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Analyses of joint variance related to voluntary whole-body movements performed in standing

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Abstract

This article investigates two methodological issues resulting from a recent study of center of mass (COM) positional stability during performance of whole-body targeting tasks (Freitas et al., 2006): (1) Can identical results be obtained with Uncontrolled Manifold (UCM) variance analysis when it is based on estimating the Jacobian using multiple linear regression (MLR) analysis compared to that using typical analytic formal geometric model? (2) Are kinematic synergies more related to stabilization of the instantaneous anterior-posterior position of the center of mass (COM_{AP}) or the center of pressure (COP_{AP})? UCM analysis was used to partition the variance of the joint configuration into a ‘bad’ variance, leading to COM_{AP} or COP_{AP} variability, and ‘good’ variance, reflecting the use of motor abundance. Results indicated (1) nearly identical UCM results for both methods of Jacobian estimation; and (2) more ‘good’ and less ‘bad’ joint variance related to stability of COP_{AP} than to COM_{AP} position. The first result requires further investigation with more degrees of freedom, but suggests that when a formal geometric model is unavailable or overly complex, UCM analysis may be possible by estimating the Jacobian using MLR. Correct interpretation of the second result requires analysis of the singular values of the Jacobian for different performance variables, which indicates how certain amount of joint angle variance affects each performance variable. Thus, caution is required when interpreting differences in joint variance structure among various performance variables obtained by UCM analysis without first investigating how the different relationships captured by the Jacobian translate those variances into performance-level variance.

Keywords

postural control; uncontrolled manifold analysis; joint coordination

Introduction

Freitas et al. (2006), in an earlier study, investigated the patterns of joint angle co-variation used by participants to stabilize the trajectory of the anterior-posterior center of mass (COM_{AP}) position during a whole-body performance performed in standing that involved

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oscillating between two targets defined by either anterior-posterior position of the center of pressure (COP_{AP}) or a range of ankle, knee or hip joint angles. The Fitts-like paradigm combined different target widths at two target amplitudes to yield six identical indices of difficulty per amplitude. These different conditions were used to investigate the robust nature of the effect of cycle-to-cycle co-variations of the joint angles, using the uncontrolled manifold (UCM) approach (Latash et al., 2002 2007; Scholz and Schöner, 1999). UCM analysis identified the relationship between small changes of the ankle, knee and hip joint angles and changes of the instantaneous COM_{AP} position, which requires estimating the Jacobian, or partial derivatives of the COM_{AP} position with respect to the joint angles. The Jacobian was derived analytically from a formal geometric model (Method 1 in the current study). Freitas et al. (2006) reported that most of the across-cycles variance of the joint configuration produced an equivalent instantaneous COM_{AP} position ('good' variance; within UCM subspace, V_{UCM}) whereas the component of joint configuration variance resulting in COM_{AP} position variability ('bad' variance; orthogonal to UCM subspace, V_{ORT}) was smaller. Two questions related to that study are investigated in the current report.

One question is whether the results of UCM analysis (comparison of the amounts of variance in the two mentioned sub-spaces) would be similar if the Jacobian was estimated from multiple linear regression (MLR) of joint angle positions on the values of the performance variable (e.g., COM_{AP} position; Method 2-COM in the current study) compared to deriving the Jacobian analytically from a formal geometric model (Method 1).

The mapping from joint space to the space of a performance variable such as COM_{AP} position through a Jacobian is always theoretically possible. However, this mapping is not straightforward when relating joint postures to performance variables such as COP_{AP} position or, in more complex systems, where the Jacobian is more difficult to derive analytically (e.g. when there are more degrees-of-freedom (DOFs) and other performance constraints must be accounted for). To solve a similar problem in multi-muscle postural coordination studies (Krishnamoorthy, Latash et al., 2003), the Jacobian that mapped changes in modes of muscle activation onto shifts in the COP_{AP} was estimated using MLR between across-trial variations in these two subspaces. The present study represents an initial test of the validity of that method by comparing results of UCM analysis when based on a Jacobian estimated from MLR and one derived analytically from a geometric model. This was possible using the kinematic data set obtained in the whole-body tasks reported in the previous manuscript (Freitas et al., 2006). If the results of UCM analysis performed with respect to stabilization of the COM_{AP} position were similar across the two methods, this would provide preliminary support for the validity of the MLR method for estimating the Jacobian.

The second question addressed in the current study was whether the COP_{AP} position, which was provided as visual feedback during one of visual feedback conditions of Freitas et al. (Freitas et al., 2006), was more strongly stabilized than the COM_{AP} position. Because the geometric mapping between COP_{AP} position and changes of joint angles is non-trivial, requiring estimation of joint torques, etc., we used only Method 2 to estimate the Jacobian relating cycle-to-cycle joint angle variations at each percentage of the time-normalized cycles, but in this case to variations of the COP_{AP} location, and then performed UCM analysis (referred as Method 2-COP). These results then were compared to those obtained for COM_{AP} position using Method 2-COM. An additional factor was the targeting task/feedback condition, i.e., to move between either a range of COP_{AP} or a range of individual joint angles. If UCM analysis reveals a stronger difference between 'good' (V_{UCM}) and 'bad' (V_{ORT}) variance for the COP_{AP} position compared to COM_{AP} position, this could imply that the stabilization of the COP_{AP} is of greater importance to the targeting tasks than

is stabilization of the COM_{AP} position. Moreover, if this result is obtained when the task involves targeting in joint angle space, this would imply that stabilization of the COP_{AP} is not due solely to the visual feedback provided. However, accurate interpretation of the results of the two analyses required additional analysis that took into account the fact that the Jacobian matrices for the two hypotheses were different, as discussed below.

