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RESEARCH ARTICLE

John P. Scholz · Darcy Reisman · Gregor Schöner

Effects of varying task constraints on solutions to joint coordination in a sit-to-stand task

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Abstract The question of how multijoint movement is controlled can be studied by discovering how the variance of joint trajectories is structured in relation to important task-related variables. In a previous study of the sit-to-stand task, for instance, variations of body segment postures that leave the position of the body's center of mass (CM) unchanged were significantly greater than variations of body segment posture that varied the CM position. The present experiments tested the hypothesis that such structuring of joint configuration variability is accentuated when the mechanical or perceptual task demands are made more challenging. Six subjects performed the sit-to-stand task without vision (eyes closed), either on a normal or on a narrow support surface. An additional constraint on the postural task was introduced in a third condition by requiring subjects to maintain light touch (less than 1 N) with the fingertips while coming to a standing position on the narrow base of support. The joint configurations observed at each point in normalized time were analyzed with respect to trial-to-trial variability. The task variables CM and head position were used to define goal-equivalent sets of joint configurations ("uncontrolled manifolds," UCMs) within which variation of joint configuration leaves the task variables unchanged. The variability of joint configurations across trials was decomposed into components that did not affect (within the UCM) and that did affect (orthogonal to the UCM) the values of these task variables. Our results replicate the earlier finding of much larger variability in directions of joint space that leave the CM unchanged compared with directions that affect CM position. This effect was even more pronounced here than in the previous experiment, probably because of the more difficult perceptual conditions in the current study (eyes closed). When the mechanical difficulty of the task was increased, the difference between the two types of joint variability was further accentuated, primarily through increase in goal-equivalent variance. This provides evidence for the hypothesis that under challenging task constraints increased variability is selectively directed into task-irrelevant degrees of freedom. Because differential control along different directions of joint space requires coordination among joint angles, this observation supports the view that the CNS responds to increased task difficulty through enhanced coordination among degrees of freedom. The adaptive nature of this coordination is further illustrated by the similar enhanced use of goal-equivalent joint combinations to achieve a stable CM position when subjects stood up under the additional constraint of maintaining light touch with the fingertips. This was achieved by channeling goal-equivalent variability into different directions of joint configuration space.

Keywords Movement · Motor control · Coordination · Degrees of freedom · Posture · Human

J.P. Scholz (✉)
Department of Physical Therapy and Interdisciplinary Neuroscience Program, University of Delaware, Newark, DE 19716, USA
e-mail: jpscholz@udel.edu
Fax: +1-302-8314234

J.P. Scholz · D. Reisman
Biomechanics and Movement Science Graduate Program, University of Delaware, Newark, DE 19716, USA

G. Schöner
CNRS, Centre de Recherche en Neurosciences Cognitives, Marseille, France

Introduction

This article extends previous experimental work which has shown that the central nervous system (CNS) makes use of the available redundancy of motor elements to produce functional motor acts, and that the form of the solution to redundancy can be used to determine the relative importance of different task variables to success at the task (Scholz and Schöner 1999; Scholz et al. 2000). This report further reinforces those conclusions by showing that the solution to joint redundancy is enhanced when performing under challenging task constraints.

Most motor acts, whether highly skilled or of the everyday variety, result from the coordination of the activity of many redundant elements by the CNS. That is, the number of elements and the number of combinations thereof available to achieve, say, the position of the hand at a target are far greater than are necessary for successful performance. Bernstein (1967) was one of the first authors to address the “problem” of motor redundancy, suggesting that a primary solution was to eliminate redundant degrees of freedom (DOFs). Many since Bernstein have suggested that the CNS solves the redundancy problem by searching for unique solutions that bring to bear additional constraints on the problem, often in the form of cost functions (for reviews, see Seif-Naraghi and Winters 1990; Latash 1996). However, strong evidence has not been forthcoming that any one or even some combination of cost functions is actually used to simplify the control of functional motor acts (Lacquaniti and Maioli 1994; Rosenbaum et al. 1996).

An alternative suggestion is that multiple, goal-equivalent solutions are typically used to accomplish a task when redundant DOFs are available. The control principle underlying this suggestion is embodied in the uncontrolled manifold (UCM) hypothesis, which suggests that the CNS typically generates whole families of solutions to joint coordination such that functionally important, task-related variables are selectively stabilized (Schöner 1995). The UCM hypothesis is consistent with the “principle of abundance,” proposed as an alternative principle to the notion that redundancy poses a problem for the motor control system (Gelfand and Latash 1998; Latash 2000; see also Gelfand and Tsetlin 1966).

According to the UCM hypothesis, successful accomplishment of a motor task depends on stabilizing a time series of variables that are important to successful performance of the task. Thus, the UCM approach links the concept of stability to control. Control of any variable by the nervous system should result in stable properties of that variable (Schöner 1995). Conversely, only through generation of a stable state can a variable be controlled. Thus, control can be operationally defined through the stability of important task-related variables. This stability is hypothesized to be accomplished by implementing a control law in which, at every point in time, the CNS specifies a manifold representing all combinations of the motor elements (e.g., joints) that are consistent with the required value of a task-related variable. This manifold has been referred to as a UCM, indicating that specification of particular combinations of the elements consistent with a UCM is not essential to preservation of the corresponding value of the task variable. Which solution is actualized on any given repetition is hypothesized to evolve based on instantaneous changes in local dynamics (e.g., interaction torque) or constraints on the task. Thus, according to the UCM hypothesis, configurations of motor elements that lead to a change in the value of a task variable are controlled (i.e., these configurations must be resisted), while configurations of the elements that are consistent with desired values of the task variable are freed from control. To emphasize, what the UCM theory hypothesizes to be freed from control are joint configurations within the UCM (i.e., any configuration therein will do, because it is, by definition, consistent with the desired value of the task variable), not individual joint postures. Coordination among the individual joints is required, however, to ensure that the joint configuration stays within the UCM. In this way, the CNS makes use of the motor redundancy available to it. We emphasize that this style of control is not essential for achieving stability of important task-related variables. A single joint configuration consistent with the required value of a task variable at a given point in its trajectory could be specified repeatedly over many repetitions of the task. If this were the strategy used by the control system, variations in the joint configuration from trial to trial would be expected to represent noise. Employing the UCM hypothesis and related method of analysis, we address the issues raised in the introductory paragraph of this article.

Evidence for the use of this style of joint control by the CNS has recently been provided for a sit-to-stand (STS) task (Scholz and Schöner 1999) and a more skilled, pistol-shooting task (Scholz et al. 2000). For example, when analyzed with respect to a hypothesis about control of the path of the CM during the STS task, joint configuration variability that was consistent with a stable path of CM positions across trials was significantly higher than joint configuration variability that altered this path (Scholz and Schöner 1999). The present investigation was an attempt to further explore this control strategy by testing the hypothesis that more challenging task constraints lead to an enhanced use of goal-equivalent solutions to joint coordination. This contrasts with the hypothesis that, as the task of controlling the CM becomes more challenging, subjects might “freeze-out” or limit the number of different joint combinations used to produce the movement (McDonald et al. 1989; Vereijken et al. 1992).

We made the task more challenging by altering the perceptual information available to guide subjects’ performance and by adding additional mechanical constraints. Many authors (Forssberg and Nashner 1982; DiFabio and Anderson 1993; Nashner 1990) have illustrated the importance of visual, proprioceptive and vestibular input in the control of posture and balance. Adult subjects demonstrate the greatest amount of postural sway when visual and proprioceptive information is unreliable (Nashner 1990). Moreover, these inputs have been shown to contribute directly to the stabilization of the head’s position (DiFabio and Anderson 1993). Thus, we had subjects stand up on all trials without the aid of vision and, in two experimental conditions, on a narrow base of support that limited feedback from the feet as well as the ability to apply force to the support surface. Vestibular information is likely to become more important for controlling posture when visual, proprioceptive, and plantar tactile input is reduced. Thus, it was hypothesized that stabilizing the head’s posture might take on increasing importance under these task conditions. An additional task constraint was imposed by requiring subjects to stand up onto the narrow base of support while simultaneously maintaining light touch (less than 1 N) with the fingertips on an instrumented bar. The results indicate that subjects enhanced their use of goal-equivalent joint combinations to stabilize the path of both the CM and head position when deprived of normal perceptual information and when the mechanical constraints of the STS task were made more challenging.

Materials and methods

Subjects

Six healthy subjects, four women and two men, mean age 27.7 years, participated in this study. All subjects gave written consent, approved by the Human Subjects Review Committee, before participating in the experiments.

Equipment and setup

A VICON (Oxford Metrics, UK) motion measurement and analysis system and two force platforms (Bertec, Worthington, Ohio) were used to collect the experimental data. The system consisted of six infrared video cameras mounted on tripods and arranged in a half-sphere on the left side of the subject. Video data was sampled on line at 120 Hz. Prior to the start of the data collection, the cameras were calibrated to the measurement volume. Measurement error was less than 2 mm for all cameras in the 2.5-m^3 measurement volume.

