

Identifying control structure of multi-joint coordination in dart throwing: the effect of distance constraint

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Abstract

Purpose: This study used the uncontrolled manifold (UCM) approach to study joint coordination underlying the control of task-related variables important for success at dart throwing skill. Success at a task can be achieved, in principle, by always adopting a particular joint combination. In contrast, we adopt a more selective control strategy: variations of the joint configuration that leave the values of essential task variables unchanged are predicted to be less controlled (i.e., stabilized to a lesser degree) than joint configuration changes that shift the values of the task variables.

Material: How this abundance of motor solutions is managed by the nervous system and whether and how the throwing in different distances affects the solution to joint coordination was investigated in this study. Our experimental task involved dart throwing to a target under three conditions (standard, short and long distance) that it performed by fifteen dart professional and semiprofessional athletes. The four joint angles of the arm were obtained from the recorded positions of markers on the limb segments. The variability of joint configurations was decomposed into components lying parallel to those sets and components lying in their complement with respect to control of the path of the arm's center of mass and spatial position of the hand.

Results: When performing the task in all three different conditions, fluctuations of joint configuration that affected arm's center of mass and spatial position variables were much reduced compared with fluctuations that did not affect these variables. The UCM principle applied to arm's center of mass and spatial position thus captures the structure of the motor control system across different parts of joint configuration space as the movement evolves in time. Moreover, constraints representing an invariant arm's center of mass or the spatial position structured joint configuration variability in the early and mid-portion of the movement trajectory, but not at the time of throwing. This specific control strategy indicate a target can be hit successfully also by controlling irrelevant directions in joint space equally to relevant ones.

Conclusions: The results suggests a specific control strategy in which changes of joint configuration that are irrelevant to success at the task are selectively released from control. As a result, the method can be successfully used to determine the structure of coordination in joint space that underlies the control of the essential variables for a given task.

Keywords: motor control, degree of freedom, motor redundancy, uncontrolled manifold, skill.

Introduction

Targeting tasks require the coordination of more joint motions than are strictly necessary to specify the arm's position in space. Different combinations of joint angles and muscle activations can be used to reach a given hand position in external space due to the "abundance" of degrees of freedom (DOFs) characterizing the redundancy of the human arm [1]. Having a large number of solutions available to coordinate the arm's motion allows for flexible performance. Yet it has been argued that motor redundancy makes control unnecessarily difficult [1, 2]. Motor redundancy or, when considered more positively, motor abundance [3] makes it possible for multiple variations of joint coordination to be used to achieve a given task performance. Therefore, how the central nervous system (CNS) manages the additional degrees of freedom (DOFs) to achieve reliable and accurate performance is of great interest to movement scientists

[4, 5, 6]. That motor abundance is actually used by the central nervous system (CNS) when coordinating the motor elements (such as joints) has been established in numerous studies of a variety of functional tasks [7, 8, 9]. These results are consistent with Bernstein's intuition that task performance typically involves "repetition without repetition" [10, 11].

From a classic control-theory perspective, multi-joint movement in tasks such as pointing, reaching, shooting, or throwing entails two problems. The first problem is one of planning. The appropriate spatial-temporal "shape" of the movement trajectories of important movement components must be specified. The nature of these trajectories also must vary appropriately as conditions of the task vary, for instance, when throwing at different distances is required. The second problem is one of control. Given a plan, the trajectory must be generated in time and a control system must be able to steer the effector system such that appropriate time courses of all involved DOFs are actually realized. These two problems are not

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independent of each other. It is not efficient to generate plans that cannot be realized. Conversely, it is not useful to design a control system that can realize movement plans that would never be produced, e.g., plans having no ecological value. It is useful, however, to recognize the two problems as separate aspects at a conceptual level. In the motor control literature, this distinction is often not made explicitly, but it will be important for us here.

A consideration of control as the problem of resolving motor redundancy has led to hypothesized solutions that involve reducing DOFs, including the direct “freezing” of DOFs, or the application of various cost functions to constrain the possible solutions to their coordination [12, 13, 14]. Such solutions have been suggested for the control of reaching tasks, at least implicitly, by a few recent studies [12,15]. Nonetheless, a clear understanding of how the abundant DOFs are constrained to simplify the motor control problem, or are exploited by the control system [3,16] remains elusive.

The researchers proposed a contrasting hypothesis about the control of multiple DOF tasks. This hypothesis, referred to as the uncontrolled manifold (UCM) hypothesis, links the control of a multi-component system to the structure of variability of individual components, allowing the discovery of how the CNS organizes the available complexity to achieve its desired goals [16]. The UCM hypothesis posits a control law linking the coordination of motor components to the stability of important task-related variables—that is, those variables most directly related to the goals of the task, such as the hand’s motion in a throwing task. The control law selectively restricts coordination solutions if they lead to changes away from the desired values of important task-related variables. At the same time, the available motor abundance is exploited by allowing an entire range of goal-equivalent solutions to be instantiated, the exact solution depending, for example, on momentary fluctuations of local movement dynamics and external constraints [17, 18]. Support for this hypothesis has been provided by the results of studies of a variety of motor tasks [19, 20]. These results indicate that a range of solutions to motor coordination are typically used to control important task-related variables, even when performance occurs under invariant task conditions [21, 22].

The UCM hypothesis served as the framework of the experimental approach used here to study joint coordination underlying the control of a throwing task. We sought to determine whether unique solutions are typically used when throwing to a given arm position from the different starting location, as the results of research suggested unique solutions are typically used when reaching to a given terminal hand position from the same starting location [15], or whether many solutions to joint coordination are used, as hypothesized by the UCM approach. A number of studies have considered joint coordination [23, 24]. The present study is unique, however, in type skill and its analysis of the structure of joint configuration variability for a 4 DOF arm (shoulder, elbow, wrist and finger joint motion) in relation

to the control of important task-related variables. We were particularly interested in understanding how this structure evolved during different phases of the throwing movement. In addition, this study evaluated whether and how the throwing under different distances conditions affected the joint coordination used to control the hand’s path.

It is argued that changes in task constraints can influence the magnitude of movement variability observed during task performance [25]. A reduction in coordination variability was also reported, as evidenced by the decrease in standard deviation of continuous relative phase at larger distances. Nonetheless, there was no increase in joint angle variability with distance, which counters previous works [26, 27]. The extent of compensatory behavior between interacting joints is conducted by researchers [26]. This is particularly important as it is the structure, and not the magnitude, of movement variability that identifies its functionality during goal-directed behavior [27]. Consequently, when expressed relative to performance outcome, it could be argued that skilled motor performance is facilitated by a functional bandwidth of movement variability, or, stated differently, a region of optimal functioning. An increased distance has been shown to instigate a reorganization of motor system dynamics. Constraints either allow individuals to explore the available phase-space [28], or alternatively, constrain the human movement system to a narrow range of kinematic solutions [29]. In other words, constraints set boundaries or limits within a dynamical system [30]. The present study is an investigation in joint level and specifically the analysis of the structure of joint configuration variability in relation to the control of important task-related variables while performing dart throwing in different distances.

Methods and Materials

Participants

The data of fifteen healthy, male subjects, 12–53 years of age, who volunteered to participate in this study, were analyzed for this report. All subjects gave written consent, approved by the Dart Association of the Yazd province, before participating. Subject characteristics are presented in Table 1. Four subjects were classified as left-handed and the remaining eleven subjects as right-handed by report of their activities of daily living and throwing history. All subjects used their dominant hand to throw to the target.

Equipment and setup

The standard darts board and tungsten darts were used to perform the throwing. Based on the rules of the World Darts Federation, the height of the center of the dart board and the throwing distance to the dart board were set to 1.73 and 2.4 m respectively, as in the normal darts game.

