

Joint angle variability and co-variation in a reaching with a rod task

M. (Marieke) C. van der Steen · Raoul M. Bongers

Received: 20 September 2010 / Accepted: 5 November 2010 / Published online: 3 December 2010
© The Author(s) 2010. This article is published with open access at Springerlink.com

Abstract The problem at the heart of motor control is how the myriad units of the neuromotor system are coordinated to perform goal-directed movements. Although for long these numerous degrees of freedom (DOFs) were considered redundant, recent views emphasize more that the DOFs should be considered abundant, allowing flexible performance. We studied how variability in arm joints was employed to stabilize the displaced end-effector in tool use to examine how the neuromotor system flexibly exploits DOFs in the upper extremity. Participants made pointing movements with the index finger and with the index finger extended by rods of 10, 20, and 30 cm. Using the uncontrolled manifold (UCM) method, the total joint angle variance was decomposed into two parts, the joint angle variance that did not affect the position of the end-effector (V_{UCM}) and the variance that results in a deviation of the position of the end-effector from its mean (V_{ORT}). Analyses showed that some angles depended on length of the rod in use. For all rod lengths, V_{UCM} was larger than V_{ORT} , and this did not differ over rod lengths, demonstrating that the arm was organized into a synergy. Finally, the variation in the joint angles in the arm as well as the degree of co-variation between these angles did not differ for the rod's tip and the hand. We concluded that synergies are formed in the arm during reaching with an extended end-effector and those synergies stabilize different parts of the arm+rod system equally.

Keywords Synergy · Uncontrolled manifold (UCM) · Joint variability · Motor coordination · Tool use · Reaching

Introduction

The ease with which we perform goal-directed movements in our daily life hides the complexity inherent to the underlying processes. This complexity originates from the fact that there are more elements, or degrees of freedom (DOFs), involved in the goal-directed movement than there are dimensions of the space in which the movement is performed. To be able to perform goal-directed movements, these redundant DOFs in the neuromotor system need to be coordinated, which is supposed to be a problem for the control of movements. Recently, Latash and colleagues (Gelfand and Latash 1998; Latash et al. 2007; cf. Latash 2008) proposed an alternative way of thinking about the numerous DOFs. In their view, the numerous DOFs are not a problem but, instead, allow for a flexible performance in a wide range of tasks. The numerous DOFs permit the central nervous system (CNS) to select the appropriate values of the involved DOFs to ensure stable but also flexible task performance. Therefore, in Latash's view, the DOFs are rather abundant instead of redundant. The current study examines whether and how the abundant DOFs are flexibly exploited to use a tool in a task where reaching movements are made with a rod.

Abundance and redundancy of DOFs in the neuromotor system is strongly related to the notion of synergies. The most influential notion of synergies comes from Bernstein (1967) according to whom the DOFs in the neuromotor system are so numerous that it is too complex to control each individual DOF. To solve this problem, Bernstein characterized synergies as functional systems in which

M. (Marieke) C. van der Steen · R. M. Bongers (✉)
Center for Human Movement Sciences,
University Medical Center Groningen,
University of Groningen, P.O. Box 196,
9700 AD Groningen, The Netherlands
e-mail: R.M.Bongers@med.umcg.nl

DOFs are temporarily linked (see also Turvey 2007). Latash and colleagues (Latash et al. 2007; Latash 2008) introduced a different notion of synergies that starts from the idea that the DOFs in the neuromotor system are abundant instead of redundant. In this view, synergies are neural organizations that stabilize (i.e., reduce variability in) a certain performance variable, such as end-effector position, through co-varying elemental variables, such as joint angles. The framework of the uncontrolled manifold (UCM) method (Scholz and Schöner 1999; see also Schöner 1995) was proposed to study this feature of stability through variability (Latash et al. 2007; Latash 2008; cf. Scholz et al. 2000). To explain this method, imagine a regular goal-directed reaching movement with the index finger. Repetitions of a goal-directed reaching movement show trial-to-trial variability in the joint angles. At each instance of the movement, this variance can be divided into two parts: there is joint angle variability that does not affect the index fingers' position (i.e., co-variation) and there is joint angle variability that results in a shift of the index finger away from its mean position. Basically, the UCM method decomposes the variability in the joint angles into one of these two types of variability. For this purpose, the state space of the system is defined as the elements (e.g. joint angles) relevant for the task. In this state space, there is a subspace (i.e., a manifold) corresponding to the mean position of the index finger at each instant over the movement trajectory. This manifold is called the UCM for the mean position of the index finger at that particular instant. The UCM method allows determining whether joint angles vary more within the UCM (i.e., keeping the index finger at its mean position) than orthogonal to the UCM (i.e., causing the index finger to deviate from this mean position). Would the joint angles in the arm vary more within the UCM than orthogonal to it, then this would mean that the arm is coordinated in a synergy to control the index fingers' position. Of course, the UCM method is not confined to a reaching task, depending on the situation, different elemental variables can be used to define the systems' state space and it can be analyzed whether these elemental variables co-vary to keep a given performance variable stable.

In the current study, we apply the UCM method to a reaching with a rod task. The general scheme of the UCM analysis is as follows: (1) selection of the appropriate elemental variables, (2) the selection of a performance variable, (3) the creation of a linear model of the system, and (4) at each instant, partitioning variance of elemental variables into variance that keeps the performance variable on its mean position (V_{UCM}) and variance as a result of which the performance variable deviates from its mean position (V_{ORT}) (Latash et al. 2007; Scholz and Schöner

1999). In the linear model of the system, the relations between small changes in elemental variables and its effect on the performance variable are computed through the Jacobian matrix. For different performance variables, V_{UCM} and V_{ORT} are compared. If V_{UCM} is higher than V_{ORT} , it is concluded that the performance variable is stabilized through co-variation in the elemental variables. Thus, the UCM method identifies how the elements in the neuromotor system are exploited to keep a performance variable stable, which gives information about the involved synergy.

