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End-state comfort and joint configuration variance during reaching

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Abstract

This study joined two approaches to motor control. The first approach comes from cognitive psychology and is based on the idea that goal postures and movements are chosen to satisfy task-specific constraints. The second approach comes from the principle of motor abundance and is based on the idea that control of apparently redundant systems is associated with the creation of multi-element synergies stabilizing important performance variables. The first approach has been tested by relying on psychophysical ratings of comfort. The second approach has been tested by estimating variance along different directions in the space of elemental variables such as joint postures. The two approaches were joined here. Standing subjects performed series of movements in which they brought a hand-held pointer to each of four targets oriented within a frontal plane, close to or far from the body. The subjects were asked to rate the comfort of the final postures, and the variance of their joint configurations during the steady state following pointing was quantified with respect to pointer endpoint position and pointer orientation. The subjects showed consistent patterns of comfort ratings among the targets, and all movements were characterized by multi-joint synergies stabilizing both pointer endpoint position and orientation. Contrary to what was expected, less comfortable postures had higher joint configuration variance than did more comfortable postures without major changes in the synergy indices. Multi-joint synergies stabilized the pointer position and orientation similarly across a range of comfortable/uncomfortable postures. The results are interpreted in terms conducive to the two theoretical frameworks underlying this work, one focusing on comfort ratings reflecting mean postures adopted for different targets and the other focusing on indices of joint configuration variance.

Keywords

pointing; end-state comfort; uncontrolled manifold hypothesis; variability

Introduction

The problem of motor redundancy has been a central focus of motor-control research ever since it was introduced by Bernstein (1967). The term *motor redundancy* has two meanings. First, it refers to the fact that the number of elemental variables (such as joint rotations,

muscle forces, etc.) that participate in natural tasks is larger than the number of constraints associated with those tasks. In particular, an infinite number of joint configurations can be used to achieve a desired location of the index fingertip in the external space. Second, each elemental variable can show an infinite number of trajectories from an initial to a final value. In this study we focus on the former aspect of motor redundancy.

Motor redundancy may not be a problem as much as an opportunity, however. If one has to flip a wall-mounted switch to turn on a light, it is good rather than bad that this task can be achieved with one's shoulder if one's arms are filled with packages. By this way of thinking, motor redundancy may be usefully re-construed as motor *abundance* (Gelfand and Latash 1998; Latash 2012a).

The motor abundance perspective underlies the approaches of the two research groups contributing to this article, who are collaborating for the first time. One group, represented by the third and fourth authors, takes a cognitive psychological approach to motor control, drawing on computational modeling of decision-making as well as psychophysical techniques. The rest of the authors take a physical approach, drawing on analysis of variance in multidimensional spaces of elemental variables. The approaches of the two groups are described next, before we turn to the experiment in which the approaches are combined.

Cognitive Psychology

Rosenbaum et al. (2001) developed a computational model of motor planning whose core claims were twofold – first, that goal postures are generally specified before movements to those goal postures are specified, and second, that goal postures and movements are specified with respect to prioritized constraints that define the task to be completed (cf. Newell 1986). Comfort ratings were used to see how well those ratings mapped onto people's choices about possible means of task performance (reviewed in Rosenbaum et al. 2012). The rationale was to identify the constraints assumed in the computational model: Constraints with high priority were assumed to receive consistently high ratings and to predict performance choices. Constraints with low priority were expected to receive consistently low ratings and to predict performance aversions. A major finding that emerged from this approach was that when participants needed to move an object from one position to another with great precision in the terminal phase, they ended with postures that had high comfort ratings. This often meant adopting postures that had low comfort ratings at the initiation of an action. Rosenbaum et al. (1990) called this the *end-state comfort*. One aim of the present study was to look for validation of the comfort concept -- that is, to have an objective measure to which comfort ratings could be related so comfort was not just defined as what feels comfortable.

A critical feature of this approach was that it did not rely on optimization based on cost functions, contrary to some earlier, classical approaches (e.g., Hogan 1984; Nelson 1983). Instead, postures and movements were assumed simply to satisfy task-relevant constraints. This was borne out in the multitude of tasks that could be simulated with the model, including writing in different planes, reaching around obstacles, reaching with tools, reaching with any given part of the body, and producing realistic grasping movements of the fingers, hand, and arm. The approach also provided a way of understanding motor learning: Solutions chosen at random from solutions satisfying constraints could have features making them adaptive for the task even if those especially adaptive features were unknown before. Through learning, those features could become new constraints, in which case the task was redefined or, said another way, refined (Rosenbaum et al. 2009).

Physics

This approach is based on the idea of motor abundance (Gelfand and Latash 1998; Latash 2012a), seeing it as useful for achieving stability (Mattos et al. 2011) and simultaneity of task performance (Zhang et al. 2008). According to these ideas, families of trajectories (and final states) that are able to solve a given motor problem are facilitated in consecutive trials. Neural organizations that produce such families of trajectories are termed *synergies*. The associated analysis, developed within the uncontrolled manifold (UCM) hypothesis (Scholz and Schöner 1999), quantifies two components of variance in the space of elemental variables (such as individual joint rotations). One has no effect on a selected performance variable (variance within the UCM, V_{UCM}), while the other does (variance orthogonal to the UCM, V_{ORT}). The difference between V_{UCM} and V_{ORT} provides an index of the extent to which the synergy stabilizes the performance variable.