A two-camera, 120-Hz Optitrack system was used to collect the kinematic data and a calibration for accuracy confirmation was performed before the start of recording (less than 1.0 mm). The cameras were mounted on tripods and were angled to be approximately 1.05 rad apart and positioned so that all reflective markers placed on the

Table 1. Subject age, height, weight, handedness

Subject	Age (years)	Height (m)	Weight (kg)	Dominant Hand
S1	46	180	79	R
S2	53	168	80	L
S3	45	181	78	R
S4	40	168	76	R
S5	38	186	72	L
S6	26	178	68	R
S7	25	175	62	R
S8	25	160	58	R
S9	24	193	77	L
S10	18	175	59	R
S11	24	170	63	R
S12	25	175	62	L
S13	16	175	52	R
S14	15	169	60	R
S15	12	144	40	R

subjects' left side (or right side for left hand subjects) could be seen by both cameras. Three-dimensional coordinates were calculated using PowerMac computers and Motive software. Six 2-cm-diameter reflective spherical markers were attached with adhesive to the skin overlying the following bony landmarks: (a) just inferior to the lateral edge of acromion process, (b) medial epicondyles of the humerus, (c) just distal to ulnar epicondyle (d) carpal bones (e) metacarpal bones (f) proximal phalanx of index.

Dart throwing motion has a little perturbation in a sagittal plane and were analyzed in only a frontal plane in the previous works [31,32]. Besides, in this study, we restrict and analyze the motion to 2-D space in a frontal plane. This restriction is necessary to promote arm motion. For these reasons, we analyze dart throwing motion in a frontal plane.

Subject Calibration

A static calibration posture of the arm was recorded prior to each data collection. This arm calibration was the basis for joint angle calculations in a body-centered coordinate frame. All joint angles were defined as 0° at this calibration posture. The subjects were told to hold their arm perpendicular to the trunk with their thumb facing upwards, the wrist kept in slightly bent backward, the elbow bent to 90 degrees, and shoulder at 90° of flexion. The position was adjusted to meet these criteria by the experimenter.

Experimental procedure

Subjects have sideways stance, with both legs turned in a vertical direction to the target (Z-axis) and shoulder-width apart. The participants were instructed to throw darts in a frontal plane (XY plane). In this study, participants throw at distances of 1.9, 2.4, and 2.9 m. The throwing distance 2.9 m defined as long distance compared to the distance of normal darts game. On the other hand, the throwing distance 1.9 m defined as short distance. Subjects performed 9 dart throws at each throwing distance. Each participant threw darts to aim at the triple area of the dartboard because this point has the

highest score in the darts match.

Instructions

Prior to each experiment, subjects were asked to assume the same starting position, which was checked by the experimenter. They were instructed to perform each trial as follows: "After hearing the experimenter's 'go' signal, throw the dart in one continuous motion to the specified target area at a fast, comfortable speed while being as accurate as possible. Try to keep the speed consistent across all trials and movement directions." Subjects were given as many trials of practice as necessary to determine an appropriate speed. In no case was this more than five trials.

Data Processing

Reconstruction of the Marker Positions

Reflective marker identification and reconstruction of the marker positions from the camera views were done using MOTIVE software. Further processing of the kinematic data was performed using customized MATLAB programs. The marker positions were filtered at 5 Hz using a forward and reverse low-pass, 2nd order Butterworth filter.

Definition of Motion

The duration of the motion is different in each throwing motion or among people. In order to compare different trials of dart throwing motion, the throwing data is normalized to 0–100%.

- The start time (0%)

The first time at which the elbow joint angular velocity rises above zero.

- The finish time (100%)

The first time at which the elbow joint angular velocity reduces to zero or less after the start time.

Joint Angle Calculations

Joint angles were obtained based on local coordinate systems defined at each joint in the subject calibration position (Figure 1). Details of the method, which used the algorithms for obtaining the necessary rotation matrices, are described in detail elsewhere [5,33]. The new extension

used in this study was to account for scapula motion. This motion was modeled as motion of the rigid body positioned on top of the shoulder with respect to the fixed trunk, and occurring about an axis located at the sterno-clavicular joint. The model was determined to be adequate by having test subjects perform controlled scapular motions. The values of the reconstructed scapular angles were found to be in close agreement with the scapular motions that the subjects performed. The joint angles measured during the throwing task were (a) scapular elevation-depression, (b) elbow flexion-extension (c) wrist flexion-extension (d) finger flexion-extension. The joint angle trajectories were normalized to 100% based on the previously defined trial onset and termination times, using a cubic spline algorithm in MATLAB.

Uncontrolled Manifold

The uncontrolled manifold (UCM) approach provides a method to partition the variance of joint angle combinations (i.e., solutions to joint coordination) across multiple repetitions of a task, performed under identical conditions, into variance components related to the control of important task-related variables. Details of the method as applied to the analysis of a similar task have recently been provided [5]. Briefly, one component of the joint configuration variance represents variations leading to a change in the value of the task-related variable being considered. This component is referred to here as NGEV or non-goal-equivalent variability. The second variance component represents joint configuration variations that are consistent with a stable value of the task-related variable and is referred to as GEV or goal-equivalent variability. The manner in which joint variance is structured with respect to these two components may differ for different task-related variables because the geometric relationship between joint angle space and task-related variable space

also differs. If the CNS employs a control law leading to the use of a range of goal equivalent solutions to joint coordination, then the GEV component is expected to be larger than the NGEV component. In contrast, if the CNS were to solve the problem of coordinating multiple DOFs by invoking additional constraints or cost functions, which lead to a unique solution to joint coordination, then both variance components are expected to be very small and close to zero. Note that this analysis requires the comparison of different hypothesized task-related variables under different experimental conditions, because variability is relative. If the NGEV component were found to be quite large compared to the GEV component, then control of the hypothesized task-related variable could be considered less crucial for task success. In this manner, control is directly related to stability of important task-related variables. The first step in applying the UCM approach is to develop a geometric model that links task variable space with the space of joint angles. For a hypothesis about controlling the spatial position of the hand, the $d=2$ -dimensional (2D) hand position is expressed as a combination of $n=4$ joint angles, the joint configuration. Having the geometric model, a linear estimate of all possible joint angle combinations that are consistent with a given hand position can be obtained. This estimate is obtained by calculating the null space of the Jacobian matrix (a matrix relating changes in the joint angle configuration to changes in a task-related variable) [4,5]. In this example, such combinations can be represented as an $n-d$ or two dimensional (i.e., $4-2$) surface embedded in the 4-dimensional coordinate frame of the joint angles. We refer to such surfaces as uncontrolled manifolds because, strictly speaking, any combination of joint angles lying within the UCM is consistent with the desired hand position. Thus, there is no need for the CNS

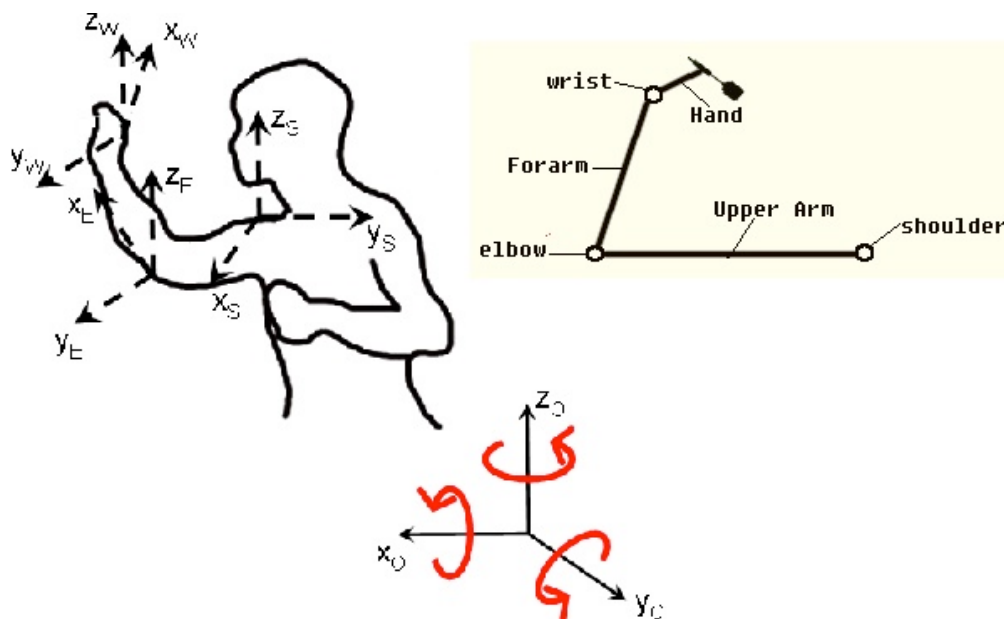


Figure 1. Illustration of the right arm's posture during the procedure to calibrate the arm position for joint angle calculations. From proximal to distal, local coordinate systems are centered at the gleno-humeral, elbow, and wrist joint centers. These are coordinate systems for reconstructing the joint angles. The same arrangements apply to the left arm.