The UCM method has successfully been applied to a wide range of tasks (Domkin et al. 2002, 2005; Jacquier-Bret et al. 2008, 2009; Scholz and Schöner 1999; Scholz et al. 2000; Tseng et al. 2002, 2003). For instance, Scholz et al. (2000) applied the UCM method to a pistol-shooting task and found that variability of the joint configuration that affected the performance variable (i.e., the line of shooting) was much more reduced compared to variability that did not affect this variable. Tseng et al. (2002, 2003) instructed participants to move a pointer in one continuous motion to the center of a designated target at a fast, but comfortable speed while being as accurate as possible. One study investigated the role of visual information and the other study investigated how the CNS organized the abundant DOFs in relation to a low or high index of difficulty. Both studies showed that during all conditions (with or without visual information, and high or low index of difficulty), the functionally important performance variables appeared to be stabilized through a flexible but task-specific synergy. Domkin et al. (2005) applied the UCM method to a 3D bimanual pointing task. They examined the coordination of joints within each arm and between arms during a two-hand pointing task involving a pointer in one hand and a target in the other hand. Results demonstrated that at each instant over a movement, the CNS stabilized the relative position of one endpoint with respect to the other more than it stabilized the position of each of the endpoints in the external space. Together, these studies suggest that the UCM method allows a quantitative assessment of the degree of stabilization of the selected performance variable through co-variation and provides information on changes in the structure of a multi-joint synergy. Overall, the above-described studies showed that during regular pointing, the abundant DOFs are organized into synergies to ensure an appropriate performance of the functionally important performance variable.

The present study is directed at the formation of synergies during tool use. In our experimental task, healthy people made reaching movements with a rod to a target. A hand-held tool extends the body and affects the forces in the muscles and the torques in the joints. These changes

demand flexibility in the coordination of the DOFs relevant for controlling the tool in a goal-directed way. The interesting thing about tools is that they allow keeping the task invariant while varying properties of the tool+body system. Therefore, tools make it possible to study how DOFs in the neuromotor system are flexibly coordinated to perform the same task while the properties of the system vary. A key goal of the current paper is to determine whether the synergies underlying the use of a tool are similar to the synergies employed when performing the same task without a tool.

To achieve this goal, it has to be determined whether during the use of the rod, the synergy in the arm keeps the hand or the tip of the rod stable. Stated otherwise, it has to be determined which performance variable is most stabilized. We expected that the synergy employed in rod reaching primarily stabilizes the rod's tip; Heuer and Sülzenbrück (2009) demonstrated that when operating a sliding first-order lever, the trajectory of the tip of the lever was straighter than that of the hand controlling it. Jacobs et al. (2009) showed that apraxic patients impaired for tool use showed less accuracy in end-effector position in a rod pointing task, while brain-damaged control patients had comparable levels of accuracy over all tool and non-tool conditions. Moreover, there is evidence that a tool in use extends the body schema (Arbib et al. 2009; Cardinali et al. 2009; for an overview see Maravita and Iriki 2004), which is in line with the idea that the tool's tip is the most stabilized end-effector. The current paper advances these findings in that (a) we examined how a synergy was built to handle a tool and (b) we examined whether it was the hand or the rod's tip that was kept most stable. Therefore, we did not focus on just the end-effector movement but, instead, we took into account variability in all the joint angles in the arm and how these joint angles co-varied to keep the hand and the rod's tip stable.

To do this, we manipulated a very basic aspect of the end-effector during tool use, that is, we modified the length of the last segment in the joint chain. Therefore, we attached a rod to the index finger that could have a length of 10, 20, or 30 cm. We choose this range of rod lengths because most tools in daily life fall into this range. Participants performed a reaching task with and without the rod attached. To ensure that variability in end-effector movement and joint angles was not affected by the fact that a tool was used or not, we adjusted the distance between the participant and the targets to the length of the rod. In this way, the different conditions could be performed with practically the same postural configuration of the arm, and thus, any differences in joint angles over rod conditions reflect coordinative processes. Therefore, the first question we addressed was whether

the joint angles in the arm depended on rod length. Second, we asked whether the synergies underlying the use of the rod depended on the length of the rod. The third question addressed whether the rod's tip or the hand was the most stabilized performance variable. We expected that the synergies in the arm were formed to stabilize the displaced end-effector, which is the tool's tip.

Materials and methods

Participants

Ten male university students (mean age 21.1 ± 1.1 years) volunteered to participate in the study. All participants were right-handed, had no neurological diseases, recent injuries or musculoskeletal problems in the neck, shoulder, arm or hand regions, and had normal or corrected to normal visual sight. The participants received verbal and written descriptions of all procedures and signed an informed consent before the experiment started.

Apparatus

Movements of the upper extremity were recorded with the Optotrak 3020 system (Northern Digital, Waterloo Ontario). Five triangular rigid bodies were fixed to the right side of the participant's body in order to measure the movements of the right arm. Following van Andel et al. (2008), the rigid bodies were fixed in the following manner: one rigid body was fixed on the thorax attached to the sternum, the second on the flat part of the acromion, the third laterally on the upper arm just below the insertion of the deltoid, the fourth laterally on the lower arm just proximal to the ulnar and radial styloids, and the fifth rigid body was placed on the dorsal surface of the hand. The rigid bodies were made of hard PVC. Two of the triangles, those on the hand and the acromion, had a leg length of 4 cm, while the other triangles had a leg length of 6 cm. In each of the three corners of the triangle, an Optotrak LED was placed. Another set of three LED's was placed at a rigid body on the holder attached to the index finger.

The rods used during this experiment were made of aluminum, had a length of 10, 20, or 30 cm and a diameter of 1 cm. Their mass was 8, 16, and 24 g, respectively. The rods were attached to the index finger with an aluminum holder, with a mass of 50 g.