Joining Comfort Ratings and the UCM

Although the two frameworks described above embrace motor abundance, they focus on different characteristics of performance. Comfort ratings can be averaged across repetitive trials and may be associated with selection of mean joint configurations. In contrast, the UCM approach deals with variability of joint configurations about the mean. The methods used by the two groups -- comfort ratings and analyses related to the UCM -- have not been brought together in a single study. We did so here.

We asked whether arm-posture comfort reflects joint configuration variance and its structure (V_{UCM} vs. V_{ORT}). We predicted that postures judged to be uncomfortable would entail less total joint configuration variance than postures judged to be comfortable. In other words, we expected a positive correlation between comfort ratings and joint configuration variance indices. We based this prediction on the observations that uncomfortable postures are ones for which the joints are closer to the limits of their rotation range, compared to more comfortable postures; for review, see Rosenbaum et al. (2012).

We also expected uncomfortable postures to entail less accurate performance at the level of task-specific variables. We based this expectation on previous reports that clumsiness and variability are positively related (Latash et al. 2002a; Sagvolden et al. 2005; Gehrman et al. 2008). Thus, we expected V_{ORT} to be higher for uncomfortable postures than for comfortable postures. If our prediction of lower total variance for uncomfortable positions were upheld, then V_{UCM} would be reduced, leading to lower synergy indices.

Our young adult participants held a rod and used it to point at various targets, directing the end of the rod, which extended beyond the thumb, toward each of the targets. Because pointing is naturally associated with the location and orientation of a pointer tip, we explored our predictions in relation to both of these performance variables. We also addressed an open question about perceived comfort. To the best of our knowledge, no previous research has asked whether ratings are influenced by how far away the hand is from the body. This issue is important in the current study because the hypothesized “limit of joint rotation” factor should be exacerbated when people point at a target close to the body. The reason is that, in general, postural comfort has been shown to be lower near the extremes of joint ranges than at or near the middle of the joint range; for review, see Rosenbaum et al. (2012). Holding the pointer near the body puts the wrist and elbow in very bent positions, as the reader can confirm for him or herself by making a (loose) fist and holding a baton (or imaginary baton) in a plane parallel to and close to the frontal plane of the body. Especially when the base of the thumb is down, the position is very uncomfortable. This same thumb-down orientation is uncomfortable when the arm is extended, but less so than when the hand is near the frontal plane. Thus, our second

hypothesis was that the putative effects of target location on V_{ORT} , V_{UCM} , and synergy indices would be stronger for targets within a plane closer to the body than for targets within a plane farther away from, but still within comfortable reach of, the body.

A more general hypothesis was that comfort ratings would correlate with variance indices computed within the UCM method. If comfort ratings do indeed correlate with variance indices computed within the UCM method, this outcome would point to the promise of joining the two approaches.

Method

Participants

Twelve right-handed adults (6 males and 6 females) volunteered for the study. Their age, body mass and height were (mean $\pm$ SD): 28 ± 3 years, 66.1 ± 13.0 kg, and 1.69 ± 0.11 m, respectively. None of the participants reported a previous history of neuromuscular disorder or trauma to their upper extremities. Each participant provided informed consent according to the procedures approved by the Office for Research Protection of Penn State University.

Experimental Setup

Participants stood on a force plate (AMTI, USA), with their eyes open and with their feet at a comfortable, self-determined width. Force plate data are not reported here because such data are not directly relevant to our hypotheses. The positions of the feet were marked on the force plate for each participant and kept constant across all trials. A plastic hoop (diameter = 0.65 m) was positioned in front of the participants at each of two distances parallel to the coronal plane. The two distances were set at 40% and 80% of the arm length for each participant ($0.4L_A$ and $0.8L_A$). The center of the hoop was aligned with the body midline at shoulder height. A reflective target marker was placed on the inner surface of the hoop at one of four possible locations depending on the particular condition tested (3, 6, 9 or 12 o'clock positions, see Figure 1). The order of target presentation was quasi-random, which ensured that all targets were tested equally often across all trials for each participant.

Procedure

Participants grasped a pointer (length = 0.29 m, handle diameter = 0.03 m) firmly but without excessive force, much like they would grasp a tennis racquet. They maintained that grasp throughout the experiment. The pointer consisted of a metal handle covered with rubber and a narrow wooden dowel attached to the handle. The mass of the pointer was 0.18 kg, which was light enough to avoid any signs of fatigue during the experiment.

At the initial position, the participant stood with his or her arms relaxed at the sides of his or her body. On the experimenter's verbal signal, the participant moved his or her right hand towards the center of the hoop in a self-paced manner, pointing to the target with the tip of the pointer while keeping the hand as close as possible to the center of the hoop's plane. Participants were asked to be as accurate as possible and to avoid trunk movement (this was controlled visually at all times by an experimenter). There were no explicit requirements regarding movement speed and accuracy. The only requirement was to produce a single, smooth movement to the target. Typical movement times were about 1 s.

