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RESEARCH ARTICLE

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The uncontrolled manifold concept: identifying control variables for a functional task

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Abstract The degrees of freedom problem is often posed by asking which of the many possible degrees of freedom does the nervous system control? By implication, other degrees of freedom are not controlled. We give an operational meaning to "controlled" and "uncontrolled" and describe a method of analysis through which hypotheses about controlled and uncontrolled degrees of freedom can be tested. In this conception, control refers to stabilization, so that lack of control implies reduced stability. The method was used to analyze an experiment on the sit-to-stand transition. By testing different hypotheses about the controlled variables, we systematically approximated the structure of control in joint space. We found that, for the task of sit-to-stand, the position of the center of mass in the sagittal plane was controlled. The horizontal head position and the position of the hand were controlled less stably, while vertical head position appears to be no more controlled than joint motions.

Key words Motor control · Trajectory formation · Coordination · Human

Introduction

A central problem in the control of multi-joint movement is the degree of freedom problem, addressed early by Bernstein (1967): given the large number of mechanical degrees of freedom of the human effector system involved in many movement tasks, how does the nervous system organize or simplify the control of these degrees of freedom. Bernstein concluded, from careful observations of functional motor tasks, that at higher levels of the nervous system the spatial aspects of the requisite movements are controlled rather than the action of specific joints or muscles.

One more modern way to pose the question is to ask, in which coordinate frame does the central nervous system represent and plan multi-joint movements (Saltzman and Kelso 1987). This question has been addressed most frequently in the context of upper extremity control and, in particular, reaching tasks (Feldman and Levine 1995; Flash and Hogan 1985; Henis and Flash 1995; Lacquaniti 1989; Lacquaniti et al. 1987; Soechting and Lacquaniti 1981; Uno et al. 1989; Won and Hogan 1995; but see Andersen et al. 1985). Morasso's (1981) work on point-to-point reaching revealed common features of hand movement trajectories (i.e., quasi-straight line, bell-shaped velocity profiles) across reaches to different spatial locations, whereas the trajectories of the (non-redundant) joints varied substantially. He hypothesized that the central command for these movements is formulated in terms of trajectories of the hand in space (p. 223).

This conclusion has been supported by a number of other studies of reaching tasks in both humans (Atkeson and Hollerbach 1985; Flash and Hogan 1985; Haggard et al. 1995; Won and Hogan 1995) and animals (Georgopoulos et al. 1993; Martin et al. 1995). Other investigators have provided evidence, however, often from tasks performed with more redundant degrees of freedom, that at least some aspect of a limb's motion must be planned in joint coordinates (Lacquaniti 1989; Lacquaniti et al. 1987; Soechting and Lacquaniti 1981; Uno et al. 1989). Other variables (e.g., the center of mass of an effector system, Suzuki et al. 1997) have also been proposed as fundamental to the planning of reaching tasks.

The underlying notion in these sorts of studies is that, the more invariant and simple a description of an ensemble of movement trajectories in a particular reference frame, the more likely that the nervous system employs

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that reference frame. Thus, kinematic regularities observed at the level of the end-effector are interpreted as evidence for end-effector control, kinematic regularities at the level of the joint configuration are interpreted as evidence for joint-level control. A similar argument can be made for yet other levels, such as patterns of EMG or of joint torques (Gottlieb 1993).

A slightly different way to pose the degree of freedom problem is exemplified by work of Gielen and his colleagues (Gielen et al. 1997; Miller et al. 1992). This work explores the validity of Donder's and Listing's laws for arm movements. Donder's law indicates that, when subjects point with their hand to targets, the end-configuration of their arm is reproducible, irrespective of the initial posture of the arm. This reproducibility can be accounted for by identifying particular rotation axes defined by the initial and the final pointing directions, such that rotation about these axes completely characterizes the movement, while rotations about remaining axes reflecting the redundant degrees of freedom are very small. This implies a reduction in the number of degrees of freedom of the system in that the number of variables that need to be assigned new values during the movement is smaller than the number of mechanical degrees of freedom. Also, by identifying the rotation axes, a particularly simple description of the movement trajectories has been found. Violations of these laws observed during pointing to targets when movement at the elbow is allowed in addition to movement at the shoulder are indicative of persistence of redundancy in these cases.

One problem with the notion, that regularity or variability at the kinematic level reveals which variables are controlled, is that these measures are often compared in an informal way across different spaces. How much variance, for instance, at the end-effector level corresponds to how much variance at the joint level? A priori, these descriptions are not comparable and, in fact, have different physical units.

A second criticism of the notion of planning in simplified coordinate frames is that what appears complicated and irregular to the scientist need not be difficult for the nervous system. Neural networks, in fact, excel at making coordinate transformations. Thus, generating new values for many variables (generating a movement involving many degrees of freedom) might not be a very difficult task that the nervous system must avoid.

Stability

An alternative theoretical basis for addressing the degrees of freedom problem is the notion of stability (Schöner 1995). Stability is meant here more generally than the mechanical sense. Thus, mechanical stability, defined as the ability to keep the center of body mass within safe limits of the base of support (Horak and Macpherson 1996), is but a special case of stability, which is more generally the capacity of the system to return to a given state after a (phasic) perturbation has driven the system away from that state.

Any real movement is always subject to multiple disturbances, which may have various origins. External perturbations may arise from interactions with objects in the world. Internal perturbations may be mechanical (such as when passive forces are generated in multi-joint effectors during motion) or nervous (such as when coupling among effector systems or to sensory systems affects motion). Thus, stability in this control-theoretical sense is a prerequisite to the reliable realization of a motor goal. Motor plans must therefore necessarily be made in terms of stable degrees of freedom. Thus, the differential stability of variables may be a signature feature that differentiates the primary variables for the nervous system's control of an act from secondary variables.

Experimentally, the stability of a particular state can be assessed by the variability of the corresponding variable in time (Scholz and Kelso 1989; Scholz et al. 1987) or the reproducibility of that variable from trial to trial (Schöner and Kelso 1990). Stability in the control-theoretical sense is a property of a particular stable state of the system (variably called the fixed point or the set-point of the control system). If that fixed-point is constant in time (such as is the case for postural states), then the fluctuations in time around the fixed-point are indicative of stability. Variability in time can be used to experimentally assess the stability of the fixed-point: The more stable the fixed-point, the less variable the system. By contrast, when the fixed-point is changing in time (such as the fixed-point of the postural system during movement), then variability in time is *not* a measure of stability (it instead measures the amount of fixed-point change). In this case, an experimental estimate of stability can be arrived at by reproducing the movement multiple times and then analyzing the system at matching points in time across the repetitions. Variability from trial to trial can now be used to assess postural stability: the more variable the system, the less stable. In this study, we employ this method to assess the stability of postural states in different directions of joint space.

The uncontrolled manifold

This latter problem can be addressed through a new concept (Schöner 1995, in preparation), the uncontrolled manifold. In simplified form, the idea can be described as follows. We define a basic configuration space, in which all analysis takes place. This space may be spanned, for instance, by all joint angles that contribute to a particular movement. An hypothesis is formulated about which variables the nervous system controls. These variables may be particular functions of the joint angles. For any given set of values of the controlled variables, joint space is divided into two orthogonal subspaces. One subspace consists of all those joint configurations that lead to the same set of values of the putative controlled variables. Motion within this subspace leaves the controlled variables unaffected. Motion orthogonal to this subspace does affect the controlled variables. The hypothesis is now tested by estimating if the variability of the joint configuration in the uncontrolled subspace is larger than the subspace orthogonal to it, in which case the hypothesis is accepted (i.e., most joint variability leaves the value of the control variable unaffected). In reality, the situation is a little more complicated. This may best be explained by referring to a simplified "toy" example.

Consider the task of drawing on a planar surface, say a table top. The arm is allowed to move in the horizontal plane, and only a single degree of freedom of motion at each of the shoulder, elbow, and wrist joints is allowed to occur (e.g., shoulder and elbow flexion-extension, wrist ulnar-radial deviation). Consider first only the final arm posture when the drawing task has terminated.

Different hypotheses can be formed about which variables are the primary focus of the nervous system's control of this task. One candidate is motion of the hand, or end-effector, here characterized by its position on the table top, measured in Cartesian coordinates, (x, y). This is a function of joint configuration: $(x, y)=f(\theta_1, \theta_2, \theta_3)$, which can be obtained from a simple geometrical model of the arm:

$$x=l_1 \cos(\theta_1)+l_2 \cos(\theta_2)+l_3 \cos(\theta_3)$$
$$y=l_1 \sin(\theta_1)+l_2 \sin(\theta_2)+l_3 \sin(\theta_3)$$

The set of joint configurations that leaves the end-effector position invariant is the set of solutions of these equations (Note, to simplify calculations, in this toy example and in what follows θ_i refers to the angle formed between the body segment and the horizontal rather than to inter-segment joint angle). There is more than one such joint configuration because the effector system (n=3) is redundant with respect to this task description (d=2): three joints control the two components of the end-effector position. In fact, this set of joint configurations forms a one-dimensional (i.e., $n–d$=1) manifold (Fig. 1). We call this the *uncontrolled manifold* (UCM), because the control of joint combinations within this manifold is unnecessary, i.e., they do not affect the task variable's position. In robotics, a related concept is called the "self-motion manifold" (Murray et al. 1994). Lacquaniti and Maioli (1994a, 1994b) introduced a similar geometric description when they analyzed the posture of cats by plotting combinations of three joint angles that lead to the same limb length and describing how the actual data was oriented with respect to the surface in joint space representing these combinations.

There is a different manifold for each position, (x, y), of the end-effector. In general, due to the nonlinear form of the geometrical model of typical effectors, the UCM is a not a linear space, but is curved. The hypothesis implies that, when the drawing movement is repeated, the joint configuration is less controlled along the UCM than along other directions. How can this hypothesis be tested? The variability of the joint configuration obtained at the end of the movement may be decomposed into the variability within the UCM and perpendicular to it. Because the UCM is curved, this requires a linear approximation to the UCM. Such a linearized UCM defines two subspaces, the uncontrolled space and its complement. The linearization requires, however, that we identify a particular joint configuration around which that linearization is obtained. That reference configuration, $(\theta_1^0, \theta_2^0, \theta_3^0)$, might be chosen, for instance, as the mean joint configuration obtained at the end of the drawing task.

The linearization is based on the Jacobian (i.e., the partial derivatives of end-point coordinates with respect to the joint angles) of the geometric model at the reference configuration:

$$J(\underline{\Theta}^0 = \begin{bmatrix} -l_1 \sin(\Theta_1^0) & -l_2 \sin(\Theta_2^0) & -l_3 \sin(\Theta_3^0) \\ l_1 \cos(\Theta_1^0) & l_2 \cos(\Theta_2^0) & l_3 \cos(\Theta_3^0) \end{bmatrix},$$

from which the UCM is obtained as the null space:

$$J(\Theta^0) \cdot \varepsilon = 0,$$

where the basis vector ε spans the linearized UCM (see Fig. 1).

The hypothesis can now be tested by projecting each different joint configuration obtained in different trials at the end of the drawing task onto the linearized UCM and its complement. In each subspace, the variance per degree of freedom is computed. If the variance per degree of freedom within the linearized UCM is larger than in its complement, the hypothesis that the end-effector defines the controlled variables is accepted.

Comparing the results of this kind of analysis for different hypothesized control variables allows a determination of the relative importance of different aspects of control. The difference in magnitude of variance within the linearized UCM and perpendicular to it is in each case an indicator of the extent to which the hypothesized set of variables is controlled. These variances are, therefore, the main dependent measures in the present experiment.

