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Differential joint coordination in the tasks of standing up and sitting down

Darcy S. Reisman [b], John P. Scholz [ab,*], Gregor Schöner [c]

[a] *Department of Physical Therapy and Interdisciplinary Neuroscience Program, University of Delaware, Newark, DE 19716, USA*
[b] *Biomechanics and Movement Science Graduate Program, University of Delaware, Newark, DE 19716, USA*
[c] *Neuroinformatik ND/04, Ruhr-Universität, Bochum, Germany*

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Abstract

We studied similarities and differences in the use of goal-equivalent patterns of joint coordination to stand up and sit down from different support surfaces, performed without vision. Sagittal plane motion of major body segments was measured and joint angles for the left upper and lower extremities and the trunk were calculated. We used a modeling strategy relating motion in the redundant space of the joints to motion of individual performance variables, such as the center of mass (CM) or head, and determined how the variability of joint combinations across trials was structured; i.e. variations in joint combinations leading to a consistent value of a performance variable (goal-equivalent variability) and variations resulting in variability of the performance variable (non goal-equivalent variability). We found the variability of joint combinations to be selectively channeled into goal-equivalent directions, leading to stable horizontal motion of the CM and of the head, during both standing up and sitting down. In contrast, when evaluating the effect of joint combination variability on the control of vertical CM motion, we found differences in the variability components between standing up and sitting down. In general, more variable vertical CM motion occurred. An important finding was an enhanced use of goal-equivalent joint combinations under challenging task conditions, whether standing up or sitting down.

Keywords: Movement; Motor control; Coordination; Degrees-of-freedom

1. Introduction

The ability to stand up from sitting is essential for independent, community-level function. Many studies have examined various aspects of this task, while the equally frequent and important task of sitting down from standing has received much less attention [1–6]. Of the few studies that have examined both tasks, normative data on variables such as force production and joint motion in different groups of subjects, including patients, has been provided [2–4,6]. The muscle activity patterns as well as many kinematic parameters have been shown to be similar between the two tasks [1,5]. However, no reports were found that compared the motor coordination of standing up and sitting down.

The present report will focus on similarities and differences in the use of goal-equivalent patterns of joint coordination between the tasks of standing up and sitting down. Given that safe and efficient performance of both tasks is often problematic in individuals with disability and in the aged, an understanding of whether and how the coordination of each task changes with age and disability will be important [6]. The current report focuses on coordination of the two tasks in young healthy individuals to provide a framework for such studies. Among task differences that might lead to differences in coordination are the length of the base of support in the direction of movement (e.g. longer forefoot than hindfoot), the role of gravity, the required muscle action (e.g. concentric vs. eccentric), and the availability of visual information (e.g. sitting down without looking backwards).

The coordination of standing up has been reported previously [7–9]. These studies examined differences in patterns of joint coordination used to control different performance variables, such as the path of the center of mass or its linear momentum. Control is defined here as

* Corresponding author. Fax: +1-302-831-4234.
E-mail address: jpscholz@udel.edu (J.P. Scholz).

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the act of stabilizing a time-series of values of performance variables, where stability was defined as the persistence of a particular value in the face of phasic perturbations [10]. A major finding of the earlier studies was that the nervous system made use of the abundant solutions to joint coordination available to it rather than unique solutions. That is, a range of different joint combinations was used to stabilize the horizontal path of the center of mass [7,8] and its linear momentum [9] when a single, appropriate, combination could have sufficed. Most interesting was the finding that the range of joint combinations used to stabilize the horizontal CM increased markedly when task conditions were made more challenging by having subjects stand up on a narrow base of support [8,9]. The task of sitting down from standing was not investigated, however.

For the current study, we hypothesized that vertical center of mass motion would be well controlled during the task of sitting down, especially under challenging task constraints, in contrast to what was previously reported for standing up [8,9]. Moreover, this would be accomplished by a similar style of joint coordination, i.e. by using a range of joint combinations to stabilize the CM rather than one unique combination. Sitting down should require more controlled vertical motion because of the need to land softly on the seat and because of the precarious nature of this task compared to standing up. In contrast, because control of the horizontal position and momentum of the center of mass with respect to the base of support is likely to be important in both tasks, we hypothesized the results for standing up and sitting down to be similar, both in terms of the stability of performance variables and in the patterns of joint coordination used to achieve that stability.

2. Materials and methods

2.1. Subjects

Five female and four male subjects, (mean: 27.8 years old; ±8.79 years), all healthy, participated in this study. Average height of the subjects was 1.75±0.105 m and average weight was 68.65±12.88 kg. All subjects gave written consent, approved by the Human Subjects Review Committee, before participating in the experiments. Six of the nine subjects participating in this study were included in our previous reports [8,9].

2.2. Equipment and set-up

A complete description of the experimental set-up and method can be found in Scholz et al. [8]. A brief report is provided here. A six camera VICON (Oxford Metrics, UK) motion measurement and analysis system was used to collect motion at 120 Hz. Measurement error, derived from camera calibration, was less than 2 mm for all cameras in the 2.5 m^3 measurement volume.

Analysis was performed using a two-dimensional sagittal plane, link-segment model. Spherical markers, 2 cm in diameter, were applied to appropriate joint centers of the extremities of the body (immediately inferior to the lateral malleolus, lateral femoral condyle, greater femoral trochanter, 2 cm inferior to the lateral aspect of the acromion process of the shoulder, the lateral humeral condyle just superior to the radiohumeral junction, styloid process of the radius). In addition, markers were placed (1) directly anterior to the external auditory meatus (EAM), (2) just lateral to the spinous process of the seventh cervical vertebrae and (3) 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 [11]).

2.3. Experimental procedure

Subjects sat on a flat piano bench adjusted in height so that the distance from the top of wooden blocks used to support the bare feet to the top of the bench seat was 75% of each subject's lower leg length. The knees were placed in 100 degrees of flexion and the foot and buttocks positions were standardized before each trial. One of three different pairs of wooden blocks was used to support the feet, depending on the experimental condition. The blocks were secured with double-sided tape to prevent rocking during the experiments. Each pair of blocks was 11 cm high and measured either 8, 11 or 35 cm in the anterior–posterior 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 or 11 cm blocks were used in two conditions for which only the mid-foot of each foot was in support. Only one of these narrow base (NB) conditions is reported here. 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 seven subjects. The blocks supported on average, 35±3% of each subject's foot length; range = 31–40%. In both conditions, subjects were instructed to hold the arms out in front of the shoulders, horizontal to the support surface. All subjects moved the arms around this initial position to some extent as needed for balance while standing up.