Methods

The data for the current analyses were obtained from a previous study (Freitas et al., 2006). The experimental methods most relevant to this report are presented here since the apparatus and experimental tasks have been reported previously in detail in Freitas et al. (2006). Ten healthy adults (mean $\pm$ SD: 31 ± 6 yr) participated in that study after providing signed, informed consent.

Participants stood in a comfortable position on a force platform (OR6-5, AMTI) with the feet at shoulder width and hands placed on the hips at all times. Data from force platform (vertical force, F_z , and medial-lateral moment of force, M_y) were used to calculate the COP_{AP} (M_y/F_z) position. Ankle, knee or hip joint motions were measured with electrogoniometers (BiometricsTM SG110 and SG150) placed on the right side of the participant's body and sampled at 100 Hz. The goniometers have a resolution of $\pm 2^\circ$ measured over a range of 180° . They also were calibrated before each data collection.

Two target zones defined by horizontal red lines were displayed on a monitor located 1-m away at the eye level of the participants. The screen position of a yellow cursor corresponded to the current value of the COP_{AP} position or joint angle. Anterior-posterior COP displacement or joint flexion-extension produced up-down motion of the cursor.

Participants performed whole-body, continuous sinusoidal oscillations "as fast and accurately as possible" between the two target zones without moving their feet. They performed 12 trials, each lasting 45 seconds, in each of four visual feedback conditions that provided feedback about the instantaneous position of the ankle, knee, and hip angle or of the COP_{AP} position. Two motion amplitudes were used for each visual feedback condition; 4.5-cm and 9-cm for the COP_{AP} task and 4.5° and 9° for joint motion tasks. Target width was varied between 0.85 to 6.82-cm (degrees for joint feedback tasks) to obtain six different indices of difficulty that were identical at each target amplitude ($ID = \log_2(2A/W) = \{1.4, 1.8, 2.2, 2.6, 3.0, \text{ and } 3.4\}$). Participants were free to select whatever patterns of body-motion they found successful for targeting.

Data processing

Data analyses were performed using MatlabTM 6.5 (Mathworks, Inc.) software. Data were filtered with a fourth-order, 10-Hz low-pass, zero-lag Butterworth filter. The last 30-s of each 45-s trial was analyzed to allow time for adaptation to the targeting task. Maxima and minima of the time series of joint or COP_{AP} motion, depending on the visual feedback condition, were automatically detected. Data between successive minima were used to define individual cycles, each of which was time-normalized to 100 frames. The number of cycles varied across IDs, depending on actual movement speed.

Computing COM_{AP} position

The COM_{AP} position at each sample was estimated using participants' anthropometric data and their ankle (θ_A), knee (θ_K) and hip (θ_H) joint angles as:

$$\begin{aligned}
COM_{AP} \approx & (\cos(\theta_A) * L_{AK}) * c_S * m_S \\
& + ((\cos(\theta_A) * L_{AK}) \\
& + (\cos(\theta_H) * L_{KH}) * c_T * m_T) \\
& + ((\cos(\theta_A) * L_{AK}) + (\cos(\theta_H) * L_{KH}) + \cos(\theta_K) * L_{HCOM}) * c_{TR} * m_{TR},
\end{aligned} \tag{1}$$

where m_S , m_T , and m_{TR} and c_S , c_T , and c_{TR} are the segmental masses (m_i) relative to total body mass and the relative position (c_i) along the segments of the COMs of the shank, thigh, and trunk, respectively. L_i are the lengths of the segments expressed as a percentage of subjects' height (Drillis and Contini, 1966), between ankle and knee joints (L_{AK}), between knee and hip joints (L_{KH}), and between hip joint and estimated COM_{AP} of the trunk (L_{HCOM}). Positive changes in joint angles were defined as flexion.

Defining the Jacobian and UCM analysis

Two methods were used to define the Jacobian required for UCM analysis. The first method, reported in Freitas et al. (2006), computed the Jacobian analytically (Method 1) as the partial derivatives of the geometric model (Equation 1) relating COM_{AP} position to individual joint angles. Numerical expression of the Jacobian $\underline{J}(\underline{\theta}_0)$ was obtained by substituting the mean joint angles ($\underline{\theta}_0$) across trials at each time-normalized percentage of the movement cycle. Basis vectors ($\underline{\varepsilon}_j$) of the null space of $\underline{J}(\underline{\theta}_0)$ then were computed numerically in MatlabTM. The null space is a linear estimate of the UCM, representing different combinations of $\underline{\theta}$ that leave the COM_{AP} position unchanged, in this case from the value corresponding to the mean joint configuration, expressed as

$$0 = \underline{J}(\underline{\theta}_0) * \underline{\varepsilon}_j. \tag{2}$$

Deviations of the joint configuration at each percentage of a given cycle from the mean configuration across cycles ($\underline{\theta} - \underline{\theta}_0$) at the same percentage were then projected onto the null space (Equation 3) and onto the subspace orthogonal to the null space (Equation 4):

$$\underline{\theta}_{||} = \sum \underline{\varepsilon}_i^T * (\underline{\theta} - \underline{\theta}_0) * \underline{\varepsilon}_i \tag{3}$$

$$\underline{\theta}_{\perp} = (\underline{\theta} - \underline{\theta}_0) - \underline{\theta}_{||} \tag{4}$$