Spherical markers, 2 cm in diameter and covered with 3M-brand retroreflective tape, were applied to the following locations on the left side of the subject's body using self-adhesive Velcro and hypoallergenic adhesive tape:

1. Base of the 5th metatarsal
2. Immediately inferior to the lateral malleolus
3. Lateral femoral condyle
4. Greater femoral trochanter
5. Two centimeters inferior to the lateral aspect of the acromion process of the shoulder
6. The lateral humeral condyle just superior to the radiohumeral junction
7. Styloid process of the radius
8. Directly anterior to the external auditory meatus (EAM)
9. Just lateral to the spinous process of C7
10. 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 the posterior to anterior iliac spines (approximately L5-S1 junction; de Looze et al. 1992).

Two Bertec force plates were placed side by side so that each of the subject's feet was supported by one plate. The force plate signals (F_x, F_y, F_z, M_x, M_y, M_z) were sampled by an analog-digital converter that was synchronized to the camera system.

Experimental procedure

Subjects sat on an adjustable, flat piano bench, the height of which was adjusted so that the distance from the top of wooden blocks used to support the feet to the top of the bench seat was 75% of each subject's lower leg length. The knees were placed in 100° of flexion (0° full extension). The piano bench had crossed legs connecting two support bars, each of which was supported on one of two force plates. One of three different pairs of wooden blocks was used to support the feet, depending on the experimental condition. One of each pair was placed on each of the two force plates in front of the bench. The blocks were secured to the force plates with double-sided tape to prevent rocking during the experiments. Each pair of blocks was 11 cm high and measured either 8 cm, 11 cm, or 35 cm in the anterior-posterior (A-P) direction. The 35-cm blocks were used for what we refer to as the "normal" (NO) support condition, in which the entire surface of the foot was supported. The 8-cm or 11-cm blocks were used in two conditions for which only the mid-foot of each foot was in support. The 11-cm-wide blocks were used for two subjects who were particularly tall and had relatively long feet, while the 8-cm-wide blocks were used for the other four subjects. On average across subjects, the blocks supported 35±3% of each subject's foot length (range: 31–40%). There were two conditions involving the narrow base of support: One condition had the subject stand up with the arms held out in front of the body (NB), while in the other condition subjects applied light touch (less than 1 N) with the fingertips to a force transducer that was rigidly mounted on a stand in front of them (TB). Subjects performed the experiments barefoot.

At the beginning of each experiment, the subject was seated and the knees and feet were adjusted to the correct starting position. Then, the position of the buttocks on the seat and that of each foot on the blocks was marked with chalk. Prior to each trial the subject's starting position was adjusted to be in alignment with these marks. The arm position at the start of each trial differed somewhat depending on the experimental condition. In the NO and NB conditions, the subject was instructed to hold the arms out in front of the shoulders, horizontal to the support surface. All subjects moved the arm around this initial position to some extent as needed for balance while standing up.

In the touch-bar condition, the subject's fingertips rested lightly on an ATI six-axis force/torque sensor that was placed on a rigid stand at arm's length in front of them. The subject had to maintain light touch contact with the force transducer throughout the trial. The vertical force signal was recorded in real time by a Labview program. A threshold was set after force sensor calibration to produce a warning sound if the subject exerted more than 1 N of force. Subjects were given enough practice to become familiar with this constraint. If subjects exceeded the threshold during a trial the trial was repeated.

To begin a trial, the subjects were given a verbal "go" command. The subjects were told that this was not a reaction time task and the verbal signal was just to alert them that they could begin to stand at anytime thereafter. The subjects were told that once they decided to initiate standing, they should stand up as rapidly as possible without falling. This was done to minimize within-subject variability of the movement time. Once obtaining the upright posture, the subjects were asked to hold that posture until told to sit down by the experimenter. The experimenter counted approximately 5 s before instructing the subject to sit down. The analyses presented in this article are primarily for the rising phase of the task, except for measurements of the center of pressure variability in the upright position. We attempted to obtain 15 successful trials (i.e., without steps off of the narrow base of support, force exceeding the 1 N limit in the TB condition, or general instability in the upright position). If there were concerns about collisions of critical marker, a few extra trials were collected.

The subject's performance under three experimental conditions is reported in this article. The conditions were designed to provide varying degrees of task difficulty. Subjects wore a 4.5-kg backpack for all experimental conditions in an attempt to make the task more challenging by changing the mass and its distribution. Their eyes were also closed during each trial of all experimental conditions, thus eliminating visual information about their orientation in the external environment. In what we called the NO condition, subjects could obtain normal information from the support surface and the ankle. In addition, the feet were able to apply typical force against the support surface. In the NB condition, information from the support surface was drastically reduced and that of the ankle was altered because only the mid-foot was in support. Moreover, the foot could not apply typical forces against the support surface to assist with balancing. The same conditions were in place for the TB condition. However, the subjects were now required to keep the fingertips in light touch (less than 1 N) with the touch surface. This condition added an additional constraint for the postural control system, eliminating some joint configurations that might ordinarily be consistent with a stable CM position (i.e., those that would take the hands off of the touch bar). At the same time, the additional tactile information provided at the fingertips might help subjects to better orient to the environment (Jeka et al. 1997).

Data reduction

The joint markers were identified and labeled offline using the VICON motion system software. This resulted in transformation of the two-dimensional marker coordinates obtained from each camera into three-dimensional coordinates. The coordinates of each reflective marker were then low-pass filtered in Matlab with a 6-Hz cutoff frequency. The force plate signals were down-sampled to 120 Hz to match the kinematics and low-pass filtered at 20 Hz, then scaled to newtons. Both signals were filtered with a bidirectional, 2nd-order, Butterworth digital filter.

The reflective marker coordinates were used to calculate sagittal plane joint angles at the ankle, knee, hip, lumbar spine, cervical spine, shoulder, and elbow. The location of the total body center of mass at each point in time was calculated using measured body segment lengths and the estimated locations of each segment's center of mass along those lengths and their proportion of the total body mass (Winter 1990).

Using the force signals, the center of pressure (COP) of each foot on their respective force plates was calculated and the total COP was obtained (Winter 1990). A-P (y) and medial-lateral (M-L; x) displacements of the COP were calculated using the following equations:

$$COP_x = (-My + (h * Fx))/F_z \tag{1}$$

$$COP_y = (M_x + (h * F_y))/F_z \tag{2}$$

where h is the height from the origin to the top of the force platform plus the height of the blocks, M_x and M_y are the moments obtained about the x- and y-axes of the force plate, while F_x, F_y, and F_z are the M-L, A-P, and vertical ground reaction forces, respectively.

The period of movement of each trial was determined using the following procedure. The horizontal and vertical positions of the CM and their accelerations were plotted using an interactive graphics routine in Matlab. The acceleration of the CM was plotted along with a horizontal line representing 5% of the peak acceleration. The first deviation of the CM acceleration trace from this line where the acceleration continued toward maximum was used to determine the time of movement onset. The end of the movement of standing up was determined as the time when the CM position trace reached a plateau after the CM acceleration trace had achieved one acceleration followed by one deceleration and returned below the 5% acceleration line. The time at which the buttocks lifted off from the seat was determined primarily from the upward motion of the greater trochanter marker with respect to the seat marker. In addition, the initial discontinuous shift of the A-P COP toward the heel marker from its initial position between the seat and feet (due to dual support of the seat and feet) was used to confirm this selection.

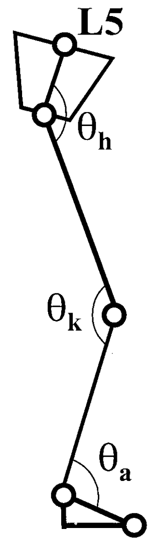
Once the movement period was determined, the portion of the trial from movement onset to termination in the upright position was normalized to 100% in 0.5% steps (200 samples) in Matlab, using a cubic spline interpolation. We first determined that the percentage of the overall movement period after liftoff from the seat accounted for about 80% of this period across trials and subjects. Therefore, the normalization procedure was actually done piecewise, with the period from movement onset to liftoff normalized to 40 samples (20% of the movement), and the time following liftoff until the end of the movement period normalized to 160 samples (80% of the movement). These data were then used for all further analyses.

Dependent variables

Movement time

Movement time was defined as the length of time between the subject lifting off the seat and when the subject's center of mass reached the fully upright position. Note that movement time as defined here is different from the movement period defined above, which included movement time and the time between initial CM motion and liftoff from the seat. The mean movement time across trials for each condition of each subject and the standard deviation across trials of each subject were obtained. The movement times were analyzed for differences among experimental conditions.

Fig. 1 Schematic of relationship between ankle (θ_a), knee (θ_k), and hip (θ_h) joint angles and the position of L5



COP variability in standing

We examined COP variability in both the A-P and M-L directions during upright stance after subjects finished standing up. The time over which this variability was calculated was determined for each subject by finding the trial with the shortest period of standing after rising and prior to sitting down. This was done to ensure that the variability was calculated over the same number of samples for each condition. Although the period of standing was intended to be 5 s for each trial, it actually varied somewhat across trials, depending on how stable a subject was after rising. COP variability for all other trials of all three conditions was then calculated for this time period after the subject stood up.

Task variable variability

The standard deviation across trials of both the horizontal and vertical positions of the CM and head were obtained at each 10% of the movement trajectory as measures of stability of the hypothesized task variables that were studied in this experiment.