To begin a trial, the subjects were given a verbal "go" command, after which they initiated standing, when they were ready, and then stood up as rapidly as possible without falling, stayed upright for 3 s (counted by the experimenter) and then sat down. We attempted to obtain 15 successful trials (i.e., without steps off of the narrow base of support or general instability in the upright position).

The two experimental 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 kept closed for all experimental conditions. In the "normal" (NO) base of support condition, subjects could obtain normal information from the support surface and the ankle and could apply typical force against the support surface. In the narrow base of support (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.

2.4. Data reduction

The joint markers were identified in each camera view, labeled off line and transformed to their three-dimensional coordinates using the VICON motion system software. The marker coordinates (6 Hz) were then filtered with a bi-directional, second order Butterworth low-pass filter in Matlab.

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 [12].

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 same procedure was followed to determine the period of sitting down.

Once the movement period was determined, the portion of the trial from movement onset to termination in either the upright or seated position was normalized to 100% in 0.5% steps (200 samples) in Matlab using a cubic spline interpolation.

2.5. Conceptual framework

A major purpose of this study was to better understand how the nervous system coordinates the many joint combinations available to achieve the control of important performance variables necessary to accomplish the tasks of standing up and sitting down. A method [7–9] was developed that allows determination of the range of joint combinations used to provide for a stable sequence of values of different performance variables. The mathematical details of this method are described in Appendix A. In this section, our goal is to provide a conceptual definition of this method and to define terminology that will be used throughout the following sections.

2.5.1. Redundancy and manifolds

Many joint angle combinations could be adopted to achieve a particular value of a performance variable, such as the position of the CM. Consider, for example, keeping your finger on the button of a doorbell while wiggling your arm around. All joint combinations performed during the wiggle are, obviously, consistent with the same position of the finger. An important question is whether on repeated presses of the button the same combination of joint angles are used each time or whether a range of the wiggles are used and, if so, how large is that range? This possibility is illustrated with a postural example in Fig. 1A. In this example, three different combinations of the ankle, knee and hip joint angles (A–C) can achieve one position of the fifth lumbar spinal segment (L51). Because only one joint combination is actually required to achieve this position, it can be said that there are an *abundance* of solutions to coordinating these three joints available to achieve this L5 position. We prefer the term "abundant" to the typically used "redundant" because of the negative implication of the latter term [13].

It is possible to obtain mathematically a linear estimate of all possible joint angle combinations that could be used to achieve a particular value of a performance variable. These combinations lie on a multi-dimensional surface in joint space referred to as a *manifold*. In our example, the joint angle combinations A, B and C of Fig. 1A lie on a manifold depicted in Fig. 1C, which represents the positional value of $L5_1$. In contrast, a different position of L5, such as $L5_2$ in Fig. 1B, is achieved by a different set of joint angle combinations (D) and is represented by a different manifold in Fig. 1C. Thus, joint angle combinations lying on this second manifold are consistent with the position of $L5_2$, but inconsistent with the position $L5_1$.

If this particular position such as $L5_1$ was, at a given point in a movement, important to successful completion of the sit-to-stand task, then keeping this position stable over multiple task repetitions could be considered a *goal* of the motor system. Consequently, all joint angle combinations that achieve this position of L5 (A, B and C in our example) can be considered *goal-equivalent* solutions to joint coordination. Thus, if variations of joint angle combinations are observed across repetitions of the

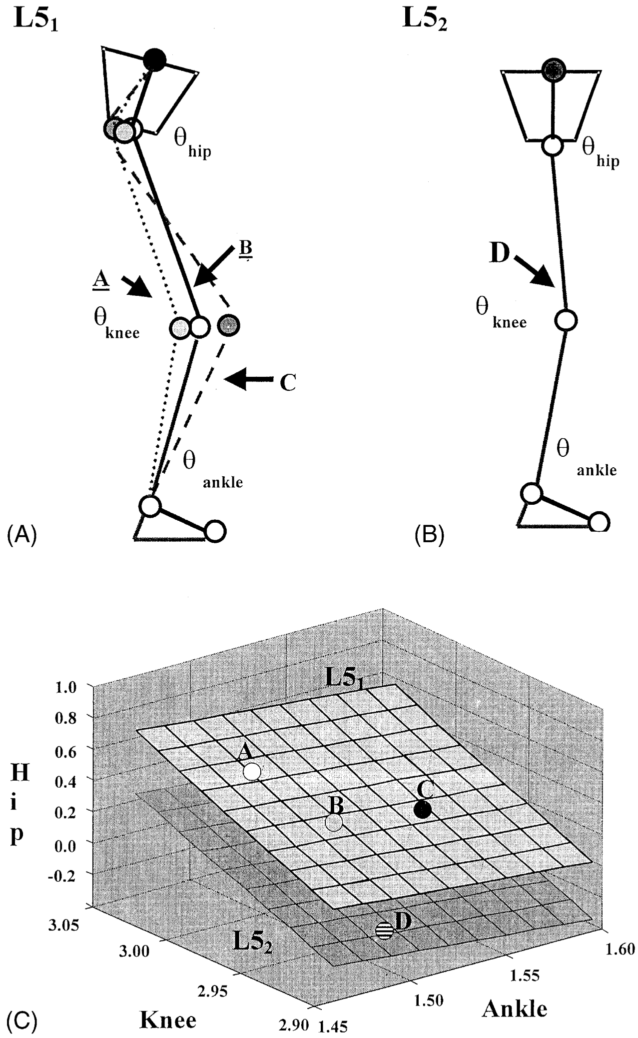

Fig. 1. Simulated examples of joint redundancy and its relationship to manifolds: (A) three different joint combinations that lead to the same position of L5 ($L5_1$); (B) a different joint combination that leads to yet another position of L5 ($L5_2$); (C) the two different manifolds representing all the possible ankle, knee and hip joint combinations that could achieve the L5 positions shown in (A) and (B).

task that lead to a consistent position of L5, these will be considered *goal-equivalent variability*. Note, however, it is theoretically possible to use only one joint combination repeatedly to achieve the same L5 position so that the use of goal-equivalent joint combinations is not, a priori, a requirement. Alternatively, observed variations in joint angle combinations across repetitions that lead to variable positions of L5, different than $L5_1$ (e.g. joint combination D in our example) will be referred to as *non goal-equivalent variability.*

2.5.2. Performance variables and joint variability

From the previous discussion, it can be seen that if we are to identify a set of goal-equivalent solutions, we must identify the variables whose stability may be important to successfully complete the task. These variables are referred to as the *performance variables*. In this study, we have identified the CM and head position and CM momentum as possible performance variables. Because the actual desired movement of these variables during sit–stand–sit is unknown, we must estimate their desired movement. For this purpose, we use the path that is consistent with the mean joint configuration subjects actually produce across acceptable trials. Because we can write down a geometric model (see Appendix A) relating mean joint angle combinations to the value of each performance variable, we can use this model to estimate the manifold of goal-equivalent joint combinations consistent with the mean value of a given performance variable. At a particular point in the movement, the actual variability of the joint angle combinations across repetitions of the task can then be partitioned into a component that lies on this manifold (goal-equivalent variability) and a component that does not lie on this manifold (non goal-equivalent variability). (Note that, in the above examples, we considered only joint angle combinations. In the case of CM momentum, however, the geometric model includes both joint angles and joint velocities, because both of these components contribute to the momentum of the CM. Likewise, we must partition actual variability of both joint angle combinations and joint velocity combinations with respect to the estimated manifolds to determine the range of goal-equivalent joint angle and velocity variability actually used to perform the task.)