In order to keep the start position of the upper extremity as stable as possible over trials, an elbow placer was positioned on the right side of the participant. The olecranon of the right arm had to be placed on a marked

location at the elbow placer that was placed at the same height as the experimental table.

Experimental procedure

Participants sat in a chair of which the back was extended in height with a board. They were with their trunk tightly strapped against this board to prevent movements of the torso and the clavicular joints, but allowing free movements of the shoulder and elbow joints. Furthermore, the index finger was fixed to prevent movement of the interphalangeal joints but allowing free motion of the metacarpophalangeal joint.

Before data acquisition started, the position of the chair and placer for the start position of the elbow in relation to the table was determined for each participant. The participant's distance to the target table was changed as a function of rod length, implying the participants could, in principle, use the same control of the hand motion and be still accurate, independent of rod length. For example: during the trials with a rod of 10 cm, the table was positioned 10 cm further away from the participant than during the trials with the index finger acting as end-effector etc.

In the initial posture of each trial, the upper arm hung comfortably next to the body and the elbow rested on the placer. The index finger or the tip of the rod was placed at the start point with the wrist in a comfortable position. A beep presented after a random time interval of 0.5–2.5 s functioned as start signal. After the beep, the participants reached as quickly and accurately as possible to the target. The trial ended with holding the pointer steady on the target for a short period. After all trials were performed, bony landmarks were digitized with a pointer (see later). Session duration was approximately 1 h.

Design

Participants had to perform reaching movements over 30 cm, either in forward or in lateral direction. The holder for the rods was always attached to the index finger. Depending on the condition, the reaching task was performed with the index finger or with a rod attached to the holder. This resulted in eight experimental conditions, based on two movement directions and four different lengths of end-effector. Every condition consisted of 20 trials; therefore, the participants performed 160 trials in total. These blocks of 20 trials were presented in random order.

Computation of joint angles

The joint configuration was based on the following rotations of the right arm: shoulder plane of elevation, shoulder

elevation, shoulder inward–outward rotation, elbow flexion–extension, forearm pronation–supination, wrist flexion–extension, wrist abduction–adduction, index finger flexion–extension, and index finger abduction–adduction. Elbow abduction–adduction, hand pronation–supination, and rotation of the index finger were excluded from the analysis because they are not anatomically available in the human body. The joint rotations were calculated following the orientations as proposed in the ISB standardization proposal for the upper extremity by Wu et al. (2005). Following the procedure in Wu et al. (2005), global and relative orientations of segment coordinate systems were calculated based on the combination of local coordinate systems constructed from bony landmarks and the displacements of the markers at the rigid bodies. To link the positions of the markers to the local anatomical coordinate system, 17 bony landmarks were digitized using a standard pointer device (cf. van Andel et al. 2008). The analysis was based on the open source package for 3D kinematics, BodyMech (<http://www.bodymech.nl>).

Computation of joint variance

In order to determine the distribution of the variance in joint space, a 3D forward kinematics model was created. To compute the UCM variables with the rod's tip as performance variable, this model was based on the nine joint rotations. For the analyses with the hand as performance variable, seven joint angles were used; index finger flexion–extension and index finger abduction–adduction were excluded. The computational methods were based on those of Domkin et al. (2005).

The distribution of variance in joint space was computed from 20 reaching movements [N] for every condition. The data were time-normalized with a cubic spline interpolation to allow alignment of trials. The normalized movement time was divided into 100 equidistant time bins. The mean joint configuration across trials [$M(t)$] was computed for each time bin. The joint configuration of each particular trial [$A_k(t)$] was subtracted from $M(t)$ for each time bin using $\Delta k(t) = M(t) - A_k(t)$. Here, Δk represents the deviation of the joint configuration of the k th trial from the mean joint configuration at each time bin (t).

This deviation of the joint configuration consisted of two components: Δk^{UCM} , which lies in the UCM and Δk^{ORT} , the component orthogonal to the UCM. The UCM was defined as the null space of a Jacobian matrix. The elements of this Jacobian matrix were the partial derivatives of the coordinates of the performance variable with respect to the joint angles in the mean joint configuration. The null space of the Jacobian matrix represented the changes of joint configurations that kept the performance variable on the mean position.

To see how changes of joint configuration affected the performance variable, namely the end-effector of the right arm, the variance per DOF was computed for the two components of Δk . The variance that affects the performance variable (V_{ORT}) and corresponds to the variance per DOF of the orthogonal component was defined as:

$$V_{\text{ORT}} = \sum_{k=1}^N (\Delta k^{\text{ORT}})^2 / (DV * N).$$

Here, DV is the dimension of the task variable, in our case DV was 3.

The variance that does not affect the performance variable (V_{UCM}) and corresponds to the variance per DOF, which lies within the UCM, was defined as:

$$V_{\text{UCM}} = \sum_{k=1}^N (\Delta k^{\text{UCM}})^2 / ((DF - DV) * N).$$

Here, DF is the number of involved DOFs. When the hand was the performance variable, DF was 7, whereas when the rod's tip was the performance variable, DF was 9.

Data analysis

The data were processed using MATLAB (The Mathworks Inc, MA, USA version 2008a). In addition to descriptive statistics, several repeated measures ANOVA's were applied for comparisons between the different conditions. If the assumption of sphericity was violated, the Greenhouse–Geisser correction was applied. To interpret the significant effects of the ANOVA's, the generalized eta-squared for effect size was used (Bakeman 2005; Olejnik and Algina 2003). The effect sizes were interpreted according to Cohen's (Cohen 1988) recommendation of 0.02 for a small effect, .13 for a medium effect, and .26 for a large effect (see Bakeman 2005). The analyses were performed with SPSS version 16.