After the movement, participants maintained the final posture for approximately 2 s. Then the experimenter gave a command to return to the initial position. The home position was held for approximately 2–3 s, and then the next trial began. This procedure was repeated 24 times ($N_{trial} = 24$) in a row for each of the four target locations and two hoop distances. This design resulted in eight blocks (2 distances $\times$ 4 target locations) with a total of 192 trials.

Four target positions were block randomized within each hoop distance. Half of the participants started the experiment with the $0.4L_A$ distance; the other half started with the $0.8L_A$ distance. After completion of the four blocks of trials representing the four target positions, the distance of the hoop was changed. After each block of pointing movements, approximately two minutes of rest were provided.

On the last trial of each block, the participant rated the perceived comfort of that block's arm posture, basing the rating on a scale of 1 to 5, with 1 being "least comfortable" and 5 being "most comfortable." Participants were told that this first round of comfort ratings was meant to familiarize them with the range of postures and comfort ratings and that they would rate the comfort of each posture again at the end of the experiment, after completing all 192 trials. They were told not to feel constrained to give the same rating for each posture the second time around. The order of the second round of test postures was randomized for each participant (one trial per target). Only data from the second round of ratings were analyzed. This was done to allow the participants to experience the whole range of postures during the first round before producing ultimate comfort scores. This procedure was adopted in accord with previous posture-comfort rating studies, as reviewed by Rosenbaum et al. (2012), where it was found that participants needed experience with the range of conditions to calibrate their ratings.

Kinematic Data Collection

Three-dimensional (3D) kinematic data were recorded at 60 Hz using a Qualisys Motion Capture System (Qualisys AB, Sweden) with five ProReflex MCU240 infrared light emitting cameras. The cameras were mounted on tripods and were positioned around the participant. The system was calibrated following the manufacturer's instructions. Calibration was assumed to be successful if the standard deviation of the wand length, provided by Qualisys Track Manager software, was less than 1 mm. The marker clusters with four reflective markers each were used to track positions and orientations of right limb segments. The marker clusters were molded to fit the shapes of the related body segment and secured with self-adherent wrap (Coban™ LF, 3M), and surgical tape (Transpore™, 3M). Four marker clusters were placed on the right side of the body, at the following locations: (1) the upper torso, at two-thirds of the distance between the neck and the acromion process; (2) the upper arm, at the half distance of the lateral midline; (3) the forearm, at two-thirds of the length and on the dorsal surface; and on (4) the hand, on the dorsal surface. Four more markers were placed on: the suprasternal notch, the acromion process, the tip of the pointer, and the base of the pointer. 3D coordinates of the suprasternal notch marker were subtracted from all markers and were used as the origin of the XYZ global coordinate system. The typical location of the markers is illustrated in Figure 2. The X-axis pointed from medial to lateral, the Y-axis pointed posterior to anterior, and the Z-axis pointed vertically upward (see Figure 1).

Anatomical Calibration

During the anatomical calibration process, participants were asked to maintain a steady posture with the right arm parallel to the floor in a parasagittal plane, with the elbow joint fully extended, and the wrist in neutral position. They held the pointer with a power grip and with the tip pointing upward. For anatomical calibration, five additional markers were placed on the body at the following locations: 2 cm below acromion process, medial and lateral epicondyles of humerus, and ulnar and radial styloid processes. The additional markers allowed for calculations of limb segments' lengths and joint centers. Local *xyz* coordinate systems were fixed to each limb segment with origins at proximal joint centers. Axes of local coordinate systems were aligned with anatomical axes, in such a way that *x*-axes pointed to the right, *y*-axes pointed posterior-anterior, and *z*-axes pointed upwards. As

a result, the axes of the local coordinate systems were parallel to those within the global coordinate system.

Data Analysis

The data analysis was based on Matlab (Mathworks Inc, MA, USA) software. Marker coordinates were low-pass filtered at 5 Hz with a zero-phase 4th-order Butterworth filter. Calculation of angles between adjacent segments was performed in two steps. First the rotation matrices that describe orientation of each segment at their current position with respect to their orientation during calibration posture were derived from markers coordinates. This was done using a procedure proposed by Soderkvist and Wedin (1993). In the second step, rotation matrices of the relative orientation of distal segments with respect to proximate segments were calculated. Then, matrices of relative orientation were parsed into angles between adjacent segments using Euler Z-X-Y sequence. For the elbow, joint x -axis was estimated from markers placed on medial and lateral epicondyles of humerus using Rodrigues' rotation formula (Murray et al. 1994). As a result, ten rotational degrees-of-freedom (DOFs) were computed and used as elemental variables in further analyses: 3 DOFs for the clavicular rotation relative to the trunk (θ_1 - about z -axis, θ_2 - about x -axis, and θ_3 - about y -axis), 3 DOFs for the relative rotation of the upper arm (θ_4 - about z -axis, θ_5 - about x -axis, and θ_6 - about y -axis), 2 DOFs for the relative rotation of the forearm (θ_7 -about estimated x -axis oblique to the local coordinate system and θ_8 - about y -axis), and 2 DOFs for the relative rotation of the hand (θ_9 -about z -axis, θ_{10} - about x -axis). All rotational angles calculated during the calibration posture were assumed to have a measurement of 0 radians.