By examining the relationship between the magnitude of goal-equivalent (GEV) and non-goal-equivalent (NGEV) variability, as well as the actual variability of the performance variables, we can begin to understand how the motor system uses goal-equivalent patterns of joint coordination to achieve stable task performance. Note that this analysis requires the comparison of different hypothesized performance variables under different experimental conditions, because variability is relative. To illustrate these points more clearly, we will refer to another example. Consider a subject performing the sit-to-stand task under three different task conditions. The above-described analysis of joint configuration variability across repetitions is performed with respect to control of the vertical position of the CM. For condition 1, we find that GEV is large and GEV>>NGEV throughout the movement. For condition 2 NGEV>GEV and both are relatively large (compared to conditions 1 and 3). For condition 3, we find GEV≈NGEV and both are relatively small. What do these differing relationships between GEV and NGEV for the three conditions tell us? In condition 1, the subject uses a range of joint angle combinations that are consistent with the mean path of CM positions across repetitions. In other words, different patterns of joint coordination are being used to achieve the same goal. Moreover, joint angle combinations that would lead to a different CM position along its path are also present but are restricted (i.e. GEV>>NGEV). This evidence would suggest that stability of the CM position is important for control of this task because the joint variability that leads to a change in this position is kept much smaller than GEV. Although a range of goal-equivalent joint combinations (GEV) are used in condition 2, variations of the joint configuration that lead to variable CM positions (NGEV) are larger. Thus, it would appear that stabilization of the CM position is not as important in this case, or that the subject is not very good at doing so. Indeed, assuming that NGEV is much larger in condition 2 than in condition 1, we expect to find that the actual variability of the CM position will be larger in condition 2 than condition 1. What about condition 3? In this case, both GEV and NGEV are low and equal. Interpretation of this finding would depend on the relative magnitudes of these components compared to the other conditions, as well as an analysis of the actual CM position variability. Suppose that both components were much smaller than in the other two conditions. Because NGEV is lower than in condition 1, control of the CM position is apparently as important as in condition 1, or even more so. However, to achieve this control a minimal set of goal-equivalent joint combinations were used, compared to condition 1. This may indicate that other performance constraints are also at work that limits the set of joint combinations that can be used. Alternatively, this reduced use of goal-equivalence in condition 3 might reflect differences in performing under a novel task condition (if this were the case), or a slightly different control strategy. For example, if GEV were found to be close to zero, this might reflect that the CNS tries to use an optimal solution to joint coordination, which is made somewhat variable as a result of small compensations occurring at lower levels of the motor system. Thus, comparisons of the components of joint configuration variability and the actual variability of performance variables can provide insight about differences in the control and coordination of a particular task under differing task conditions.

The mathematical procedure used to estimate GEV and NGEV is described in greater detail in Appendix A and Ref. [10].

2.6. Dependent variables

2.6.1. Performance variable variability

The standard deviation across trials of both the horizontal and vertical positions of the CM and the head and the horizontal and vertical linear momentum of the CM were obtained at each 10% of each task (i.e. standing up and sitting down) as measures of stability of the hypothesized performance variables that were studied in this experiment. Linear momentum of the center of mass was calculated using the following formula:

$$L = mv$$

where m equals the mass of the subject in kilograms and v equals the velocity of the center of mass of the body.

2.6.2. Goal and non goal-equivalent variability

The two components of joint combination variability, GEV and NGEV, determined according to the procedure outlined above, were used to evaluate the extent to which goal-equivalent patterns of joint coordination are used to achieve the tasks of standing up and sitting down, and how that use is effected by altering the task conditions. See Appendix A for mathematical details.

2.7. Data analysis

Three separate repeated measures ANOVAs were performed to analyze the structure of joint combination variability for (1) the CM position, (2) the head position, and (3) linear CM momentum. Factors in the ANOVAs were (a) experimental condition (NB and NO), (b) task (standing up or sitting down), (c) phase of the movement (e.g. early, middle or late in ascending and descending), (d) movement dimension (i.e. horizontal and vertical) and (e) component of joint combination variability (i.e. GEV and NGEV). When there was a significant effect of a factor or interaction related to our hypotheses, planned contrasts were performed using the SPSS m-matrix structure.

The statistical analyses were performed on averaged data, where the periods for averaging differed depending on the performance variable. For the momentum variables the period chosen was where these variables demonstrated their greatest change. For linear momentum this range was 10–60% and 30–80% of the task period for the horizontal and vertical directions, respectively. For the task variables head and CM position, the averages were taken over three periods in rising and the same three periods in sitting down. Those periods were 10–30% (early), 40–80% (middle) and 90–100% (late). The decision to use averages over these periods was based on several facts. First, the middle period was chosen because 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 these periods 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 and head position hypotheses were consistent across the percentages over which averages were taken.

3. Results

3.1. Joint combination variability

The relationship between GEV and NGEV joint combination variability varied as a function of the performance variables CM and head path, the task (standing up or ascending vs. sitting down or descending), whether the movement occurred in the horizontal or vertical direction, the movement phase (early, middle, late), as well as the support condition (normal vs. narrow base of support) ($F_{2,\ 16}$=50.94, p<0.0001). The relationship of GEV to NGEV in the combined joint position and joint velocity space, related to the control of linear momentum, was affected by the interaction of support condition and task ($F_{1,\ 8}$=7.26, p<0.05). Further analyses were performed, therefore, to evaluate the variables of primary interest and effects that revealed similarities or differences between standing up and sitting down.