Joint configuration variability

To address the question of how joint redundancy is used in the control of the STS task, variability of the joint configuration across repetitions was partitioned into two components. One component of variability represents fluctuations of the joint configuration that does not change the value (across repetitions) of the task-related variable under consideration. The second component of variability leads to a change in the value of the task variable across repetitions; i.e., it represents fluctuations of the task variable itself.

Here, we illustrate the UCM method for partitioning variance of the joint configuration across repetitions with respect to particular task variables by a simple example. Consider the importance of controlling the horizontal position of the center of mass in upright standing (Pai and Rogers 1990). For simplicity, we assume that the CM is located in the lower lumbar spine when standing relatively upright and consider horizontal motion only (The vertical position of the L5 is not important for our example). This task of control-

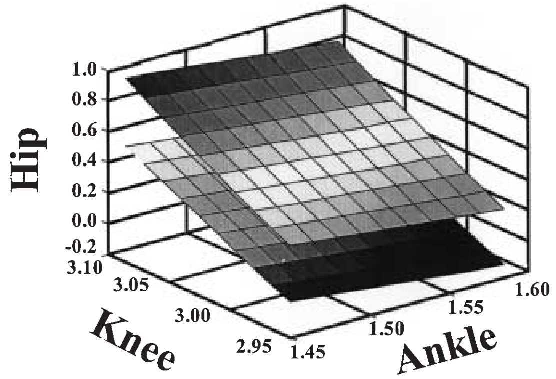


Fig. 2 Two surfaces in the space of the ankle, knee, and hip joint angles, within which lie all joint angle combinations that lead to an identical horizontal position of L5 (–0.05 m and 0.0 m for the two surfaces). Each surface forms part of an uncontrolled manifold for the control of the L5 vertebral position, and represents goal-equivalent solutions to the problem of controlling the horizontal position of this task variable

ling the position of L5 is redundant with respect to joint control, because the task variable, having one DOF, is a function of three joint angles (we assume in this simple illustration that the foot is fixed on the floor; see Fig. 1).

Each surface, or UCM, shown in Fig. 2 is embedded in the space of the three joint angles and represents possible combinations (though not all possible) of ankle, knee, and hip angles that lead to the same horizontal position of L5. Figure 2 illustrates the fact that joint combinations consistent with different positions of the task variable, L5, are represented by a different UCM. One might think of movement between two consecutive positions of L5 being accomplished by a shift between two corresponding UCMs in the space of joint control. Moreover, the manifold will differ for different task variables under consideration, because the geometric model relating joint angles to, say, head position, is different from the model relating these angles to CM position.

If a goal of the control system is to keep stable a given position of L5, any combination of angles of the three joints that lie on the appropriate UCM will work. In that sense, variability of the joint configuration from trial to trial lying within the UCM is goal-equivalent variability (GEV) and is referred to as such in this article. Trial-to-trial variability of the joint configuration that does not lie on the appropriate UCM obviously leads to a different position of L5 than was desired and is referred to in what follows as non-goal-equivalent variability (NGEV). These two components of variability are the primary dependent variables of this study, evaluated separately with respect to different hypothesized task variables.

The formal assessment of joint configuration variance makes use of a mathematical procedure that approximates the UCMs linearly and then decomposes actual variations in the joint configuration across trials into components parallel and perpendicular to this linear subspace. Because this mathematical method has been described in detail elsewhere (Scholz and Schöner 1999; Scholz et al. 2000), we provide only a brief account here.

The initial step in a formal analysis is to obtain the geometric model relating the task variable r (e.g., the horizontal, y, and vertical, z, position of the CM) to the joint angle configuration θ. In our experiment, the joint configuration for the hypotheses about controlling CM position is composed of eight angles (angle of the foot with horizontal, and the ankle, knee, hip, lumbar spine, cervical spine, shoulder, and elbow joint angles). Six angles make up the joint configuration that affects the head's position (the same angles except for the shoulder and elbow). Small changes in r are related to changes in θ through the Jacobian, which is the matrix of partial derivatives of the task variable r with respect to the joint angles θ. For example, if the task variable under consideration is the horizontal position of the head, the geometric model relating horizontal head position and the joint configuration is:

$$\begin{aligned} y_{head} = {} & y_{toe} + l_{foot} * \cos(\theta_{foot}) \\ & + l_{shank} * \cos(\theta_{ankle} + \theta_{foot} - pi) + \ldots \\ & + l_{head} * \cos(\theta_{c7} + \theta_{ls} + \theta_{hip} - \theta_{knee} + \theta_{ankle} + \theta_{foot} - pi) \end{aligned} \tag{4}$$

The second step is to estimate the linear approximation to the UCM from the geometrical model. Because the UCM differs for each value of the task variable, a decision is necessary as to what value to use for the estimation. In reality, both joint configurations and task variables vary from trial to trial. Based on the conception of movement as a sequence of postures, we computed the mean joint configuration $\overline{\underline{\theta}}$ at each 1% of movement. Effectively, the value of the task variable $\bar{y}_{head}$ associated with that mean joint configuration was used to construct the UCM.

The linear approximation to the UCM was obtained from the geometrical model, linearized around the mean joint configuration:

$$y_{head} - \bar{y}_{head} = \underline{\underline{J}}(\overline{\underline{\theta}}) \cdot (\underline{\theta} - \overline{\underline{\theta}}) \tag{5}$$

Here, $\underline{\underline{J}}$ is the Jacobian, composed of $\partial y/\partial\theta_j$, where j={foot, ankle, knee, hip, lumbar spine (ls), cervical spine (cs)}. The linear approximation of the UCM is then simply the null-space of the Jacobian (the linear subspace of all deviations from the mean joint configuration that are mapped onto zero by the Jacobian). Matlab was used for the numerical computation of the null-space. At each sample value, the deviation of each trial's joint configuration vector from the mean joint configuration vector was obtained. This deviation vector was then projected onto the null-space, yielding a scalar value that represents how much of the deviation leaves invariant the value of the task variable that corresponds to the mean joint configuration. The complement of this projection is also obtained. The components of the deviation vector of the joint configuration lying within the UCM and those in its complement are then squared, summed across dimensions of the UCM (i.e., sum of squares), and averaged across all trials, resulting in variance measures. The variance estimates were then divided by the appropriate number of DOF. For example, for the hypothesis about controlling horizontal head position, the joint configuration space is six-dimensional and the task variable is one-dimensional. Therefore, the null-space has five dimensions. Thus, variability of the joint configuration that lies parallel to the UCM is divided by 5. The variability perpendicular to the UCM (i.e., variability that changes the value of the task variable from its mean value) is divided by 1. The square root of this normalized variance was obtained for the data analyses, which is reported as variability per DOF.

Comparisons between the joint control structure of different hypothesized task variables can reveal differences or similarities in the importance of different task variables to success at the task. In the present report, we evaluate the use of joint redundancy with respect to hypotheses about control of CM, head, and wrist position. Control of the CM position with respect to the base of support is essential to the maintenance of balance, and its importance has been discussed in previous work (Pai and Rogers 1990; Millington et al. 1992; Hirschfeld et al. 1999; Mourey et al. 2000). A relatively stable path of the head's position may be important for the effective use of vestibular information to assist that control, especially under the deprived perceptual conditions studied in this experiment. Separate hypotheses are tested about control of the horizontal and vertical positions of these variables because of differences found in a previous study of this task (Scholz and Schöner 1999). We also examine the structure of joint configuration variance with respect to control of wrist position to confirm the effectiveness of our additional constraint condition, i.e., where subjects had to maintain light touch of their fingers on the touch bar. Although other, perhaps more dynamic, variables may be of equal or even greater importance to successful task performance (Pai and Patton 1997; Toussaint et al. 1998), we do not address such variables here. A recent analysis of the structure of joint coordination underlying the control of linear momentum and rota-

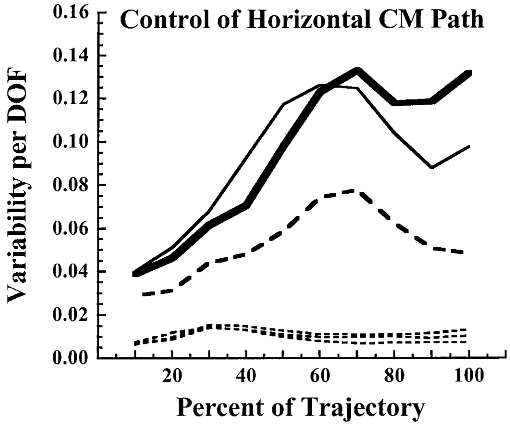


Fig. 3 Goal-equivalent joint configuration variability (GEV), consistent with a stable path of horizontal center of mass (*CM*) positions (narrow base of support condition, *thick solid line*; narrow base of support with touch bar condition, *thinner solid line*; normal base of support condition, *thick dashed line*), and nongoal-equivalent (NGEV) joint configuration variability, leading to a change in the path of the CM. NGEV was nearly equivalent for all conditions and is represented by the *thinner dashed lines* for all conditions (DOF degrees of freedom)

tional momentum about the CM during the STS task revealed similar results to those reported in this article (Reisman et al. 2001).