to specify a particular value. In practice, other factors or task constraints may lead to some restriction of that space. At each percentage of normalized time of the hand's path, the average (across trials) joint configuration was used to parameterize the Jacobian. This yielded a sequence of UCMs, one corresponding to each percentage of the hand's path. To analyze how joint configuration variance was structured with respect to the UCMs (i.e., the extent to which that variance lay within the UCM), the vector of 4 joint angles for each trial and at each point in time was projected onto each dimension of the UCM and of a surface orthogonal to the UCM. The variance of each projection across trials yielded the two variance estimates, GEV and NGEV, respectively. (See appendix for mathematical details.) Note that some amount of NGEV is expected because a range of hand (and CM) paths are likely to be consistent with successful task performance. The desired hand path that the CNS attempts to produce in throwing to a target is unknown. Thus, the UCM analysis must be based on an estimate of the desired hand path. For this purpose, we use the hand path that is consistent with the mean joint configuration subjects actually produce across acceptable trials. If the desired hand path is identical to this mean path, then NGEV is expected to reflect noise or error in executing the desired hand path. Most joint configuration variance should be partitioned into GEV. To the extent that this mean path only approximates the desired path, some NGEV will be due to the fact that a range of hand paths is actually acceptable, each hand path being associated with a different sequence of joint angle combinations or UCMs than the UCM representing the mean hand path. At present, we have no way to distinguish between these contributions to NGEV.

Experimental Hypotheses

Because of the nature of the task, it is apparent that the end-effector position will be stabilized at the target for successful performances. We hypothesized that this would be achieved by structuring the variability of joint configurations in a specific way, that is, $GEV > NGEV$, and this would be the case throughout the movement, not only near the target. This prediction implies that the CNS makes use of available motor abundance to control the hand's position, rather than using a unique solution to joint coordination. Note that the latter strategy could also be consistent with a stable path and terminal position of the end-effector. We also evaluated how the joint variance was structured to control the arm's center of mass (CM) position. The researchers suggested that the arm's CM was more controlled than the hand's trajectory when subjects performed a non-redundant reaching task [34]. Evidence against this hypothesis was presented in a study of a multi-DOF pistol-shooting task [5] and pointing task [6]. Here, we sought to determine if the full path of the center of mass was also stabilized for the two-dimensional, redundant throwing task and, if so, whether this was accomplished by a similar or stronger use of goal-equivalent joint combinations than for the control of the hand path.

We also hypothesized that the variance of joint

configurations would be increased when targeting in the different throwing conditions. This prediction was based on two factors. A previous study of the coordination of a postural task indicated that performance under challenging task conditions led to an enhanced use of goal equivalent joint configurations [35]. Thus, GEV would be expected to increase if a similar effect were to result from throwing in the short and long distances. Second, probably performance under challenging task conditions induce to an inaccuracy of the sensorimotor representation of the target [36]. Such uncertainty should lead to more inconsistency from trial to trial in selecting an appropriate joint configuration needed to produce a reliable hand trajectory and, thus, to an increase in NGEV compared to throwing in the standard condition. Thus, both components were expected to increase. It was of interest to determine which predicted effect was strongest and whether it depended on the skill of the arm used to perform the throw.

Dependent Variables

Components of Joint Variance. The dependent variables of primary importance to this study were the two components of the variance of the joint configuration, GEV and NGEV, calculated at every 1% of the movement period with respect to the 3D position of the pointer-tip and the 3D position of the arm's CM. These variances were then averaged and evaluated with respect to the experimental hypotheses over the periods of 0–20% (early phase), 30–50% (middle phase), and 70–90% (late phase) of the movement path, as well as at movement termination (100%).

Additional Kinematic Variables

The following kinematic variables were also examined:

1. Movement time: duration from the onset to the end of the movement;
2. Time to peak velocity: Peak velocity was calculated by taking the first derivative of the arm's path using central differences method. Then, an automatic algorithm was applied to find the time of the maximum velocity using MATLAB. The time to peak velocity was expressed as percentages (%) of the total movement time.
3. Path variability of the end-effector and CM: This was calculated by taking the standard deviation of the end-effector and CM's position at each percentage of the normalized movement across all trials, and then averaging across 0–20%, 30–50%, and 70–90% of the movement.

Independent Variable

The independent variables directly manipulated in the experiment were the arm with which subjects threw (right and left) and the distance conditions (short, standard and long distances).

Statistical Analysis

The hypotheses were analyzed with repeated measure analyses of variance (ANOVA) using the SPSS statistical package. Separate analyses were performed to analyze the effects of independent variables on measures related to

the paths of the end-effector and of the arm's CM. Factors in the ANOVA included the independent variables and the components of variance (GEV and NGEV). Each ANOVA was performed separately on data for three different phases of the movement (early, middle, late).

Results

Movement time

No subject had difficulty completing the task, keeping the movement speed relatively consistent across different throwing conditions (Table 2). Movement time variability across trials was also not significantly different between experimental conditions ($P > 0.05$). Individual differences in movement time were evident, however: the range of movement times, however, the range of movement times was from 2.2 to 2.7.

Below, general features of the movement kinematics are presented, followed by the main results on joint coordination and their relation to throwing performance.

Time to Peak Velocity

The total movement time was similar across conditions (Table 2), while the time to peak velocity, or the acceleration phase, expressed as the percentage of the total movement time, depended on the availability of throwing distances (Table 2). The arm accelerated faster when throwing in the long distance than with the short and standard distance ($F = 6.74, p < 0.05$). In other words, the mean peak velocity of movement was smallest for starting positions closest to the target (short distance) and largest for the conditions initiated from the 2.9 m distance ($F = 39.72, p < 0.05$). Moreover, the throwing time was larger when throwing in the long distance than with the short and standard distance ($F = 5.38, p < 0.05$).

Joint kinematics

Figure 2 shows the mean path of each joint angle of the arm of one randomly chosen subject. Note the variability of the trajectories across trials. The scapula and forearm motions exhibited the smallest movement compared to other joints of the hand. The finger motions exhibited the largest excursion across all experimental conditions. Joint motions were most similar across all trials and subjects for all experimental conditions, while individual differences were apparent for joint angles variability. The average joint excursions of the four joint angles that contributed to

throwing motion across all trials and subjects are shown in Fig. 3.

Figure 4 presents the range of excursion (maximum-minimum) observed across trials for the four joint angles, averaged across the fifteen subjects for each experimental condition. All angles exhibited variability across trials. Finger and wrist angles exhibited the most variability, while the magnitude of variability was more dependent on the condition. Thus, contributions to joint configuration variability were distributed along the kinematic chain, although variability was clearly greatest at the most distal segment.