3.2. Joint combination variability underlying horizontal movement control

Fig. 2 reveals the structure of joint combination variability underlying control of the horizontal movement path of the CM (A) and head (C). The following results are of note:

1. Irrespective of standing up or sitting down, or the support condition, GEV was an order of magnitude higher than NGEV, especially in the middle of the movement (Fig. 2A, C).
2. Differences in the amount of GEV between the narrow (NB) and normal (NO) base of support conditions depended on the phase of standing up and sitting down (CM: $F_{2,\ 16}$=11.30, p<0.001; head: $F_{2,\ 16}$=23.60, p<0.0001). The differences were most apparent in late ascent and early descent. Nevertheless, GEV was consistently higher when performing in the NB compared to the NO condition, for both CM ($F_{1,\ 8}$=9.66, p<0.05) and head ($F_{1,\ 8}$=34.0, p<0.0001) control.
3. In contrast, differences between the NB and NO conditions in the variance of joint combinations that affected the horizontal CM and head paths (i.e. NGEV) were quite small, although still significantly higher for NB than NO (CM: F1, 8=8.25, p<0.05; head: F1, 8=10.07, p<0.05).
4. Differences between NO and NB conditions in the use of goal-equivalent joint combinations (i.e. GEV) to control the CM path were slightly greater during standing up than during sitting down ($F_{1,8}$=11.16, p<0.01; Figure 2A).
5. For control of the horizontal linear momentum of the CM, GEV>NGEV for the NB condition and NGEV>GEV for the NO condition ($F_{1,\ 8}$=47.39, p<0.0001). Although joint position and velocity variance was higher overall for sitting down than for standing up ($F_{1,\ 8}$=6.63, p<0.05; Fig. 3A), the difference between GEV and NGEV did not differ across the tasks (p<0.137).

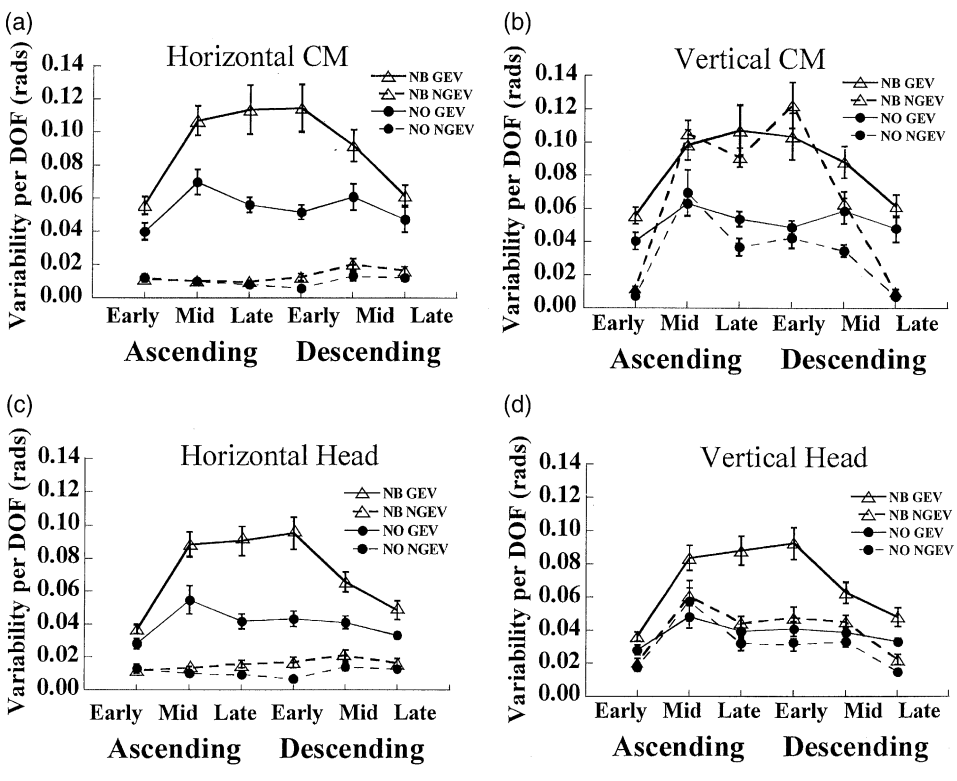

Fig. 2. Joint coordination underlying the CM (A and B) and head (C and D) trajectories in the horizontal (column 1) and vertical (column 2) directions. The early, middle and late portions of the ascending and descending tasks are represented on the x axis with the ascending portion on the left and the descending portion on the right. Solid lines represent goal-equivalent variability (GEV) and dashed lines represent non-goal equivalent variability (NGEV). Lines with triangular symbols represent the NB condition and lines with solid circles represent the NO condition.

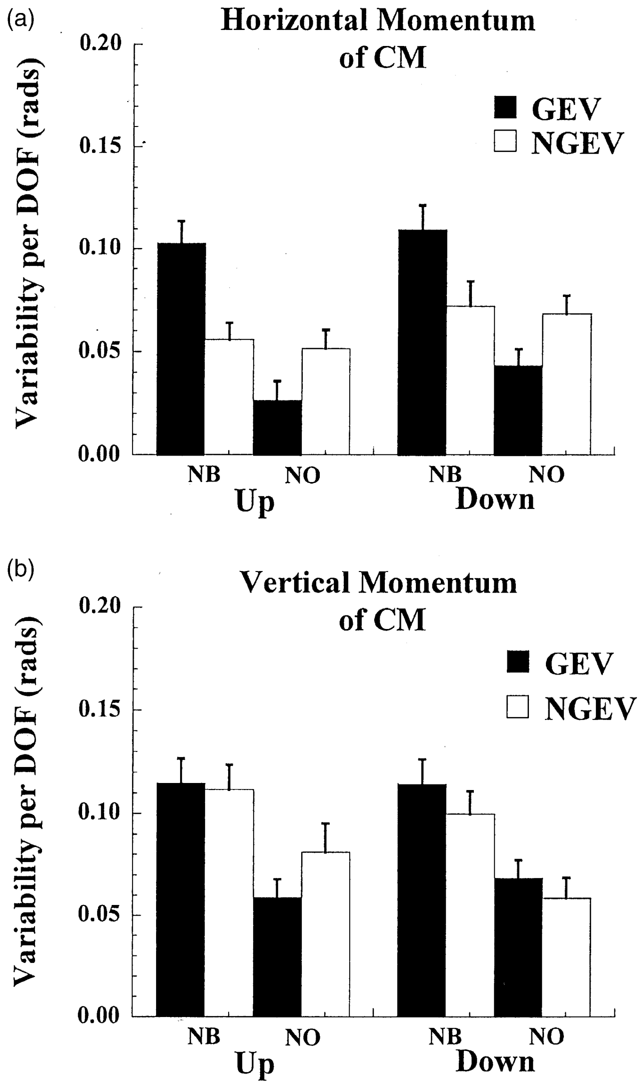

Fig. 3. Joint coordination underlying linear momentum of the CM in the horizontal (A) and vertical (B) directions. Solid bars represent goal-equivalent variability (GEV) and open bars represent non-goal equivalent variability (NGEV). The leftmost pair of bars for both the ascending and descending tasks represents the NB condition and the right pair of bars represents the NO condition.