This analysis obviously makes two additional assumptions. First, by computing the variance per degree of freedom, we assume that the different joint angles can be compared to each other. This may appear problematic if there is a very different amount of movement with respect to the different joint angles. Appropriate choice of the basic joint-configuration space must address this concern. By performing this sort of analysis around different points (x, y) in the workspace [and, hence, around different reference configurations $(\theta_1^0, \theta_2^0, \theta_3^0)$ in joint space], the robustness of the hypothesis can be evaluated.

Second, this analysis is essentially an analysis of posture. This analysis can be applied at various points during a movement only to the extent to which movement can be approximated as a sequence of postural states. Experimental evidence for such a mode of control has been provided in a number of contexts (Feldman 1986; Feldman and Levin 1995; Flash 1987; Flash and Hogan 1985; Latash 1992, 1993; Rosenbaum et al. 1996). To implement the analysis in the context of movement, the

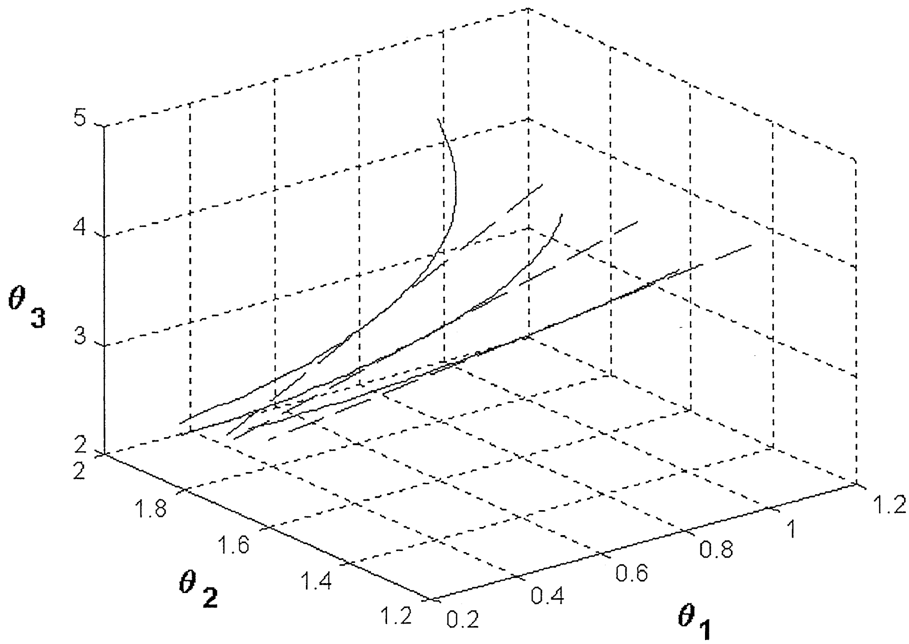


Fig. 1 Uncontrolled manifolds (UCM) of the simple toy model described in the text are illustrated in space of the three joint angles: θ_1, θ_2, and θ_3. Each *solid line* represents a set of joint angles that correspond to a particular invariant end-effector position (x=0.5, y=1.2, 13, 14 from top to bottom). These uncontrolled manifolds were determined as solutions of the geometric model (l_1=1, l_2=0.8, l_3=0.3). Linear approximations to these uncontrolled manifolds around a particular joint configuration are shown as *dashed lines*. The basis vectors, ε, lie parallel to the linearized UCMs

movement trajectories of the joints and relevant task-level or end-effector variables are normalized to 100% based on the movement cycle. It is assumed that, at each percentage of the trajectory, the same postural state is specified by the nervous system. The UCM can then be calculated at each percentage or at other meaningful intervals along the trajectory.

Model behavior for testing the theory: sit-to-stand

For many functional tasks, the primary control variables may not be as apparent as for a task such as reaching to a target. Consider, for example, a whole body task such as sit-to-stand (STS). The performance of STS presents a complex coordination problem for the nervous system. Neuromuscular forces must be coordinated with constantly changing gravitational and inter-segmental forces as well as with changing task constraints for smooth and efficient control to occur. How such dynamic coordination is achieved is still largely unknown. Thus, an important question for understanding the neural control of such tasks is what are the controlled variables of primary importance?

During STS, the body's mass is raised from a relatively stable support to a position of much lower mechanical stability, with intervening periods of transport where mechanical stability is precarious. Therefore, control of the body's center-of-mass (CM) trajectory may be of particular importance. Control of the head's trajectory might also be important, as such control might make visual and vestibular information more reliable (Pozzo et al. 1990, 1991). If the trajectory of the head or that of the CM is the primary focus of control for this task, joint motion should be coordinated to minimize head and/or CM trajectory variability. In view of these hypothesized control variables, the STS task maximizes the redundancy of the system because it involves the motion of all major joints of the body. This makes this task a good test-bed for a method of analysis based on the concept of an uncontrolled manifold.

Control of this task has previously been investigated in infants using a somewhat related method (Scholz and Brandt 1997). The results suggested that: (1) the focus of control lies on global task variables rather than individual joint trajectories; (2) control of the CM is of particular importance; and (3) control of the head's trajectory is also important, but only in the horizontal dimension and after lift-off from the seat (Scholz and Brandt 1997). The method used to analyze the structure of joint-configuration variability was based on propagating individual joint variability independent of the end-effector error. This method may detect correlations among the joint angles. These may lead to less end-effector variance than predicted from the Jacobian if the correlations are of the type that lead to an UCM; that is, joint angles co-vary so as to keep the end-effector invariant. The correlations may also lead to more end-effector variance than predicted from the Jacobian if, by contrast, the joint angles co-vary so as to maximize end-effector variance. The degree to which the Jacobian method detects correlations among joint angles depends, however, on the orientation of the UCM relative to the coordinate frame used in joint space. This is why the Jacobian method is not a reliable method in general. Another limitation of the previous study was that the control of the CM could only be tested more indirectly (Scholz and Brandt 1997). Both limitations are overcome with the present method. Moreover, task requirements are varied in this study so as to change the relative importance of the different hypothesized control variables.

In the present study, only motion in the sagittal plane was taken into account. The body's CM in that plane was hypothesized to be the primary control variable for this act. The importance of this control variable was hypothesized to increase as the task was made more difficult from a mechanical point of view. Control of the head's trajectory also was predicted to be important, but only with respect to its horizontal movement dimension, based on the results of previous infant studies (Scholz and Brandt 1997). A hypothesis about the control of the hand's movement trajectory was tested as well on the basis that the arms might be used in a controlled manner to assist in generating momentum for standing up, especially when the task is made more difficult. Moreover, this weaker hypothesis might fail, providing us with an example for rejection of a hypothesis about uncontrolled manifolds. All hypotheses were approached in a stepwise manner, separately testing control of the individual Cartesian components of each hypothesized end-effector (i.e., CM, head, and hand motion) and then the combined planar position vector, when appropriate (i.e., when no differences were found between hypotheses formed in terms of individual Cartesian components).

Materials and methods

Subjects

Nine healthy subjects, five female and four male, 22–28 years of age participated in this study. All subjects gave written consent, approved by the Human Subjects Review Committee, before participating in the experiments.

Equipment and set-up

An Elite motion-measurement system was used to collect the experimental data. The system consisted of two infrared-sensitive CCD cameras, the scans of which were controlled by a personal computer. The cameras were mounted on a floor-to-ceiling metal rod positioned approximately 5 m to the left side of the subject. One camera was mounted near the ceiling and angled downward toward the subject, while the other was mounted near the floor and angled in an upward direction. The scanned camera images were digitized on-line by the computer at 100 Hz. Prior to data collection, the cameras were calibrated to the measurement volume by digitizing a rigid frame with reflective markers of known relative positions. A direct linear transformation (Miller et al. 1980) was used to transform the two-dimensional coordinates of each reflective marker placed on the subjects into three-dimensional coordinates. For the present analysis, only motion in the sagittal plane of the body was analyzed because motion was largely restricted to that plane.

Spherical markers, 2 cm in diameter and covered with 3M retro-reflective tape, were applied to the following locations on the left side of the body using double sided, hypo-allergenic adhesive tape (Fig. 2): (1) base of 5th metatarsal, (2) ≈2 cm inferior to the lateral malleolus, (3) lateral femoral condyle, (4) greater femoral trochanter, (5) inferior to the lateral aspect of the acromion process of the shoulder, (6) the lateral humeral condyle just superior to the radiohumeral junction, (7) the styloid process of the radius, (8) immediately anterior to the external auditory meatus (EAM), and (9) on the skin over the left pelvis, approximately 20% of the distance from the greater trochanter to the shoulder and one-third of the distance from posterior to anterior iliac spines (approximate L5/S1 junction: deLooze et al. 1992). Markers also were applied to the posterior trunk at the level of the 12th thoracic (no. 10 in Fig. 2) and 7th cervical (no. 11 in Fig. 2) vertebrae. For the boot condition (see below), the ankle and toe markers were placed on the boot directly over the appropriate bony landmarks.

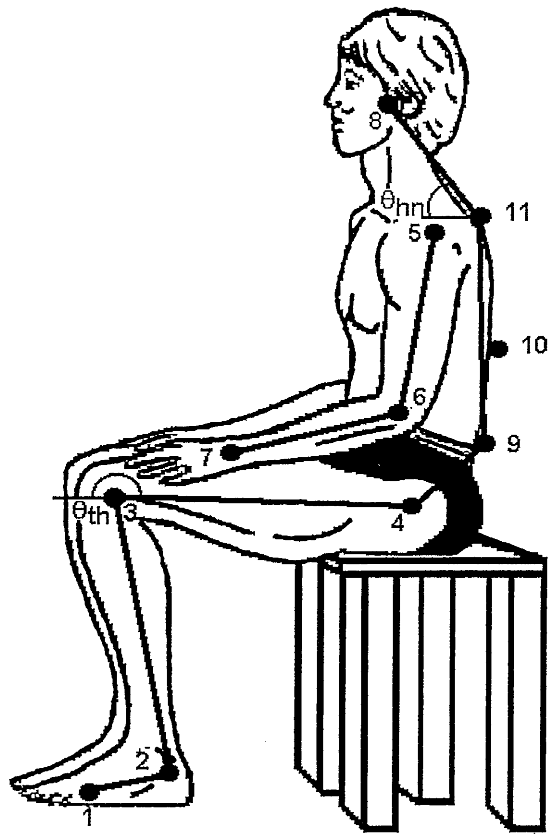


Fig. 2 Schematic of the subject set-up with superimposed stick figure connecting the reflective markers (*filled circles*). Examples of the segmental angles used in the Jacobian analysis for the thigh (Θ_{th}) and head/neck (Θ_{hn}). All other angles were formed similarly for the other segments (foot, shank, pelvis, trunk, arm, forearm). *Numbers* in figure refer to marker positions defined in the Method section

Experimental procedure

Subjects sat on a standard wooden chair measuring 0.445 m in height, with the left side of their body facing the cameras. They were asked to sit upright with the buttocks and thigh resting on the chair up to the point where the lateral hamstring tendon becomes prominent. The knees were in about 80° of flexion (180° = full extension) and the feet symmetrically positioned on the floor in the starting position. The hands rested lightly on the subject's knees prior to each trial. Subjects were asked to stand up after they were given a verbal signal to begin, coinciding with triggering of data collection. It was emphasized that this was not a reaction time task, i.e., that they were not to react as fast as possible to the instruction to begin, but that they should begin when ready after the signal and then stand up rapidly. The speed instruction was an attempt to minimize within-subject variability of the period of rising, which could potentially affect the nature of the task's control. Subjects were also instructed that they could do anything with their arms while standing up except to push off of their knees or to throw the arms downward and backwards, which would occlude the knee marker. After each trial, subjects were asked to assess whether they had inadvertently pushed off of the knees with their hands. If they had, the trial was repeated.