The steady-state of each pointing posture was defined as the time interval when the pointer-tip speed (estimated by differentiating the norm of the pointer-tip position vector) was less than 0.05 m/s. Thirty consecutive samples (500 ms) taken from the middle of each identified steady-state were used in further analysis.

The referent joint configuration vector ($\bar{\theta}$) was calculated at each time sample of a pointing posture by averaging joint angles across trials. A forward kinematic model was used (Scholz et al. 2000) to link changes in elemental variables (joint angles, $\bar{\theta}$) to two performance variables: pointer position (X -, Y - and Z -coordinates) and pointer orientation (α , β and γ - orientation angles of the pointer in XYZ global coordinate system). The dimensionality of each performance variable was $d = 3$. The kinematic model of the system was assumed to be linear in the range of small changes of joint angles. Using a forward kinematic model, the Jacobian matrix, $\underline{J}(\bar{\theta})$, was computed for each time step. Such a matrix determines how infinitesimal deviations of joint angles from the average configuration affect any dimension of the selected performance variable. Subsequently, the null space of $\underline{J}(\bar{\theta})$ was computed using the singular value decomposition. The null-space was used as a linear approximation of the UCM subspace (see Appendix 1 for more detail on the UCM analysis).

Variance per dimension within the UCM and orthogonal sub-space were computed as:

$$V_{UCM} = \frac{\sum |\bar{\theta}_{UCM}|^2}{(n-d) \cdot N_{trial}}, \quad (1)$$

$$V_{ORT} = \frac{\sum |\bar{\theta}_{ORT}|^2}{d \cdot N_{trial}}, \quad (2)$$

where θ_{UCM} and θ_{ORT} are projections of joint configuration onto the UCM and its orthogonal complement. Further, we computed an index of synergy (ΔV) reflecting the relative amount of V_{UCM} :

$$\Delta V = \frac{V_{UCM} - V_{ORT}}{V_{TOT}}, \quad (3)$$

where V_{TOT} is total variance and all variance indices are computed per DOF. Further, ΔV was normalized using modified Fisher's z-transform:

$$\Delta V_z = 0.5 \cdot \log \left(\frac{|\Delta V_{lower}| + \Delta V}{\Delta V_{upper} - \Delta V} \right) - 0.5 \cdot \log \left(\frac{|\Delta V_{lower}|}{\Delta V_{upper}} \right), \quad (4)$$

where ΔV_{lower} is the lower limit and ΔV_{upper} is the upper limit of ΔV ; $V_{UCM} > V_{ORT}$ ($\Delta V > 0$) was interpreted as a synergy in the joint configuration space that kept the performance variable unchanged (cf. Latash et al., 2007).

Overall, six dependent variables were calculated: $V_{UCM-POS}$, $V_{ORT-POS}$, ΔV_{Z-POS} , $V_{UCM-ORI}$, $V_{ORT-ORI}$ and ΔV_{Z-ORI} where the subscripts *POS* and *ORI* reflect analysis with respect to pointer tip position and pointer orientation, respectively.

Statistical Analysis

All descriptive statistics are reported in the text and figures as means and standard errors unless stated otherwise. Median values are used for variables, such as comfort ratings, that are not expected to show close to normal distributions; for these variables, we present the 25%–75% ranges. In order to explore whether perceived comfort varied between pointing positions, the Friedman nonparametric test was applied to target position (*Target*, four levels, 3, 6, 9 or 12 o'clock) and position of the hoop (*Distance*, two levels, 0.4L_A and 0.8L_A). Wilcoxon's tests with Holm-Bonferroni corrections were used to further analyze significant effects.

Two-way repeated-measures ANOVAs were used to test effect of *Distance* and *Target* on joint ranges measured in the final position across trials and the six indices computed within the UCM-based analysis, $V_{UCM-POS}$, $V_{ORT-POS}$, ΔV_{Z-POS} , $V_{UCM-ORI}$, $V_{ORT-ORI}$ and ΔV_{Z-ORI} . To fulfill the assumption of normality, dependent variables were log-transformed when needed. Tukey's HSD multiple comparison tests with Bonferroni corrections were run to analyze significant effects. To test the hypothesis that perceived comfort is related to postural stability, we computed polychoric correlation coefficients (Jaspens 1946) between comfort ratings and pointer position- and orientation-related variance indices. For this purpose, the variance indices were averaged across comfort ratings for each subject. The significance was set at $p=0.05$ for all statistical tests, which were performed with SPSS 19.0 (IBM Corporation, USA) and Matlab (Mathworks Inc, MA, USA).