3.3. Joint combination variability underlying vertical movement control

The relative amount of GEV and NGEV differed in relation to control of the vertical paths of the CM and head, as illustrated in Fig. 2C–D, and was dependent on the support surface for control of the vertical head path.

1. GEV was consistently higher than NGEV for control of the head's vertical movement path when standing up or sitting down on the narrow base of support (F=53.42, p<0.0001; Fig. 2D, open triangles). This difference depended on the phase of the movement for the normal support condition, however ($F_{2, 16}$=4.44, p<0.05; Fig. 2D, solid circles).
2. The difference between the support conditions in the structure of joint combination variability related to vertical head control was due primarily to GEV. Differences in NGEV between the support surface conditions did not reach significance (p=0.06) regardless of the task (p=0.134), while GEV did ($F_{1, 8}$=37.13, p<0.0001). The magnitude of GEV differences between NB and NO were largest in the late phase of ascending and early phase of descending ($F_{2, 16}$=26.33, p<0.0001).
3. Fig. 2B indicates that selective stabilization of the vertical path of the CM was not a consistent feature of the task in either support condition. Whether GEV (open triangles with solid line) was greater than NGEV (open triangles with dashed line) during performance on the narrow base of support was dependent on the phase of the task and the task itself ($F_{1, 16}$=28.71, p<0.0001).
4. GEV was higher than NGEV for control of the vertical CM path during both the middle and late phases of sitting down whereas this was true only for the early phases of standing up (Fig. 2B). This result occurred for both the narrow ($F_{2, 16}$=15.52, p<0.0001) and normal ($F_{2, 16}$=6.86, p<0.05) base of support conditions.
5. There was no consistent structure of joint position and velocity variability related to control of vertical linear momentum of the CM (Fig. 3B), other than the fact that variability was higher overall in the NB condition than in NO ($F_{1, 8}$=33.63, p<0.0001).

3.4. Performance variable variability

Performance variable variability depended on the support surface condition, the movement direction, the phase of either standing up or sitting down, and between the head and CM ($F_{2, 16}$=4.6, p<0.05; Fig. 4). Variability of the linear momentum of the CM depended only on the support condition and movement direction ($F_{1, 8}$=7.48, p<0.05; Fig. 5).

3.4.1. Horizontal dimension

1. Horizontal CM motion was more variable for the NB than the NO condition for the task of sitting down but not when standing up (Fig. 4AA; $F_{1, 8}$=11.89, p<0.01).
2. Variability of the horizontal head position was generally higher for the NB compared to the NO condition except for the early phase of standing up (Fig. 4C; $F_{2, 16}$=8.20, p<0.01). Moreover, the difference in horizontal head variability between the NB and NO conditions was higher overall for the task of sitting down than for standing up ($F_{1, 8}$=8.32, p<0.05).
3. Variability of horizontal CM momentum did not differ across support conditions, whether standing up or sitting down (Fig. 5A).

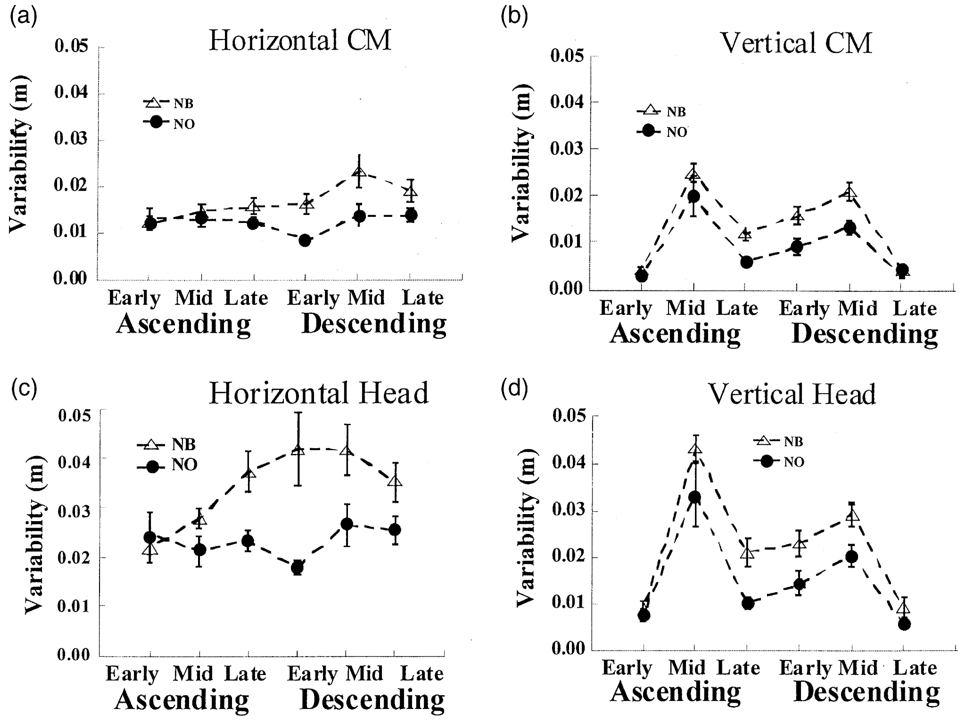

Fig. 4. Variability of the CM (A and B) and head (C and D) in the horizontal (column 1) and vertical (column 2) directions. The early, middle and late portions of the ascending and descending tasks are represented on the *x*-axis with the ascending portion on the left and the descending portion on the right. Lines with the triangular symbols represent the NB condition and those with solid circles represent the NO condition.

3.4.2. Vertical dimension

1. Overall variability of the vertical CM path was highest during the middle phases of standing up and sitting down, where the CM was furthest from the seat, and in the fully upright position ($F_{2,\,16}$=72.69, p<0.0001).
2. Differences between the NB and NO conditions in vertical path variability of the CM depended on the phase of standing up and sitting down ($F_{2,\,16}$=6.36, p<0.01). The condition differences were largest during the late phase of standing up and the early and middle phases of sitting down (Fig. 4B).
3. Head path variability tended to be higher during the middle phases of standing up and sitting down (Fig. 4D), similar to vertical CM variability (cf. Fig. 4B), although it was substantially higher during standing up than during sitting down ($F_{2,\,16}$=23.84, p<0.0001).
4. For vertical momentum of the CM, variability was higher for the NB condition than for the NO condition (Fig. 5B; $F_{1,\,8}$=7.32, p<0.05), independent of the task of standing up from or sitting down to the seat.