Performances under three experimental conditions are described in this report: (1) standing up onto a solid platform, as they would do normally (NORM); (2) standing up on the same surface while wearing a stiff pair of ski boots, which severely restricted ankle motion (BOOT); and (3) standing up onto a narrow, padded base of support NROW). The ten trials for which the period of rising was most consistent were chosen for statistical analysis. For one subject, the NORM condition was unavailable for analysis because of persistent problems with a missing wrist marker.

The NROW condition was used in an attempt to increase the difficulty of controlling the center of mass. In this condition, the feet were positioned on a narrow, padded block of wood, which was fixed securely to the floor with double-sided carpet tape. The block was 7.75 cm in height and 7.75 cm in width and supported the feet only between the anterior edge of the heel and the ball of the foot. The height of the block prevented the toes from contacting the surface of the floor. A 1.0×1.0 m platform of identical height to the narrow block was positioned under both feet for the NORM and BOOT conditions so that the relative position of the knee with respect to the chair could be kept constant for all conditions. The BOOT condition was used to eliminate one degree of freedom of lower-extremity motion to determine whether this affected the level of control of the hypothesized task variables. The control of ankle motion is important for maintaining balance in upright stance (Nashner and McCollum 1985). Thus, eliminating motion at this joint may lead to changes in control strategy.

Data reduction

The coordinates of each reflective marker were filtered using a bidirectional 4th-order Butterworth filter with a low-pass cutoff of 6 Hz. The reflective-marker coordinates were used to calculate sagittal plane angles between each body segment and the left horizontal using a customized Matlab routine (Fig. 2). These angles included the foot, shank, thigh, pelvis, trunk *(*L5–C7 vertebrae), head-neck (C7-EAM), arm, and forearm for the reported analysis. The location of the total-body center of mass at each point in time was calculated based on measured body-segment lengths and the estimated locations and proportions of segmental masses (Winter 1990). Linear velocities of the head and CM as well as angular velocities of the segment angles were obtained by differentiating the position and angle coordinates, respectively, using a finite difference algorithm (Winter 1990).

The period of each trial was determined as the difference between the time of the onset of forward horizontal CM movement, which continued toward standing, and the time at which the vertical CM excursion reached its peak value (i.e., upright). These times were determined as the time when the acceleration in the horizontal or vertical direction of the CM crossed zero in the appropriate direction. The time of liftoff from the seat was determined from the positive acceleration of the vertical coordinate of the CM.

Dependent variables

The main dependent variables in this study are the components of variance of the joint configuration, calculated relative to the mean joint configuration, that lie (1) parallel and (2) perpendicular, respectively, to the uncontrolled manifold of each hypothesized task variable. The goal of the analysis was to test hypotheses about which hypothesized control variables (i.e., CM, head, or hand trajectory) define an uncontrolled manifold. All analyses, then, are specific to a hypothesis about what particular variables are control variables.

A forward kinematic model links the joint configuration, $\underline{\Theta}$, to the vector of the hypothesized control variable, $\underline{r}$, without any free parameters. In the case of the center of mass (CM), this geometric model includes estimates of the segment masses. The configuration of the effector system is described by a set of angles, $\Theta_i=(\Theta_1,...,\Theta_8)$, where i=1–8 refer to the angles formed between the foot, shank, thigh, pelvis, trunk, head/neck, forearm, and arm segments with the horizontal. Body-segment angles formed with the horizontal rather than joint angles were used in the estimation procedure to simplify the model equations. The number of dimensions of the "joint" configuration space are thus n=8 for hypotheses about control of the CM, n=7 for hypotheses about control of the hand position (where the head/neck does not play a direct role), and n=6 for hypotheses about the control of the head (where the arm and forearm does not play a direct role).

The hypothesized task variable, r, expresses a hypothesis about which degrees of freedom are stabilized against perturbations and fluctuations. We examined single-task variables, such as the horizontal head-position, but also 2-dimensional task variables, such as the CM, which spans a d=2-dimensional task space (or end-effector space). Thus, the effector system is redundant (n>d) with respect to motion of the hypothesized task variable. The forward kinematics relating joint configuration to end-effector position are listed in the Appendix for the three types of end-effectors that we tested (involving CM, head position, and hand position).

We base our analysis on the sequence of positions traversed during a movement, that is, the movement path. Alternatively, the rate of change of those positions, that is, the path velocity, might have been used. Results based on path velocity were not substantially different from the results for position. We thus limit our analysis to the latter. All movement trajectories were re-scaled in time so that the sit-to-stand movements in different trials could be aligned. The underlying assumption is that, at each percentage of the trajectory, the system has a specific state with respect to the timing of the movement (e.g., an equivalent point in the virtual trajectory). Thus, as the movement is repeated, the joint configurations at corresponding percentages of the complete sit-to-stand cycle were analyzed. Statistical analysis will be presented for the points at which the sit-to-stand movement is 45, 60, and 75% complete.

At each time slice, the analysis of the UCM requires a linear approximation of the UCM. The postural state or reference joint configuration, $\underline{\Theta}^0$, around which this linear approximation is performed was determined by computing the mean joint configuration across trials. This approximation is valid to the extent that the forward kinematics is linear within the range of configurations obtained across the different trials.

The linearized forward kinematics around the reference configuration, $\underline{\Theta}^0$, is

$$\underline{r} - \underline{r}^0 = \underline{J}(\underline{\Theta}^0) \cdot (\underline{\Theta} - \underline{\Theta}^0)$$

where $\underline{r}^0$ is the value of the task variable corresponding to the reference configuration of joint angles, $\underline{\Theta}^0$. $\underline{J}(\underline{\Theta}^0)$ is the d×n Jacobian matrix obtained at the reference configuration.

The precision with which this linearization approximates the forward kinematics can be assessed by computing the deviation between the values of the task variables predicted by the linearized model and those predicted from the full forward kinematics. We applied this approach to the model for estimating head position and found the deviations from linearity to be in the range of the variability of actual head position (see Fig. 6): 2.78±2.52 cm and 1.97±1.81 cm for estimating head horizontal and vertical position, respectively. Thus, deviations from linearity are negligible.

In this limit case, the uncontrolled manifold is approximated linearly by the null-space of the Jacobian matrix, $\underline{J}(\underline{\Theta}^0)$. The null-space represents those combinations of joint angles that leave the end-effector or task variable unaffected. The null space is spanned by basis vectors, $\underline{\varepsilon}_i$, solving

$$0 = \underline{J}(\Theta^0) \cdot \varepsilon_i.$$

There are n–d basis vectors, so that the null space has n–d dimensions. The basis, $\underline{\varepsilon}_i$, of the null space was computed numerically at each time slice using MATLAB. The deviations of joint vectors from the mean joint configuration at each trial, $\underline{\Theta}$–$\underline{\Theta}^0$, were resolved into their projection onto the null space:

$$\underline{\Theta}_{\parallel} = \sum_{i=1}^{n} \underline{\varepsilon}_i \cdot \left(\underline{\Theta} - \underline{\Theta}^0\right)$$

and the component perpendicular to the null space:

$$\underline{\Theta}_{\perp} = \left(\underline{\Theta} - \underline{\Theta}^{0}\right) - \underline{\Theta}_{\|}$$

The amount of variability per degree of freedom within the uncontrolled manifold was estimated as

$$\sigma_{\|}^{2} = (n-d)^{-1} \cdot \left(N_{\text{trials}}\right)^{-1} \cdot \sum \Theta_{\|}^{2},$$

where $\Theta_{\|}^{2}$ is the squared length of the deviation vector, $\Theta_{\|}$, lying within the linearized UCM. Analogously, the amount of variability per degree of freedom perpendicular to the uncontrolled manifold was estimated as

$$\sigma_{\perp}^{2} = d^{-1} \cdot \left(N_{\text{trials}}\right)^{-1} \cdot \sum \Theta_{\perp}^{2}.$$

The UCM hypothesis states that the central nervous system specifies only a stable state in the task space, not in joint space. As a result, the overall variability of the configuration perpendicular to the UCM is predicted to be much smaller than that parallel to the UCM. When this prediction is invalid, then the hypothesis about which variables are stabilized and which are not must be rejected. This test was applied separately to hypotheses about control of the center of mass, head, and hand trajectories. In addition, we separately considered hypotheses about the horizontal and vertical movement dimensions of each putative task variable, based on the results of a similar analysis of this task in infants (Scholz and Brandt 1997).

The primary dependent variables used in subsequent analyses of the differences between Cartesian coordinates and experimental conditions for each hypothesized control variable are $\sqrt{\sigma_{\|}^{2}}$ and are $\sqrt{\sigma_{\perp}^{2}}$ referred to in what follows as ||UCM and ⊥UCM, respectively. These variables are not directly comparable across hypotheses about different task variables (i.e., CM, head, or hand) because of differences in the degrees of freedom comprising the configuration spaces for each. Therefore, the variable

(||UCM/⊥UCM)*100

was derived to compare the different control hypotheses statistically.

The dependent variables were calculated for each subject's data at increments of 15% of the normalized task period from 15% to 90% of the trajectory of each condition. The 45% point occurred immediately before liftoff from the seat. Because of the similarity of results at some percentages of the task period and because our main focus is the period during which control of the CM is most difficult, we present and statistically analyze only the phases 45%, 60%, and 75% of the task period. This was also necessary in view of the number of levels of the factors compared with the number of subjects. In addition, the inter-trial standard deviation of each hypothesized control variable, i.e., the CM, head, and trajectories, were calculated.

Independent variables

The independent variable that was directly manipulated was the experimental condition (NORM, NROW, and BOOT). In addition, the hypothesized control or task variable (CM, head, hand), the movement dimension (horizontal, vertical), and the phase of the task (45, 60, and 75% of the task period) were treated as independent factors for the statistical analyses.

Data analysis

We hypothesized that: (1) the CM trajectory would always be controlled more than joint motion, i.e., ||UCM–⊥UCM>0, regardless of the experimental condition; (2) control of the CM would increase with increased task difficulty, especially in the NROW condition; (3) control of the CM would always have priority over control of the head or hand trajectories; (4) control of the head's trajectory would be important only in the horizontal dimension (based on similar analyses in infants, Scholz and Brandt 1997); and (5) control of the hand's trajectory would increase in the BOOT condition as the arms are used more to assist with momentum generation. To test these specific hypotheses, different repeated measures analyses of variance (ANOVA) were performed using the SYSTAT statistical package. The number of factors included in the ANOVA depended on the hypothesis. For example, hypothesis 4 was performed without condition as a factor. When particular interaction effects that were related to our hypotheses were found to be significant, post-hoc contrasts using the CMATRIX command of SYSTAT was used.

Results

End-effector variability

The horizontal dimension of ten repeated movement paths of one subject for the three putative control variables are shown in Figs. 3, 4, 5 for the BOOT, NORM, and NROW conditions, respectively. For all conditions, the hand's path displayed greater inter-trial variability than either the CM or head. Path variability of the head and CM appear similar for the NORM condition (Fig. 4), whereas, for this subject, the movement path of the head appears more stable from trial to trial than does the CM path for the BOOT (Fig. 3) and NROW (Fig. 5) conditions.

Each panel of Fig. 6 presents the mean movement path variability (±SEM) at 45–75% of the movement cycle for, from left to right, the BOOT, NORM, and NROW conditions. Figure 6A–C present the data for the three control hypotheses for the horizontal movement dimension, and Fig. 6D–F present the result for the vertical dimension. Examination of Fig. 6 indicates that the variability of the three end-effector variables, expressed in absolute distances in measurement space, differ, with CM path variability (Fig. 6A, D) always lowest and hand path variability (Fig. 6C, F) always highest. The larger standard error of estimating mean variability suggests more inter-subject variability for the hand movement trajectory. After liftoff from the seat (60 and 75%), the movement trajectory of the CM and head appears to be less variable in the horizontal dimension than in the vertical dimension (Fig. 6A, B vs. Fig. 6D, E), although these differences are rather small. The direction of differences between the horizontal and vertical movement dimension varied across different phases of the movement for the hand trajectory (Fig. 6C, F).