RESULTS

Comfort Ratings Of Pointing Postures

Comfort ratings varied consistently across the four target-marker positions at both distances from the body. All five ratings were used by the participants at comparable frequencies; in particular, ratings from 1 to 5 were used 19 (1), 17 (2), 18 (3), 21 (4), and 21 (5) times. Overall, higher ratings were observed for the targets closer to the body (0.4L_A) and for the targets at the 9 and 12 o'clock positions. Figure 3 shows the median values of the comfort ratings. There were statistically significant differences in perceived comfort for *Target* ($\chi^2_{(3)} = 22.59$, $p < 0.001$) and *Distance* ($\chi^2_{(1)} = 4.5$, $p = 0.03$). Wilcoxon tests confirmed

significant differences between the 3 o'clock and 12 o'clock positions and also between the 6 o'clock and both 9 and 12 o'clock positions

Joint Excursions

Prior to the analysis of joint configuration variance, we confirmed that all rotational DOFs were involved during pointing to different targets. Figure 4 shows the mean joint excursions measured in the final position across the trials, calculated across all participants. Excursion was defined for all joints as the range of motion (maximum - minimum angle) for each pointing posture. While there were differences in joint excursion across targets, all rotational DOFs were involved in all pointing movements. The lowest grand average joint excursion was observed for the 12 o'clock target at the near distance ($1.13 \times 10^{-1} \pm 6.28 \times 10^{-3}$ rad) and the highest for the 6 o'clock target at the far distance ($1.88 \times 10^{-1} \pm 1.78 \times 10^{-2}$ rad). Two-way ANOVA confirmed main effect of *Target* on joint excursions ($F_{(3, 33)} = 10.74$, $p < 0.001$). Overall, joint excursion values were slightly higher for far targets ($1.43 \times 10^{-1} \pm 5.93 \times 10^{-3}$ rad) than for near targets ($1.33 \times 10^{-1} \pm 4.01 \times 10^{-3}$ rad). However, no effect of *Distance* or interaction was found.

Joint Configuration Variance

For both distances and for all target positions, most joint configuration variance was consistently confined to the UCM. This was true for both position-related and orientation-related analyses. In other words, there were multi-joint synergies stabilizing both pointer position and orientation across trials. These results are illustrated in Figure 5. Note the different scales for the V_{UCM} and V_{ORT} indices; $V_{UCM} > V_{ORT}$. This is also reflected in the consistently positive ΔV indices. The bottom panels of Figure 5 show averaged across subjects ΔV_Z indices. Overall, V_{Z-POS} indices were consistently higher than ΔV_{Z-ORI} values (0.57 ± 0.03 vs. 0.44 ± 0.02 , $F_{(1, 192)} = 15.32$, $p < 0.001$).

Indices of joint configuration variance differed across the four targets but were similar for the two distances. This was true for both position-related and orientation-related analyses. Overall, lower variance indices were observed for the 12 and 9 o'clock targets as compared to the 3 and 6 o'clock targets. Two-way ANOVA confirmed main effects of *Target* on both V_{UCM} and V_{ORT} for both position-related and orientation-related analyses ($F_{(3, 33)} > 7.0$, $p < 0.001$). The index of synergy (ΔV_Z) showed an effect of *Target* for position-related analysis only ($F_{(3, 33)} = 4.64$, $p < 0.01$). No effects of *Distance* and no interactions were observed.

Tukey's HSD tests showed that $V_{UCM-POS}$ for the 6 o'clock target position ($5.34 \times 10^{-3} \pm 7.82 \times 10^{-4}$ rad²) was higher than for the 3 o'clock ($1.92 \times 10^{-3} \pm 1.45 \times 10^{-4}$ rad²) and 12 o'clock ($1.73 \times 10^{-3} \pm 2.35 \times 10^{-4}$ rad²) positions. Similarly, $V_{UCM-ORI}$ at 6 o'clock position ($4.80 \times 10^{-3} \pm 6.85 \times 10^{-4}$ rad²) was higher than at 3 o'clock ($2.00 \times 10^{-3} \pm 1.59 \times 10^{-4}$ rad²) and 12 o'clock ($1.67 \times 10^{-3} \pm 2.10 \times 10^{-4}$ rad²) positions. $V_{ORT-POS}$ at 3 o'clock ($1.07 \times 10^{-3} \pm 2.53 \times 10^{-4}$ rad²) and 6 o'clock target positions ($1.43 \times 10^{-3} \pm 2.21 \times 10^{-4}$ rad²) was higher than for the 12 o'clock position ($4.79 \times 10^{-4} \pm 6.85 \times 10^{-5}$ rad²). For $V_{ORT-ORI}$ the difference was significant between the 6 o'clock ($2.71 \times 10^{-3} \pm 4.38 \times 10^{-4}$ rad²) and 12 o'clock ($6.31 \times 10^{-4} \pm 1.07 \times 10^{-4}$ rad²) positions only. The index of synergy ΔV_{Z-POS} differed significantly between the 3 and 9 o'clock target positions (0.371 ± 0.071 vs. 0.726 ± 0.068) only.

Relationship Between Comfort Ratings And Joint Configuration Variance

When the joint configuration variance indices were analyzed across different comfort ratings (pooled over target positions with identical comfort ratings), a trend toward lower variance indices was found for higher comfort ratings. This trend was present for both position-related and orientation-related analyses, as shown in Figure 5. Note that both V_{UCM} and

V_{ORT} dropped with comfort rating (on average by 41.5% from the rating of 1 to the rating of 5), while changes in the ΔV_Z indices were relatively minor.