Data analysis

Repeated-measures analyses of variance (ANOVAs) were performed using the SPSS statistical package to determine differences in the structure of joint configuration variance and actual task variable variability resulting from standing up onto normal (NO condition) and narrow bases of support, the latter with (TB condition) and without (i.e., NB condition) the added touch bar constraint. The dependent measures were evaluated for different control hypotheses, namely, control of the CM and head in both the horizontal and vertical directions. In addition, the control of the resultant wrist position was examined to determine the effectiveness of the touch bar constraint. Our interest here is only in how wrist control differs from the comparable condition where STS was performed on a narrow base of support, NB. Thus, in addition to the experimental condition, within-subjects factors in the analysis of joint configuration variability were (a) the variability component (GEV and NGEV), (b) the hypothesized task variable (head and CM), and (c) the direction of movement (i.e., horizontal and vertical). Wrist position control was evaluated in a separate ANOVA. The same within-subjects factors, except for the variance component, were present in the analysis of task-variable stability, i.e., variability of the CM, head or wrist.

Because we had a light touch condition, we used the opportunity to evaluate the effect of this light touch on variability of the COP during the period following standing onto the narrow base of support and compare the results to those of Jeka et al. under less challenging task conditions (Jeka and Lackner 1994; Jeka et al. 1997). A two-way ANOVA including experimental condition and spatial direction (A-P and M-L) was performed to evaluate COP variability in standing. When there was a significant effect of a particular factor or interaction related to our hypotheses, planned contrasts were performed using the SPSS m-matrix structure.

The analyses presented in this article are limited, with a few exceptions, to the mid-range of the movement, between 40–70% of the movement period. (The data were normalized in time such that liftoff from the seat occurred at 20% of the movement period.) This decision was based on several facts. First, it was during this period that the CM was farthest from both the initial and final base of support. Second, changes in the experimental variables of interest during this period were relatively consistent from one percentage of the movement path to another. Finally, differences among task conditions in the structure of joint control for the CM hypothesis were consistently largest during this period (Fig. 3).

Results

Task success

All subjects reported that performing the STS task on the narrow base of support, without the added light touch, was substantially more difficult than when rising on the normal surface. Most subjects reported that the added use of a touch bar made it easier to stand up. A few subjects reported that trying to maintain their finger force below the prescribed 1 N created added difficulty which countered any positive effect of the enhanced sensory information. Generally, subjects were relatively successful at standing up on the narrow base of support. The number of trials that were judged unsuccessful, and subsequently eliminated from the UCM analysis, illustrates the challenge posed by this condition. These trials were deemed unsuccessful because of a loss of balance, leading to a forward or sideward step, asymmetrical posture in an attempt to maintain balance, or instability in the upright position (i.e., subject not fully upright and oscillating back and forth before falling back to the seat). For example, the six subjects performed 92 trials successfully in the NB condition, while 32 trials were judged unsuccessful due to falls for one of the reasons noted here. In contrast, 97 successful trials were performed in the TB condition, while only 4 trials were rejected because the subject lost balance or stepped. There were actually more trials in which the subjects failed to maintain the force below the specified level in the TB condition, but we deleted most of these trials immediately and do not have an accurate count. In contrast, there were no unsuccessful trials in the NO condition (N=91 trials). Because the nature of failures varied substantially (stepping off forward, stepping off to one side, or falling back into the seat immediately or after unstable oscillation in the near-upright position), these trials were not analyzed further.

Movement time

There were significant differences in movement time among the three experimental conditions ($F_{2,10}=16.626$, $P<0.001$). Pairwise comparisons revealed a shorter movement time when rising onto the NO base of support (154.93±8.08 ms) compared with rising onto the narrow base of support, whether with (TB: 182.68±8.21 ms; $P<0.004$) or without (NB: 174.16±6.39 ms; $P<0.014$) the added TB constraint. There were no significant differences in movement time between the NB and TB conditions.

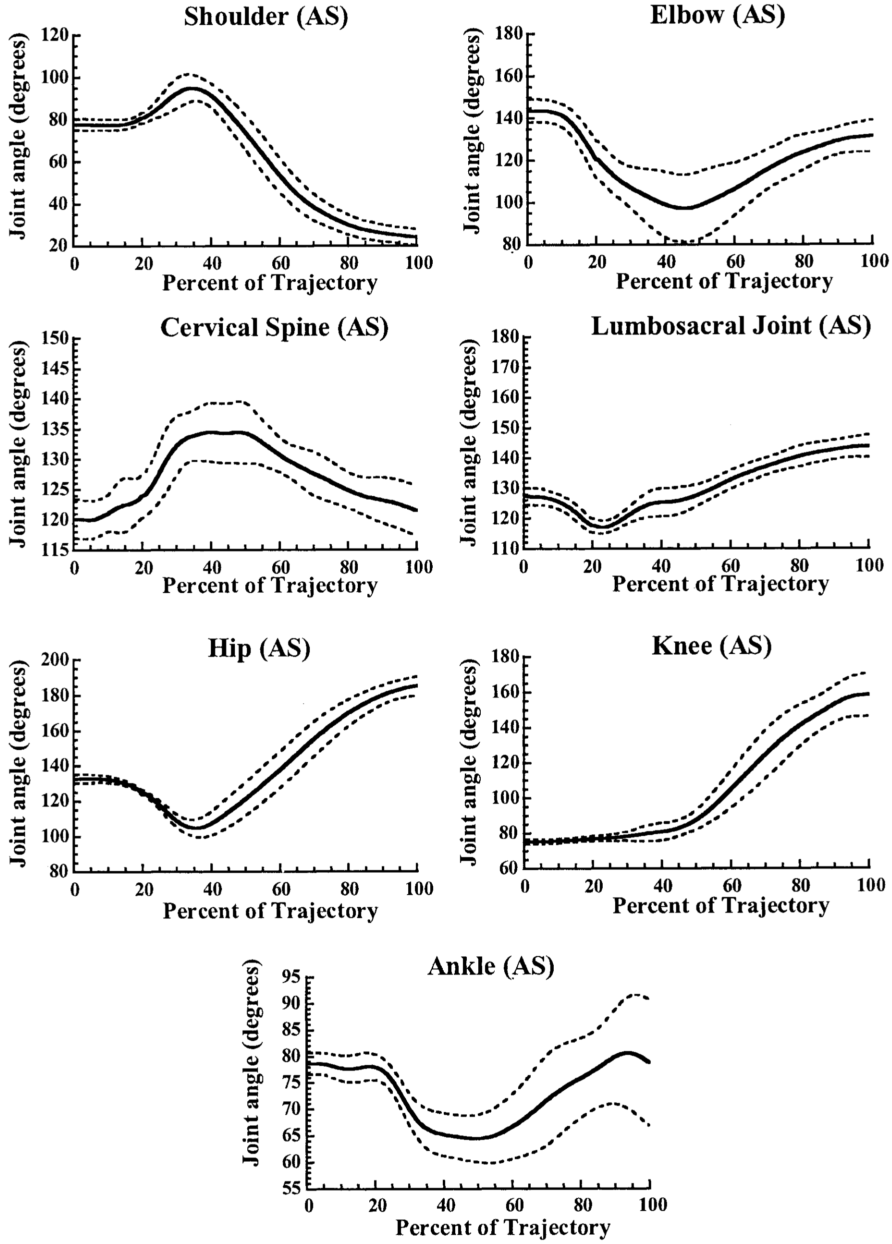


Fig. 4 Mean joint excursion for subject A.S. in the TB condition: shoulder flexion (*upper left panel*), elbow flexion (*upper right*), cervical spine extension (*2nd row, left*), lumbar spine extension (*2nd row, right*), hip extension (*3rd row, left*), knee extension (*3rd row, right*), and ankle plantarflexion (*bottom*). *Dashed lines* represent ±1 SD about the mean excursion

Movement excursion variability

The variability of joint movement excursion across ten trials of the STS task is illustrated for the TB condition in Figs. 4 and 5 for two different subjects, respectively. Subject A.S. had the most difficulty of all subjects in maintaining postural stability on the narrow base of support, with and without the added touch bar. Subject E.D. was one of the subjects with the least difficulty performing the task.

Stability of the task variables

The mean (across subjects) standard deviation of the CM and head, calculated over all trials of a condition, is presented in Fig. 6 for the horizontal movement direction and in Fig. 7 for the vertical movement direction. There was a significant main effect of task variable, with CM variability always lower than head position variability, regardless of condition or movement direction ($F_{2,10}$=12.96, P<0.01).