Significant effects were found for the main effect of task variable or control hypothesis ($F_{2,16}$=47.68, P<0.00001) and the interaction of control hypothesis, movement phase, and movement dimension ($F_{4,32}$=4.25, P<0.01). Both effects are consistent with the pattern of results illustrated in Fig. 6 and described above.

The results suggest that the nervous system's priority for controlling these trajectories is CM>head>hand. This result does not allow us to determine whether the consistency of the CM trajectory is an indirect result of precise control of individual joint trajectories or whether CM control has primacy, occurring despite relatively large joint trajectory variability. The analysis of the components of joint trajectory variability with respect to the UCM of each hypothesized control variable sheds light on this question.

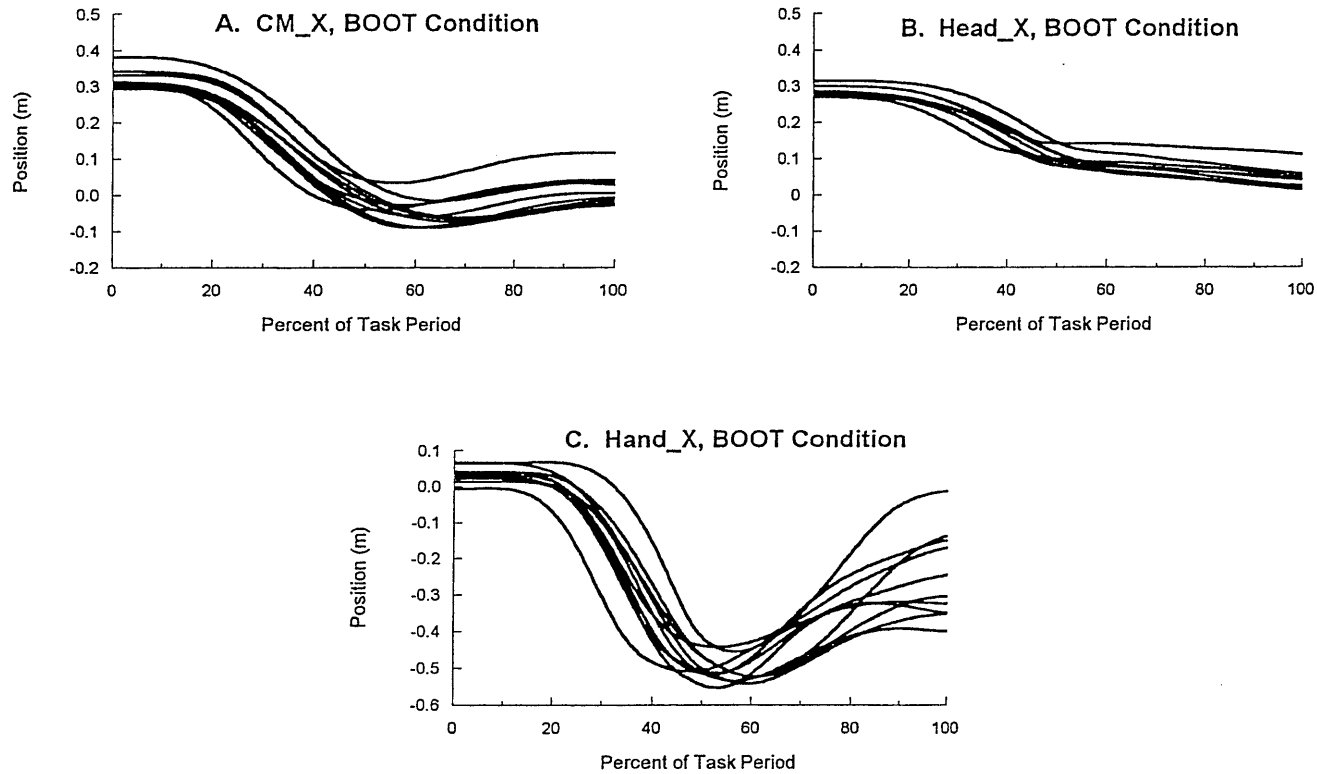


Fig. 3A–C Trajectory plots (n=10) of the horizontal dimension of the CM (**A**), head (**B**), and hand (**C**) during the BOOT condition for one subject

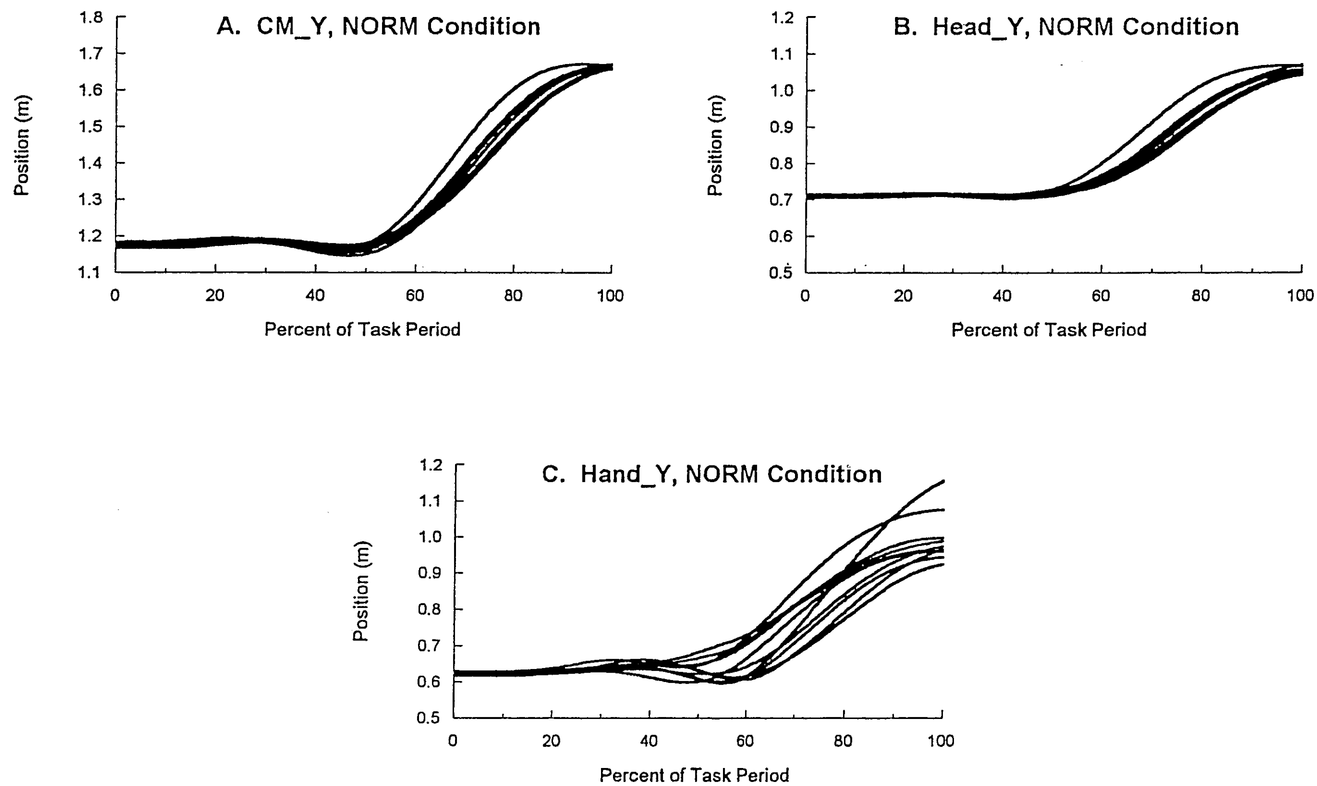


Fig. 4A–C Trajectory plots (n=10) of the vertical dimension of the CM (**A**), head (**B**), and hand (**C**) during the NORM condition for one subject

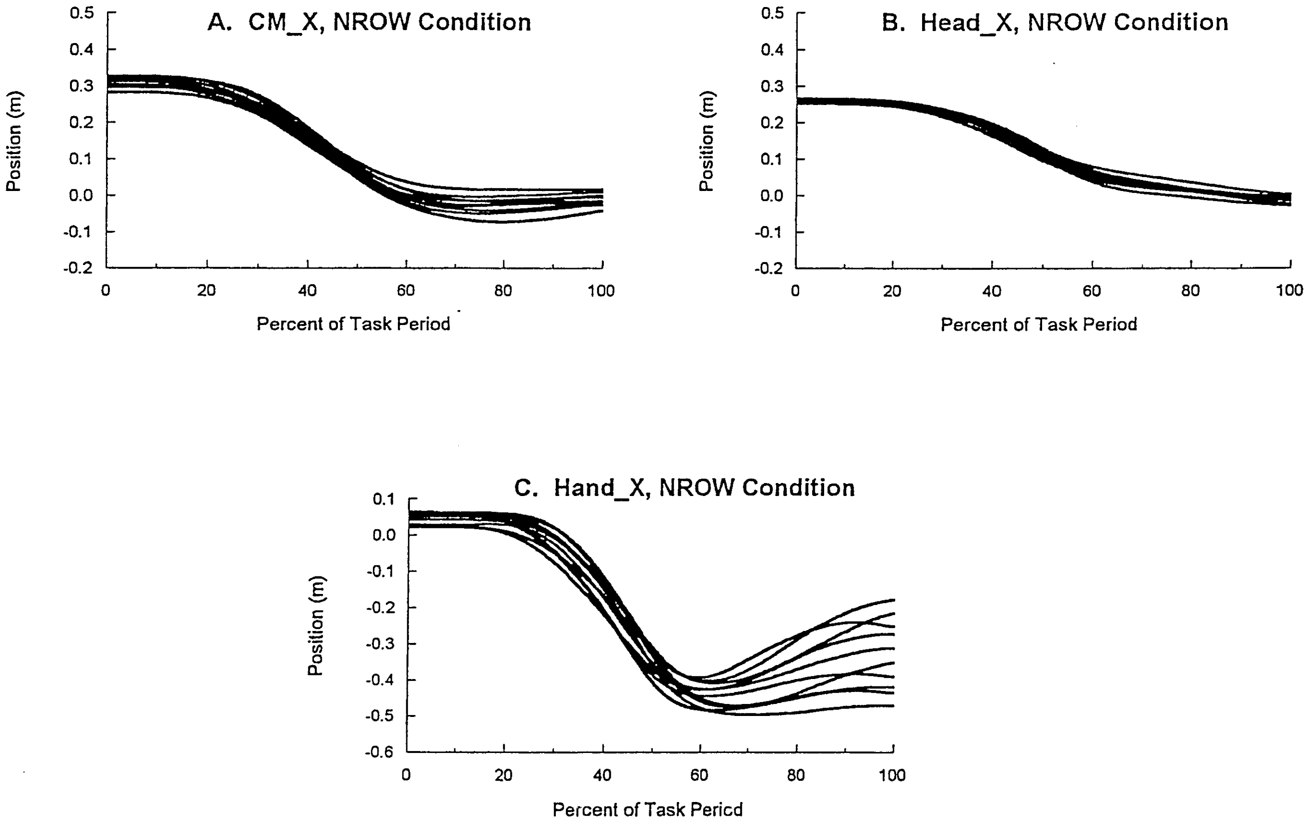


Fig. 5A–C Trajectory plots (n=10) of the horizontal dimension of the CM (**A**), head (**B**), and hand (**C**) during the NROW condition for one subject

Joint configuration variability

Figures 7 and 8 illustrate the results for the horizontal and vertical movement dimensions, respectively, for hypotheses about control of the CM (A), head (B), and hand (C) trajectories. At each percentage of the task period, three pairs of adjacent bars are presented. The leftmost bar of each pair indicates the component of joint configuration variance that lies parallel to the estimated uncontrolled manifold for the BOOT (solid), NORM (hatched), and NROW (bricked) conditions, in that order. The rightmost bar of each pair indicates the component of joint configuration variance lying perpendicular to the estimated UCM. Open bars are used in the latter case for all conditions to increase the contrast between ||UCM and ⊥UCM. To the extent that the leftmost bar of each pair (||UCM) is greater than the rightmost bar (⊥UCM), the hypothesis about the control variable can be accepted.