Results

Casual perusal of the data showed that participants were, in general, very consistent in their behavior; the range of the angles in the arm over repetitions of trials was rather small, even over the different conditions (Fig. 1). However, between participants, behavior varied. Most participants mainly changed the plane of elevation and inward rotation in the shoulder, the elbow most often changed from a flexion to an extension angle, and wrist was regularly in abduction. However, some participants used very little supination in the elbow but more adduction in the finger, while others used relatively a lot of supination in the elbow together with flexion in the finger. Also the absolute

magnitude of the angles varied between participants. In the following paragraphs, we first present the analyses on the angles before we turn to the UCM analyses.

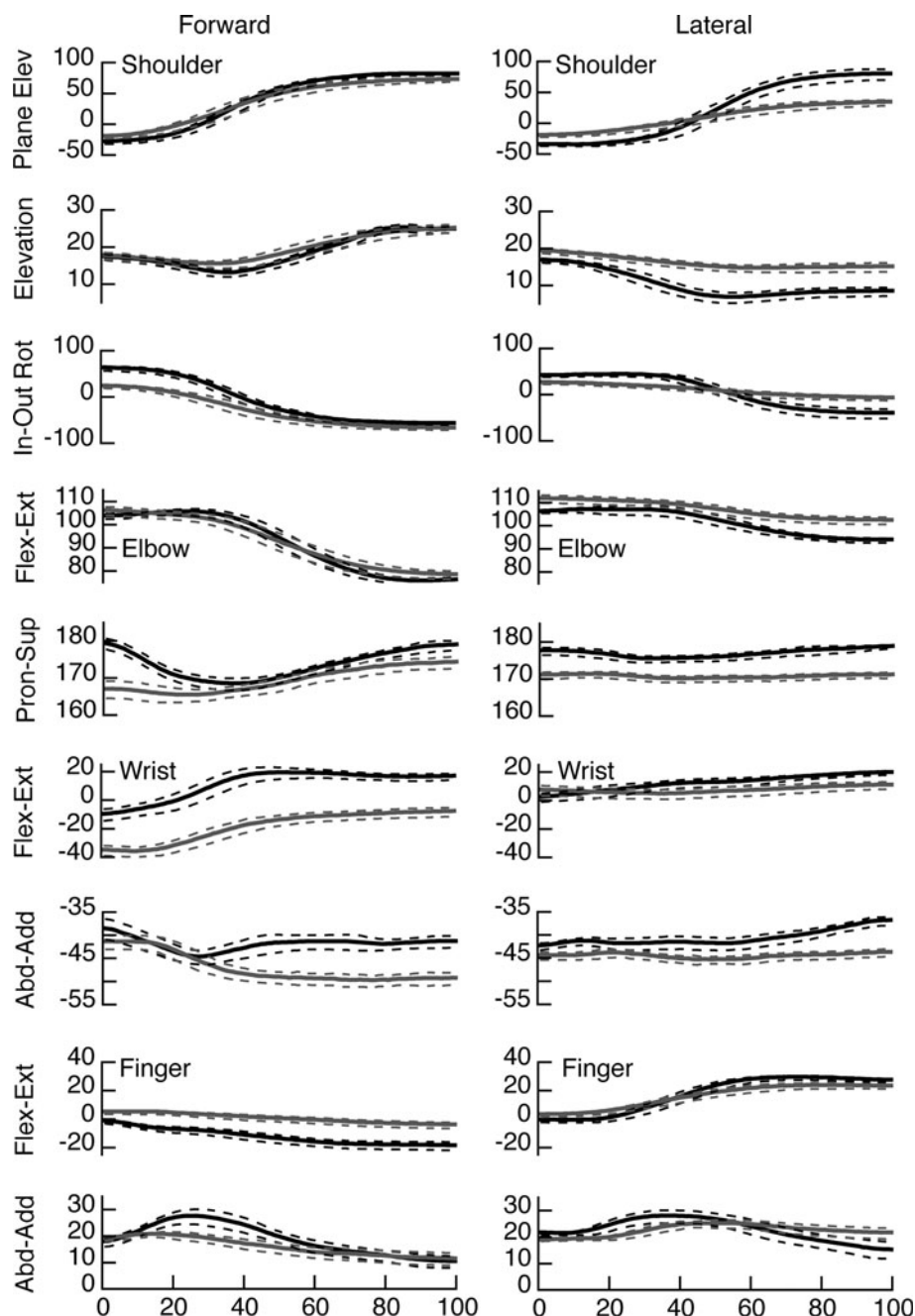
Joint angles

To analyze the changes in angles over time, we selected five instances, namely at 1, 25, 50, 75, and 100% of the movement time. Each of the nine joint angles was analyzed by means of a three-way repeated measures ANOVA with end-effector length (index finger, rod of 10 cm, rod of 20 cm and rod of 30 cm), movement direction (forward and lateral), and instance (1, 25, 50, 75, and 100% of the movement time) as within-subject variables. Given the number of analyses, we wanted to reduce the chance on making a Type I error; therefore, we used Bonferroni correction and used an alpha level of $0.05/9 = 0.006$. The analyses over the nine joint angles revealed 12 significant main effects, presented in Table 1, and seven significant interaction effects, discussed below. The large part of the effects was, as expected, related to the effects of movement direction and instance.

The effects presented in Table 1 showed that the plane of elevation of the shoulder increased and shoulder angle changed from inward rotation to outward rotation when the movements evolved. This effect moderately interacted with movement direction ($F_{1.57;14.13} = 25.67$, $P < 0.001$, $\eta^2 = 0.14$). During the movements in forward direction, the humerus showed a larger angle of plane of elevation as the movement evolved, compared to the lateral direction. The elevation angle of the shoulder stayed more or less the same during movements in lateral direction. On the contrary, for movement in forward direction, the humerus was more elevated over the movement, as indicated by a small interaction effect between movement direction and instance ($F_{1.07;9.62} = 24.49$, $P = 0.001$, $\eta^2 = 0.08$). The inward–outward rotation in the shoulder was also weakly affected by movement direction and instance ($F_{1.50;13.50} = 5.76$, $P = 0.004$, $\eta^2 = 0.05$). Movements in both directions started with outward rotation in the shoulder; during the movements, this angle changed to inward rotation. For movements in the forward direction, this change was larger than for movements in the lateral direction.