CM position variability

Variability of the horizontal path of CM positions was significantly less in the NO condition than in the TB condition ($F_{1,5}$=37.92, P<0.05) or the NB condition ($F_{1,5}$ =6.68, P<0.05; Fig. 6). In contrast, there was no significant difference between the CM variability in the NB and TB conditions. Thus, the added constraint posed by

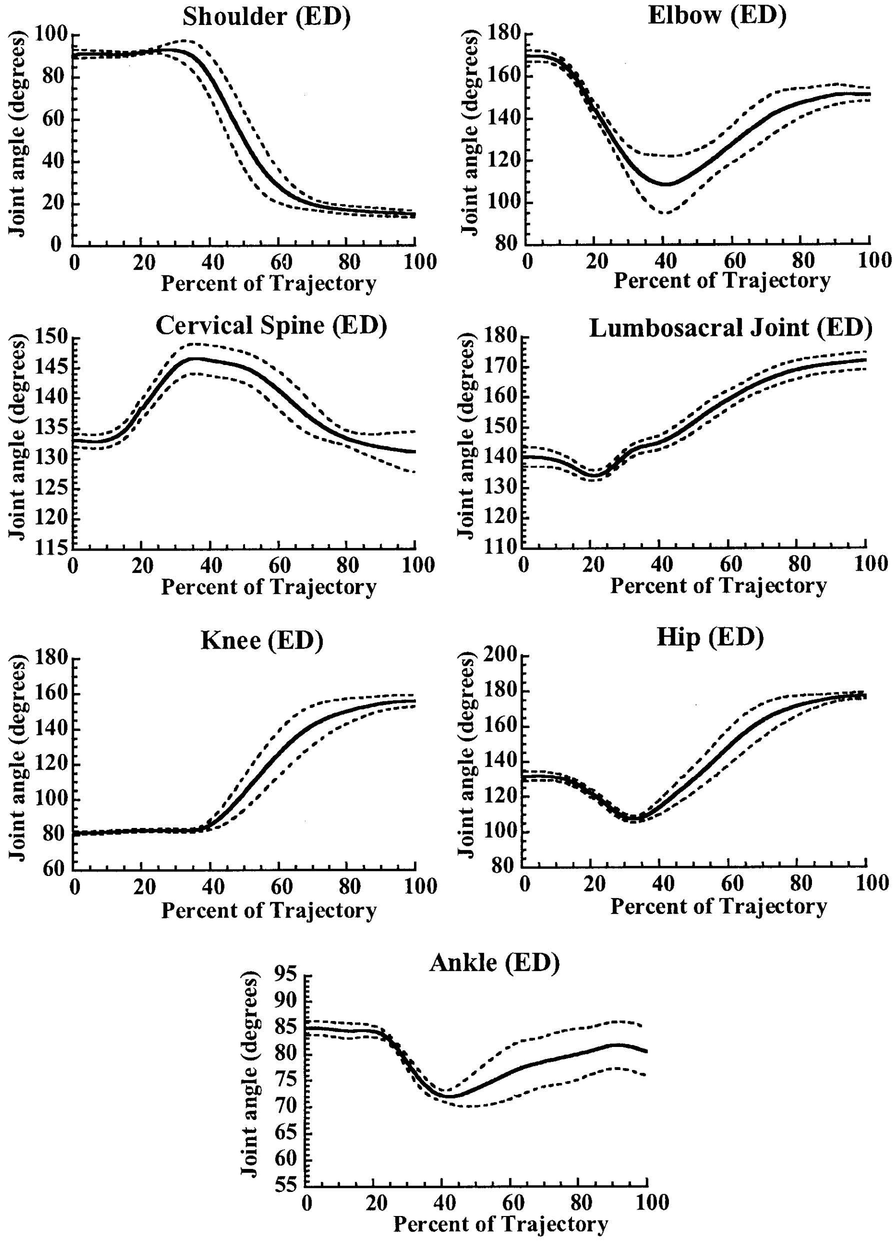


Fig. 5 Mean joint excursion for subject E.D. in the TB condition: shoulder flexion (*upper left panel*), elbow flexion (*upper right*), cervical spine extension (*2nd row, left*), lumbar spine extension (*2nd row, right*), hip extension (*3rd row, left*), knee extension (*3rd row, right*), and ankle plantarflexion (*bottom*). *Dashed lines* represent ±1 SD about the mean excursion

keeping the fingertips on the touch bar provided neither an advantage nor a disadvantage in terms of the stability of CM position.

Although the data exhibited a similar trend (Fig. 7), CM variability was not significantly different among the conditions in the vertical movement direction.

Head position variability

A significant difference in head position variability was present only between the TB and NO conditions for the horizontal movement direction. Head variability in NO was lower ($F_{1,5}$=46.29, P<0.001). The quantitative differences, NB > TB > NO, in vertical head position variability were not significant (P>0.05).

Wrist position variability

The different experimental conditions placed different constraints on the wrist position, as intended by the TB condition. Note that it was the fingertips that were required to remain stationary on the touch bar during the TB condition, so that some variability of wrist position was expected. Unfortunately, we did not have a marker on the fingers. Thus, the wrist marker was the most distal marker that could be examined.

The results for wrist variability are consistent with the different requirements of the NB and TB conditions. Wrist position variability was significantly lower in the TB condition (0.0154±0.0019 m) than the NB condition (0.0475±0.0062 m; $F_{1,5}$=23.516, P<0.01) or the NO condition (0.0335±0.0064 m; $F_{1,5}$=8.726, P<0.05). There

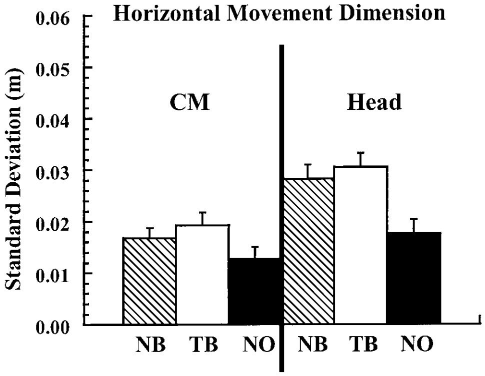


Fig. 6 Mean (+ SEM) task variable variability in the horizontal movement direction for center of mass (*CM*) and head (*HD*) position in the mid-portion of the movement. Adjacent sets of *bars* for each task variable represent the results for the narrow base of support (*NB*, *diagonal fill*), narrow base of support with touch bar (*TB*, *open bar*), and normal base of support (*NO, black fill*) conditions

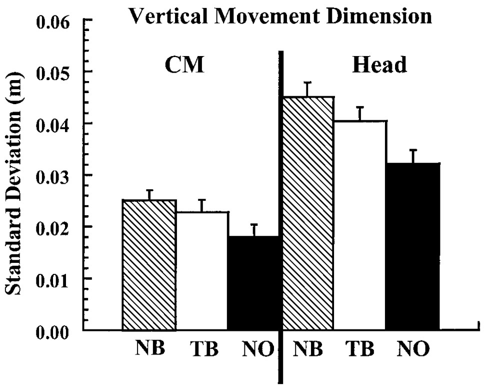


Fig. 7 Mean (+ SEM) task variable variability in the vertical movement direction for center of mass (*CM*) and head position in the mid-portion of the movement. Adjacent sets of bars for each task variable represent the results for the narrow base of support (*NB, diagonal fill*), narrow base of support with touch bar (*TB, open bar*), and normal base of support (*NO, black fill*) conditions

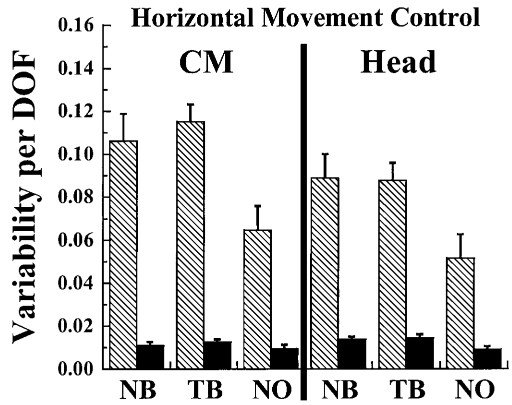


Fig. 8 Mean (+ SEM) components of joint configuration variability per DOF underlying control of the CM and head positions in the horizontal movement direction. Adjacent pairs of *bars* represent GEV (*left, diagonal filled bar*) and NGEV (*right, black filled bar*) components in the mid-portions of the movement for the narrow base of support (*NB*), narrow base of support with touch bar (*TB*), and normal base of support (*NO*) conditions. Note the dramatically lower variability in directions in joint space that affect the horizontal positions of the CM and head than in directions that do not affect these positions. Moreover, the value of NGEV is relatively independent of the experimental condition, while GEV reveals an increase in the use of goal-equivalent joint configurations for the two conditions with a narrow base of support (NB and TB)

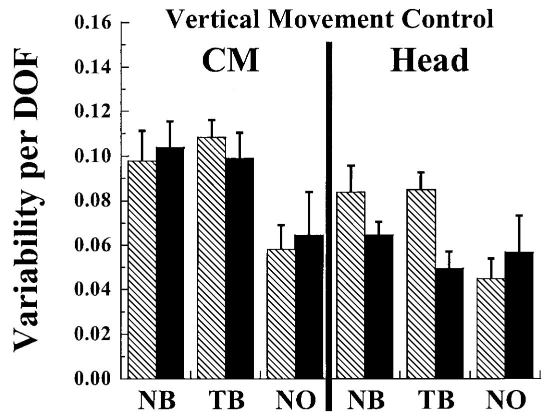


Fig. 9 Mean (+ SEM) components of joint configuration variability for the control of the vertical positions of the CM and head. Adjacent pairs of *bars* represent GEV (*left, diagonal filled bars*) and NGEV (*right, black filled bars*) in the mid-portion of the movement for the narrow base of support (*NB*), narrow base of support with touch bar (*TB*),and normal base of support (*NO*) conditions

were no significant differences in wrist variability between the NB and NO conditions (P=0.13).