CM

We first examine the hypothesis about the CM trajectory. The component of joint variance lying parallel to the UCM is greater than the component perpendicular to the UCM for the CM trajectory under all conditions and at all phases of the task (Figs. 7A and 8A). Moreover, this difference is quite large! This results in a significant main effect for the UCM (i.e., ||UCM vs. ⊥UCM) in the ANOVA ($F_{1,8}$=74.41, P<0.0001). This indicates that the CM is a controlled variable in the sense that fluctuations in joint configuration affecting CM are reduced relative to fluctuations in joint configuration that do not affect CM.

The differences between controlled and uncontrolled directions in joint space were not strongly affected by the experimental condition, although there was a trend for the difference to be greatest for the BOOT condition (Figs. 7A and 8A). The interaction of experimental condition by UCM was non-significant ($F_{2,16}$=1.66, P=0.22). There was, however, a significant 3-way interaction of experimental condition by movement dimension by UCM ($F_{1,8}$=30.65, P<0.01). Post-hoc exploration of this result indicated that the differences between ||UCM and ⊥UCM for the CM hypothesis were significantly different only between the BOOT and NROW conditions in the vertical movement dimension ($F_{1,8}$=6.3, P<0.05; Fig. 8A). The difference ||UCM–⊥UCM was larger for the BOOT condition.

Head

The hypothesis that the horizontal position of the head is controlled was confirmed by the greater variability of joint configurations parallel compared with perpendicular to the corresponding UCM (Fig. 7B). This effect is not as strong as for the CM control hypothesis and is absent in

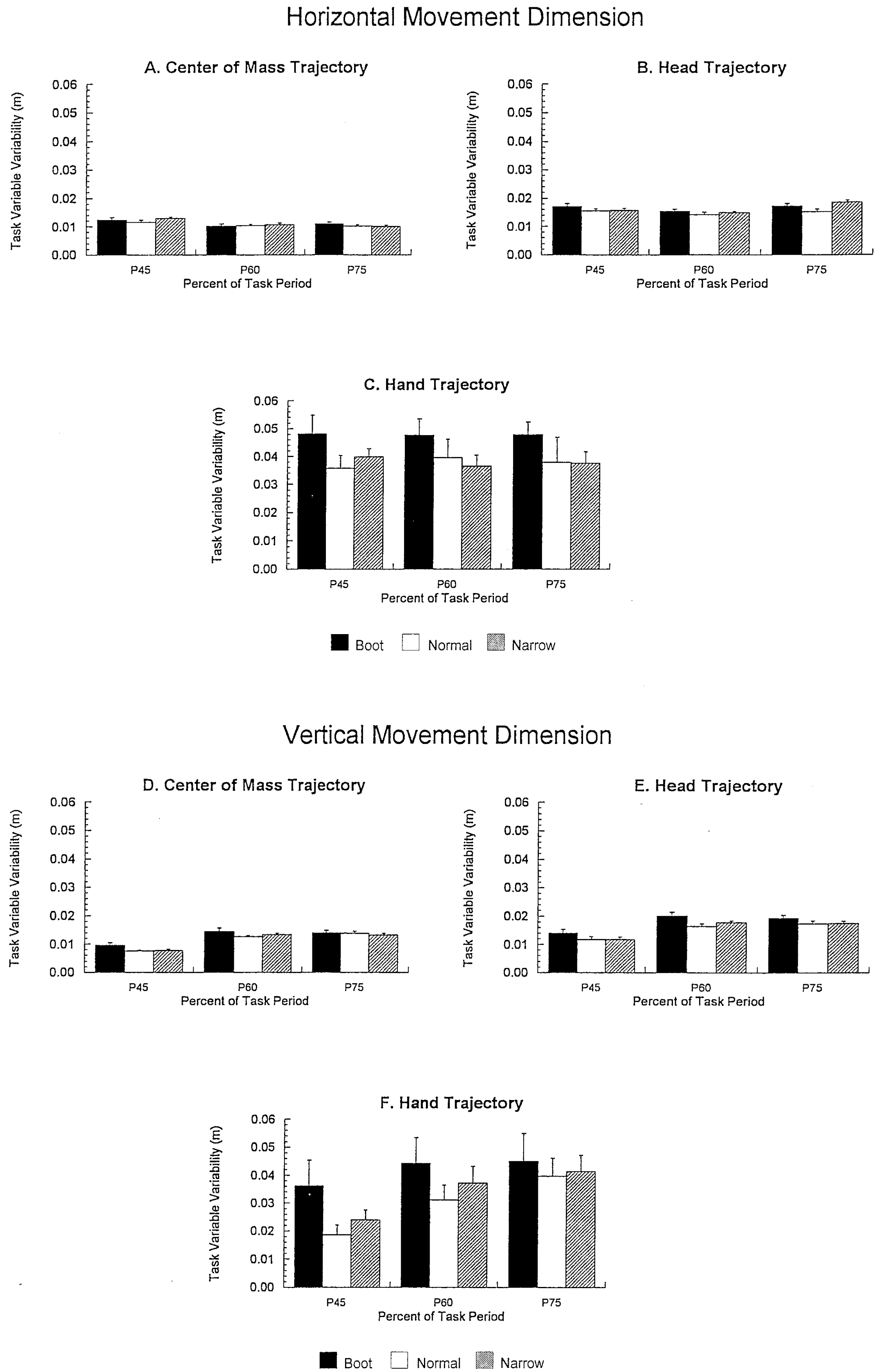


Fig. 6A–F Mean (±SEM) movement path variability for the hypothesized control variables horizontal center of mass (CM) (**A**), horizontal head (**B**), horizontal hand (**C**), vertical CM (**D**), vertical head (**E**), and vertical hand (**F**) at 45% (*P45*), 60% (*P60*), and 90% (*P75*) of the task period. *Adjacent sets of bars* for each percent of the task period represent the results for the BOOT, NORM, and NROW conditions (from left to right)

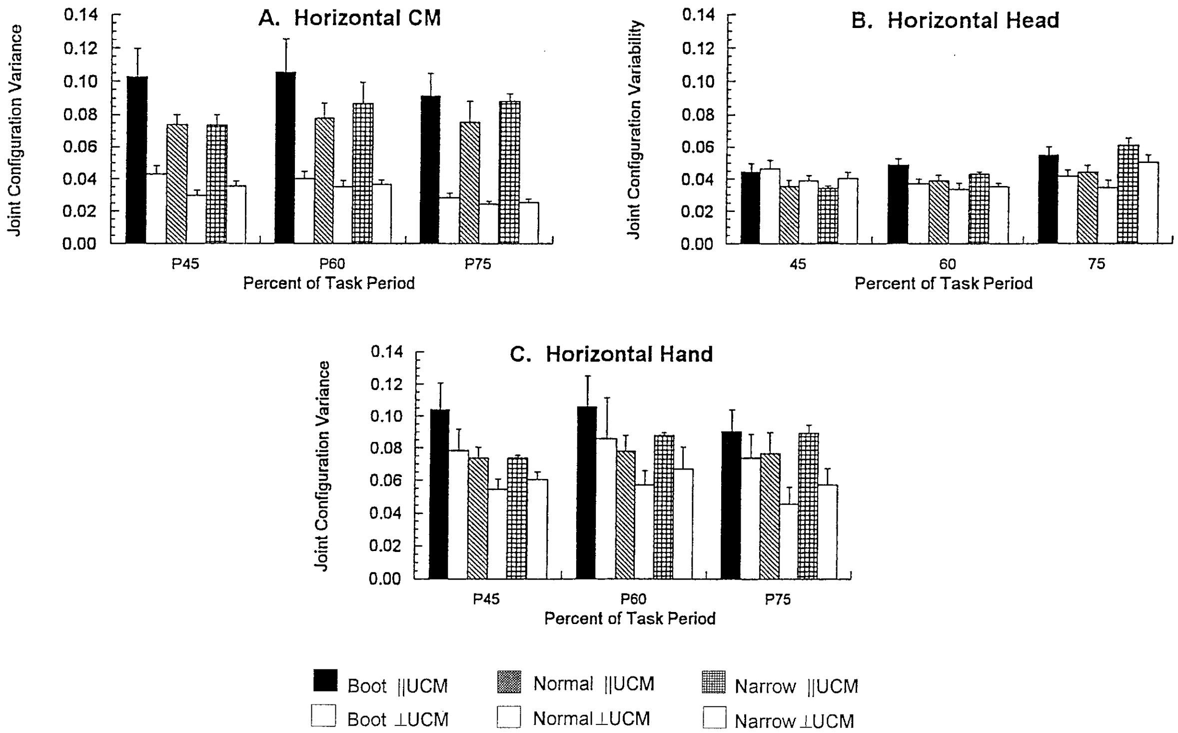


Fig. 7A–C Mean (±SEM) joint configuration variance parallel to (*//*) and perpendicular to (*⊥*) the linearized uncontrolled manifold (*UCM*) for hypotheses about controlling the horizontal movement dimension of the center of mass (*CM*) (**A**), head (**B**), and hand (**C**) trajectories. *Adjacent pairs of bars* at each of 45% (*P45*), 60% (*P60*), and 75% (*P75*) of the task period represent ||UCM for each of the boot (*solid*), normal (*diagonals*), and narrow (*bricks*) performance conditions. ⊥UCM for each condition is represented by *open bars* to increase contrast

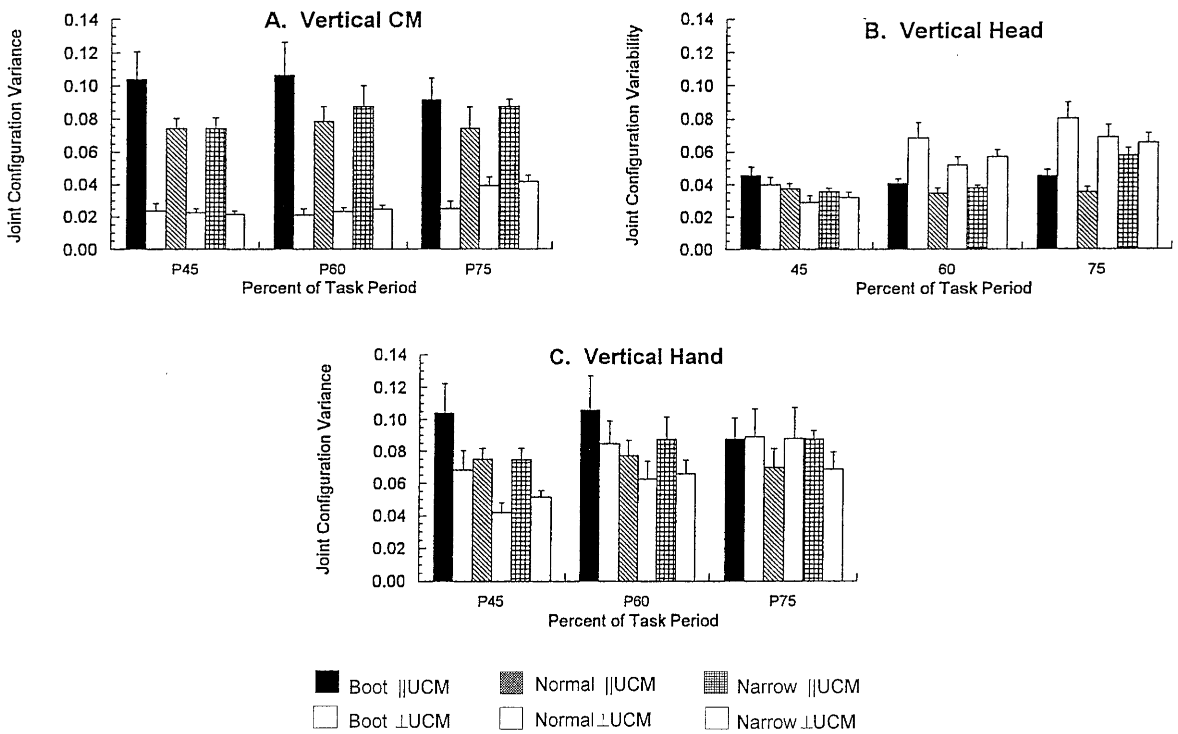


Fig. 8A–C Mean (±SEM) joint configuration variance parallel to (*//*) and perpendicular (⊥) to the linearized uncontrolled manifold (*UCM*) for hypotheses about controlling the vertical movement dimension of the center of mass (*CM*) (**A**), head (**B**), and hand (**C**) trajectories. *Adjacent pairs of bars* at each of 45% (*P45*), 60% (*P60*), and 75% (*P75*) of the task period represent ||UCM for each of the boot (*solid*), normal (*diagonals*), and narrow (*bricks*) performance conditions. ⊥UCM for each condition is represented by *open bars* to increase contrast