Figure 6 presents results of the polyserial correlation analyses between comfort ratings and joint configuration variance indices. Most of the variance indices show significant negative correlations with comfort ratings. Only $V_{ORT-POS}$ and ΔV_{Z-POS} failed to show a significant negative relationship with comfort ratings.

Discussion

In this study we asked whether and how the perceived comfort of pointing postures is related to the amount and structure of joint configuration variance. We addressed this question by combining a cognitive psychological approach and a physical approach. We predicted that comfort ratings would correlate with variance indices computed within the framework of the uncontrolled manifold (UCM) hypothesis (Scholz and Schöner 1999). Consistent with this hypothesis, we found that joint configuration variance both within the UCM and orthogonal to the UCM declined for higher comfort ratings. On the other hand, our first specific hypothesis, that less comfortable postures would be associated with lower total joint configuration variance, was contradicted: Postures that received lower comfort ratings were associated with *higher* variance indices, both within the UCM and orthogonal to the UCM. We did expect V_{ORT} to be higher for those postures, but our expectation of lower V_{UCM} and lower synergy index (ΔV) was not confirmed. Both target position and distance from the body had no effects on the synergies that stabilized final pointing postures. These observations went against our second specific hypothesis that the putative effects of target location on V_{ORT} , V_{UCM} , and synergy indices would be stronger within a pointing plane closer to the body than within a pointing plane farther from the body.

Why Were Less Comfortable Postures Associated With More Rather Less Total Joint Configuration Variance?

As just noted, our study turned up a surprising result: The relation between comfort ratings and total joint-configuration variance was negative rather than positive. In other words, postures that were perceived by the subjects as being less comfortable were associated with *more*, not *less*, total joint configuration variance.

Entering this project, we expected less comfortable (more extreme) postures to have less total joint configuration variance than more comfortable (less extreme) postures. The basis for this expectation was that approaching the limits of the joint rotation range necessarily leads to a decrease in the available range of joint angle variation. In addition, feeling that a movement is less comfortable might be equivalent to feeling that it is clumsy, and stereotypical movements are associated with clumsiness (Latash et al. 2002a; Sagvolden et al. 2005; Gehrman et al. 2008). Given these seemingly sensible reasons for expecting lower variance for less comfortable postures, why, in hindsight, did we find the opposite?

One possibility is that when participants performed tasks that left them feeling uncomfortable, they sought more comfortable joint configurations, leading to a wider range of joint angles. This *search-for-greater-comfort* hypothesis is supported by the data in Figure 3, which shows that less comfortable target locations (such as the 6 o'clock location) were associated with larger ranges of joint excursions across trials in the final position.

Another possible reason for the finding that less comfortable postures had larger joint-configuration variance is fatigue. While we designed the experiment to avoid fatigue, it is possible that some tiring did occur. The amount of fatigue could reasonably be expected to have differed across target locations due to natural changes in muscle length and effective

loads and, in particular, to have been higher for the less comfortable postures than for the more comfortable postures. Because fatigue is known to lead to increased motor variability (reviewed in Enoka and Duchateau 2008; Enoka et al. 2011), this factor could have led to the increased variance for the less comfortable postures. It is potentially possible to explore the fatigue hypothesis by manipulating such task parameters as additional load attached to the arm and speed requirements. However, this would require running a separate experiment to avoid additional fatigue associated with doubling or tripling the number of trials. Setting aside that possible experiment for the future, we can note for now that the fatigue hypothesis is not mutually exclusive with the *search-for-greater-comfort* hypothesis offered above.

Yet another possible reason for the finding that less comfortable postures had larger joint-configuration variance (not mutually exclusive with the ones offered above) is related to force and torque requirements. Higher forces and torques are generated by passive tissues at postures closer to the limits of joint rotation. To overcome these passive-tissue forces and torques, actively generated counteracting muscle forces and torques might have been generated at those postures. Then, because of signal-dependent noise – the tendency for noise to increase with stronger signals (cf. Jones et al. 2002) – this tendency might have led to greater muscle-force variability, translating to higher joint-configuration variance. We did not record muscle activation levels, so this explanation is necessarily speculative, as are the two previously introduced accounts. Proper analysis of this hypothesis would require estimating muscle co-contraction levels and introducing a single metric for comparison of joint torques across the many axes of rotation of the human arm. These analyses are beyond the framework of the current study.

Multi-Joint Synergies And Comfort

Another remaining challenge is to develop a better understanding of our finding that the synergy index computed for the pointer *position* showed no correlation with comfort ratings, whereas the index for the pointer *orientation* showed a significant *negative* correlation with comfort ratings (Figure 6). Both pointer position and orientation were stabilized by co-varied adjustments of joint angles across trials. For both performance variables, V_{UCM} exceeded V_{ORT} ; an outcome that has been interpreted as a reflection of a neural synergy stabilizing those two variables (Scholz et al. 2000; Mattos et al. 2011). Pointing to different targets was associated with close-to-parallel changes in V_{UCM} and V_{ORT} so the synergy index (ΔV) remained mostly unchanged.