Components of joint configuration variability

The results of decomposing joint configuration variance into GEV and NGEV are shown for both CM and head position control in Figs. 8 (horizontal direction) and 9 (vertical direction). In each adjacent pair of bars for each condition, the GEV component of joint configuration variability is represented by the bar with diagonal-fill pattern, while the solid black bar represents the NGEV component.

Significant main effects were found for experimental condition ($F_{2,10}$=7.412, P<0.05), task variable ($F_{1,5}$=92.59, P<0.0001), movement direction ($F_{1,5}$=51.83, P<0.001), and component of joint variability ($F_{1,5}$=98.46, P<0.0001). There were also several significant two- and three-way interactions as well as a significant four-way interaction ($F_{2,10}$=16.181, P<0.001). The nature of the four-way interaction can be seen in Figs. 8 and 9, where it is apparent that the difference between the GEV and NGEV components depends on the experimental condition, the task variable, and the direction of movement. We focus here on significant effects that are most related to differences between experimental conditions and contrasts between different hypothesized task variables that might reveal differences in their relative importance (e.g., con-

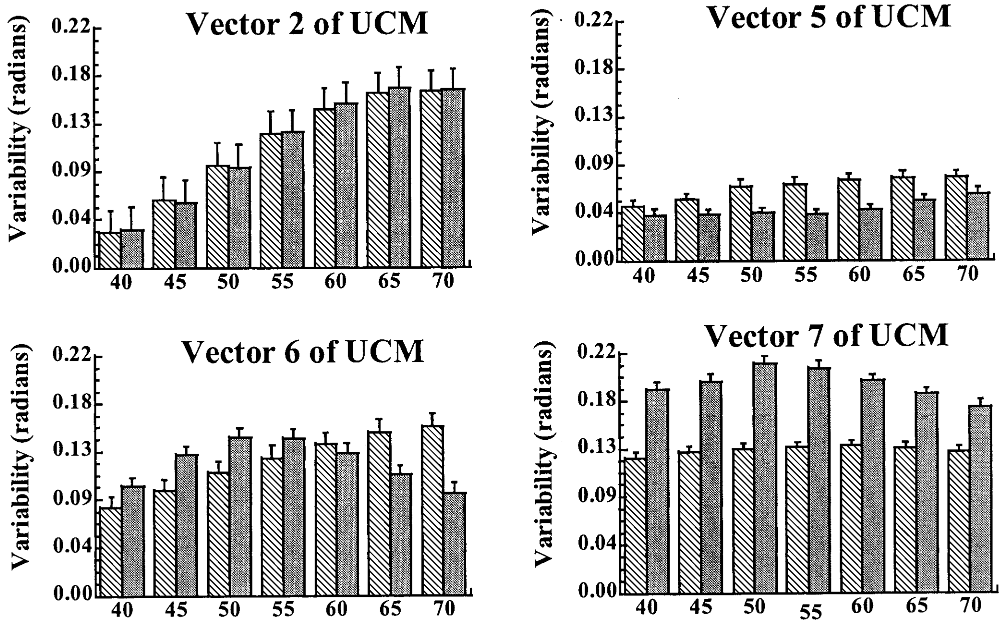


Fig. 10 Vector components of joint configuration variability for four different dimensions of the uncontrolled manifold (*UCM*) related to control of the horizontal path of CM positions. Each plot displays the mean (across subjects + SEM) GEV component along that dimension of the UCM for the NB (*bar with diagonal fill*) and TB (*solid gray bar*) conditions at each 5% of the mid-portion of the movement

trol of horizontal CM compared with vertical CM in the more challenging conditions vs the NO condition).

Structure of joint configuration variability for control of CM position

For the horizontal movement direction, the GEV component underlying the control of the CM position was substantially greater than the NGEV component in all experimental conditions ($F_{1,5}$=372.111, P<0.0001; Fig. 8). In contrast, for the vertical movement direction, GEV ≈ NGEV for all conditions ($F_{1,5}$=0.455, P=0.530; Fig. 9).

When comparing results for different directions of the CM path, GEV was of similar value for the horizontal and vertical paths while NGEV was substantially and significantly higher for the vertical than for the horizontal path of the CM ($F_{1,5}$=57.1, P<0.001; cf. Figs. 8 and 9, left sides). Thus, trial-to-trial variations of the joint configuration related to control of the vertical path of CM positions were nonselective. That is, they tended to change the vertical path of the CM from trial to trial from its mean value as often as not.

There also was a significant effect of the support surface on the structure of joint configuration variability. The GEV component of joint configuration variability was more than 1.5 times higher in both NB and TB conditions compared with NO ($F_{1,5}$=9.4, P<0.05), independent of the movement direction (Figs. 8, 9). Thus, a greater range of goal-equivalent joint combinations, i.e., consistent with a stable CM position, were used in the more challenging task conditions (NB and TB) than in the NO condition. In comparison with the GEV component, NGEV was relatively low and did not differ between the experimental conditions (P=0.07) for horizontal CM control (Fig. 8, left side). Thus, the difference GEV > NGEV was larger for the difficult task conditions. In contrast, for vertical CM control, the NGEV component also increased under the more challenging task conditions (NB and TB) compared with the NO condition (Fig. 9, left side), although, as noted above, *GEV ≈ NGEV for vertical CM control in all experimental conditions*.

Structure of joint configuration variability for control of head position

Overall, the GEV component of joint configuration variability was significantly higher than NGEV for control of the horizontal path of head positions ($F_{1,5}$=70.410, P<0.0001; Fig. 8, right side). The difference GEV >NGEV was also significant for the control of vertical head position ($F_{1,5}$=8.046, P<0.05). The magnitude of the GEV >NGEV difference was largest for horizontal CM control, however ($F_{1,5}$ =26.56, P<0.01; Fig. 8).

In addition, differences in the support surface condition resulted in quantitative (Fig. 8, right side) and qualitative (Fig. 9, right side) differences in the structure of joint configuration variability. For example, the difference GEV > NGEV, related to vertical head control, was only significant for the more challenging NB and TB support conditions, while NGEV > GEV for the NO condition (Fig. 9, right side). And although the GEV > NGEV difference that was related to horizontal head control held for all experimental conditions (Fig. 8, right side), the GEV component was significantly higher in the NB and TB conditions compared with the NO condition, which was true for vertical head control also ($F_{1,5}$=23.07, P<0.05). Thus, differences in the structure of joint configuration variability for control of vertical and horizontal head position were primarily due to differences in the selectivity of that structuring, NGEV related to vertical head control being more substantial ($F_{1,5}$=28.2, P<0.003).

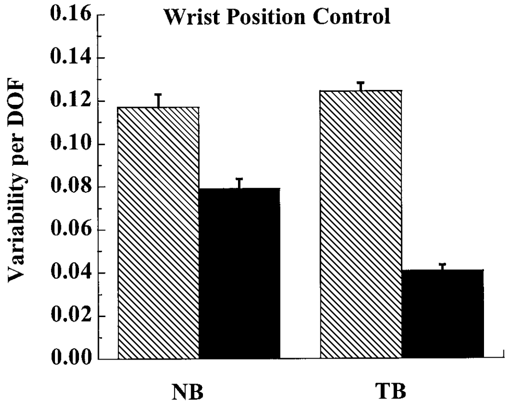


Fig. 11 Mean (+ SEM) components of joint configuration variability for the control of the resultant position of the wrist. Adjacent pairs of *bars* represent GEV (*left, diagonal filled bars*) and NGEV (*right, black filled bars*) in the mid-portion of the movement for the narrow base of support (*NB*) and narrow base of support with touch bar (*TB*) conditions

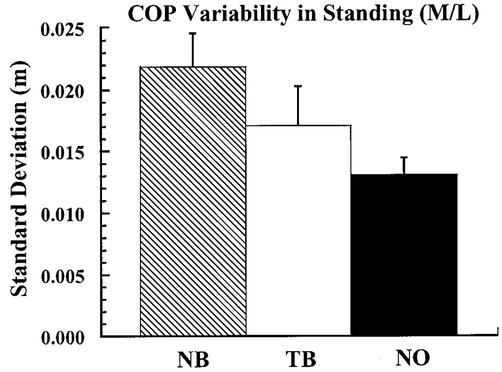


Fig. 12 Mean (+ SEM) center of pressure (COP) variability in medial-lateral (M/L) direction during the standing phase of the task

Effect of touch bar on joint configuration variability

Neither the GEV nor the NGEV component of joint configuration variability differed significantly between the NB and TB conditions ($P>0.05$). This was true for joint configuration variability partitioned with respect to both the head and CM hypotheses. Thus, the added touch bar constraint did not appear to provide an advantage or disadvantage in stabilizing the path of CM or head positions (see CM position variability) or with respect to the style of joint coordination underlying that control.

