight) mounted on two supports (15 cm high) was placed on the floor in front of them at a distance of either 5 or 45 cm. They were then asked to reach with both hands for the object and to lift it as quickly as possible to shoulder height, with the upper limbs extended and near horizontal. This final position was to be held for 2 s.

Subjects were tested under two conditions. Under the free condition (F), the subjects were asked to lift the object without instruction in order to study hand trajectories during natural and volitional movements. Under the instructed condition (I), however, the subjects were told to produce straight hand trajectories during the lift. Before each experimental session, the subjects trained for a 2-min period to become familiar with grasping the object from the 5 and 45 cm distances.

Body segments kinematics were monitored with the 'elaboratore di immagini televisive' (ELITE) system, which is a dedicated hardware system based on automatic real-time processing of TV images. The two-camera system recognizes multiple passive markers and computes their co-ordinates. The cameras were placed one above the other and located at heights of 1 and 2 m from the ground, respectively, on the left side of the subject. The distance between the cameras and the plane of movement was 3 m. The field of view was 1.5 × 2 m. The accuracy was 1.5 mm for linear displacement and 1.5° for angular position. Twelve hemispherical markers (5 mm in diameter) were placed on head, neck, upper limb, trunk, and lower limb. These markers were subsequently used to construct stick figures that consisted of eight links. The marker located at the joint between the metacarpus and the phalange was chosen to define the hand trajectory. Each recording session comprised eight trials (two experimental conditions × four repetitions). Data were sampled at a rate of 100 frames/s. The raw data were processed with a 4th order Butterworth filter without phase shift, and using a cut-off frequency of 6 Hz.

To compare the extent of hand trajectory curvature (i.e. deviation from straightness), the maximal perpendicular distance (D_{max}) was measured from the actual path to the straight line interpolated between the initial and final end points of the trajectory. The distance between these two points was called (L). The ratio D_{max}/L was used to quantify hand curvatures [11]. In order to compare the contribution of different segmental subdivisions of the body with hand trajectory formation, the locations of three different centers of mass were calculated, using the model of Chandler and colleagues [3]: whole-body (CoM_b), lower limb (CoM_l) and upper body (i.e. head plus trunk) (CoM_u). The mass of the object was integrated in the model as a single-point mass located at the handle of the box. Sagittal displacements (Table 1) and the ratio D_{max}/L were calculated for the three centers of mass. The c variable [9], defined as the ratio between the instantaneous peak velocity and the average velocity, was used to compare hand velocity profiles under each condition (Table 2). A two-way analysis of variance (ANOVA) with repeated measures on both factors (two conditions × distances) was performed. Differences were considered significant at $P < 0.05$ level. A Scheffé-test post-hoc was used to test significant differences between values (with significant $P < 0.05$ level).

Fig. 1 shows hand and centers of mass trajectories. Under the F condition (Fig. 1A,B), subjects produced hand paths that were generally curved. In contrast, under the I condition (Fig. 1C,D), subjects produced straight trajectories. As a consequence, the D_{max}/L value decreased significantly ($F(1, 7) = 25.87$, $P < 0.05$) under the I condition compared with the F condition and under the distance 1 compared with the distance 2 ($F(1, 7) = 17.33$, $P < 05$). This ratio also decreased significantly, on average from 0.11 to 0.05 for F

Table 2
c Ratio values (average values and SDs) for hand velocity for each condition (free and instructed) and each distance (D1 = 5 cm, D2 = 45 cm)