For horizontal and vertical positions of finger, the results show the joint variability at all throwing distances were statistically higher than ones for wrist, elbow and shoulder ($p < 0.05$). Thus it was elucidated that throwers coordinate shoulder, elbow, and wrist joints in order to achieve a specific kinematics of finger position during dart throwing motion. In the case of wrist and elbow for either horizontal or vertical direction, the degrees of joint coordination at all throwing distances were statistically higher than one for shoulder ($p < 0.05$). For vertical position of wrist, the degree of joint coordination at each throwing distance were statistically higher than one for elbow ($p < 0.05$).

The Structure of Joint Coordination and Task Variable Control

Figures 5 and 6 illustrate for all subject the components of joint configuration variability per DOF that lie parallel (\parallel UCM) and perpendicular (\perp UCM) to the UCM for hypotheses about spatial position of the hand (Fig. 5) and movement path of the arm's CM (Fig. 6). For the hypothesis about spatial position of the hand, \parallel UCM \gg \perp UCM at 70% of the movement path for all experimental conditions. Just prior to the mid-point of the movement, \perp UCM was more than \parallel UCM, especially for the long condition. However, thereafter \perp UCM is less than \parallel UCM. Thus, there is evidence that the central nervous system (CNS) constrains joint variability along directions that keep the spatial position of the hand invariant near the mid-point of the movement while allowing joint configuration fluctuations in directions that do not affect this position. Note, however, that the difference \parallel UCM - \perp UCM for the hypothesis about spatial position is often smaller and less

Table 2. The Mean Movement Time and Time to Peak Velocity for Each Experimental Condition

Movement variables	Distance Conditions		
	Standard	Short	Long
Movement time (s)	2.5	2.2	2.76
Time to throw (%MT)	75.38*	70.53*	82.91*
Time to peak velocity (%)	40.35*	32.28*	43.69*

*Significant difference at $p < 0.05$

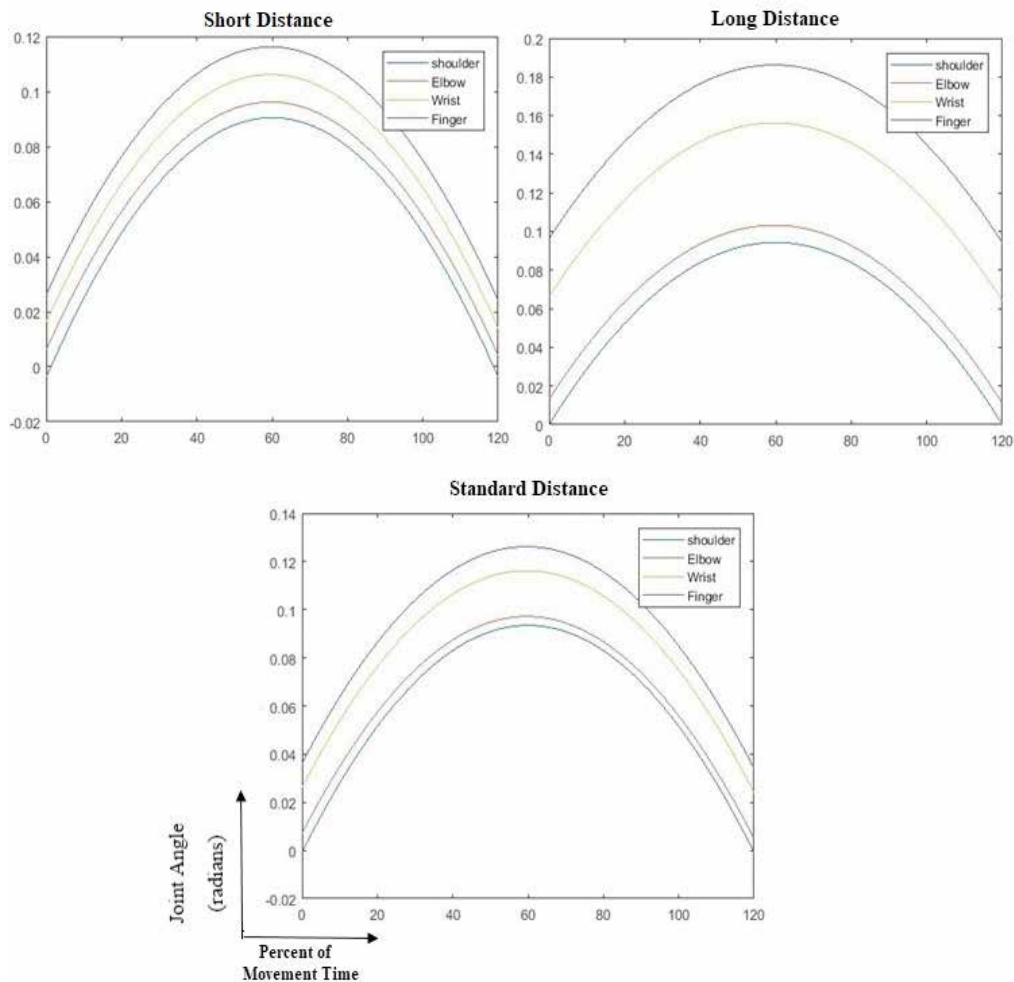


Fig 2. Mean joint excursions for arm calculated across all trials for a representative subject’s data in different throwing conditions.

consistent across conditions than for the hypothesis about center-of-mass position.

Results of the ANOVAs were consistent with this pattern of differences. For the control hypothesis about spatial position, significant differences between \perp UCM and \parallel UCM were present ($F=97.4$, $P<0.005$). The magnitude of this effect was dependent also on the part of the movement cycle examined ($F=6.42$, $P<0.005$) and on the experimental conditions ($F=8.29$, $P<0.005$). The first interaction was due to larger differences between the variability components at the middle phases and thereafter than were present earlier in the movement trajectory (Fig. 5). Nonetheless, \perp UCM was greater than \parallel UCM for portions of the trajectory (10 and 50 %), and for long distance condition ($F=5.38$, $P<0.05$). The magnitude of the difference between \perp UCM and \parallel UCM was approximately the same for standard and short distances conditions, where the differences were smaller overall than for the other condition ($F>8.71$, $P<0.05$). This smaller difference was due to the fact that variability parallel to the UCM was smaller than for the other condition.

For the control hypothesis about the arm’s center of mass, the overall difference between \perp UCM and \parallel UCM was significant ($F=59.41$, $P<0.01$), as was the interaction of this factor with the portion of the trajectory ($F=11.36$,

$P<0.01$). There were significant effects involving experimental conditions. At both 10% and 50% of the movement trajectory, \perp UCM was more than \parallel UCM for long distance condition ($F=7.84$, $P<0.05$). The difference between \perp UCM and \parallel UCM was lesser in the short and standard distance conditions ($F<8.17$, $P<0.05$). While in the long distance \perp UCM was significantly larger than \parallel UCM at 10% and 50% of the trajectory ($F=38.75$, $P<0.05$), \perp UCM was significantly in short and standard distance conditions approximately equal to \parallel UCM ($F=14.57$, $P<0.01$). In fact, beyond 60–70% of the trajectory, \perp UCM was less than \parallel UCM for the short and long distances, suggesting that joint configuration space was structured in a way specific to the position of the center of mass near the time of throwing, while this was not the case for the standard distance condition.