Why was the synergy index for pointer position uncorrelated with comfort ratings, while the synergy index for pointer orientation was negatively correlated with comfort ratings? It is possible that pointing is associated with strong multi-joint synergies that are present across directions and distances from the body. The lack of change in the structure of joint configuration variance in the presence of a scaling of the amount of variance with comfort ratings could mean that synergies that develop over the lifetime are robust to changes in factors that affect kinematic variance and perceived comfort. Future research will be needed to shed light on this new question.

It is important to remember, however, that only the V_{ORT} component of variance had a direct effect on the performance variable. Both pointer position and orientation had higher V_{ORT} for target positions with lower comfort ratings. Thus, these more difficult, and likely less experienced, joint configurations/target locations resulted in more difficulty in limiting joint variance increases to the UCM subspace, even though V_{UCM} was higher than V_{ORT} for all target locations. This latter fact indicates a decoupling of UCM and orthogonal joint spaces, such that most joint variance was restricted to the UCM. However, when the target location reached the limits of comfort, this decoupling was obviously less effective, leading to an increase in V_{ORT} equal to the increase in V_{UCM} . Apparently, for pointer orientation,

the decoupling was slightly more effective because the negative correlation between ΔV_{Z-ORI} and comfort rating indicated a slightly greater increase in V_{UCM} than in V_{ORT} when the joint variance increased in more extreme positions. It would be interesting to determine the effects of practice of the less comfortable positions on this joint space decoupling.

Concluding Remarks

To summarize, our experiment has shown that arm postures with low comfort ratings are associated with higher rather than lower joint configuration variance. At the same time, the relative amount of “good” variance (and synergy indices) was similar across the postures. Apparently, multi-joint synergies stabilized the pointer position and orientation similarly across a range of comfortable/uncomfortable postures. Note that indices of multi-joint synergies can show major changes with movement kinematics and other task and performance variables (Scholz et al. 2000; Tseng et al. 2003; Tseng and Scholz 2005; Gera et al. 2010). So, the current findings are not trivial reflections of multi-joint synergies always stabilizing all relevant performance variables to a high degree.

There were drawbacks of the present study, which we wish to acknowledge. First, we did not quantify effects of trunk motion on endpoint location and orientation. To minimize such effects, we asked our subjects to avoid trunk movements during the pointing tasks. Second, the 3D coordinates of the suprasternal notch marker (base marker) were subtracted from all markers. Despite these precautions, it is possible that trunk motion contributed to the pointer position and orientation. Third, we allowed our subjects to select their preferred movement times and trajectories while placing no explicit demands on the speed, accuracy, and other characteristics of their movements. This could have affected the results.

The most important concluding remark we wish to offer, however, pertains to the fruitfulness of the liaison of approaches that this study represents. Within the cognitive posture-based motion planning theory of Rosenbaum et al. (2001), goal postures and movements to those goal postures are assumed simply to satisfy task constraints. This approach departs from optimization in that it relies on “satisficing” – a term introduced by the cognitive psychologist Herbert Simon (1955) based on studies of complex decision-making. The satisficing approach as embodied in the posture-based motion planning theory allows for selection of any acceptable motor solution for a task at hand. The highest-level constraint allows for elimination of many possible actions, the second-highest-level constraint allows for elimination of more possible actions, the third-highest-level constraint allows for elimination of still more possible actions, and so on. This approach also allows for discovery of new constraints that enable better performance following random selection of candidates from among satisfactory sets (Rosenbaum et al. 2009). What was a low-level constraint may become a higher-level constraint for a task, or what was a high-level constraint may become a lower-level constraint. The latter method permits better and better performance over the course of practice on a task.

The motor abundance idea combines the ideas of optimization and facilitation of families of solutions for motor tasks (Latash 2012b). A recent series of studies (Park et al. 2010, 2011, 2012) suggests that optimization processes (cf. Seif-Naraghi and Winters 1990; Todorov 2004) may be used to identify the center of a family of acceptable solutions, while the shape of the distribution reflects stabilization of certain performance variables. The implementation of the UCM hypothesis allows for quantification of the variance within sub-spaces of elemental variables and interpretation of outcomes of this analysis with respect to stabilization of relevant performance variables (Scholz and Schoner 1999). In this context, the term “stabilize” implies both low variance of performance variables across repetitions and dynamic stability in the presence of extrinsic and intrinsic perturbations (Scholz et al.

2000; Martin et al. 2009; Mattos et al. 2011). As with the cognitive approach, better performance is possible not by *a priori* specification of single best solutions, but by organizing a hierarchical set of constraints.