4. Discussion

The new results of this study were the identification of both similarities and differences in the way joints are coordinated during the task of standing up compared to sitting down. These results also provide insight about how the nervous system organizes the abundant patterns of joint coordination available to achieve this task and how this organization differs in relation to the control of different performance variables, providing an indication of their relative importance.

4.1. Control of vertical motion of the CM and head differed between standing up and sitting down

We hypothesized that the *selective* use of goal-equivalent patterns of joint coordination to provide a stable path of the vertical CM and head would be most evident during sitting down rather than standing up. Indeed, this tended to be the case. Fig. 2B shows that the GEV>NGEV difference was present for control of the vertical CM position during both the middle phase, where the CM is farthest from both the old and new base of support, and the late phase of sitting down, whereas this was true only during the early phase of standing up. Previous studies have emphasized the added importance of decelerating the body against the effect of gravity when sitting down, which is consistent with this finding [2,4]. In addition, a stronger GEV>NGEV difference was present for control of the vertical head path during sitting down compared to standing up (Fig. 2D).

4.2. The use of goal-equivalent joint combinations to control vertical CM motion was phase dependent

The strongest difference between GEV and NGEV related to the control of the vertical CM path occurred in the early phase of standing up and the late phase of

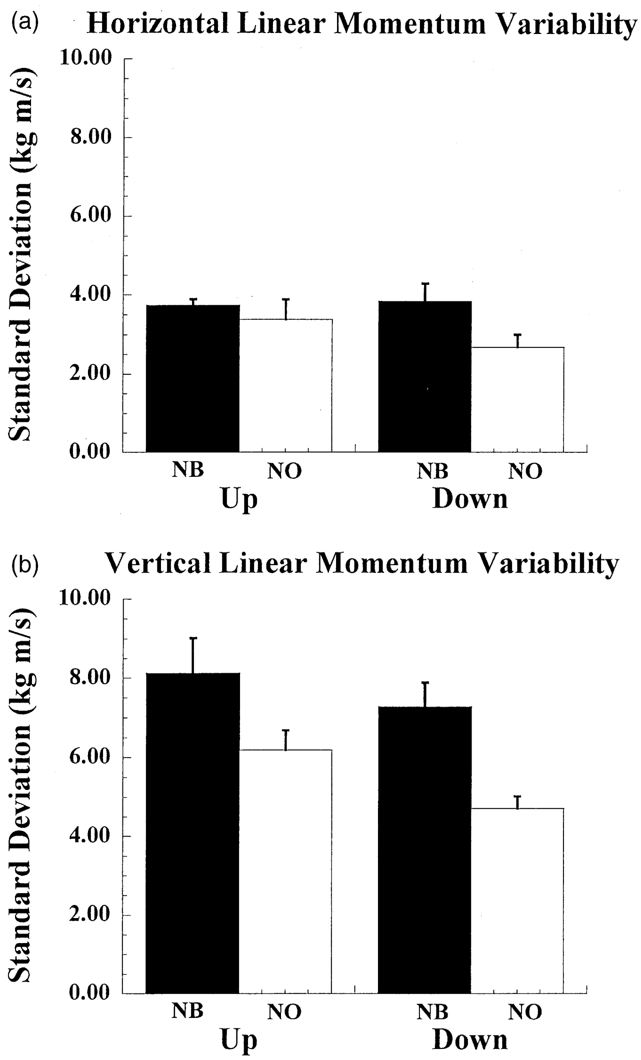

Fig. 5. Variability of the linear momentum of the CM in the horizontal (A) and vertical (B) directions. Solid bars represent the NB condition and open bars represent the NO condition. The ascending task is on the left side of the graph and the descending task is on the right.

sitting down. In these phases, NGEV was also quite small (Fig. 2B), indicating that most of the variability of joint combinations was consistent with the use of goal-equivalent patterns of coordination. In early standing up, the body has to be launched vertically as well as forward. During the final descent to the seat, control of vertical motion may be most crucial to ensure a soft landing, as suggested above. Thus, it would be interesting to determine how the relationship between GEV and NGEV differs, if at all, in elderly individuals who are prone to falling or otherwise have difficulty performing the task.

4.3. The use of goal-equivalent patterns of joint coordination to control horizontal motion did not differ substantially between standing up and sitting down

We found that joint configuration variability was strongly biased toward joint combinations that were consistent with a stable horizontal path and linear momentum of the CM and, to a lesser extent, head path. This finding is consistent with earlier studies examining standing up alone [8,9]. This was true in all phases of the task and in both support surface conditions. Thus, unlike control of the vertical CM path, control of horizontal CM motion was consistently achieved by a style of coordination that channeled most joint combination variability into goal-equivalent directions, i.e. those that stabilized horizontal motion.

The authors of several studies have argued that the horizontal momentum of the CM is more tightly regulated than vertical momentum when standing up because of the need to maintain upright equilibrium at the end of the movement [15,16]. Furthermore, modeling studies have suggested that a relatively small region within the CM position–velocity phase plane is compatible with successful completion of standing up, potentially requiring more precise control over these variables [17,18]. There appear to be similar constraints on the control of horizontal momentum during sitting down as when standing up. For example, a study of failed sit-to-stand performances found that even during a “sit-back failure”, horizontal CM momentum was decreasing at seat contact, presumably to prevent falling further backward [19]. These results provide possible explanations for our finding that, unlike vertical CM position and momentum, the use of goal-equivalent patterns of joint coordination to control the horizontal position and momentum of the CM did not differ qualitatively across the tasks of standing up and sitting down. Overall then, stability of the horizontal CM path and its momentum appears most critical to successful task completion. It is important to keep in mind, however, that CM control could be achieved through use of a unique combination of joints by applying some type of cost constraints to solve the redundancy “problem” [20]. Thus, it appears that the nervous system prefers to make use of the abundant solutions to joint coordination available to it, presumably with some advantage.