To facilitate a more direct comparison of the two hypotheses, the ratio \parallel UCM to \perp UCM was examined. A significant effect of condition ($F=5.73$, $P<0.05$), percentage of the trajectory ($F_{2,16}=6.00$, $P<0.05$), and hypothesis ($F=48.82$, $P<0.01$) was found, as well as a significant interaction between the hypothesis and both experimental condition ($F=4.93$, $P<0.01$) and percentage of the trajectory ($F=27.35$, $P<0.01$). Simple main effects revealed that the value of this ratio was larger for the

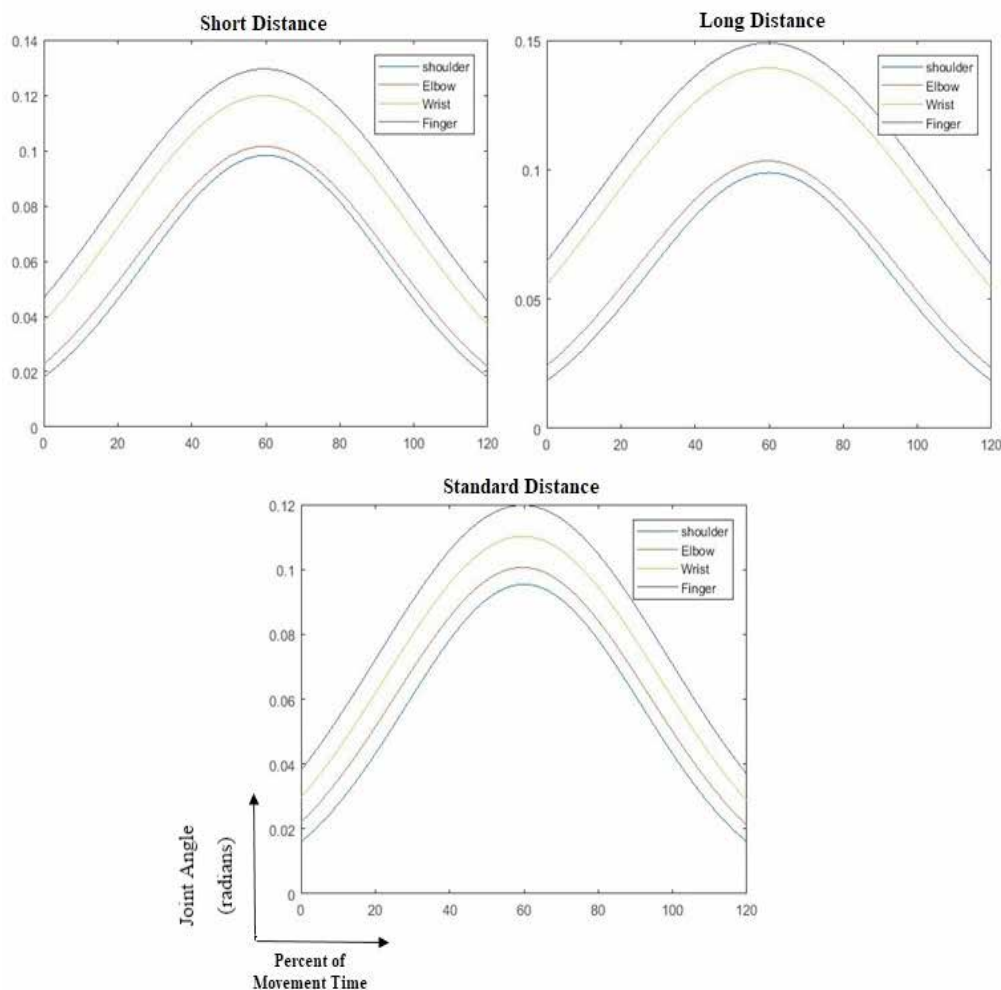


Fig 3. The total joint excursion, averaged across all trials for each subject and then across subjects, for each of 4 joint angles in different throwing conditions.

hypothesis about arm's center of mass than for the other hypothesis at approximately all points examined in the trajectory ($F=12.67$, $P<0.05$). The ratio \parallel UCM to \perp UCM was significantly less than one for both hypotheses at the beginning of the movement trajectory. However, that was the opposite, at the middle phase and later.

We also examined how joint configuration variability parallel to the UCM was distributed along each dimension of the UCM. For the hypothesis about spatial position of the hand, the UCM has two dimensions (i.e., four joint angles – two orientation angles). Figure 7 provides an indication of how this variability, expressed as the square root of the individual variance component, is distributed along each dimension of the UCM at each 20% of the movement trajectory. This figure reveals that the variability is distributed somewhat non-homogeneously across dimensions. The dimension of the UCM exhibiting the largest variability varies somewhat across the movement trajectory, although there is relative consistency across conditions for a given point in the trajectory. Unfortunately, these variability components cannot be related directly to the variability of individual joints, because the dimensions of the UCM are not aligned with but cut across the seven axes in joint space.

Discussion

One objective of the present study was to identify the structure of the joint control system for a skilled motor task, namely, dart throwing to a target. A requirement for successful throwing performance is the production of a stable hand path. There are theoretically many ways to achieve this stabilization. We found that control of the hand's movement path and that of the CM was achieved through the use of a range of goal-equivalent joint combinations. Our results suggest that only certain directions in the space of joint configurations are restricted—that is, those leading to a change in the value of important task-related variables—while a range of goal-equivalent joint configurations are actually utilized. This finding is consistent with the results of studies of the coordination of a number of very different tasks [37]. Unlike those tasks, dart throwing is ballistic and targeting motor skill which depend more strongly spatial position of the hand and arm's center of mass. We found that these task variables structured the joint control system throughout the movement, not only near the time of throwing and terminal phases of the movement.

We Examined the spatial position of the hand and

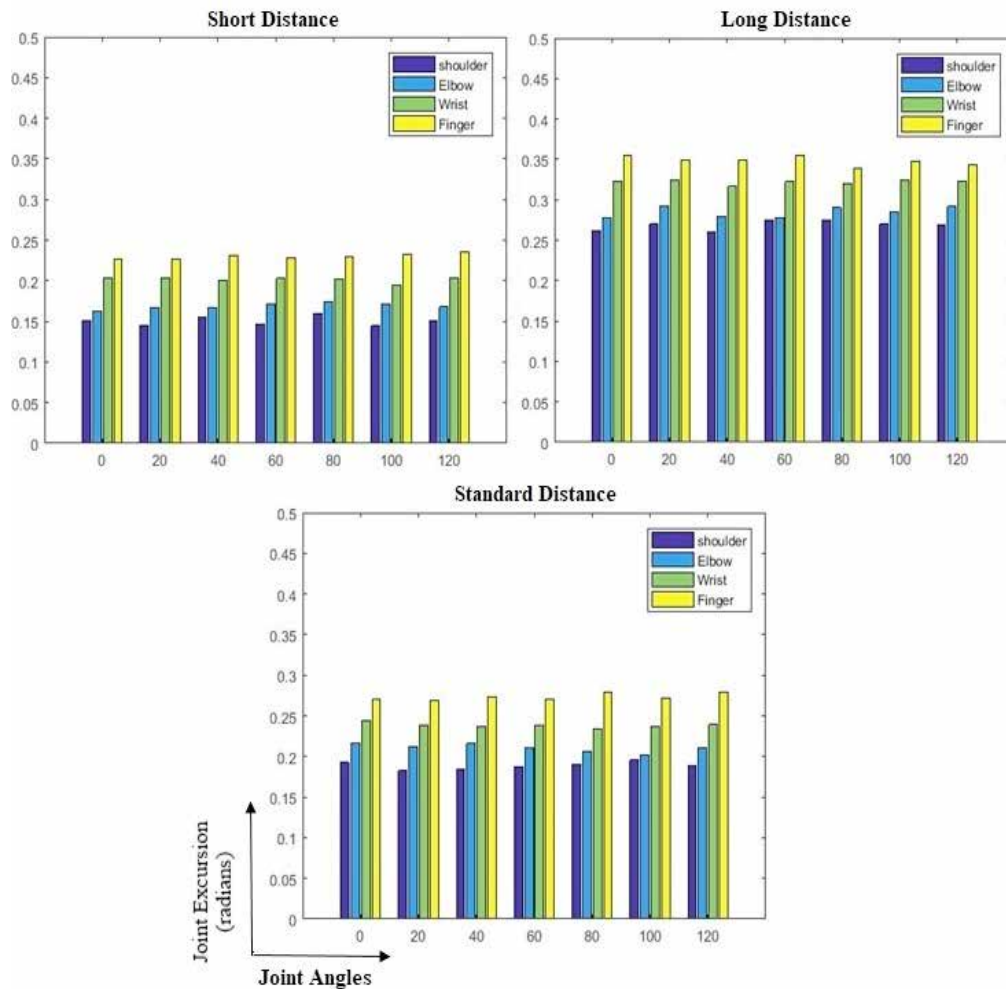


Fig 4. The range of joint excursion across all trials (maximum-minimum excursion) of each experimental condition for each joint angle.