The elbow angle was flexed for movements in lateral direction, while for movements in forward direction, on average, the elbow was extended. During the movements, the elbow angle changed from flexion to an extension angle. The forearm also got less pronated over the movement, but this disappeared at the end of the movement. Furthermore, the elbow flexed a little less with a longer end-effector. For the flexion–extension angle in the elbow, movement direction and instance strongly interacted

Fig. 1 Joint angles (average and standard deviation) of one participant's reaching movements in *forward* (left column) and *lateral* direction (right column) for two conditions: The *black lines* reflect the movements with the index finger, and the *gray lines* reflect the movements with a rod of 30 cm



($F_{1,15;10,34} = 312.17$, $P < 0.001$, $\eta^2 = 0.43$). The flexion in the elbow decreased over time for both movement directions, but this decrease was larger for movements in forward direction. For movements in forward direction, the elbow flexion–extension angle became even smaller than 90° that indicates an extension angle.

The wrist had somewhat more abduction with a longer end-effector. Remarkably, there was no effect of wrist flexion.

The finger was flexed during movements in forward direction and extended during movements in lateral direction. As the movement evolved, the finger changed

from extension to flexion, while the adduction of the finger declined. Finger flexion–extension showed a moderate interaction between end-effector length and direction ($F_{3,27} = 34.51$, $P < 0.001$, $\eta^2 = 0.19$). In the forward movement condition, the finger was most extended when no rod was used and this extension decreased for larger lengths of the end-effector, so that in the 30-cm rod condition, the finger was even slightly flexed. For moving laterally, the finger was always flexed and this flexion was smaller with larger lengths of the end-effector. Also the effects of movement direction and instance interacted strongly ($F_{1,94;17,48} = 695.58$, $P < 0.001$, $\eta^2 = 0.50$). In

Table 1 Mean, SD averaged over participants, F , P , and η^2 for the significant effects

Dependent variable	Within-/between subject factor		Mean	SD	F	df	P	η^2	
<i>Shoulder angles</i>									
Plane of elevation (°)	Instance	1%	−2.86	28.07	140.04	1.29;11.64	<0.001	0.39	
		25%	13.75	28.65					
		50%	43.54	27.50					
		75%	61.31	24.06					
		100%	65.89	23.49					
Elevation (°)	Movement direction	Forward	27.50	9.74	47.26	1;9	<0.001	0.15	
		Lateral	20.63	6.88					
Inward–outward rotation (°)	Movement direction	Forward	−7.45	32.09	14.44	1;9	<0.005	0.02	
		Lateral	−18.33	40.68					
	Instance	1%	18.91	31.51	89.09	1.33;11.93	<0.001	0.54	
		25%	4.58	30.94					
		50%	−18.33	29.79					
		75%	−32.69	29.22					
100%	−36.67	29.22							
<i>Elbow angles</i>									
Flexion–extension (°)	Movement direction	Forward	86.52	18.33	39.42	1;9	<0.001	0.24	
		Lateral	95.11	8.02					
	Instance	1%	103.13	8.59	436.64	1.32;11.87	<0.001	0.66	
		25%	100.84	7.45					
		50%	91.10	9.17					
		75%	80.79	12.61					
	End-effector length	Index finger	100%	77.92	13.75	5.24	3;27	=0.006	0.02
			10 cm	89.38	15.47				
			20 cm	91.10	14.33				
	30 cm	91.10	14.33	20.57	1.35;12.15	<0.001	0.02		
92.25		14.90							
165.10		10.89							
162.81		10.89							
Pronation–supination (°)	Instance	50%	162.81	11.46					
		75%	165.68	11.46					
		100%	166.82	12.03					
		166.82	12.03						
<i>Wrist angle</i>									
Abduction–adduction (°)	End-effector length	Index finger	−28.65	14.32	7.09	3;27	=0.001	0.06	
		10 cm	−32.66	17.19					
		20 cm	−33.80	17.76					
		30 cm	−34.38	18.91					
<i>Finger angles</i>									
Flexion–extension (°)	Movement direction	Forward	−5.16	10.89	49.87	1;9	<0.001	0.53	
		Lateral	10.31	12.03					
	Instance	1%	−2.29	6.89	107.10	1.29;11.59	<0.001	0.15	
		25%	−0.57	7.45					
		50%	4.58	13.18					
		75%	5.73	17.76					
100%	4.58	18.91							

Table 1 continued

Dependent variable	Within-/between subject factor		Mean	SD	<i>F</i>	<i>df</i>	<i>P</i>	η^2
Abduction–adduction (°)	Instance	1%	14.32	13.18	58.71	1.45;13.04	<0.001	0.04
		25%	16.04	13.75				
		50%	13.75	14.32				
		75%	10.31	14.90				
		100%	8.02	15.47				

the forward movement condition, the finger further extended while the movement continued. This is in contrast with movements in lateral direction; while these movements continued, the finger was flexed more. A small three-way interaction effect of end-effector length, movement direction, and instance ($F_{12,108} = 53.52$, $P < 0.001$, $\eta^2 = 0.05$) indicated that the latter interaction effect of movement and instance was affected by end-effector length. The extension and flexion of the finger was less when the participants moved with a longer end-effector.

Taken together, the analyses of the joint angles showed that most joint angles changed over instance, indicating that all arm angles, except both wrist angles, were used to move the end-effector. Particularly, the angle of plane of elevation and inward–outward rotation angle of the shoulder and the flexion–extension angle of the elbow changed when the participants performed the movements. As expected, the joint angles differed between the movements in lateral and forward direction. Importantly, the length of the end-effector affected significantly the flexion–extension angle of the elbow and the abduction–adduction angle of the wrist. In addition, for the flexion–extension angle of the finger, the end-effector length interacted with movement direction and instance.