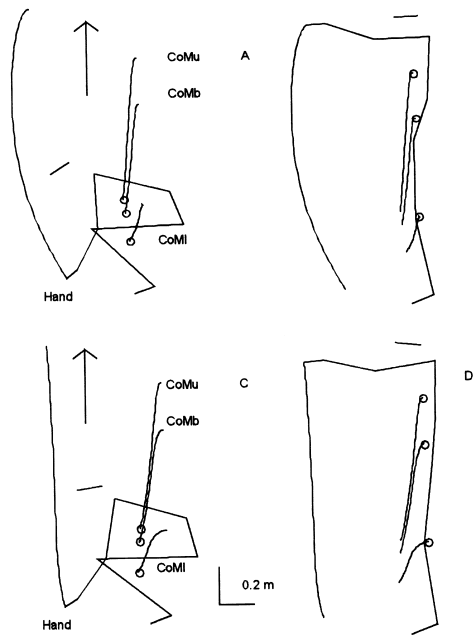|	Hand c ratio
F condition, distance 1	1.92 ± 0.24
F condition, distance 2	1.82 ± 0.19
I condition, distance 1	1.79 ± 0.18
I condition, distance 2	1.79 ± 0.21

Fig. 1. Sagittal plane trajectories of the hand and the centers of mass for one typical subject and one trial at distance 1 = 5 cm ((A,B) F condition; (C,D) I condition). The arrows indicate the movement direction. The path of trajectory of CoMs are indicated in the same diagram.

and I conditions, respectively, for the 5 cm distance (Table 3). In addition, subject-to-object distance affected the ratio average with significantly lower values for the 45 cm distance (from 0.07 to 0.05 for F and I conditions, respectively). Thus, trajectory instruction and distance affected significantly the shape of hand trajectory.

The D_{max}/L ratio showed no significant differences for the centers of mass trajectories either under the two conditions or for the two distances. Concerning the CoM_b, these data show an invariant trajectory and stabilization of CoM_b in the anterior-posterior direction. Thus, CoM_b appears to be independent of task constraints. The interaction analysis showed a significant effect ($F(1, 7) = 7.62$, $P < 0.05$) between both factors (i.e. distance × condition), the Scheffé-test showed a significant effect for only the free condition at the distance 1.

Hand velocity profiles were examined by using the c ratio (instantaneous maximal velocity/average velocity). Velocity profiles were invariant, in that the values did not show significant differences either between the two conditions (Fig. 2A,B) or for the two distances (Fig. 2C,D). Data showed similar single-peaked velocity profiles that were not affected by kinematics constraints. Mean values for the ratio of acceleration duration to total duration (between 37.43 and 40.61%, respectively, for the two conditions and the two distances) indicated gently asymmetric velocity profiles, with the duration of hand acceleration being shorter than that of deceleration under all experimental conditions and object distances. Maximal acceleration occurred earlier under the I condition than under the F condition at the 45

cm distance (7.81 and 10.86% of the total duration, respectively, for the I and F conditions).

In the present study, we have investigated the effects of kinematics constraints on hand trajectory formation. We have found that hand paths show important curvatures when subjects are not instructed to perform a straight trajectory. The invariant shape of the hand path under this condition indicates that subjects execute only one form of trajectory when not instructed to do otherwise, and that natural trajectories are curvilinear. Conversely, when so instructed, subjects can produce a straight path.

The above findings are consistent with those of studies on pointing, reaching, and planar movements that found spontaneous movements to be slightly curved [1,2,8,10,12]. Furthermore, subjects use the same tangential velocity profiles to make radically different movements indicating that velocity characteristics (the c ratio) are not related to path characteristics. The finding that the c ratio is invariant suggests an equivalence condition [9], which is necessary between the velocity profiles under the two conditions.

The question now arises as to why subjects who lift without instruction (F condition) produce curved trajectories. It has been proposed [14] that although subjects try to make straight-line movements, the actual movements are curved because of misperception of the curvature of the movement which contributes to the curvature seen in normal movements. The present study suggests that a performance error is not a likely cause to produce curved path because subjects under the instructed condition (I) were able to produce a straight path.