Variance of the lengths of these projections across cycles within each subspace (Equations 5–6) then was computed and normalized to the number of DOFs comprising each subspace ($d = 1$ for orthogonal subspace, representing changes in COM_{AP} ; $n-d = 2$ for UCM; $n = 3$ is the number of joints) to obtain V_{UCM} and V_{ORT} . More details about this method can be found in Scholz and Schöner (1999).

$$V_{UCM} = \left(\sum (\underline{\theta}_{||})^2 / (N - \text{trials}) \right) * (n - d)^{-1} \tag{5}$$

$$V_{ORT} = (\sum (\theta_{\perp})^2 / (N - \text{trials})) * (d)^{-1} \quad (6)$$

The difference between the variance components normalized to the total joint variance was then computed as

$$\Delta V = (V_{UCM} - V_{ORT}) / ((2 * V_{UCM} + V_{ORT}) / 3) \quad (7)$$

Method 2 was similar to that used in recent multi-muscle postural coordination studies (Krishnamoorthy, Latash et al., 2003). The Jacobian $\underline{J}(\theta_0)$ was estimated at each percentage 'i' of the time-normalized cycle across all cycles 'j' as the coefficients 'k' of multiple linear regression (MLR) between mean-free joint angles $(\theta_{ij} - \theta_i^0)$, where $\theta_{ij} = [\theta_{i,ankle} \ \theta_{i,knee} \ \theta_{i,hip}]^T$ and θ_i^0 are the average joint angles across cycles) and changes in the mean-free instantaneous COM_{AP} position $(COM_{AP,ij} - COM_{AP,i}^0)$, i.e.

$$COM_{AP,ij} - COM_{AP,i}^0 \approx k_{ank,i} * (\theta_{ank,i}^0 - \theta_{ank,i}^0) + k_{knee,i} * (\theta_{knee,i}^0 - \theta_{knee,i}^0) + k_{hip,i} * (\theta_{hip,i}^0 - \theta_{hip,i}^0) \quad (8)$$

Thus, $\underline{J}(\theta_i^0) \approx [k_{ank,i}, k_{knee,i}, k_{hip,i}]$. UCM analysis for Method 2-COM was then performed in the same way as described for Method 1.

For the second experimental question, Method 2 was applied to identify the relationship between joint angles and the COP_{AP} position using MLR (referred as Method 2-COP), i.e.,

$$COP_{AP,ij} - COP_{AP,i}^0 \approx k_{ank,i} * (\theta_{ank,i}^0 - \theta_{ank,i}^0) + k_{knee,i} * (\theta_{knee,i}^0 - \theta_{knee,i}^0) + k_{hip,i} * (\theta_{hip,i}^0 - \theta_{hip,i}^0), \text{ where } \underline{J}(\theta_i^0) \approx [k_{ank,i}, k_{knee,i}, k_{hip,i}]. \quad (9)$$

At least 180 cycles were used to estimate the Jacobian with MLR for each participant and feedback/tracking condition. These results were then compared to those obtained for COM_{AP} using the same approach (i.e., MLR).

We also performed singular value decomposition of the Jacobian matrices obtained when comparing COM_{AP} and COP_{AP}, to compute the singular values of the range space vectors (λ_{ORT}) at each percentage of the cycle, the range space comprising those directions in joint space where changes in the joint configuration lead to a change in the value of the performance variable. Eigenvalues for the null space (λ_{UCM}) are zero by definition. Thus, λ_{ORT} provides an indication of how much a given amount of joint variance actually affects the value of the performance variable (COM_{AP} or COP_{AP}), or how much change of the performance variable can be expected for a unit change of the joint configuration. This depends, for example, on the current joint configuration, because both the COM_{AP} and COP_{AP} are (different) cosine functions of the joint angles. Thus, an equal amount of 'bad' joint variance, i.e. V_{ORT} , for analyses of both the COM_{AP} and COP_{AP} positions actually could lead to different amounts of COM_{AP} and COP_{AP} variability if λ_{ORT} differs for the two

analyses. This results from the fact that different models relate the joint configuration to the different performance variables. Likewise, although V_{ORT} could be higher for the analysis of the COM_{AP} compared to the COP_{AP} , no difference or even higher variance of COP_{AP} could occur if λ_{ORT} is substantially larger for COP_{AP} than for COM_{AP} .

Statistical analyses

Statistical analyses were performed in SPSS 16.0 (SPSS Inc., Chicago, USA). Comparisons of results of Methods 1 (geometric model) and 2 (MLR), when COM_{AP} was the performance variable, were evaluated by separate linear regressions between the variance components, V_{UCM} and V_{ORT} , computed for each method and for each visual feedback condition ($n=120$; 10 subjects * 2 amplitudes * 6 IDs).