Are there synergies underlying rod reaching?

To determine whether synergistic coordination with which the task was performed depended on rod length, we analyzed V_{UCM} and V_{ORT} . V_{UCM} is the part of the total variance at each instant that does not affect the mean position of the end-effector, and V_{ORT} is the part that shifts the end-effector away from its mean position. To facilitate the statistical analyses, the variance components were divided into four equal phases and then averaged over these phases, resulting in the mean V_{UCM} and V_{ORT} over four phases of the movement (1–25, 26–50, 51–75, and 76–100%). We performed a five-way repeated measures ANOVA on variance with type of variance (V_{UCM} and V_{ORT}), performance variable (hand and rod tip), end-effector length (index finger, rod of 10 cm, rod of 20 cm, and rod of 30 cm), movement direction (forward and lateral), and phase (1–25, 26–50, 51–75, 76–100% of the data) as within-subject

variables. The analysis showed four weakly and one moderately significant effect. The mean distribution of V_{UCM} and V_{ORT} with 95% confidence intervals over the within-subject factors are presented in Fig. 2.

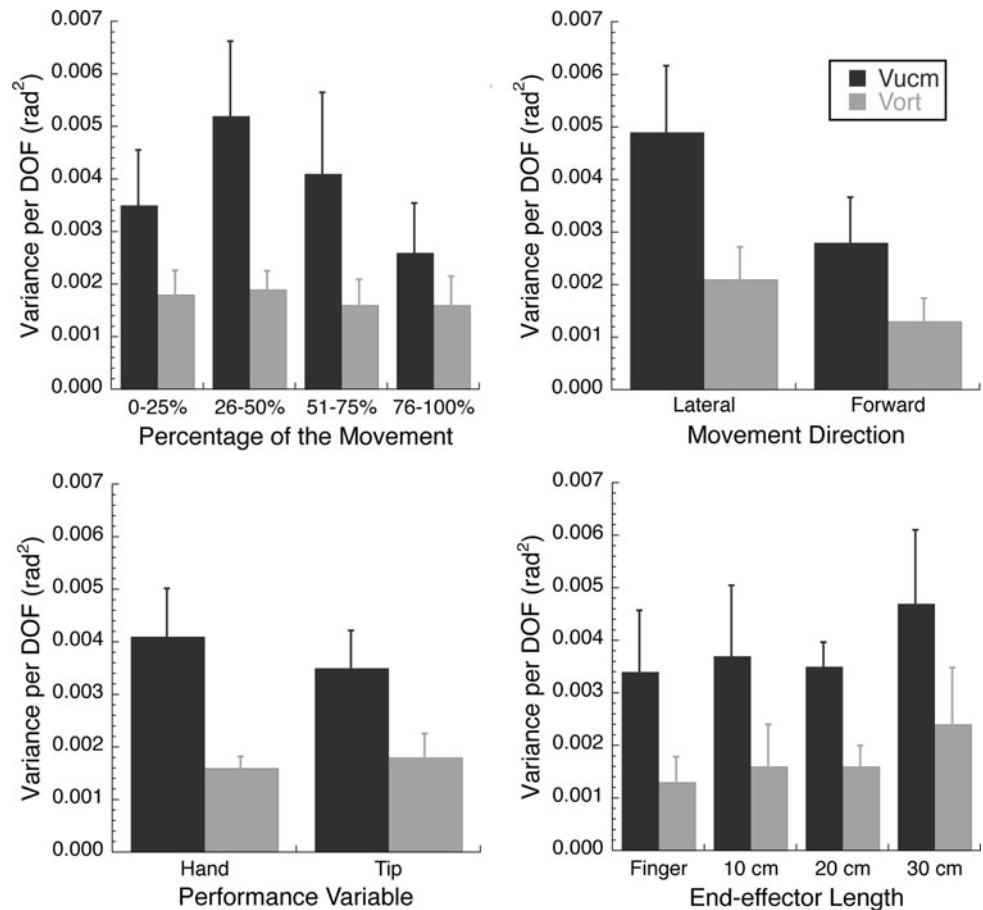
As can be clearly seen in all the subplots of Fig. 2, V_{UCM} (0.004 (0.003) radians squared; mean (standard deviation)) was larger than V_{ORT} (0.002 (0.002) radians squared), indicated by a moderate significant effect of variance ($F_{1,9} = 33.33$, $P < 0.001$, $\eta^2 = 0.16$). We also found a weak effect of phase ($F_{1.65,14.88} = 3.92$, $P = 0.05$, $\eta^2 = 0.04$) (1–25% = 0.003 (0.002), 26–50% = 0.004 (0.003), 51–75% = 0.003 (0.003), 76–100% = 0.002 (0.002)). The interaction between these two main effects was weakly significant ($F_{3,27} = 5.50$, $P < 0.005$, $\eta^2 = 0.03$). With Bonferroni correction, all pair wise comparisons between V_{ORT} and V_{UCM} at the four phases of the movement were significant (all P 's < .01) (Fig. 2).

Furthermore, overall variance was larger for movements in the forward direction (0.003 (0.004) radians squared) than in the lateral direction (0.002 (0.002) radians squared) leading to a weak effect of movement direction ($F_{1,9} = 9.31$, $P < 0.05$, $\eta^2 = 0.08$). This effect of direction interacted weakly with the effect of end-effector length ($F_{3,27} = 3.56$, $P < 0.05$, $\eta^2 = 0.04$) indicating that in the lateral direction, the variance was rather independent of the length of the end-effector, whereas in the forward direction, the variance was larger for longer end-effector lengths.

Figure 2 shows that V_{UCM} and V_{ORT} differ for the performance variable and for the length of the end-effector, respectively. However, these differences were not systematic and did not result in significant effects.