Although no difference was found in the magnitude of the variability components between the NB and TB conditions, there were differences in how GEV was structured within the UCM for each condition. This is shown in Fig. 10 for control of the horizontal CM path. The figure presents the joint configuration variability along four (of the seven) different basis vectors defining the dimensions of the UCM to illustrate this point. The results are presented at each 5% of the mid-portion of the CM trajectory (i.e., the period over which all other analyses were performed). Note that the variance at each 5% represents variance for successive UCMs along the CM trajectory (see Materials and methods section). For some dimensions of the UCM (e.g., vector 2), there were no differences in joint configuration variability between the NB (bar with diagonal fill) and TB (bar with solid gray fill) conditions. Along other dimensions of the UCM (e.g., vector 6), the difference in variance between the conditions depended on the percentage of the trajectory examined. Still other dimensions (vectors 5 and 7) show differences in variability between the two conditions. For example, greater variability along null-space vector 7 was found for the TB condition than the NB condition, indicating a greater range of goal-equivalent joint configurations utilized in the TB condition that lie along this dimension of the UCM. It is important to point out that, because the UCM cuts across joint space, a particular dimension of the UCM cannot be easily related to particular joint angles. Again, the variability is of the entire joint configuration.

Structure of joint configuration variability for control of wrist position

Joint configuration variability was structured in a way that was consistent with the requirement that subjects maintain light fingertip touch in the TB condition, requiring a more consistent wrist position than in the other conditions. Of primary interest here is the comparison between the TB and NB conditions, which were identical except for the light touch required in the TB condition. There was a significant interaction ($F_{1,5}=43.28$, $P<0.001$) between the experimental condition (NB vs TB) and the variance component (GEV and NGEV). Figure 11 reveals that this was due to a substantially larger difference GEV > NGEV in the TB condition, which had higher GEV and lower NGEV than the NB condition. The difference between GEV and NGEV was also significant for the NB condition ($F_{1,5}=35.87$, $P<0.01$), indicating that the wrist position was controlled to some extent even when this was not a requirement. However, NGEV was significantly higher in the NB than in the TB condition ($F_{1,5}=7.84$, $P<0.05$), indicating more consistent stabilization of the wrist in the TB condition, a finding consistent with the lower task variable variability found in this condition (see Task variable variability).

COP during standing

The variability of the center of pressure during upright standing, after rising from the seat, differed between the experimental conditions for both the A-P and M-L spatial directions ($F_{2,10}=10.401$, $P<0.004$; Figs. 12, 13). Planned contrasts revealed significant differences between the NB and TB conditions, with lower variability in the TB condition for both A-P ($F_{1,5}=12.921$, $P<0.05$) and M-L ($F_{1,5}=11.673$, $P<0.05$) spatial directions. COP vari-

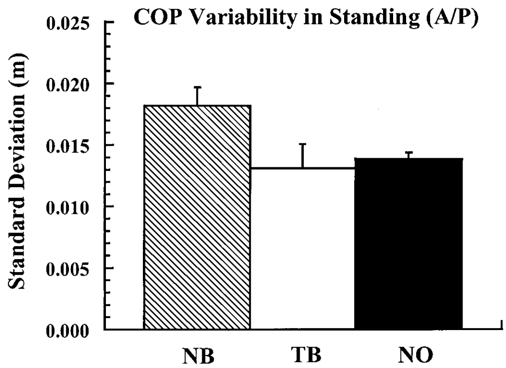


Fig. 13 Mean (+ SEM) COP variability in anterior-posterior (A/P) direction during the standing phase of the task

ability was also significantly less in the NO condition compared with NB in both spatial directions (A-P: $F_{1,5}$=321.198, P<0.001, M-L: $F_{1,5}$=26.732, P<0.01). There were no significant differences between the TB and NO conditions in either direction.

Discussion

When the STS task was performed under challenging task conditions, a significant increase in joint configuration variability was observed, along with a slight increase in the variability of task-related variables such as the horizontal path of CM and head positions (Fig. 6). Nonetheless, it is clear from the UCM analysis that much of the increase in joint configuration variability did not result in increased task variable variability. Instead, joint configuration variability was selectively channeled into increased goal-equivalent joint combinations, i.e., combinations that were equivalent with respect to the task of stabilizing the position of the CM and head. This style of control is consistent with the task dynamic control strategy proposed by Saltzman and Kelso (1987). The finding of differential control along different directions of joint space supports the view that the CNS responds to increased task difficulty through enhanced coordination among the component DOFs. The results of this study also corroborate previous work of Scholz and Schöner (1999), which showed that coordination of the STS task, performed under less stringent task constraints, was characterized by the use of many goal-equivalent joint combinations, rather than the use of a select joint control strategy.

The manipulations used to make the STS more challenging in this study, particularly the narrow base of support, were novel for our subjects. The observed increase in the range of joint combinations used under these challenging conditions, representing a "freeing" of DOFs, contrasts with earlier work suggesting that "freezing" of DOFs occurs in the early stages of learning a novel task (Bernstein 1967; McDonald et al. 1989; Vereijken et al. 1992). For example, Vereijken et al. (1992) have found that the mean cross-correlation between pairs of lower limb joint motions were quite high in the early stage of learning a novel skiing task. These correlations decreased as the subjects became more skilled at the task. Let's assume that the joints were coupled to produce stable motion of a task variable such as the position of the CM. Then their result suggests that a greater number of alternative and equivalent joint combinations (i.e., in terms of the control of some task variable) were being used to accomplish the task after learning had progressed sufficiently. Differences in interjoint correlations also were reported by McDonald et al. (1989) between the dominant and nondominant limb when learning to throw a dart. These authors reported relatively consistent hand trajectories for either hand, while the interjoint correlations underlying the hand trajectories were significantly lower in the dominant arm. This suggested a greater freeing of DOFs when performing with the dominant hand, a difference that was reported to persist throughout learning (McDonald et al. 1989).

It is important to point out, however, that the methods used to address coordination in those studies were quite different from those employed in our study. In the studies cited here, pairs of joint motions were correlated in time. Thus, their measures represent indices of stability of timing relationships rather than of postural stability (see Schöner 1995). In contrast, our method looks at the stability within the joint configuration space across repetitions at each point along a movement trajectory. Although our results suggest some consistency in the use of goal-equivalent solutions along the entire movement path (Fig. 3), they do not address timing stability directly. Keeping these differences in mind, our study indicates a type of "freeing-up" (i.e., increase in the number of goal-equivalent solutions used) rather than "freezing out" of the joint configuration for a relatively automatic and well-learned task when performed for the first time under challenging task conditions (i.e., TB and NB).

What advantage might this control strategy provide? As noted elsewhere, the activation of even one-joint muscles results in interaction torque at adjacent joints. Interaction torque must lead to additional control action if the desired posture or movement pattern is to be preserved (Hollerbach and Flash 1982). Thus, if control action can be limited to that which is essential, the need for additional control action to compensate for its effects at other joints would be reduced. A control strategy that frees joint combinations from control along dimensions of joint space that do not affect important task variables would confer advantages. According to this scheme, the exact joint configuration used for a particular instantiation of the task would depend on local factors, including interaction torque that is unavoidable. While our results do not provide evidence for a direct relationship between the level of interaction torque and the range of goal-equivalent joint combinations used, it is interesting to speculate that the control strategy identified in this study may provide such an advantage. In many everyday tasks, the actor needs to combine accuracy in task execution with compliance in directions that do not endanger task success to avoid injury in case of an unpredictable perturbation (Scholz et al. 2000). Note that perturbations are, in general, not specific to the functional task but perturb all DOFs equally. A control law that stabilizes an uncontrolled manifold may ensure a degree of “yielding” which is compatible with successful task execution. Therefore, it is likely that when the risk of external perturbations increases, as occurred under the challenging task conditions in this study, the need to minimize mechanical perturbations by reducing control action becomes increasingly important. This contrasts with an alternative style of control in which one or a small number of joint combinations are used to achieve a particular value of important task variables.

Structure of joint control in different movement directions

The results discussed above apply primarily to control of the horizontal motion of the CM and the head. In contrast, control of vertical movement was characterized more by nonselective joint coordination. Although an increase in the range of goal-equivalent joint configurations, related to control of vertical CM and head position, also occurred in the NB condition compared with the NO condition, a generally equivalent increase in joint configuration variability occurred that changed the value of these task variables. Thus, control of the vertical position of the CM or head is apparently not as important as control of the horizontal position of these task variables. This finding is understandable given that the horizontal location of the CM with respect to the base of support is, in particular, critical to maintaining body equilibrium in such tasks (Pai et al. 1994; Pai and Patton 1997; Buchanan and Horak 1999). It is noteworthy though that the structure of joint configuration variability for control of vertical CM position was quite different in this study compared with that reported by Scholz and Schöner (1999). There, both horizontal and vertical CM position exhibited similar joint coordination. In the more challenging task conditions of the present experiment, the less-apparent joint coordination for control of vertical CM position may reflect a trade-off required to enhance coordination related to control of the horizontal CM position. This contrasting result with the previous study further supports a relative difference in the importance of controlling horizontal and vertical movement for task success.