A four-way, repeated measures analysis of variance (ANOVA) with the factors feedback (4 levels), performance variable (2 levels), amplitude (2 levels), ID (6 levels) compared the ΔV results obtained when the performance variable was the COM_{AP} position versus the COP_{AP} position. A five-way, repeated measures ANOVA was also carried out to further investigate the source of ΔV , i.e. what combination of increases or decreases in V_{UCM} and V_{ORT} led to these values. The factors were feedback provided (4 levels), performance variable (2 levels), amplitude (2 levels), ID (6 levels) and variance component (V_{UCM} and V_{ORT}). A four-way, repeated measures ANOVA with factors feedback provided (4 levels), performance variable (2 levels), amplitude (2 levels) and ID (6 levels) was also run to compare the standard deviation of COM_{AP} position with COP_{AP} position, which served as a measure of the performance-variable variability.

Data were subjected to normality test and were log transformed to normalize data when necessary. Post-hoc tests with Bonferroni adjustments were also used when appropriate to test for individual effects. The level of significance was set at $p<0.05$.

Results

Comparison of Jacobian $\underline{J}(\theta_0)$ computed analytically and estimated through multiple linear regression

The coefficients (k_1, k_2, k_3) of $\underline{J}(\theta_0)$ computed analytically or estimated through MLR related to the control of COM_{AP} or COP_{AP} position are presented in Table 1. Data are the averages ($\pm$ S.E.) across all combinations of amplitude and ID (12 tasks total) and participants. Note the similarity between $\underline{J}(\theta_0)$ computed analytically from a formal geometric model compared to $\underline{J}(\theta_0)$ based on MLR. Different values of entries in $\underline{J}(\theta_0)$ were obtained, however, when comparing the COP_{AP} versus COM_{AP} position, each based a Jacobian estimated with MLR, as can be expected based on the different relationship between joint angles and these two performance variables.

Comparison of variance components between different methods used to identify $\underline{J}(\theta_0)$: geometric model (Method 1) vs. MLR (Method 2-COM)

Linear regression was performed between each component of variance to verify the validity of the MLR approach (Method 2-COM) for estimating the $\underline{J}(\theta_0)$ relating joint postures to the COM_{AP} position. Correlation coefficients were obtained for each component of joint variance, V_{UCM} and V_{ORT} , and for each feedback condition (COP, ankle, knee and hip). Both V_{UCM} (Figure 1A) and V_{ORT} (Figure 1B) obtained with Methods 1 and 2-COM were highly correlated ($R^2 > 0.999$). To verify the validity of the linear regressions, we also ran the analysis separately for each participant ($n=12$) and, again, we found very strong correlation between Methods 1 and 2 for all feedback conditions (average $R^2=0.999$, S.D.=0.00008 for V_{UCM} and average $R^2=0.999$, S.D.=0.002 for V_{ORT}). The degree of

agreement between these two methods was also evaluated by computing the Intraclass correlation coefficient (ICC and 95% Confidence Interval) using a 2-way mixed effect model. ICCs assess the degree of exact agreement between the values of the two results. For V_{UCM} , near perfect agreement between methods was found for all visual feedback conditions: COP_{AP} ([ICC]=0.999; 95% CI: 0.999–1); Ankle ([ICC]=1; 95% CI: 0.999–1); Knee ([ICC]=1; 95% CI: 0.999–1) and Hip ([ICC]=1; 95% CI: 0.999–1). For V_{ORT} , excellent agreement between methods was also found: COP_{AP} ([ICC]=0.998; 95% CI: 0.997–0.998); Ankle ([ICC]=0.999; 95% CI: 0.999–0.999); Knee ([ICC]=0.999; 95% CI: 0.999–0.999) and Hip ([ICC]=0.999; 95% CI: 0.998–0.999). The fact that comparable results were found between methods suggests that MLR can be used successfully to estimate the relationship between individual joint motions and changes of COM_{AP} position. The MLR method for estimating the Jacobian will be used to answer our next question of the current manuscript.

In addition, the average ΔV results of UCM analyses from Methods 1 and 2-COM related to stabilization of COM_{AP} position are presented in Table 2. As could be expected from the analysis of the individual variance components, similar ΔV results were observed regardless of the method used to estimate $\underline{J}$ for all visual feedback conditions related to stabilization of the COM_{AP} position.

Comparison of indices of stability of different performance variables: COM_{AP} position vs. COP_{AP} position

The ΔV values related to stabilization of the COM_{AP} position (Method 2-COM) versus stabilization of the COP_{AP} position (Method 2-COP), averaged across amplitudes and IDs, are presented in Table 2 for each visual feedback condition separately. Overall, higher ΔV values were observed for the hypothesis of COP_{AP} stabilization. A four-way, repeated measures ANOVA with factors feedback condition (4), performance variable (2), amplitude (2) and ID (6) revealed a significant main effect of performance variable ($F(1,9)=21.03$, $p=0.001$; $\eta^2=0.7$) which was consistent across changes in all other factors (e.g., feedback: $F(3,27)=2.25$, $p=0.105$; $\eta^2=0.2$; amplitude: $F(1,9)=4.18$, $p=0.07$; $\eta^2=0.32$ and ID: $F(5,45)=1.32$, $p=0.27$; $\eta^2=0.13$). Also, no significant interactions were observed ($p>0.29$). That is, the COP_{AP} trajectory appeared to be stabilized better than the COM_{AP} trajectory based on the comparative UCM analysis.