In summary, the analyses showed that during the entire movement, the involved amount of V_{UCM} was larger than that of V_{ORT} , indicating that the joint angles co-varied in a synergy. Importantly, the difference between V_{UCM} and V_{ORT} did not differ over the two performance variables indicating that the co-variation in the joint angles in the arm was the same for these two of the arm+rod system. Note that we did not find a main effect of end-effector length suggesting that the stabilizing of the rod by means of the joint angles was independent of rod length. With longer rods, the total variance increased a bit for movements in the forward direction, showing that overall joint variability

Fig. 2 The mean distribution of V_{UCM} and V_{ORT} with 95% confidence intervals over the within-subject factors percentage of movement, movement direction, performance variable, and end-effector length



increased in these conditions but this could not be attributed to an increase in specifically V_{UCM} or V_{ORT} .

Overall, we found very few significant effects. To make sure that we did not miss any differences between V_{UCM} and V_{ORT} over conditions, we computed V_{ratio} (V_{UCM}/V_{ORT}) and analyzed this variable. We performed a four-way repeated measures ANOVA with V_{ratio} as dependent variable and performance variable (rod tip and hand), end-effector length (index finger, rod of 10 cm, rod of 20 cm, and rod of 30 cm), movement direction (forward and lateral), and phase (1–25, 26–50, 51–75, 76–100% of the data) as within-subject variables. Only the main effect of performance variable was significant but its effect size was too small to report. This analysis suggested that joint angles functioned as a synergy that kept the end-effector stable and that this synergy did not significantly differ over performance variable, end-effector length, movement direction, and movement phase (see also Fig. 2).

Discussion

The purpose of this study was to scrutinize control during a reaching task with and without a rod attached to the index

finger. In order to do this, we applied the UCM method. This method proposes that trial-to-trial variability in motor performance reflects neuromotor control processes stabilizing the performance variable in a flexible manner, that is, through a synergy that keeps the end-effector trajectory stable through co-variation in joint angles. We found that three joint angles (i.e., elbow flexion–extension, wrist abduction–adduction, and finger flexion–extension) did change over rod conditions. Note that these differences reflected coordinative processes because in our experimental setup, participants could, in principle, use the same postures over the different rod lengths and still be accurate. Moreover, we found that V_{UCM} was larger than V_{ORT} , demonstrating that variability of the joint angles was used to keep the movement of the end-effector stable. Importantly, we found no differences in variability over the different end-effector lengths indicating no differences in control between the tip of the index finger in the no rod condition and the tip of the rod in the rod conditions. Moreover, analyses showed no differences between the rod tip and the hand in the co-variation in the joints that kept those performance variables stable.

Our findings showed that the reaching movement depended on rod length; the elbow was less flexed, the

wrist more abducted, and the finger flexion–extension angle depended on end-effector length. So, each rod length was controlled with a different posture, which is interesting given that the difference between participant and target is adjusted to rod length ensuring that practically the same joint angles could be used for all the rods while accuracy was not affected. This indicates that motor coordination processes may vary with end-effector length, which makes it relevant to examine the synergistic organization underlying movements without and with rods of different lengths. The results of the UCM analyses suggested that the degree of co-variation in the joints was independent of the length of the end-effector, that is, we did not find an increase in V_{UCM} with longer rods. It might be the case that the adjustments in the distance between participant and target made that the movements were too similar for the different rod lengths to find differences in V_{UCM} . However, at this point, we can only speculate whether this is the case. Future experiments will address whether this conclusion also holds when the distance between the targets and the participants is not adjusted to the length of the rod.

Other studies have reported an increase in V_{UCM} with a higher uncertainty of target position (de Freitas et al. 2007) and with higher obstacles that needed to be avoided (Jacquier-Bret et al. 2009). Such an increase in V_{UCM} increases the flexibility so that more coordinative solutions can be explored. Interestingly, the neuromotor system does not need more flexibility (i.e., larger V_{UCM}) when the finger is extended by a rod of a length that falls into the range of daily utensils. Note that participants were never explicitly instructed to keep the end-effector stable during the movement. Only at the end of the movement, where the end-effector reaches the target, stabilization of its tip is necessary to successfully complete the task. Our results showed that V_{UCM} was larger than V_{ORT} in all portions of the movement; this is remarkably because it seems to suggest that the end-effector was stabilized throughout the whole movement trajectory and not just at the endpoint. This could be seen as an argument in favor of trajectory control models of motor control. Moreover, the difference between V_{UCM} and V_{ORT} was relatively larger in the mid-portion of the movement. This indicates that in the middle phase of the movement, joint angles were more variable compared to the beginning and the end, while in the mean time, the angles co-varied to keep the end-effector stable. It might be that at the end of the movement, the arm posture is relatively close to the limit of the range of motion for some of the joints. Therefore, there is not that much room left for variability in the joints, which might have resulted in a smaller V_{UCM} at the end of the movement.

An important issue in the current study was which performance variable was most stabilized by the synergy in the arm; was it the hand or the tip of the tool? One of the

ideas behind this study was that increasing the length of the finger through attaching rods to it would cause the finger to be used more as an additional segment of the arm. Note that in regular pointing, the wrist, the hand, and the pointing finger are generally considered to function as a rather rigid structure. Increasing the length of the finger might change this; would the finger function as an extra segment of the arm, then we would expect that variation in the wrist and finger angles co-varied with the variation in the other joints to keep the rod's tip stable. Manipulating rod length allows examining how co-variation in the joints in the arm keeps different parts of the arm stable, something that has not been studied in reaching tasks with the UCM method, as far as we know. In both our analyses on measures of the UCM, we found no differences in the amount of co-variation in the joints between the hand and the rod's tip indicating that the degree of stabilization does not differ for those two variables.