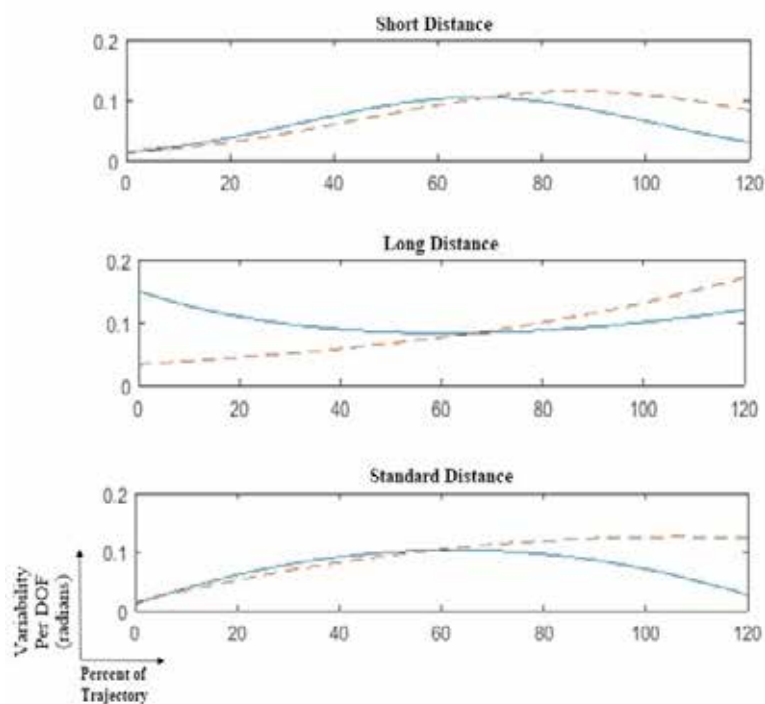


Fig 5. Mean (across subjects) of components of joint configuration variability per DOF lying parallel (thin dashed line) and perpendicular (thick solid line) to the uncontrolled manifold for the hypothesis of controlling the spatial position of the arm in different throwing conditions.

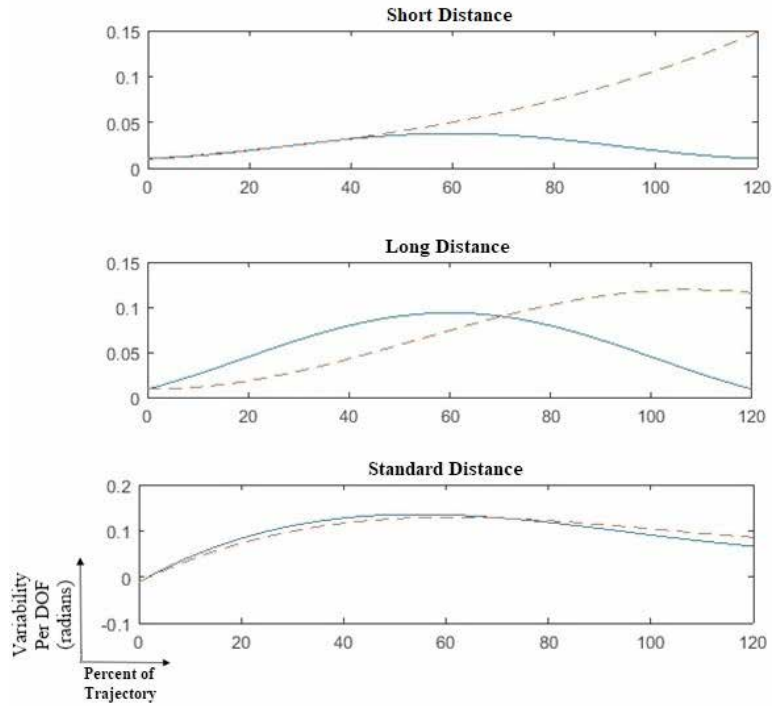


Fig 6. Mean (across subjects) of components of joint configuration variability per DOF lying parallel (thin dashed line) and perpendicular (thick solid line) to the uncontrolled manifold for the hypothesis of controlling the arm's center of mass position in different throwing conditions.

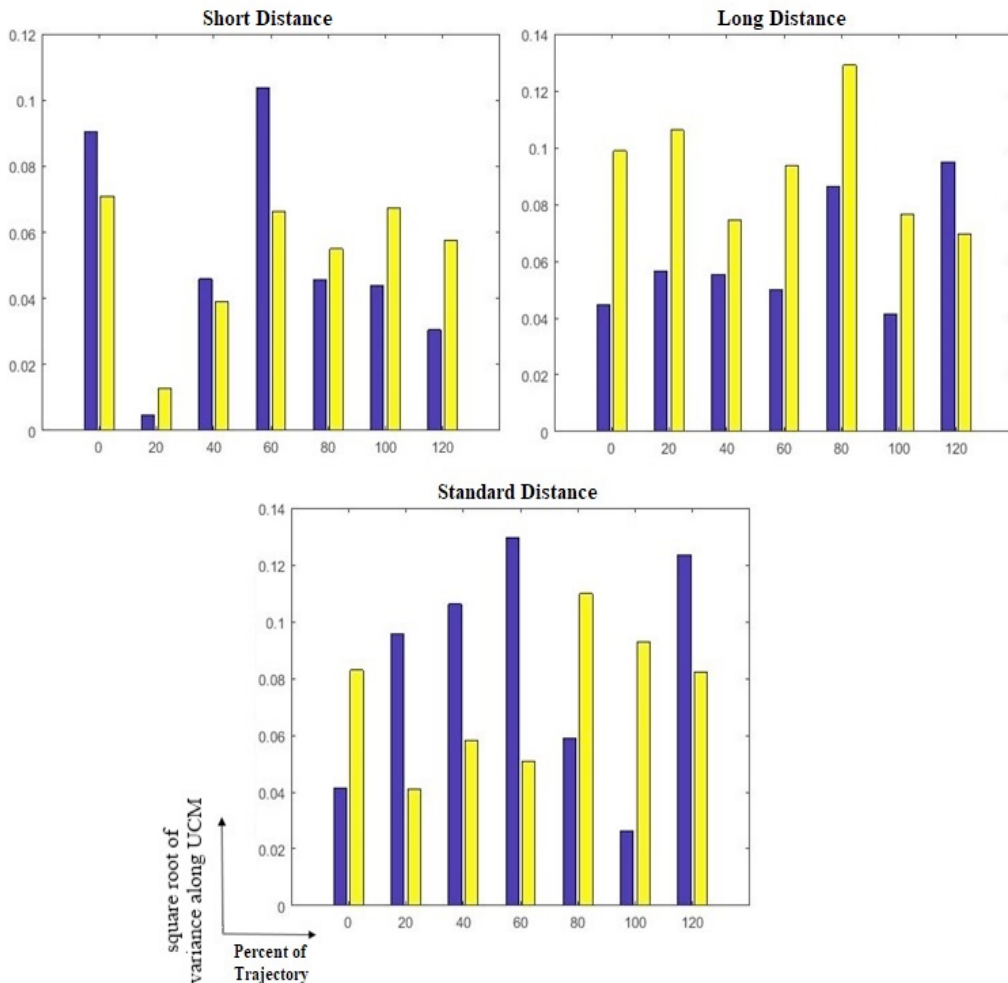


Fig 7. The components of joint configuration variability parallel to the UCM along each of its dimensions for the hypothesis about controlling arm's spatial and center of mass position. The two components are represented by bars of different shading in the same order at each 20% of the movement trajectory for different throwing conditions.