4.4. The effect of the support surface depended on the phase of standing up and sitting down

While the pattern of joint coordination used to stabilize the horizontal CM position was generally consistent for both standing up and sitting down, there were differences between support surface conditions in different phases of each task. When performing on the narrow base of support, the use of goal-equivalent patterns of joint coordination was substantially greater than when performing on a normal base of support, regardless of the task. In contrast, NGEV differed minimally between the support conditions. Why would the use of different patterns of joint coordination be useful in the more challenging task conditions? Restricting the range of joint combinations to one or a few requires enhanced neuromuscular control. However, muscle activation results in the generation of interaction torque at adjacent joints. This additional interaction torque would require additional control action if the desired posture or movement pattern is to be preserved [22]. Thus, a control strategy that frees joint combinations from unnecessary control along dimensions of joint space that do not affect important performance variables would presumably confer an advantage. Under difficult task conditions, such as standing up on a precarious base of support, this strategy may be especially important to limit needless additional perturbations. Further support for this hypothesis is suggested by the differences found between support conditions near the time of upright standing (late ascending and early descending phases). During these phases, control of both horizontal and vertical CM paths were marked by a slightly decreased amount of GEV when performing on a normal support surface. In contrast, GEV did not change or even increased slightly when standing up on a narrow base of support (Fig. 2A, B).

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 in the more difficult task conditions. Establishing this link will require further study. However, because the increased use of goal-equivalent joint combinations when performing on a narrow base of support was found in all subjects and for both standing up and sitting down, our conclusion that this strategy confers an important advantage seems justified.

It is important to note that this *selective* increase in the use of goal-equivalent joint combinations when standing up on a narrow support is not trivial. Being on a precarious base of support would be expected to lead to an increased variability in joint motion and a resulting increase in body sway. Thus, one could expect an increase in the variability of performance variables such as the CM path. This was indeed the case, as is discussed below. But, in our analysis, this would be reflected by an increase NGEV. However, the vast majority of the increased joint motion variability that occurred on the narrow base of support was channeled into GEV. Thus, the motor system was able to coordinate the variations in joint motion effectively to minimize its effect on important performance variables.

The structure of joint combination variability related to stability of the head path was qualitatively similar for both the horizontal and vertical dimensions and for standing up and sitting down. However, there was still a stronger effect when standing up on the narrow base of support. This is in contrast to the results of our earlier study of sit-to-stand [7], which found that joint combination variability was less well structured to stabilize the head's movement path compared to that of the CM. That study had subjects stand up with normal vision. Thus, this difference may be related to the sensory constraints imposed by the conditions utilized in the current study where, in all conditions, the subjects were required to close their eyes and to move as quickly as possible without falling. It is possible that, under these conditions, information from the vestibular system becomes relatively more important for maintaining balance [21]. If subjects were more dependent on vestibular information to sense the body's position in space, then our result is not surprising.

4.5. Actual variability of movement properties of the CM and head were consistent with non-goal-equivalent variability

Trial-to-trial fluctuations of the value of performance variables, such as the position or momentum of the CM, result only from joint variability that is non-goal-equivalent. Variability that lies within a manifold for that particular performance variable is, by definition, goal-equivalent. Nonetheless, the relationship between performance-variable variability and NGEV is not a simple one. Not only is this relationship nonlinear, as evidenced by the geometric model, but the exact relationship varies with the limb–trunk geometry throughout the movement path [7,8]. Thus, a comparison between variability in the joint space and that in task space requires caution, especially with respect to variance magnitude.

With this caveat in mind, the qualitative relationship between performance variability (Figs. 4 and 5) and NGEV (Figs. 2 and 3) was striking. Variability of both horizontal and vertical CM and head paths was higher in the NB than in the NO support condition, as was the case for joint combination variability. Variations of NGEV and task-variable variability across different movement phases were also in general agreement. For example, NGEV related to control of the vertical CM path was smaller during subjects' descent to the seat than during standing up. The same was also true for vertical CM variability.

5. Conclusions

Understanding how the nervous system manages the redundant DOFs available to perform a motor task is an important part of understanding how human movement is controlled [23]. In this study we utilized a method that allowed us to investigate how the nervous system manages joint redundancy to stabilize variables important to task success. The results indicate that variability of joint combinations were coordinated (i.e. channeled into goal-equivalent combinations) to consistently stabilize horizontal motion of the CM and head during both standing up and sitting down. In contrast, the extent to which this was true for control of vertical motion was influenced more by the changing demands of the task. Control of vertical motion was greater during sitting down than during standing up. Thus, there were more phase-dependent differences between standing up and sitting down for vertical CM control in particular. Consistent with previous studies of standing up alone [8,9], the use of goal-equivalent patterns of joint coordination was enhanced when performing under more challenging task-conditions. Moreover, differences with a previous study [7] in joint coordination related to control of the head path were consistent with the apparently greater dependence on vestibular information for postural control in the present experiment. Thus, the use of motor redundancy by the control system, i.e. channeling the variability of joint combinations into goal-equivalent directions, appears not only to provide an important advantage to the control of functional motor tasks, but also, to be influenced by task demands.

Appendix A. Procedure to estimate GEV and NGEV

The initial step in estimating GEV and NGEV is to obtain the geometric model relating the task variable, r, (e.g., the horizontal, y, and vertical, z, linear momentum of the CM or the horizontal, y and vertical, z, position of the CM or head) to the state-space configuration: θ and ω, in the case of the momentum task variables and θ alone in the case of the position performance variables. In our experiment, the state-space configuration for the hypothesis about controlling the linear momentum of the CM is composed of eight angles (foot, shank, thigh, pelvis, trunk, head/neck, arm and forearm segment angles with the horizontal) and their respective instantaneous velocities. The joint configuration for the hypotheses about controlling the 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 (and ω for momentum hypotheses) through the Jacobian, which is the matrix of partial derivatives of the task variable, r, with respect to the body segment angles, θ (and angular velocities ω, when considering momentum). For example, if the task variable under consideration is the horizontal linear momentum of the CM, the geometric model relating horizontal linear momentum of the CM and the state-space configuration is

$$\mathrm{LM}_{\mathrm{CM}y} = \mathrm{LM}_{\mathrm{FOOT}y} + \mathrm{LM}_{\mathrm{SHANK}y} + \mathrm{LM}_{\mathrm{THIGH}y} + \ldots + \mathrm{LM}_{\mathrm{C\text{-}SPINE}y}$$

where, for example,

$$LM_{shank\text{-}y} = m_{shank}\dot{CM}_{shank}$$

and

$$\mathrm{CM}_{\mathrm{shank}} = \mathrm{y}_{\mathrm{toe}} + \mathrm{l}_{\mathrm{foot}}\cos(\theta_{\mathrm{foot}}) + \mathrm{m}_{\mathrm{shank}}\mathrm{r}_{\mathrm{shank}}\cos(\theta_{\mathrm{shank}}).$$