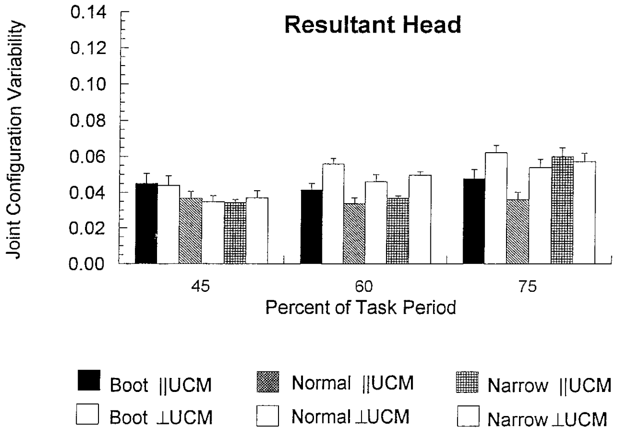
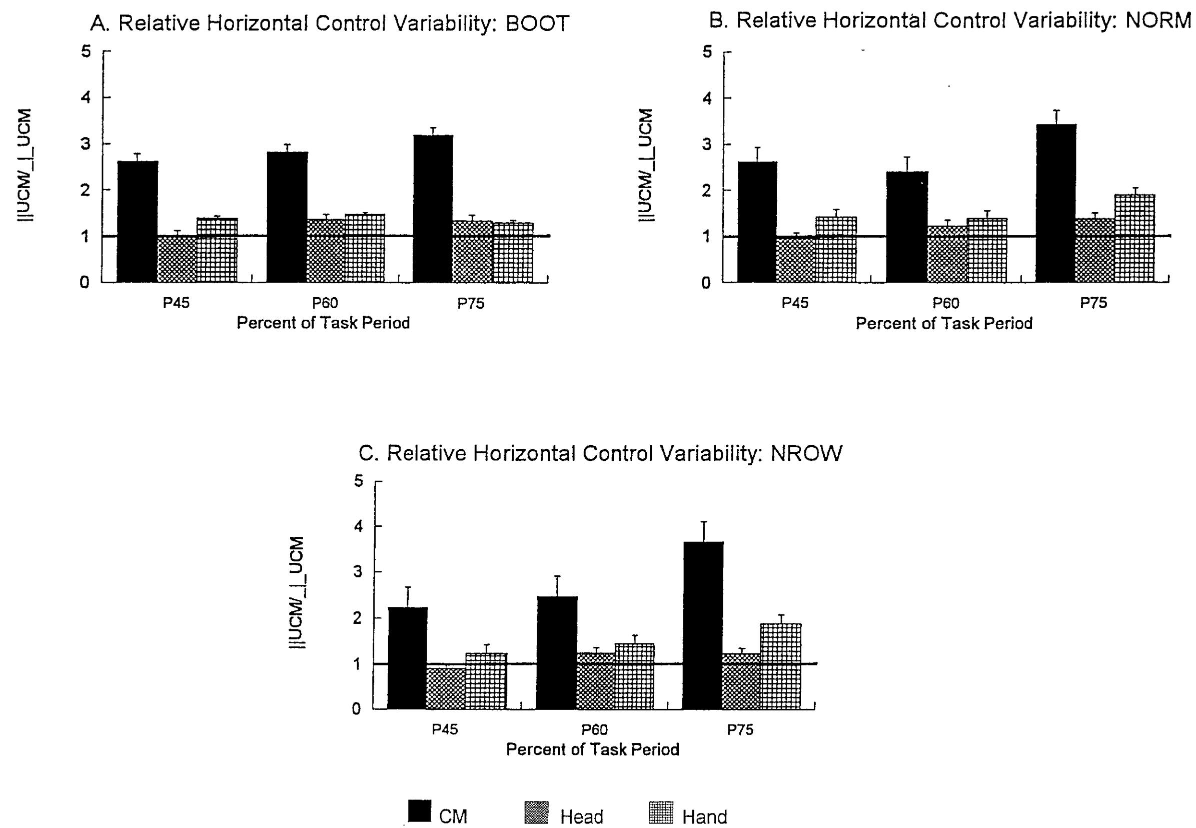


Fig. 9 Mean (±SEM) joint configuration variance parallel to (*//*) and perpendicular to (⊥) the linearized uncontrolled manifold (*UCM*) for the hypothesis about controlling the resultant head trajectory. *Adjacent pairs of bars* at each of 45% (*P45*), 60% (*P60*), and 75% (*P75*) of the task period represent ||UCM for each of the boot (*solid*), normal (*diagonals*) and narrow (*bricks*) performance conditions. ⊥UCM for each condition is represented by *open bars* to increase contrast

Fig. 10A–C Mean (±SEM) ratio of joint configuration variance parallel to (*//*) and perpendicular to (⊥) the linearized uncontrolled manifold (*UCM*) (||UCM/⊥UCM) for the hypothesis about controlling the horizontal movement trajectory of the center of mass (*CM*, *solid*), head (*diagonals*), and hand (*bricks*) at each of 45% (*P45*), 60% (*P60*), and 75% (*P75*) of the task period for the BOOT (**A**), NORM (**B**), and NROW (**C**) conditions



the pre-liftoff phase. By contrast, in the vertical movement dimension, ||UCM is, on average, always smaller that ⊥UCM after liftoff from the seat (Fig. 8B), indicating that control of the head trajectory in this dimension is no greater than joint trajectory control. Moreover, the experimental condition did not affect strongly these differences.

The result was supported by the significant interaction of movement dimension with UCM for the head trajectory control hypothesis ($F_{1,8}$=41.67, P<0.001). The three-way interaction of experimental condition, movement dimension, and UCM was not significant (P=0.06), although the interaction of the latter two variables with movement phase was significant ($F_{2,16}$=32.20, P<0.00001). However, there was a significant four-way interaction of condition, movement phase, movement dimension, and UCM ($F_{4,32}$=2.99, P<0.05). Simple interaction effects indicate that the interaction between movement dimension and UCM for the head trajectory hypothesis was significant overall at all movement phases, regardless of experimental condition (45%: $F_{1,8}$=5.71, P<0.05; 60%: $F_{1,8}$=49.53, P<0.0001; 75%: $F_{1,8}$=44.91, P<0.001), with the direction of the difference between ||UCM and ⊥UCM reversing across movement dimensions (cf. Figs. 7B and 8B). Simple interaction effects involving the experimental condition revealed only a difference in the head control hypothesis (i.e., ||UCM vs. ⊥UCM) between the NROW condition and both the NORM ($F_{1,8}$=34.57, P<0.001) and BOOT ($F_{1,8}$=18.96, P<0.01) conditions at 75% of the task period. Larger differences exist between the NROW and the other conditions for the vertical movement dimension than for the horizontal dimension.

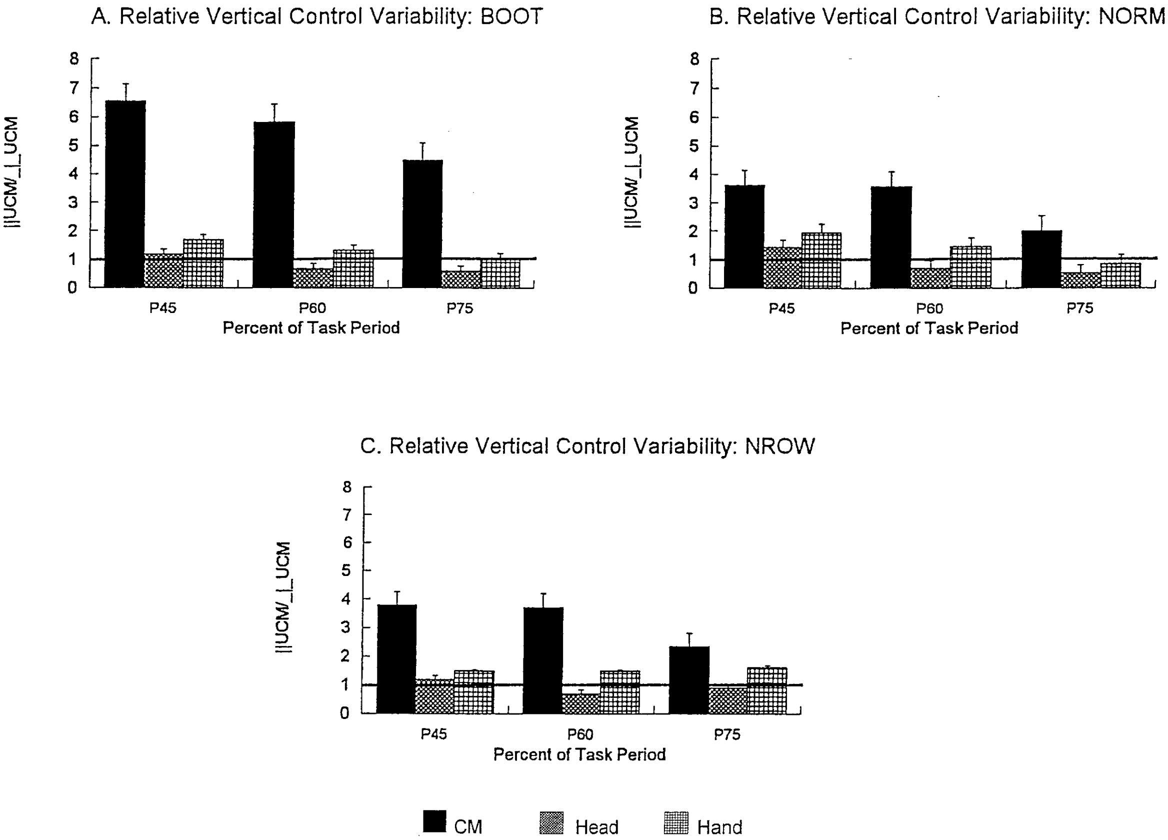


Fig. 11A–C Mean (±SEM) ratio of joint configuration variance parallel to (*//*) and perpendicular to (*⊥*) the linearized uncontrolled manifold (*UCM*) ((||UCM/⊥UCM) for the hypothesis about controlling the vertical movement trajectory of the center of mass (*CM*, *solid*), head (*diagonals*), and hand (*bricks*) at each of 45% (*P45*), 60% (*P60*), and 75% (*P75*) of the task period for the BOOT (**A**), NORM (**B**), and NROW (**C**) conditions

The results reported above support the importance of carefully considering the control hypothesis for a given task. That is, had the two-dimensional head path been tested without consideration for differences between vertical and horizontal, a different conclusion would have been reached. This is illustrated in Fig. 9, which presents ||UCM and ⊥UCM for each condition for the hypothesis of controlling the two-dimensional head position. In this case, following liftoff from the seat (i.e., 60 and 75%), ⊥UCM was generally greater than ||UCM for each condition, leading to the conclusion that the head was relatively uncontrolled compared to the joint trajectories. Although the differences between the two variance components were relatively small for the hypothesis about controlling horizontal head trajectory, they were significantly so, indicating that this conclusion is spurious.