To explore this issue further, we investigated whether the components of variance (V_{UCM} and V_{ORT}) obtained for each performance variable were affected differently by such factors as the feedback condition, performance variable, amplitude, and ID. That is, a higher ΔV for analysis of one performance variable compared to the other could be due to greater V_{UCM} , smaller V_{ORT} , or some combination of the two. The results presented in Figure 2 indicate that, overall, V_{UCM} was greater and V_{ORT} was smaller for the hypothesis of stabilization of COP_{AP} position compared to the stabilization of COM_{AP} position. A five-way, repeated measures ANOVA with factors feedback condition (4 levels), performance variable (2 levels), variance component (2 levels), amplitude (2 levels) and ID (6 levels) confirmed this finding revealing significant main effects of all five factors (feedback: $F(3,27)=9.77$, $p<0.001$; $\eta^2=0.52$; performance variable: $F(1,9)=65.65$, $p<0.001$; $\eta^2=0.88$; variance component: $F(1,9)=295.6$, $p<0.001$; $\eta^2=0.97$; amplitude: $F(1,9)=79.78$, $p<0.001$; $\eta^2=0.90$ and ID: $F(5,45)=9.45$, $p<0.001$; $\eta^2=0.51$). A reduction of both components of variance was observed with an increase in ID (i.e., with the task difficulty) for both amplitudes. Both components of variance increased with an increase in amplitude. The effects of amplitude and IDs have been reported in the previous manuscript (Freitas et al., 2006). The present analysis confirmed the previous findings using a different method to estimate the relationship between changes of COM_{AP} position and joint angles and extended this to a new hypothesis, stabilization of COP_{AP} position. The ANOVA also revealed a significant

performance variable vs. variance component interaction $F(1,9)=53.55$, $p<0.001$; $\eta^2=0.86$). Based on the difference in V_{ORT} between UCM analyses for COM_{AP} versus COP_{AP} position, it appears that the COP_{AP} position was stabilized better than the COM_{AP} position regardless of the feedback information provided during the movements. As we will see below, however, consideration of the results of this analysis alone when comparing hypothesizes about stabilizing different performance variables can lead to spurious conclusions.

Measures of stability of the COM_{AP} and COP_{AP} positions

Standard deviations of COP_{AP} position and COM_{AP} position were computed across cycles at each percentage of the cycle and then, averaged across the cycle to obtain one value for each amplitude and ID condition as a measure of the stability of these two performance variables (Figure 3). Overall, for all feedback conditions, greater stability (lower standard deviation) was observed for COM_{AP} position compared to COP_{AP} position, regardless of the movement amplitude. The standard deviation values of both performance variables dropped with an increase in ID. These findings were confirmed by a four-way, repeated measures ANOVA with factors feedback condition (4 levels), performance variable (2 levels), amplitude (2 levels) and ID (6 levels) revealed main effects of all four factors ($F(3,27)=4.30$, $p=0.013$; $\eta^2=0.32$; $F(1,9)=9.84$, $p=0.012$; $\eta^2=0.52$; $F(1,9)=30.57$, $p<0.001$; $\eta^2=0.77$ and $F(5,45)=12.85$, $p<0.0001$; $\eta^2=0.59$, respectively).

Effect of a given amount of joint variance on the performance variables

Comparisons of the results of UCM analysis and analysis of the standard deviations relative to both COM_{AP} and COP_{AP} positions suggest conflicting results. To resolve this apparent conflict, we performed singular value decomposition of each Jacobian matrix to obtain the singular values (eigenvalues) of the range space, i.e., those directions in joint space that affect the performance variables. The average results are presented parenthetically in Figure 3. These values express how much of a change in the performance variable should be expected for a unit change in the joint configuration. No differences were found across ID conditions ($p>0.05$). An ANOVA was run, therefore, to compare the singular values for the performance variables COM_{AP} and COP_{AP} across movement amplitudes and feedback conditions. Amplitude ($F(1,9)=7.2$, $p=0.026$; $\eta^2=0.44$) and feedback condition ($F(3,27)=4.4$, $p=0.012$; $\eta^2=0.33$) did affect the magnitude of the differences between the singular values for the COM_{AP} and COP_{AP} analyses, but they did not affect the direction of the difference. The singular values always were greater for COP_{AP} position than for COM_{AP} position ($F(1,9)=27.1$, $p=0.001$; $\eta^2=0.75$), as can be seen from the parenthetical values in Figure 3. Thus, although V_{ORT} was found to be smaller for the UCM analysis related to the control of COP_{AP} position, the singular values for this performance variable were more than twice as large as those for the COM_{AP} position, emphasizing that a given amount of joint variance had a smaller effect on the COM_{AP} compared to the COP_{AP} position.

Discussion

In the current report, we addressed two issues, one purely methodological and the other involving a new comparison between two performance variables with methodological implications. Applications of UCM analysis require identification of a Jacobian, or partial derivatives of a performance variable relative to a set of elemental variables. Recent analyses that treated modes of muscle activation (EMGs) as elemental variables and shifts in the COP_{AP} as the performance variable (Krishnamoorthy, Goodman et al., 2003; Krishnamoorthy et al., 2004; Krishnamoorthy et al., 2007), estimated the Jacobian matrix using MLR because a geometric model relating these two spaces would be extremely difficult to derive, requiring estimation of a significant number of parameters. Our first

analysis provided an initial attempt to validate this approach by comparing results of UCM analysis obtained in a previous report of a targeting task in kinematic space (Freitas et al., 2006), which used a Jacobian computed analytically, to a re-analysis of that data where the Jacobian was estimated using MLR.