The problem is whether to know if the curved trajectory is the result of equilibrium constraints or joint constraints. Our results show different hand path for the two distances of the object to lift. The modification of the shape of hand path implies the use of different joint configuration suggesting that joint variables did not represent the primary planned variables. In contrast, we found invariant center of mass displacements indicating that postural constraints rather than joint configuration are planned. In addition, the invariant trajectory of CoM_b whatever the curved or straight trajectory produced indicates that equilibrium constraints play a strong role in the movement planning. The two kinds of trajectories reported here support the assumption that trajectories could be initially planned at the end-effector level and could be subsequently transformed into the

Table 3
D_{max}/L ratio values (average values and SDs) for hand velocity for each condition (free and instructed) and each distance (D1 = 5 cm, D2 = 45 cm)

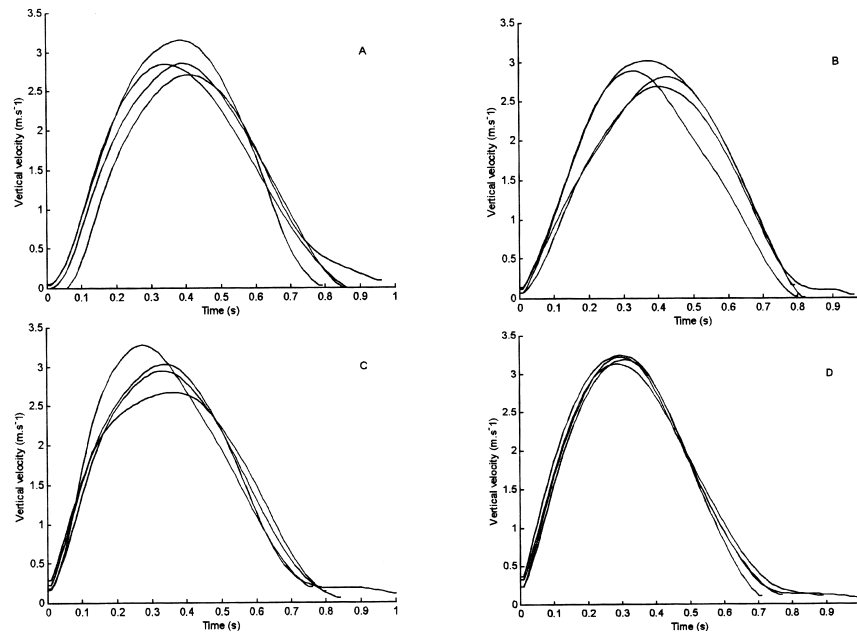|	D_{max}/L ratio (hand)
F condition, distance 1	0.11 ± 0.03
F condition, distance 2	0.07 ± 0.02
I condition, distance 1	0.05 ± 0.02
I condition, distance 2	0.05 ± 0.02

Fig. 2. Superimposed hand velocity profiles for one typical subject: (A) F condition, distance 1 = 5 cm; (B) F condition, distance 2 = 45 cm; (C) I condition, distance 1 = 5 cm; (D) I condition, distance 2 = 45 cm).

required joint positions because of postural constraints. In a similar approach, it has been shown that subjects could use a frame of reference that is intermediate to one fixed in space and one fixed to the forearm to define the hand's orientation [13].

Therefore, voluntary movements appear to reflect both postural and task demands. Postural compensation might occur at the hip or knee level or at a focal level (e.g. by an increase of the elbow angle in the frontal plane). Such compensatory postural control would be advantageous to the motor system by helping it to cope with the dual constraints of postural stability and desired hand position. The results reported here suggest that subjects can perform different hand trajectories for similar displacements of CoM_b in the sagittal plane. We can assume that a postural compensation exists for the body segments to maintain an invariant sagittal displacement of CoM_b during whole-body lifting tasks. The production of such movements requires both kinematics and dynamic control [7]. The findings of this study support the idea that movement contributes to postural control and, reciprocally, that CoM_b is a robust and controlled variable [6] which plays an important role in hand trajectory formation.

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