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Appendix 1

Uncontrolled manifold analysis (more details in Scholz and Schoner (1999) and Scholz et al. 2000)

The reference joint configuration vector ($\bar{\theta}$) was calculated at each time step of a pointing posture by averaging joint angles across trials. We used forward kinematic model parameters (Scholz et al. 2000) to create Jacobian matrix ($\underline{J}(\bar{\theta})$). This matrix determines

how infinitesimal deviations of each joint from $\underline{\theta}$ affect performance variable (pointer position or pointer orientation). Subsequently, the null-space of $\underline{J}(\underline{\theta})$ was numerically obtained from the singular value decomposition, solving

$$\underline{J}(\underline{\theta}) \cdot \underline{E} = 0, \quad (5)$$

where each column of $\underline{E}$ is a basis vector. The null-space of $\underline{J}(\underline{\theta})$ represents configurations of joint angles that keep the performance variable unchanged; it was used as a linear approximation of the UCM. The deviation of joint angles from the reference configuration ($\underline{\theta} - \underline{\theta}$) were projected onto the null-space at each time step, using:

$$\underline{\theta}_{UCM} = \underline{P} \cdot (\underline{\theta} - \underline{\theta}), \quad (6)$$

where $\underline{P}$ is the projection matrix

$$\underline{P} = \underline{E} \cdot (\underline{E}^T \cdot \underline{E})^{-1} \cdot \underline{E}^T. \quad (7)$$

The projection of the deviations of the joint configuration from its average value on the orthogonal subspace ($\underline{\theta}_{ORT}$) was computed as:

$$\underline{\theta}_{ORT} = (\underline{\theta} - \underline{\theta}) - \underline{\theta}_{UCM}. \quad (8)$$

The following formulas for calculating per dimension variance along $\underline{\theta}_{UCM}$ and $\underline{\theta}_{ORT}$ projections were used

$$V_{UCM} = \frac{\sum |\underline{\theta}_{UCM}|^2}{(n-d) \cdot N_{trial}}, \quad (9)$$

$$V_{ORT} = \frac{\sum |\underline{\theta}_{ORT}|^2}{d \cdot N_{trial}}. \quad (10)$$

The total variance V_{TOT} was computed as

$$V_{TOT} = \frac{\sum |(\underline{\theta} - \underline{\theta})|^2}{n \cdot N_{trial}}. \quad (11)$$

Figure 1.

Experimental setup showing the plastic hoop at the two relative distances: 40% and 80% of the participant arm length. The center of the hoop was aligned with the vertical midline and adjusted so that it was at shoulder height. A reflective target marker was placed one the inner surface of the hoop either at 3, 6, 9, and 12 o'clock positions. X, Y, and Z-axes represent global coordinate system with origin at suprasternal notch marker.

Figure 2.

An illustration of the calibration position for the computation of joint angles, including depiction of the rigid bodies on each segment and additional markers used to determine the joint locations and segment lengths. All angles in the configuration position were zero by default.

Figure 3.

Median comfort ratings of pointing postures for the four targets (3, 6, 9, and 12 o'clock positions) placed at 40% and 80% of arm length. Integer comfort ratings ranged from 1 (least comfortable) to 5 (most comfortable). Error bars show the 25%–75% ranges, Stars show statistically significant differences ($p < 0.05$).

Figure 4.

Mean joint excursions (with standard error bars), averaged across all participants for each pointing posture. Each graph represents excursion (range of motion) of individual joints at different target marker position (3, 6, 9, and 12 o'clock), for two relative hoop distance (40% or 80% of the arm length). Local coordinate systems of each segment originated at proximal joint centers. During the anatomical calibration, local coordinate systems were aligned with global coordinate system in such a way that x -axes pointed to the right, y -axes pointed posterior-anterior, and z -axes pointed upwards. DOFs were defined as follow: For clavicular rotation relative to the trunk, θ_1 , θ_2 , θ_3 are rotations about z -axis, x -axis, and y -axis, respectively; for the relative rotation of the upper arm, θ_4 , θ_5 , θ_6 are rotations about z -axis, x -axis, and y -axis, respectively; for the relative rotation of the forearm, θ_7 is a rotation about x -axis estimated from markers placed on medial and lateral epicondyles, and θ_8 is a rotation about y -axis; for the relative rotation of the hand, θ_9 and θ_{10} are rotations about z -axis and x -axis, respectively.

Figure 5.

Average indices of the UCM analysis with standard error bars for different targets. The top panels show variance within the uncontrolled manifold, UCM ($V_{UCM-POS}$ and $V_{UCM-ORI}$); the middle panels show variance orthogonal to the UCM ($V_{ORT-POS}$ and $V_{ORT-ORI}$); and the lower panels show z-transformed indices of synergy (ΔV_{Z-POS} and ΔV_{Z-ORI}). The left columns present results of analysis with respect to pointer position, and the right columns – with respect to pointer orientation.

Figure 6.

Averaged variance indices (with standard error bars) grouped by level of comfort rating that ranged from 1 (least comfortable) to 5 (most comfortable). The left columns show results of the pointer position-related analysis; the right columns show results of the pointer orientation-related parameters. A, D - variance within the uncontrolled manifold, UCM ($V_{UCM-POS}$ and $V_{UCM-ORI}$), B, E - variance orthogonal to the UCM ($V_{ORT-POS}$ and $V_{ORT-ORI}$), and C - z-transformed index of synergy (ΔV_{Z-POS} and ΔV_{Z-ORI}). The trend of the variance indices with higher comfort ratings is represented by linear regression line (solid, black). Polyserial coefficients (r) and significance levels (p , $N = 5$) for correlations between comfort ratings and variance indices for pointer position-related and pointer orientation-related analyses. Variance indices were averaged across comfort rates. * Statistically significant at the 0.05 level.