Can comparable results of UCM analysis be obtained with different methods of computing the Jacobian?

The results of UCM analysis based on MLR to estimate the Jacobian, performed separately for the different feedback/tracking conditions, yielded nearly identical results to those obtained from the analysis based on the Jacobian derived analytically from a formal geometric model. These results suggest that MLR analysis can be used to estimate accurately the Jacobian, providing initial validation of previous studies that have used this method (Krishnamoorthy, Goodman et al., 2003; Krishnamoorthy et al., 2004; Krishnamoorthy et al., 2007). One attractive aspect of using this approach is that several other performance variables (i.e., shifts of the COP_{AP}) can be investigated when a formal geometric model mapping them to different sets of elemental variables is difficult or impossible to derive analytically. For example, although it is possible in principle to identify a formal mathematical model relating muscle EMG patterns to, say, the motion of an end-effector (Buchanan et al., 2004), such models involve estimation of many parameters that cannot be defined with high accuracy, and tend to be limited to muscle activations relative to a small number of joints. In addition, there also are many kinematic situations where the geometric model is either extremely complex and/or difficult to estimate without error, particularly when the number of DOFs is large and other constraint equations are needed to provide an accurate account (e.g., both feet in firm contact with the floor for the estimation of COM_{AP} location from joint motions). Thus, it was useful to determine whether a MLR approach to estimate the Jacobian would produce acceptable results of UCM analysis compared to the same analysis performed with the Jacobian based on a geometric model (Freitas et al., 2006). However, it is important to mention that only three joints were used in the analyses of the present report. Further studies of movement tasks involving more DOFs should be investigated to confirm the validity and robustness of this method.

Is the COP_{AP} position more strongly stabilized by kinematic synergies during postural tasks than the COM_{AP} position?

The second methodological issue arose as we performed an extended analysis of the data of Freitas et al. (2006), which had investigated how kinematic synergies act to stabilize the COM_{AP} position and trunk orientation. The rationale of that investigation was that the COM_{AP} position must be stabilized within some bounds of the base of support to maintain balance. However, although the stability of these variables was likely important for successful tracking performance and postural stability, neither variable was explicitly constrained by the experimental conditions. It has been argued that the COM_{AP} position is stabilized actively by controlling the position of the COP_{AP} (Winter et al., 1998). Moreover, one of Freitas et al.'s tasks involved targeting that required active translation of the COP_{AP} position, which was provided as feedback to the participants. Thus, in this report, we investigated whether the COP_{AP} position might have been stabilized more strongly by the kinematic synergy than was the COM_{AP} position. However, conflicting results of the UCM analyses and analyses of the variability (standard deviation) of the COP_{AP} and COM_{AP} across movement cycles raised a question about conclusions derived on the basis of UCM analysis alone, as discussed below.

When the COP_{AP} position was provided by Freitas et al. (2006) as feedback under the requirement to move that position between targets, one could expect that the importance of producing a consistent COP_{AP} trajectory would increase when the task was made more

difficult (i.e., by decreasing target width or the distance between targets, target amplitude). Indeed, V_{ORT} related to control of the COP_{AP} position was lower for the smaller target width for both amplitudes, although there was no difference in the ΔV index between ID conditions because of a concomitant decrease in V_{UCM} with higher IDs. This result with respect to the COP_{AP} , then, extends those of previous study by Freitas et al. (2006) on COM_{AP} and trunk stabilization.

The main question here, however, was whether stabilization of the COP_{AP} position was stronger than stabilization of the COM_{AP} position. Comparison of the results of UCM analysis of both variables revealed significantly lower V_{ORT} related to stabilization to the COP_{AP} position than to stabilization of the COM_{AP} position. When combined with a slightly higher V_{UCM} , the ΔV index also was larger for COP_{AP} compared to COM_{AP} position. This was observed even for conditions where movement of an individual joint angle was used to perform the targeting task and was provided as visual feedback to the participants, indicating that the results for COP_{AP} position cannot be attributed to the provision of visual feedback of COP_{AP} position alone. However, although it is tempting to conclude from these results that COP_{AP} position is better stabilized than COM_{AP} position, examination of the across-cycle variability of these two performance variables shows that this would be a spurious conclusion.

Variability of the COP_{AP} position at each percentage of the movement cycle was actually larger than variability of the COM_{AP} position. What may appear surprising about this is that as noted above, the only component of joint configuration variance that can directly affect performance-variable variability, i.e. V_{ORT} , was significantly smaller for analysis of COP_{AP} position. How can we account for this apparent discrepancy?