The mass of the segment is m_i, r_i is the distance of the CM of the segment from the distal end, and θ_i is the angle of the segment with the horizontal. The geometric model relating angular momentum about the CM to the state-space configuration is:

$$(I_{\mathrm{foot}}\omega_{\mathrm{foot}} + \mathrm{m}_{\mathrm{foot}}(\mathrm{d}_{\mathrm{foot}x}\mathrm{v}_{\mathrm{foot}})_x) + (\mathrm{I}_{\mathrm{shank}}\omega_{\mathrm{shank}} + \mathrm{m}_{\mathrm{shank}}(\mathrm{d}_{\mathrm{shank}x}\mathrm{v}_{\mathrm{shank}})_x) + \ldots + (\mathrm{I}_{\mathrm{forearm}}\omega_{\mathrm{forearm}} + \mathrm{m}_{\mathrm{forearm}}(\mathrm{d}_{\mathrm{forearm}}\mathrm{v}_{\mathrm{forearm}})_x).$$

Each term can be expanded to:

$$\mathrm{I}_i\omega_i + \mathrm{m}_i(\mathrm{d}_{yix}\mathrm{v}_{zi})_x - \mathrm{m}_i(\mathrm{d}_{zi}\mathrm{v}_{yi})_x,$$

where

$$d_{yi} = CM_{yi} - CM_y, d_{zi} = CM_{zi} - CM_z$$

$$v_{yi} = \dot{CM}_{yi} - \dot{CM}_y = (\dot{y}_{i-1} - r_i\sin\theta_i\omega_i) - \dot{CM}_y$$

$$v_{zi} = \dot{CM}_{zi} - \dot{CM}_z = (\dot{z}_{i-1} - r_i\sin\theta_i\omega_i) - \dot{CM}_z$$

where $y_{i\text{-}1}$ and $z_{i\text{-}1}$ represent the segment distal to segment i, r_i is the distance from the CM of segment i to the distal end of segment i, θ_i is the segment angle with the horizontal, ω_i is the angular velocity of segment i and CM_{yi}, CM_{zi} are the horizontal and vertical position of the CM of segment i, respectively. The terms CM_y, CM_z, coordinates of the CM of the body, and $y_{i\text{-}1}$, $z_{i\text{-}1}$, coordinates of the joint center distal to the current segment i, are also expressed in terms of the full geometric model (i.e. in terms of segment lengths and angles). The model for linear momentum, CM and head position and their partial derivatives with respect to each body segment angle (and angular velocity when considering momentum) (i.e. for the Jacobian) were developed step by step using Maple.

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 performance variable, a decision is necessary as to what value to use for the estimation. In reality, both joint combinations and performance variables vary from trial to trial. Based on the assumption that the normalization of movement time has aligned matching states of the underlying (theta, omega) state space across trials, we computed the mean joint combination, $\bar{\theta}$ (and $\bar{\omega}$ for momentum) at each percent of the movement. Effectively, the value of the performance variable, $\bar{y}_{\mathrm{CM}}$, associated with that mean joint combination, was used to construct the UCM. Again, continuing with the example for horizontal linear momentum, the linear approximation to the UCM was obtained from the geometrical model, linearized around the mean state-space configuration:

$$y_{CM} = \bar{y}_{CM} = \underline{\underline{J}}(\bar{\theta},\bar{\omega})\begin{pmatrix}\theta-\bar{\theta}\\ \omega-\bar{\omega}\end{pmatrix}$$

Here, $\underline{\underline{J}}$ is the Jacobian, composed of $\partial y/\partial\theta_i$and $\partial y/\partial\omega_i$, where i={foot, shank, thigh, pelvis, trunk, head/neck, arm, forearm}. The linear approximation of the UCM is then the null-space of the Jacobian (the linear subspace of all deviations from the mean state-space configuration that are mapped onto zero by the Jacobian). Using Matlab™ for the numerical computation of the null-space, the actual value of the state-space configuration minus the mean state-space configuration at each point along the movement path of each trial is decomposed into a component that lies within this null space and a component in its complement. 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 estimates of variance were then divided by the appropriate number of degrees of freedom (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 five. The variability perpendicular to the UCM (i.e. variability that changes the value of the task variable from its mean value) is divided by one. The square root of this normalized variance was obtained for the data analyses, which is reported as variability per DOF.

For the momentum performance variables, the state space is composed of variables having different dimensions, i.e. angles in radians and angular velocities in radians per second. Thus, a scaling of the Jacobian was necessary before estimating the null space to render the dimensions of the space commensurate. In addition, a corresponding scaling of the mean-free state-space vector of each trial was performed before its projection onto the null space to determine the variability components. The following relationship was used as a basis for this scaling. Harmonic motion involves the following relationship between position and velocity variables:

$$\mathrm{scale}(\dot{\theta}) = (2\pi/T)*\mathrm{scale}(\theta),$$

where T is the movement period, or twice the movement time. Thus, the scaling was accomplished by multiplying the velocity components of the state-space vector by (MT/π) and by multiplying the appropriate velocity terms of the Jacobian matrix (e.g. $\partial\mathrm{LM}/\partial\omega_i$) by ($\pi$/MT) so that all dimensions had units of radians. The variance (across trials) of the projected components of each trial's harmonically scaled state space vector was then calculated for each experimental condition and normalized by the number of degrees of freedom. The rest of the procedure is the same as for the other performance variables.

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Darcy S. Reisman received a BA in Health Sciences in 1991 and an MA in Physical Therapy in 1993 from the college of St Scholastica in Duluth, MN. She was a practicing Physical Therapist until 1999. Since 1999 she has been a doctoral student in the Biomechanics and Movement Science Graduate Program at the University of Delaware, Newark, DE. Her general research interests are in the areas of normal and disordered motor control. Most recently she has been studying the differences in the motor coordination and postural control between healthy and neurologically impaired individuals.

John P. Scholz received his degree in physical therapy from the University of Pennsylavania in 1973, a MA degree in physical therapy from the University of North Carolina in 1978 and a PhD in Experimental Psychology from the University of Connecticut in 1985. He is currently Associate Professor of Physical Therapy and in the interdisciplinary Biomechanics and Movement Science Graduate Program at the University of Delaware. Dr Scholz' research interests are in the area of the control and coordination of functional motor tasks in healthy individuals and individuals who have suffered a stroke.

Gregor Schöner studied physics at the Universität des Saarlandes (Germany) and obtained a PhD in theoretical physics from the Universität Stuttgart (Germany in 1985). His research interests cover a wide range including biological movement, perception, cortical neurophysiology and autonomous systems but is always based on shared theoretical models from dynamical systems, neural networks, and stochastic dynamics. He is currently Chair of Theoretical Biology at the Institut für Neuroinformatik, Ruhr Universität Bochum (Germany) and was previously Directeur de Recherche at the Centre de Recherche en Neurosciences Cognitives, CNRS, Marseille (France).