arm's center of mass as task variables that might structure control in joint configuration space. We examined spatial position to consider the possibility that subjects might attempt to shoot from the same final hand position to reduce variability of one variable that might affect task success [5]. The center of mass was considered, in part, because it is especially important to the movement dynamics. In addition, the results of a study of reaching by researchers [5,34] were used to argue that center of mass position is more controlled than end-effector position in such tasks. In each case, those changes of joint configuration that would change the current value of a task variable are assumed to be more constrained than changes that do not change the current value of the task variable if that variable is essential to successful task performance. Thus, the variability of joint configuration from trial to trial at corresponding points in time during a movement is analyzed as a measure of stability, decomposing it into its component that keeps the task variable unchanged (fluctuations parallel to the UCM) and its component that changes the value of the task variable (fluctuations perpendicular to the UCM). A completely different style of control could be used, however, i.e., if joint configuration variability was severely constrained in all directions. This would indicate that specific postural states of the arm and their sequences were specified to achieve the goal. An advantage of a UCM control strategy (i.e., freeing certain directions in joint configuration space from control) may be a reduction of unnecessary perturbations [5]. That is, applying control signals to the muscles to limit certain joint combinations leads to additional interactive torques because of mechanical coupling of the movement segments. These additional interaction torques would need to be compensated to preserve a particular kinematic signature [38].

The UCM analysis for the two hypotheses concerning the arm's CM and spatial position of the hand did not reveal structure in joint configuration space to the same extent. In both cases, variability per DOF perpendicular to the UCM was larger than variability per DOF parallel to the UCM, but only early in the trajectory. This may indicate that task constraints such as control of the position of the end-effector and of the center of mass contribute more strongly to the structure of the control system the later aiming phase compared with the early in the transport phase. In the final phases of the movement trajectory and for both the hypotheses in the all conditions (Except for the short distance condition in the hypothesis about arm's CM), both variability components decreased. The decrease in joint configuration variance as the target was approached and at movement termination may reflect additional control action taken by the CNS to help ensure movement accuracy. Note that, despite this overall reduction in joint configuration variability, goal-equivalent variability was still significantly larger than NGEV. However, the stability of the hand path was ultimately preserved as shown by the reduction of overall joint configuration variability and the enhanced structure of $GEV > NGEV$ when the hand decelerated toward the target. This corroborates

that stability of task-related variables is defined as its resistance to transient perturbation. Thus, a temporary disturbance, like a stronger effect from inter-segmental dynamics, eventually will be resolved if this variable is important for task success.

For the hypotheses about the arm's CM and spatial position of the hand, we found that variability per DOF parallel to the UCM was substantially and significantly less than variability perpendicular to the UCM. This was true from very early in the movement trajectory and only in the long distance condition, but beyond 60% of the trajectory, variability parallel to the UCM was greater than variability per DOF perpendicular to the UCM. Thus motor control system is highly structured in joint space in a way that is captured by the variance of spatial position of the hand and arm's CM, only in the early of the movement trajectory: those changes of arm configuration from trial to trial that change the spatial position and arm's CM are resisted much less than those changes of arm configuration that do not change that position. For the hypotheses about the arm's CM and in the short distance condition, at the early in the movement trajectory, variability parallel and perpendicular to the UCM was equal. This lack of a difference resulted both from increased variability perpendicular to the UCM and decreased variability parallel to the UCM. Another reason may well be that the motor control system is structured in joint space in a way that is the hypothesized invariance of spatial position of the hand and arm's CM. However, at the middle and terminal phases of the movement trajectory, variability parallel to the UCM was larger. This can be due to the coordination of motor components to the stability of important task-related variables. For both the hypotheses in the all conditions (Except for the short distance condition in the hypothesis about arm's CM), early in the movement path, variability parallel to the UCM was less than variability per DOF perpendicular to the UCM. This apparently leads to a limitation of the motor equivalent solutions available for throwing (i.e., $\parallel UCM$ or GEV), rather than increased variability of the arm's CM and spatial position of the hand to the target (i.e., $\perp UCM$ or $NGEV$).

The variability perpendicular to the UCM determines the variability of the spatial position of the hand and arm's CM. That variability must remain within particular bounds in order to accomplish the task. This does not imply, however, that the variability parallel to the UCM must necessarily be larger. In fact, the variability parallel to the UCM simply does not matter for the accomplishment of the task. It may be larger than, equal to, or smaller than the variability perpendicular to the UCM. The fact that fluctuations of joint configuration conserve the arm position relative to the target, even while the hand is not actually aiming at the target, further illustrates that the control structure discovered here is not a trivial consequence of success at the task. The increase in the use of goal-equivalent joint combinations that we observed when subjects threw in the different distances could have been a compensatory strategy used to help

reduce potentially disturbing internal perturbations (due to interaction torque that would be generated by unnecessary control action).

The magnitude of the difference between \parallel UCM and \perp UCM was significantly smaller on average when the throwing was performed in standard distance compared with the other two conditions. However, this result was due to reduced variability parallel to the UCM after the mid-point of the movement compared with the other three conditions, and not to differences in variability perpendicular to the UCM. If the decrease and/or increase in distance had introduced errors in the timing of the arm trajectory across trials, then the basis for our trial alignment procedure, prior to time normalization, would have been violated. However, this would have resulted in greater variability perpendicular to the UCM. Thus, our assumption is reasonable and conservative with respect to the hypotheses. (For example, with timing errors, the joint configuration at 50% of the arm trajectory for different trials could be associated with events occurring slightly before, slightly after, or at the time of peak velocity and, thus, with different UCMs. Because the UCM on which the analysis is based is estimated from the mean joint configuration at the same percentage of the trajectory for all trials, under the assumption of consistent timing of the task variable's trajectory, such timing errors would lead to increased variability perpendicular to the UCM. Timing variability of the joint trajectories, i.e., one joint getting ahead or behind another joint from trial to trial, could contribute to increased variability either parallel or perpendicular to the UCM. Although we cannot determine this effect from the present data, there is no reason to expect that the probability of joint timing errors contributing to one variability component would be greater than to the other.

Joint configuration variability was distributed along all dimensions of the UCM for the hypotheses about controlling the arm's CM and spatial position of the hand, although this distribution was nonhomogeneous. As already noted, there is no direct correspondence between dimensions of the UCM and specific joint angles. The fact that joint configuration variability is distributed along all dimensions of the UCM indicates that all joints contributed to the motor equivalent solutions suggested by the UCM analysis (i.e., for stabilizing arm trajectory).

Conclusion

In the current study, the geometric model captures the relationship between joint configurations and the task-related variables only at the level of kinematics. Moreover, movement dynamics, which were not formally considered in this analysis, must play an important role in determining the control structure of such movements. This may be especially important in the early stage as the limb is accelerated. The finding that center of mass position structured joint configuration variability in a similar way to spatial position early in the movement is consistent with this importance. Nonetheless, although movement dynamics and passive biomechanics must

influence the control of this task, the contribution of such constraints is unlikely to be as important in such targeting tasks as perceptual-motor constraints posed by the external target. This argument is supported by the finding that, despite starting from three different initial arm positions that involved different muscle lengths, a very similar structuring of the joint configuration variability was observed. In addition, it is difficult to explain how dynamics might account for the fact that the arm and end-effector trajectory to the target structured joint configuration variability in a particular way even early in the movement trajectory.

Our observation that the arm position structures variability in joint space in the way predicted by the UCM principle is evidence for a particular control strategy compatible with the task (out of an ensemble of other possible strategies). This particular control principle consists of releasing from control (to a degree) those DOFs that are not essential to task success. It is important to realize that it is not individual joint angles that are released from control, but particular combinations of joint angles. Because all joint angles are mechanically coupled, releasing from control particular combinations of joint angles requires, in general, that coordinated signals are sent to all joints. Thus, release from control is an active strategy, not just a trivial failure to send command signals to particular joints.