This apparent discrepancy can be reconciled by recognizing that the extent to which a given amount of joint variance affects variability of a performance variable depends on how those two spaces are related mathematically, including system geometry. Although this comparison of UCM results between COP_{AP} and COM_{AP} was performed using a Jacobian estimated from MLR analyses that did not explicitly take into account system geometry, the Jacobian estimated this way still reflects the system geometry, as was shown by our analysis of the first methodological issue. The important point is that the relationships between the joint configurations and either COM_{AP} position or COP_{AP} position differ, as reflected by differences in the respective Jacobian (Table 1). The manner in which differences in the structure of the Jacobian affects the influence of joint variance on the variability of two performance variables can be evaluated directly by examining the eigenvalues of the range space (λ_{ORT}), or those directions of joint configuration space that lead to changes in the performance variable, obtained from singular value decomposition of the Jacobian. These values indicate how much of a change in the performance variable should be expected for a unit change in the joint configuration (see, for example, Scholz and Schöner, (1999)). This measure is similar to the tolerance measure reported by Müller and Sternad (2004). Differences in λ_{ORT} for the Jacobian relating joint variance to COP_{AP} position compared to COM_{AP} position are obvious in the lower panels of Figure 3, where λ_{ORT} is printed over each standard deviation bar. The singular values for different experimental and feedback conditions related to the COP_{AP} position were more than twice those for COM_{AP} position. As a result, greater variance of the COP_{AP} position is expected for the same amount of joint configuration variance, consistent with our results. This is an important point to be considered when using UCM analysis to derive conclusions about differences in the importance of different performance variables for a given task. Thus, it would be wrong to conclude from the current UCM results that the COP_{AP} trajectory is stabilized more strongly than the COM_{AP} position. Shifts of the COP_{AP} likely reflect passive biomechanics as much as active neuromuscular control process (Zatsiorsky and Duarte, 1999).

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Figure 1.

Linear regression of V_{UCM} (A) and V_{ORT} (B) results obtained from Methods 1 and Methods 2-COM for four different visual feedback conditions (COP_{AP}, Ankle, Knee and Hip).

Figure 2.

Components of joint variance, V_{UCM} (gray) and V_{ORT} (white), related to stability of the COM_{AP} (circles, Method 2-COM) and COP_{AP} (triangles, Method 2-COP) positions for each target amplitude (4.5 and 9-cm or degrees, depending on the feedback condition) and ID. All values presented are average values across participants, $\pm$ standard error of the mean.

Figure 3.

Standard deviation of the COM_{AP} (circles) and COP_{AP} (triangles) positions for each target amplitude (4.5 and 9.0 cm or degrees, depending on the feedback condition) and ID. Each panel presents data for a different feedback condition (i.e. COP_{AP}, Ankle, Knee or Hip). All values presented are average values across participants, $\pm$ standard error of the mean. Numbers in parentheses represent eigenvalues of the range space of the Jacobian, averaged across participants and IDs for each task.

Table 1

Coefficients (K) of the Jacobian obtained when using a formal geometric model (Method 1, for COM_{AP} only) and with multiple linear regression (Method 2, both COM_{AP} and COP_{AP}), averaged ($\pm$ S.E.) across-participants, amplitudes and IDs.

Task Variable	Method to Estimate Jacobian	Visual feedback	Coefficient		
			K1	K2	K3
COM _{AP}	Geometrical Model	COP	-0.453 $\pm$ 0.068	-0.058 $\pm$ 0.068	0.265 $\pm$ 0.068
		Ankle	-0.447 $\pm$ 0.067	-0.053 $\pm$ 0.067	0.260 $\pm$ 0.067
		Knee	-0.452 $\pm$ 0.067	-0.058 $\pm$ 0.067	0.265 $\pm$ 0.067
		Hip	-0.451 $\pm$ 0.068	-0.057 $\pm$ 0.068	0.261 $\pm$ 0.067
COM _{AP}	Multiple Linear Regression	COP	-0.452 $\pm$ 0.068	-0.058 $\pm$ 0.068	0.265 $\pm$ 0.068
		Ankle	-0.446 $\pm$ 0.067	-0.053 $\pm$ 0.067	0.260 $\pm$ 0.067
		Knee	-0.451 $\pm$ 0.067	-0.057 $\pm$ 0.067	0.264 $\pm$ 0.067
		Hip	-0.451 $\pm$ 0.068	-0.058 $\pm$ 0.068	0.261 $\pm$ 0.067
COP _{AP}	Multiple Linear Regression	COP	-0.561 $\pm$ 0.248	0.30 $\pm$ 0.17	0.09 $\pm$ 0.121
		Ankle	-0.383 $\pm$ 0.236	0.180 $\pm$ 0.117	0.027 $\pm$ 0.078
		Knee	0.479 $\pm$ 0.220	-0.218 $\pm$ 0.097	-0.098 $\pm$ 0.066
		Hip	-0.451 $\pm$ 0.272	0.266 $\pm$ 0.131	0.044 $\pm$ 0.069

Table 2

Averaged across-subject ($\pm$ S.E.) ΔV results obtained with Methods 1 and 2 for both COM_{AP} and COP_{AP}, for each amplitude (4.5 and 9.0 cm or degrees), ID and visual feedback condition (COP_{AP}, ankle, knee or hip position).