Hand

Surprisingly, joint motion appears to be constrained to minimize hand trajectory variability to some degree under all conditions during at least part of the movement trajectory (Figs. 7C and 8C). The only exception appears to be in the vertical direction at 75% of the movement period, well after liftoff from the seat. Here, ⊥UCM>||UCM for the BOOT and NORM conditions (Fig. 8C). None of the effects involving task condition were significant (P>0.07), probably due to the larger inter-subject variability of the variance measures pertaining to hand hypotheses.

Both the main effect for UCM ($F_{1,8}$=22.18, P<0.001) and the interaction of movement phase, movement dimension and UCM ($F_{2,16}$=16.02, P<0.001) were significant. Further post-hoc analyses showed that the differences between ||UCM and ⊥UCM were significant for the horizontal movement dimension at all phases of the task period (all $F_{1,8}$>18.81, P<0.01). However, for the vertical movement dimension, ||UCM and ⊥UCM were statistically different only at 45% of the task period ($F_{1,8}$=10.39, P<0.05).

Comparison of control hypotheses

The absolute values of ||UCM and ⊥UCM are not strictly comparable among control hypotheses (i.e., for CM, head, and hand) because of differences in the degrees of freedom comprising the joint configuration space. The ratio of ||UCM and ⊥UCM, however, allows a relative comparison of the degree of control of each hypothesized control variable. This is illustrated in Figs. 10 (horizontal) and 11 (vertical) for the two movement dimensions of each experimental condition (A–C). Values equal to or below unity (i.e., horizontal line in figures) indicate that the control hypothesis can be rejected, i.e., joint configuration variance leads more often to changes in the value of the hypothesized control variable.

These figures clearly illustrate the primary importance of controlling the CM trajectory in both movement dimensions. The value of this variable for the CM control hypothesis was both substantially greater than unity, indicating that most joint configuration variance left the CM position invariant, and it was generally more than twice the value for the head or hand hypothesis. This difference between control hypotheses appears to be especially large for the BOOT condition compared with the other conditions in the vertical movement dimension (cf. Figs. 10 and 11). Surprisingly, control of the hand's path actually appears to be greater than control of the head's trajectory.

These differences are supported by a significant effect of the control hypothesis (i.e., CM, head, or hand) in the ANOVA ($F_{2,16}$=83.19, P<0.00001) as well as a significant 3-way interaction of control hypothesis, movement dimension, and condition ($F_{4,32}$=7.63, P<0.001). Post-hoc analyses collapsing across the phase of the movement and experimental condition revealed that this variable for the CM hypothesis was significantly larger than that for the head or hand hypotheses for each movement dimension as well as when collapsed across movement dimension (all $F_{1,8}$>31.92, P<0.001). Moreover, the value for the hand-control hypotheses was typically larger than that for the hypothesis on head control (all $F_{1,8}$>14.8, P<0.01), although this difference was somewhat dependent on experimental condition and movement phase (Fig. 10A). Post-hoc exploration of the effect of condition revealed that the variable for the CM hypothesis differed between conditions in the vertical dimension only. Control of the CM in the vertical dimension was stronger when performing under the BOOT condition than when performing under the NROW condition ($F_{1,8}$=6.38, P<0.05). The difference between BOOT and NORM conditions approached, but did not reach significance (P=0.058), while there was no difference between the NORM and NROW conditions (P=0.65).

Discussion

This article presents the results of experiments designed to test the concept of the uncontrolled manifold. That concept provides a basis for distinguishing between different degrees of freedom in terms of their control-theoretical stability. Those task variables can be said to be "more stable" or "controlled" that structure fluctuations in joint space, such that changes of joint configuration preserving the values of these variables are less constrained than changes in joint configurations that change the values of the task variables (Schöner 1995). The theory is evaluated by testing hypotheses about the motor control of standing up from a chair. To the extent that the concept of an uncontrolled manifold helps to identify controlled variables and distinguish more-controlled from less-controlled variables, the concept is useful.

To apply the concept of an uncontrolled manifold, a forward kinematic model must be formulated that relates joint angles to a particular hypothesized control variable. Around a reference joint configuration, computed from a mean trajectory (across trials), the forward kinematic model is linearized. The null space of the corresponding Jacobian matrix represents a linear approximation to the uncontrolled manifold for the hypothesized control variable. The UCM represents those directions in joint space which leave the value of the control variable unchanged.

Trial-to-trial variability of the joint motion paths were resolved into their components that lie parallel to (||UCM) and perpendicular to (⊥UCM) the UCM. The variance difference along these two directions in joint space provides an indication of the degree to which joint motion is coordinated to stabilize the motion of the hypothesized control variable. If ||UCM>⊥UCM, this indicates that more of the fluctuations at the joint level leave the hypothesized control variable unaffected, indicating that stabilization of the task variable is of primary importance. If ⊥UCM>||UCM, then joint motion variability is structured in ways other than to minimize end-effector variability. This may reflect that end-effector variables other than the tested are controlled. Comparing such results for different hypothesized control variables under different experimental conditions provides an indication of the relative importance of such variables to the task.

The application of this method assumes that a movement trajectory can be represented as a sequence of postural states. Although there are differing opinions on this issue, recent experimental and theoretical work is based on this assumption (Feldman and Levin 1995; Flash and Hogan 1985; Latash 1992, 1993; Rosenbaum et al. 1996; Schöner 1994, 1995). We assumed that variation in the speed of a movement trajectory for a particular condition and under a particular, fixed instruction was due to extrinsic factors rather than variations in the planned (virtual) trajectory of postural states (Latash 1993). Based on this assumption, the beginning and end point of the STS task was determined for each trial, and this portion then was normalized to 100%. More generally, the characterization of different degrees of freedom in terms of their control-theoretical stability is based on the identification of underlying stable states or fixed-points. Beyond posture, such stable states can be identified by choosing appropriate variables, which map movement patterns onto such states. For the coordination of rhythmic movement, for instance, variables such as relative phase map the coordination pattern onto fixed-points of relative phase. The stability of relative timing within those patterns can then be assessed on the basis of the variability (in time or across trials) of relative phase (Scholz and Kelso 1989; Scholz et al. 1987; Schöner and Kelso 1990).

Based on previous work in the sit-to-stand task (Scholz and Brandt 1997), we expected that the center-of-mass trajectory is a controlled variable. This makes sense, given the balance requirements for successful accomplishment of the STS task. The results showed a clear and strong effect: those joint combinations that leave CM invariant fluctuate much more strongly from trial to trial than those that induce CM variance (Figs. 7A, 8A, 10, and 11).

Although the experimental condition had less than the predicted effects on the control of different task variables, control of the vertical CM path was significantly stronger for the BOOT than for the NROW condition (Fig. 11). The difference between the BOOT and NORM conditions on this variable also approached significance. This result is somewhat surprising, because forward ankle motion was restricted in the BOOT condition, somewhat limiting the ability to get the CM forward. Thus, one might expect the need for enhanced control of the horizontal CM trajectory. However, most subjects had little experience standing up wearing ski boots, so that more experience or practice may be required to observe substantial alterations in the control structure for the task. Why enhanced control in the vertical dimension was a consistent feature for the BOOT condition is not clear.

The results confirm control of the center of mass as a primary control goal of the whole-body movement sit-to-stand. This structure of the control system is probably deeply seated, so that changes in current mechanical condition do not greatly affect this structure. Changing this control structure might require practice and, possibly, a more severe constraint on mechanical stability.

A finding similar to that observed in a previous experiment on the development of this task in infants (Scholz and Brandt 1997) was the limitation of control of the head's trajectory after liftoff from the seat to the horizontal movement dimension (cf. Figs. 7B and 8B). The difference between ||UCM and ⊥UCM was negative for the vertical movement dimension (Fig. 8) at all post-liftoff phases of the task (e.g., 60% and 75% of the task period).

This difference between vertical and horizontal head position control is surprising at first sight. How can this result be reconciled with the fact that variability of the head itself is about the same in the horizontal and vertical direction (Fig. 6B, E)? To understand this apparent discrepancy, we analyzed the linear relationship between head position and the variation of the joint configuration acting perpendicular to the corresponding uncontrolled manifold, i.e., the proportion of joint variance that moves the head around. That manifold has $n\text{–}d=5$ dimensions for each control hypothesis (i.e., horizontal and vertical head position). Thus, the orthogonal space is one dimensional. A single number, obtained by multiplying the Jacobian with the basis vector spanning the space perpendicular to the UCM, describes by how much the head position changes if the joint configuration is changed perpendicular to the UCM. Figure 12 shows this sensitivity measure for vertical and horizontal head motion. Apparently, while horizontal motion sensitivity remains relatively constant, vertical head position depends less sensitively on joint configuration changes perpendicular to the UCM after lift-off in all conditions, especially at 75% of the task cycle. Thus, although joint variability tends to enhance variability of head motion in the vertical dimension (Fig. 8B), that does not lead to more variability of vertical head position because vertical head motion depends less sensitively on joint variability! Intuitively, this is quite obvious: toward the end of the sit-to-stand transition, joints are all near full extension, and, therefore, further changes in joint configuration affect vertical head position little.

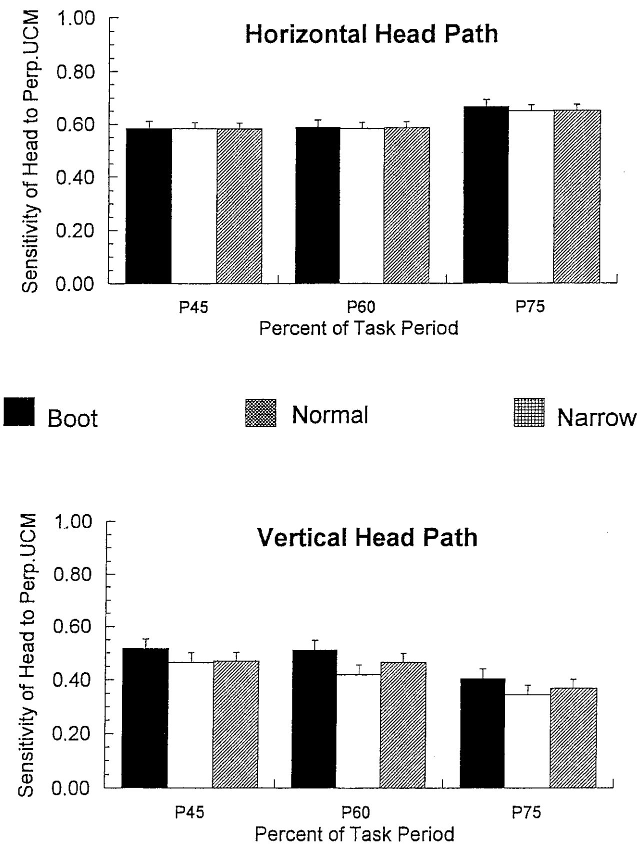


Fig. 12 Mean (±SEM) sensitivity of head variability to joint configuration variance acting perpendicular to the linearized uncontrolled manifold (*UCM*) for each of the BOOT (*solid*), NORM (*diagonals*), and NROW (*bricks*) conditions at 45% (*P45*), 60% (*P60*), and 75% (*P75*) of the task period. Horizontal (*upper panel*) and vertical (*lower panel*) movement dimensions

This outcome shows that, to interpret the structure of fluctuations in joint configuration space, the relationship between these fluctuations and the induced end-effector fluctuations must also be taken into account. Note that separately analyzing the horizontal and vertical component of head position and finding differences between these two does not imply that these two degrees of freedom are somehow controlled "independently" of each other.