The nonessential DOFs are released throughout the entire trajectory, even while the arm is not actually aiming to the target. During the movement, the arm configuration goes through different regions of configuration space. In these different regions, the UCM is, in general, quite different. Therefore, the exact combination of joint angles that are released from control varies along the trajectory. It actually provides a common principle that predicts in which different regions of joint configuration space DOFs are released from control. Why would it be a useful strategy to release from control some combinations of kinematic DOFs to achieve success in a difficult task? When the DOFs problem is invoked at the planning level, the computational load to specify the time course of many variables is sometimes viewed as the problem. Thus, reducing the number of DOFs that require planning makes the problem more tractable.

What does the UCM principle imply for the problem of planning multi-joint movements? A direct experimental implication concerns the reproducibility of trajectories that define the space of the UCM; in our case, the joint position configuration. If postural states of a control variable that have reduced stability with respect to particular directions in joint space are passed through during the movement, then the joint configuration obtained at the end of the movement (or at any intermediate point, for that matter) may not be perfectly reproducible. Depending on the movement path, different types of perturbations may have been encountered along the trajectory, which may have led to varying shifts of the joint configuration along the UCM through which the trajectory passes. As a result, the final joint configuration may depend on the starting

position of the effector system.

There are two ways in which release from control could be achieved. One possibility is that the viscoelastic properties of the motor apparatus are tuned to the task, reducing the effective stiffness of the arm configurations in the task-irrelevant directions in joint space and/or increasing stiffness in the directions in joint space along which arm position changes during movement. Such a control principle would, no doubt, be quite complex in view of the large number of DOFs and the prevalence of multi-joint muscles. This also makes it quite difficult to test such an account, as the stiffness matrix is very difficult to measure in this system during the act of shooting.

An alternative account would assume that release from control arises from higher levels of motor control and planning. Essentially, planning would specify entire UCMs and their evolution in time, rather than specific joint trajectories. In this way, the nervous system may make use of redundancy to provide flexibility of movement patterns while preserving the stability of important task variables. The problem of motor redundancy, then, should be considered not as a problem but as an inherent part of the solution for the problem of multi-joint coordination. In either account, what must be learned or developed in order for skill to emerge is the task-specific structure of the motor control system in joint configuration space.

Applications and limitations

According to the results of the research, in order to achieve precision control, individuals must stabilize a body part position which is close to the finger in throwing motion. Moreover, the nervous system makes use of redundancy to provide flexibility of movement patterns while preserving the stability of important task variables. This ability of the controller to use the flexibility may be impaired in people with motor disorders, leading to a diminished capability to take advantage of the flexibility. The routes to applying UCM approaches to clinical studies face a number of challenges. In particular, although identification of elemental variables may be relatively straightforward in people who are healthy, this essential step in the UCM analysis may pose problems in patients with neurological disorders whose ability to change apparent elemental variables independently of each other may be impaired. The present study has used analysis of variability across consecutive trials at a particular task to quantify the 2 components of variance. However, it may be unrealistic to expect patients with neurological disorders to be able to perform many trials using the same control strategy. Development of the UCM method so that it can be used for analysis of single trials or small groups of trials is urgently needed.

The results of this study indicated that the longer and shorter throw induced the new motor control strategy of precision control and force generation. The authors' future research will measure and analyze dart-throwing motion on different conditions, changing a weight of dart arrows, foot stance or arm path. In this study, the UCM analysis was applied to dart throwing motion in order to investigate

the precision control ability by joint coordination. In future work, we need to combine the “muscle synergy,” which is the motor primitive for redundant muscle; and the “motor synergy,” which is a neural mechanism for generating joint coordination. Although based on the available equipment, a two-camera system was used to collect the kinematic data, it is imperative to use more cameras for more accurate recording and a more detailed review of the orientation of the darts to the target.

Appendix: Uncontrolled Manifold Analysis

The UCM approach allows the variance of joint angle combinations (i.e., solutions to joint coordination) across multiple trials, performed under identical conditions, to be partitioned into two variance components. Unlike a principal components analysis, where partitioning of variances is without reference to a priori control hypotheses, the UCM method partitions the joint configuration variance with respect to specific control hypotheses about task-related variables, such as the direction of the pointer-tip's movement. One component of the partitioned joint configuration variance is inconsistent with a stable value of the hypothesized task-related variable. The second variance component represents goal-equivalent solutions to the value of the task-related variable—that is, multiple solutions to joint coordination that preserves the stability of the task-related variable with respect to which the partitioning is performed. Thus, the approach allows for the identification of different styles of control of important task-related variables. The manner in which joint variance is structured with respect to these two components may differ for different task-related variables because the geometric relationship between joint angle space and task-related variable also differs. In this study, the component of variance that affects the value of a task-related variable is referred to as NGEV (non-goal-equivalent variability), while the component that is consistent with a stable value of a task-related variable, (i.e., does not affect the value of that variable) is referred to as GEV (goal-equivalent variability). (See Methods and Materials for details regarding the interpretation of various differences between GEV and NGEV.)

Formally, a forward kinematic model is used to link the joint angles to the vector representing values of the task-related variable. The model describes each value of the hypothesized task-related variable, r , in terms of joint angles θ . The configuration of the arm is described by a set of n -joint angles. In this study, the dimension of $n=4$. For determining how variability in joint angle space is structured with respect to hypotheses about controlling the spatial position of the hand and the position of the arm's center of mass, the task-related variable has $d=2$ dimensions. The effector system is redundant ($n>d$), therefore, with respect to motions of the hypothesized task-related variables.

The statistical analysis of joint configuration variability requires that the UCM be approximated linearly. The linear approximation is performed at each time slice of the trajectory, around a postural state or reference

joint configuration θ^0 . The postural state is estimated by calculating the mean joint configuration across trials of identical condition at each time slice. The linearized forward kinematics around each reference configuration, θ^0 , is

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

where r^0 is the value of the task-related variable corresponding to the reference configuration of joint angles, θ^0 . $J(\theta^0)$ is the $d \times n$ Jacobian matrix computed at each time slice for the reference configuration. In this case, the UCM is approximated by the null-space of the Jacobian matrix, $J(\theta^0)$. The null space represents those joint angle combinations that leave the task-related variable unaffected. The null-space is spanned by basis vectors ε_i , solving

$$0 = J(\theta^0) \cdot \varepsilon_i$$

There are $n-d$ basis vectors, so that the null-space has $n-d$ dimensions. The ε_i vector is computed numerically at each time slice using MATLAB. Then, at each time slice, deviations of the vector of joint angles of each trial from the vector of mean joint angles, $\theta - \theta^0$, are resolved into their projection onto the null space:

$$\underline{\theta}_{\parallel} = \sum_{i=1}^{n-d} \left(\frac{\underline{r} \cdot (\underline{\theta} - \underline{\theta}^0)}{\varepsilon_i} \right) \varepsilon_i$$

and the component perpendicular to the null-space:

$$\underline{\theta}_{\perp} = (\underline{\theta} - \underline{\theta}^0) - \underline{\theta}_{\parallel}$$

The amount of variability per DOF within the UCM is estimated as:

$$\sigma_{\parallel}^2 = (n - d)^{-1} \cdot (N_{\text{trials}})^{-1} \cdot \sum_{\text{trials}} \underline{\theta}_{\parallel}^2$$

where θ_{\parallel}^2 is the squared length of the $\underline{\theta}_{\parallel}$ deviation vector lying within the linearized UCM. Analogously, the amount of variability per DOF perpendicular to the UCM is estimated as:

$$\sigma_{\perp}^2 = (d)^{-1} \cdot (N_{\text{trials}})^{-1} \cdot \sum_{\text{trials}} \underline{\theta}_{\perp}^2$$

As noted earlier, these variance components are referred to as GEV (σ_{\parallel}^2) and NGEV (σ_{\perp}^2) in the body of this article.

Conflict of interests

The authors declare that there is no conflict of interests.

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