		Amplitude		9			
		4.5					
Visual feedback	ID	COM _{AP} Method 1	COM _{AP} Method 2	COP _{AP} Method 2	COM _{AP} Method 1	COM _{AP} Method 2	COP _{AP} Method 2
COP	1.4	0.65 $\pm$ 0.07	0.65 $\pm$ 0.07	1.04 $\pm$ 0.11	0.91 $\pm$ 0.08	0.9 $\pm$ 0.08	1.11 $\pm$ 0.07
	1.8	0.72 $\pm$ 0.16	0.72 $\pm$ 0.16	0.92 $\pm$ 0.12	0.65 $\pm$ 0.09	0.65 $\pm$ 0.09	0.95 $\pm$ 0.1
	2.2	0.77 $\pm$ 0.12	0.76 $\pm$ 0.12	1.11 $\pm$ 0.14	0.77 $\pm$ 0.1	0.77 $\pm$ 0.1	1.05 $\pm$ 0.1
	2.6	0.64 $\pm$ 0.13	0.64 $\pm$ 0.13	0.89 $\pm$ 0.13	0.7 $\pm$ 0.1	0.7 $\pm$ 0.1	0.89 $\pm$ 0.1
	3.0	0.65 $\pm$ 0.15	0.65 $\pm$ 0.15	0.92 $\pm$ 0.16	0.57 $\pm$ 0.12	0.56 $\pm$ 0.12	0.97 $\pm$ 0.11
	3.4	0.44 $\pm$ 0.25	0.44 $\pm$ 0.25	1.07 $\pm$ 0.14	0.63 $\pm$ 0.11	0.63 $\pm$ 0.11	0.94 $\pm$ 0.08
Ankle	1.4	0.66 $\pm$ 0.12	0.67 $\pm$ 0.12	1.16 $\pm$ 0.07	0.65 $\pm$ 0.11	0.65 $\pm$ 0.11	1.1 $\pm$ 0.08
	1.8	0.68 $\pm$ 0.14	0.68 $\pm$ 0.14	0.98 $\pm$ 0.1	0.68 $\pm$ 0.12	0.68 $\pm$ 0.12	1.07 $\pm$ 0.07
	2.2	0.8 $\pm$ 0.06	0.8 $\pm$ 0.06	1.21 $\pm$ 0.03	0.65 $\pm$ 0.14	0.65 $\pm$ 0.14	1.15 $\pm$ 0.06
	2.6	0.78 $\pm$ 0.13	0.77 $\pm$ 0.13	1.02 $\pm$ 0.09	0.67 $\pm$ 0.11	0.67 $\pm$ 0.12	1.14 $\pm$ 0.06
	3.0	0.85 $\pm$ 0.07	0.85 $\pm$ 0.07	1.19 $\pm$ 0.05	0.75 $\pm$ 0.07	0.75 $\pm$ 0.07	1.17 $\pm$ 0.08
	3.4	0.77 $\pm$ 0.1	0.78 $\pm$ 0.1	1.06 $\pm$ 0.09	0.68 $\pm$ 0.09	0.68 $\pm$ 0.09	1.06 $\pm$ 0.11
Knee	1.4	0.6 $\pm$ 0.23	0.6 $\pm$ 0.23	0.87 $\pm$ 0.12	0.54 $\pm$ 0.19	0.55 $\pm$ 0.19	1.01 $\pm$ 0.08
	1.8	0.66 $\pm$ 0.13	0.66 $\pm$ 0.13	0.86 $\pm$ 0.1	0.65 $\pm$ 0.16	0.65 $\pm$ 0.16	0.99 $\pm$ 0.1
	2.2	0.55 $\pm$ 0.19	0.55 $\pm$ 0.19	0.8 $\pm$ 0.12	0.73 $\pm$ 0.07	0.73 $\pm$ 0.07	1.07 $\pm$ 0.07
	2.6	0.47 $\pm$ 0.18	0.47 $\pm$ 0.18	0.91 $\pm$ 0.09	0.65 $\pm$ 0.16	0.65 $\pm$ 0.16	1.03 $\pm$ 0.04
	3.0	0.50 $\pm$ 0.18	0.50 $\pm$ 0.18	0.87 $\pm$ 0.12	0.70 $\pm$ 0.13	0.70 $\pm$ 0.13	0.98 $\pm$ 0.06
	3.4	0.51 $\pm$ 0.25	0.51 $\pm$ 0.25	0.98 $\pm$ 0.1	0.59 $\pm$ 0.17	0.59 $\pm$ 0.17	1.07 $\pm$ 0.08
Hip	1.4	0.98 $\pm$ 0.07	0.98 $\pm$ 0.07	1.08 $\pm$ 0.11	0.95 $\pm$ 0.06	0.94 $\pm$ 0.06	1.13 $\pm$ 0.06
	1.8	0.76 $\pm$ 0.14	0.75 $\pm$ 0.14	1.11 $\pm$ 0.09	0.91 $\pm$ 0.13	0.91 $\pm$ 0.13	1 $\pm$ 0.08
	2.2	0.67 $\pm$ 0.16	0.66 $\pm$ 0.16	0.98 $\pm$ 0.12	0.88 $\pm$ 0.11	0.88 $\pm$ 0.11	1.07 $\pm$ 0.08
	2.6	0.82 $\pm$ 0.06	0.81 $\pm$ 0.06	0.99 $\pm$ 0.11	0.87 $\pm$ 0.07	0.87 $\pm$ 0.07	1.06 $\pm$ 0.07
	3.0	0.89 $\pm$ 0.07	0.89 $\pm$ 0.07	1.08 $\pm$ 0.09	0.85 $\pm$ 0.11	0.85 $\pm$ 0.11	1.05 $\pm$ 0.13
	3.4	0.8 $\pm$ 0.11	0.8 $\pm$ 0.11	1 $\pm$ 0.09	0.86 $\pm$ 0.14	0.86 $\pm$ 0.14	1.05 $\pm$ 0.09