Control of head motion

Because subjects performed the STS task without vision and they had reduced contact information about the support surface in the NB conditions, they may have been more dependent on vestibular information for spatial orientation (Massion 1994). Somatosensory information from the soles of the subjects’ feet was impoverished and visual information was eliminated. Somatosensory, visual, and vestibular information all are important to maintaining balance (Shumway-Cooke and Woollacott 1995). It has been demonstrated that body sway in standing increases with decreased cutaneous information from the soles of the feet (Magnusson et al. 1990). Postural sway further increases when subjects close their eyes. Buchanan and Horak (1999) have demonstrated that the horizontal position of the head and CM was more variable without vision during sinusoidal support surface translations. Hence, in the narrow base of support conditions of the present study, alteration of sensory information should make balance more challenging. Indeed, this was a consistent report of the subjects who performed this task.

If subjects were more dependent on vestibular information for control of the body in this experiment, then we would predict enhanced joint coordination related to control of the head position. In fact, the absence of vision itself was apparently sufficient to produce this effect. That is, even when standing up onto a normal base of support, the range of goal-equivalent joint configurations used to stabilize the horizontal path of head positions was substantially greater than the range of joint configurations inconsistent with head position invariance across trials. This contrasts with a previous report of STS performed with vision, where the two components of joint configuration variability were nearly identical (Scholz and Schöner 1999). Moreover, although the NGEV component of joint configuration variability was relatively high under all performance conditions in the current study (Fig. 9), GEV was significantly higher than NGEV when subjects performed on the narrow base of support. This contrasts with the result for vertical CM control. In combination, then, these results are consistent with enhanced coordination of joint motions related to stabilizing the path of the head when the task was made more challenging.

Relationship between joint configuration and task variable variability

Task variable variability was significantly lower for the horizontal CM position than for horizontal head position (Fig. 6). This was true for all task conditions. This contrasts with our finding that the component of joint configuration variability that changes the task variable away from its mean position (NGEV) was relatively low overall and not substantially different for head and CM control (Fig. 8). How can these results be reconciled? We have shown in earlier work that, depending on where one is in the workspace and the nature of changes within the joint configuration, a task variable can be more or less sensitive to changes in the joint configuration reflected by the NGEV component (Scholz and Schöner 1999). For example, near the end of the sit-to-stand movement, vertical head position was shown to be less sensitive than horizontal head position to changes in the joint configuration. This is not surprising if one visualizes how

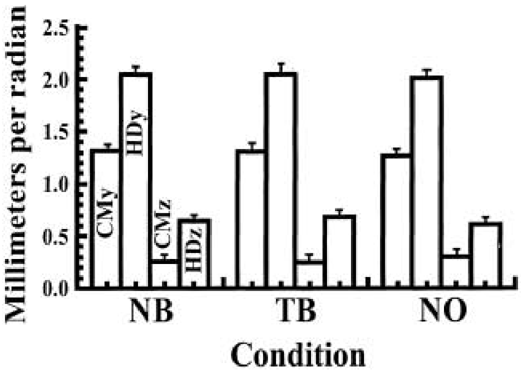


Fig. 14 The effect of non-goal-equivalent joint configuration variability on the value of the task-related variables CM and head (*HD*) position in both the horizontal and vertical movement directions. The UCM lying in the eight- and six-dimensional joint space for control of the CM and head path (i.e., a given direction of either CM or head motion), respectively, is seven and five dimensions. Thus, variability of the joint configuration along one dimension orthogonal to either UCM (i.e., NGEV) will lead to a change of the task variable's position. The height of the *bars* represent how many millimeters of change of the CM and head position is predicted for 1 rad of change along this one dimension in joint space, i.e., the sensitivity of the task variable to changes in the joint configuration. Presented is the mean (+ SEM) of this measure across the identical part of the movement trajectory for which the other measures were calculated (Figs. 6, 7, 8, 9). NB, TB, and NO are the experimental conditions as defined previously. The *labels in each bar* for the NB condition indicate the task variable and movement direction represented. The sequence is the same for the other conditions

ankle rotation in the fully upright standing position would differentially influence the head's motion in the horizontal and vertical directions. A similar explanation appears to account for the differences between horizontal CM and horizontal head variability observed in this study, despite similarly low NGEV for both task variables. This point is illustrated in Fig. 14.

Figure 14 presents a measure of the sensitivity of task variable variability to changes in the joint configuration that tend to change the value of the task variable. This analysis was possible because the control hypotheses were formed separately for each movement direction for both the CM and head. Thus, in joint space there was a single direction along which NGEV variability changed. In contrast, seven and five dimensions, respectively, were associated with GEV, i.e., variability consistent with a stable CM and head position. The sensitivity of the task variables to variations of the joint configuration along this single axis of NGEV can be characterized by multiplying the Jacobian matrix with a unit vector spanning that axis. A single value (in millimeters per radian) results, the absolute value of which represents how much task variable change (in millimeters) is generated by a unit change of the joint configuration in the NGEV direction (in radians; i.e., orthogonal to the UCM). One can see from the figure that, for the horizontal (y) movement direction, the head is more sensitive than the CM to the same amount of change in the joint configuration, which is consistent with the higher variability of horizontal head position. A similar analysis can be applied to explain apparent discrepancies in the NGEV component of joint configuration variability and task variable variability for control of vertical CM and head positions (Fig. 14). While the NGEV component was higher for CM than for head control, vertical CM motion was also substantially less sensitive to that variability than was vertical head motion (Fig. 14).

The effect of light touch

The TB condition was added to impose an additional constraint on the already challenged postural control system to determine how it would adapt. That subjects fulfilled this constraint was evident from examination of joint coordination related to control of the wrist position (Fig. 11). Note that the requirement to keep the fingertips in contact with the touch bar limits the number of joint configurations that can be used to stabilize a particular CM position. That is, there probably are joint combinations consistent with a particular value of the CM position which take the hands away from the touch bar. Those conditions cannot be used while fulfilling the touch bar constraint. One might have expected, then, a decrease in the range of goal-equivalent joint configurations used in the TB condition compared with NB. This was not the case. This expectation presupposes that all possible joint combinations consistent with a stable value of a task variable will typically be realized. In practice, this is highly unlikely. The CNS apparently adapted to the added touch bar constraint by channeling joint configuration variability into different directions of the UCM (Fig. 10), thus allowing for a similar freeing of DOFs, i.e., increased range of goal-equivalent joint combinations, in both narrow base conditions.

Recent studies have shown that light fingertip touch can improve postural stability, defined by variability of the COP, during quiet tandem stance without vision (Jeka and Lackner 1994; Lackner et al. 1999). This led us to ask whether the added touch information might confer a similar advantage during the dynamic phase of rising to standing. Assuming that this condition actually did provide enhanced information to the subject about their spatial position, the result indicates that it did not confer an advantage, at least with respect to the variables we examined. Variability of the CM or head did not differ between the TB and NB conditions. We also examined the relative position between the CM and the COP, including its variability, during the dynamic portion of the task, and found no difference across conditions (unpublished result).

A secondary finding of the present investigation, however, was that light fingertip touch did confer an advantage, in terms of reducing COP variability, while standing on the narrow base of support after subjects were upright. Thus, this result extends those of Jeka et al. (Jeka and Lackner 1994; Lackner et al. 1999) to parallel stance on a narrow base of support, indicating that light touch has a stabilizing effect on the COP in both the A-P and the M-L direction under these challenging conditions.

Conclusions

The results of this study are consistent with recent work indicating that, in the performance of many functional tasks, the CNS makes use of the abundant solutions available to it to achieve control over important task-related variables (Scholz and Schöner 1999; Scholz et al. 2000). This style of control is consistent with other recently proposed control schemes (Saltzman and Kelso 1987; Gelfand and Latash 1998) although the presumed problem posed by joint redundancy could be solved by bringing other constraints to bear to produce unique joint configurations (Seif-Naraghi and Winters 1990; Rosenbaum et al. 1996), this does not appear to be a general strategy used by the CNS. Moreover, this study further supports the UCM hypothesis, which suggests that the structure of joint control can provide important insights about the relative importance of different task variables for success at the task. The fact that most of the variability of joint configurations was consistent with goal-equivalent solutions underlying the control of horizontal position of the head and CM, especially when the task was made more challenging, provides evidence for the importance of these variables. In contrast, the structure of joint variability underlying control of the vertical positions of the CM and head indicate nonselective control. This is not meant to imply that other, perhaps more dynamic variables, that were not examined here are not of equal or even greater importance to control of the STS task. For example, we recently have shown that a similar style of joint coordination underlies control of horizontal momentum of the CM as well as rotational momentum about the CM (Reisman et al. 2001).

The current results show that changes in task constraints can lead to an enhanced use of goal-equivalent joint configurations. In the present study, the NB condition in particular was perceived by the subjects as more challenging, as evidenced by a greater tendency to lose balance and step in comparison with the other conditions. The enhancement of the joint control structure found in this condition contrasts with what might be expected from other lines of reasoning (McDonald et al. 1989; Vereijken et al. 1992). Thus, there is apparently an advantage to the increased use of the available joint redundancy, at least in tasks such as STS, where loss of balance can have injurious consequences. Whether this control strategy is a general feature of functional motor tasks or only postural tasks awaits further study.

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