Figures 10 and 11 show that differences in the degree of stabilization of joint configurations related to hypothesis of the head (and hand) are always smaller than those related to hypotheses involving the CM. In that sense, one can say that the CNS is more concerned about stabilizing the CM than those other end-effector variables. This result is not as apparent when the absolute end-effector variability is examined (Figs. 3, 4, 5, 6), but is consistent with the trend in those data.

The fact that there is a statistically significant directional difference between the horizontal and vertical head dimensions on ||UCM–⊥UCM (Figs. 7B and 8B) shows the importance of considering the control hypotheses carefully if there is reason to believe that each dimension is controlled differently. When a two-dimensional control hypothesis for head motion is considered, the effect of the vertical head motion dominates the result (Fig. 9), leading to the conclusion that joint variability is not structured in ways minimizing variability of the head's movement path. Although the difference in effect between vertical and horizontal head dimensions is small in this task, there is a clear difference that may be accentuated when task constraints are sufficiently changed or in other tasks.

Finally, the hand trajectories were analyzed in part to examine a hypothesis that was likely to be rejected. The results of an earlier study had shown that the hand trajectory during standing up from a seat was not controlled in developing infants (Scholz and Brandt 1997). Adolescent subjects did show controlled hand trajectories for the same task, however. The task in that study differed, however, because it involved a combination of standing up and reaching for an object. The adolescents appeared to combine reaching with the motion of standing up. The present study did not include reaching to an object. Instead, subjects were told that they could do anything they wanted with their hands except to push off of the legs or to throw the arms down to the side. The hand trajectories were most variable, especially after liftoff from the seat (Figs. 3C, 4C, 5C, 6C). Nonetheless, ||UCM was significantly greater than ⊥UCM, indicating some level of importance ascribed to the control of this variable (Figs. 7C and 8C). This was especially true for the horizontal movement dimension. It is possible that, by placing some restriction on what the subjects could do with their arms, although minimal (see Methods), we imposed a degree of control over arm and hand motion that would not have normally appeared without such an instruction. The instruction was necessary because of the need for the two cameras to always view all of reflective markers. Nonetheless, the difference between ||UCM and ⊥UCM was much smaller than for the CM, indicating that less importance is ascribed to control of hand motion. Thus, the results of this analysis are consistent with a task-specific control structure and, as such, are consistent with several recent models of movement control (Saltzman and Kelso 1987; Schöner 1994, 1995).

General discussion

In summary, a novel theoretical approach to identifying the important control variables for movement tasks is introduced. With this approach, the structure of a motor control system can be uncovered within the space of joint configurations. At each point in time, the different joint configurations realized in different trials are used to probe the directions of joint space along which the instantaneous postural state is more stable and the directions along which the postural state is less stable. These different directions are predicted from hypotheses about controlled variables. The components of variability that lie in those directions of joint space along which the values of the task variables remain constant are predicted to be larger than the components of variability that lie in those directions of joint space along which the task variables change.

The experimental results provide initial support for the validity and utility of the theoretical approach. In particular, we found clear evidence in favor of preferential stabilization of the center of mass during sit-to-stand. Horizontal head position was likewise more controlled than joint motion. By contrast, the control of vertical head position was released in joint space, even though vertical head position has similar variability as horizontal head position. This release was probably due to the reduced sensitivity of vertical head position to changes of joint configuration. Such reduced sensitivity frees up joint degrees of freedom for correlations minimizing other degrees of freedom (here, those stabilizing center of mass). In other words, variability involving combinations of joint angles that lead to the same position of the center of mass was much larger than variability involving combinations of joint angles that shifted the center of mass. Horizontal head position was also controlled in that same sense, although much less so. Thus, variability in directions of joint space along which horizontal head direction remains constant was larger, but not much, than variability along all other directions. Vertical head position was, by contrast, not controlled in this sense. In fact, the opposite pattern of joint variability was observed, but this effect could be explained by the body reaching its work-space limits in the vertical direction, so that the effective number of degrees of freedom was reduced. The gradient of decreasing differential control of CM, head, and hand shows how this technique can be used to characterize the structure of a motor control system.

The absence of substantial effects of movement condition on the structure of fluctuations in joint angle space suggest that this structure is due to deep-lying structures of the control system, which cannot be changed simply by changing task conditions. We suspect that such changes can be brought about only by practicing tasks that are sufficiently difficult to force release of some degrees of freedom in joint space.

What does the observation of an uncontrolled manifold imply for the problem of trajectory formation, that is, for the problem of generating changes of joint configuration in time? Clearly, only those combinations of joint angles can be assigned new values during movement that are stabilized in a postural sense. The presence of uncontrolled (or less controlled) directions in joint space implies that perturbations acting during movement (such as uncompensated passive forces in multi-link effectors) may shift the joint configuration along uncontrolled directions. This may lead to variable joint space trajectories, as well as to systematic shifts of joint space trajectory when the pattern of perturbations change. In particular, this may lead to different joint configurations at the end-point of the movement induced by different starting configuration. Thus, uncontrolled manifolds of the postural states that the system moves through may lead to violations of Donder's law (Gielen et al. 1997).

Appendix: geometric models

A The geometric model relating head position to joint configuration space is:

$$x_{\text{head}}=-l_{ft}\sin(\theta_{ft})-l_{sh}\sin(\theta_{sh})-l_{th}\sin(\theta_{th}) -l_{pv}\sin(\theta_{pv})-l_{tr}\sin(\theta_{tr})-l_{hn}\sin(\theta_{hn}),\text{ and}$$

$$y_{\text{head}}=l_{ft}\cos(\theta_{ft})+l_{sh}\cos(\theta_{sh})+l_{th}\cos(\theta_{th}) +l_{pv}\cos(\theta_{pv})+l_{tr}\cos(\theta_{tr})+l_{hn}\cos(\theta_{hn})$$

where *ft*=foot, *sh*=shank, *th*=thigh, *pv*=pelvis, *tr*=trunk, *hn*=head/neck, θ_i are segment angles, and l_i is the length of body segment *i*. The trunk was assumed, for simplicity, to form one rigid segment between the 5th lumbar and 7th cervical vertebrae, while the pelvis was defined as the segment from the hip joint to the 5th lumbar vertebra.

B The geometric model relating hand position to joint configuration space is:

$$x_{\text{hand}}=-l_{ft}\sin(\theta_{\text{ft}})-l_{sh}\sin(\theta_{\text{sh}})-l_{th}\sin(\theta_{th})-l_{pv}\sin(\theta_{pv}) -l_{tr}\sin(\theta_{\text{tr}})-l_{ar}\sin(\theta_{\text{ar}})-l_{fa}\sin(\theta_{fa}),\text{ and}$$

$$y_{\text{hand}}=l_{ft}\cos(\theta_{\text{ft}})+l_{sh}\cos(\theta_{\text{sh}})+l_{th}\cos(\theta_{th})+l_{pv}\cos(\theta_{pv}) +l_{tr}\cos(\theta_{\text{tr}})+l_{ar}\cos(\theta_{\text{ar}})+l_{fa}\cos(\theta_{fa}).$$

where *ar*=arm and *fa*=forearm segments. (All other segments are the same as in A, except that the head/neck segment is not included in the estimation of hand position.)

C The geometric model relating CM position to joint configuration space is:

$$\begin{aligned}CMx=[&0.0145\, l_{ft}\cos\theta_{ft}+0.093\, l_{ft}\cos\,\theta_{ft}\\ &+0.05273\, l_{sh}\cos\theta_{sh}+0.2(l_{ft}\cos\theta_{ft}+l_{sh}\cos\theta_{sh})\\ &+\ldots 0.113\, l_{th}\cos\theta_{ft}+0.0142(l_{ft}\cos\theta_{ft}+l_{sh}\cos\theta_{sh}\\ &+l_{h}\cos\theta_{th})+0.0149\, l_{pv}\cos\theta_{pv}\\ &+\ldots 0.355(l_{ft}\cos\theta_{ft}+l_{sh}\cos\theta_{sh}+l_{th}\cos\theta_{th}\\ &+l_{pv}\cos\theta_{pv})+0.2237\, l_{tr}\cos\theta_{tr}\\ &+\ldots 0.181(l_{ft}\cos\theta_{ft}+l_{sh}\cos\theta_{sh}+l_{th}\cos\theta_{th}\\ &+l_{pv}\cos\theta_{pv}+l_{tr}\cos\theta_{tr}+l_{hn}\cos\theta_{hn})\\ &+\ldots 0.056(l_{ft}\cos\theta_{ft}+l_{sh}\cos\theta_{sh}+l_{th}\cos\theta_{th}\\ &+l_{pv}\cos\theta_{pv}+l_{tr}\cos\theta_{tr})+0.0244\, l_{ar}\cos\theta_{ar}\\ &+\ldots 0.044(l_{ft}\cos\theta_{ft}+l_{sh}\cos\theta_{sh}+l_{th}\cos\theta_{th}\\ &+l_{pv}\cos\theta_{pv}+l_{tr}\cos\theta_{tr}+l_{ar}\cos\theta_{ar})\\ &+\ldots 0.030\, l_{fa}\cos\theta_{fa}]/M_{tot}\end{aligned}$$

$$\begin{aligned}CMy=[&0.0145\, l_{ft}\sin\theta_{ft}+0.093\, l_{ft}\sin\theta_{ft}\\ &+0.05273\, l_{sh}\sin\theta_{sh}+0.2(l_{ft}\sin\theta_{ft}+l_{sh}\sin\theta_{sh})\\ &+\ldots 0.113\, l_{th}\sin\theta_{th}+0.0142(l_{ft}\sin\theta_{ft}+l_{sh}\sin\theta_{sh}\\ &+l_{th}\sin\theta_{th})+0.0149\, l_{pv}\sin\theta_{pv}\\ &+\ldots 0.355(l_{ft}\sin\theta_{ft}+l_{sh}\sin\theta_{sh}+l_{th}\sin\theta_{th}\\ &+l_{pv}\sin\theta_{pv})+0.2237\, l_{tr}\sin\theta_{tr}\\ &+\ldots 0.181(l_{ft}\sin\theta_{ft}+l_{sh}\sin\theta_{sh}+l_{th}\sin\theta_{th}\\ &+l_{pv}\sin\theta_{pv}+l_{tr}\sin\theta_{tr}+l_{hn}\sin\theta_{hn})\\ &+\ldots 0.056(l_{ft}\sin\theta_{ft}+l_{sh}\sin\theta_{sh}+l_{th}\sin\theta_{th}\\ &+l_{pv}\sin\theta_{pv}+l_{tr}\sin\theta_{tr})+0.0244\, l_{ar}\sin\theta_{ar}\\ &+\ldots 0.044(l_{ft}\sin\theta_{ft}+l_{sh}\sin\theta_{sh}+l_{th}\sin\theta_{th}\\ &+l_{pv}\sin\theta_{pv}+l_{tr}\sin\theta_{tr}+l_{ar}\sin\theta_{ar})\\ &+\ldots 0.030\, l_{fa}\sin\theta_{fa}]/M_{tot}\end{aligned}$$

where *tr*=trunk above umbilicus and all other abbreviations are as in the models above. The constants represent the product of a segment's mass as a proportion of total body mass times its location from the proximal joint, as a propotion of the total segment length. M_{tot} is the total body mass.

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