This finding challenges the literature which indicates that control of a tool would be displaced to the new end-effector (cf. Arbib et al. 2009; cf. Cardinali et al. 2009; Heuer and Sülzenbrück 2009; Jacobs et al. 2009; cf. Maravita and Iriki 2004). Before we discuss this finding in a broader perspective, we first examine two possible explanations of it. First, it could be that the amount of co-variation in the arm joints was similar for the rod's tip and the hand because the hand and rod formed a rigid structure. This would imply that the finger joint is not actually used and, thus, the co-variation in the arm angles to compensate for variation in hand movements equally compensate for variability in movement of the rod's tip. However, our findings clearly showed that hand and rod were not rigidly connected; the angles of the finger depended on how far the movement was evolved, the movement direction and the rod length. Hence, this explanation was not supported by the data. Second, it might be that small corrections of the rod, for instance to end up in the target, are made with just the finger, and therefore, that such corrections are not compensated for by co-variation of joint angles in the arm. In this way, it is the tip of the rod that is actually stabilized because the corrections bring the tip in the target. However, since such corrections are not accompanied by co-variation in the joints in the arm, they would decrease the V_{UCM} of the rod's tip, which also would lower V_{ratio} . However, there is no indication for this to happen since V_{UCM} and V_{ratio} at the end of the movement do not differ for the hand and for the rod's tip. Hence, these findings do not support the idea that small correction movements with the rod at the end of the movement cause equal stabilization of the hand and the rod's tip. In sum, we are left with the conclusion that a synergy is formed in the arm that co-varies joint angles to stabilize movement of the rod's tip equally well to that of the hand. It has been shown that the neuromotor system is

able to stabilize two variables at the same time in prehension tasks (Zhang et al. 2008, 2009) and in a postural control task (Klous et al. 2010). Our own finding is interesting because it shows that the synergy in the arm during a reaching task does not stabilize one specific variable, but the variation in joints in the arm co-varies so that more parts of the moving arm + tool are kept stable. How these stabilizing mechanisms also bring the rod's tip in the target is a question that requires further research. The current data are not up to the task to establish this.

How do these conclusions relate to other studies? The studies of Heuer and Sülzenbrück (2009) and that of Jacobs et al. (2009) come closest to the current study. The main difference between these studies and ours is that none of these studies took into account the angles in the arm and how these angles were organized to use the new end-effector, as we did. Jacobs et al. had apraxic patients impaired for tool use and left-brain-damaged non-apraxic patients make pointing movements with and without rods. Their main focus was on the endpoint accuracy and on smoothness of the movement trajectory. Apraxic patients were much more inaccurate and had less smooth movements than the control patients. Moreover, the differences between the tool and the non-tool conditions were much larger for the apraxic than the non-apraxic patients, which led Jacobs et al. to conclude that the control of patients' end-effector was displaced to the rod, whereas this was not the case for the apraxic patients. Importantly, the study of Jacobs et al. did not take into account the joint angles and how they co-vary to keep the tool's tip stable, as is done in the UCM method. Hence, Jacobs et al. take a different view on motor control processes than we do; theirs focuses only on the end-effector while we take the whole arm into account.

Heuer and Sülzenbrück (2009) had healthy participants make pointing movements with a first-order sliding lever and compared movement of the hand and the tip of the lever. They found that movements of the lever's tip were straighter than movements of the hand implying that the new end-effector was controlled. Different from Jacobs et al. (2009), the study of Heuer and Sülzenbrück did not just look at the tool tip but also at the hand. Heuer and Sülzenbrück examined the shape of the trajectories of the hand and the lever's tip. They did not examine how variability in the hand, or in the arm, was related to variability of the lever's tip. So, also the study of Heuer and Sülzenbrück takes a different approach to motor control than the UCM method we used. In that respect, it would be interesting to measure the joint angles of participants making goal-directed reaches with a first-order sliding lever to be able to apply the UCM method. Such an experiment would allow relating the straightness of the

trajectories of hand and lever's tip with the trial-to-trial variability and co-variation in the joint angles of the arm. This would further our understanding of the motor control processes underlying the use of extensions of the body.

Tseng et al. (2003) studied the effect of accuracy on the structure of joint variability. Participants had to move a pointer tip in one continuous motion to the center of a target. The width of the target was changed, which led to targets with a different index of difficulty (ID). A higher ID (i.e., smaller target) asks for more accuracy at the end-effector. Tseng and colleagues (Tseng et al. 2003) found that increasing the ID led to an overall reduction in joint variability, particularly of V_{UCM} . Nevertheless, higher V_{UCM} than V_{ORT} was present regardless of the ID. These findings relate to our study since there seems to be an implicit relation between ID and length of the end-effector. When reaching with a longer rod, rotation at a more proximal joint results in larger effects on the tip of the rod (cf. Bongers et al. 2004). Thus, to keep the tip of a longer rod as stable as the tip of a shorter rod, more stabilization (i.e., more co-variation in the joints) is necessary. Therefore, for the control system, reaching with a longer rod compared to a shorter rod seems analogue to reaching to a target with a high ID compared to a target with a small ID. For instance, Baird et al. (2002) found in a task where participants reached to targets of different ID with rods of different length that movement time increased with both targets with higher ID and with longer rods. Therefore, effects of rod length could have effects congruent with the effects of target size known from the literature. However, we did not find a reduction in joint variability as result of a longer end-effector, as was found with a higher ID. The results did show that the end-effector was stabilized by means of the joint angles independent of its length. Thus, most of the variability in the joint angles had no effect on the end-effector. Apparently, for the CNS, changing the complexity of the task, due to a longer end-effector, is not the same as changing the complexity of the task, due to a smaller target.

The current study indicated that synergies are formed during reaching with an extended end-effector. The main conclusion was that synergies in the arm are formed during tool use and that the tool is included in this synergy. The second contribution of this study was that more parts of the arm+tool system were kept stable during the movement; both the variation in the joint angles in the arm and the co-variation between them did not differ for the hand and the rod's tip. These two findings demonstrated the flexibility of the neuromotor system. These findings might have implications for rehabilitation. It opens routes to understand how the CNS copes with changes in the neuromotor system after people get injured or have to get a prosthesis after an amputation.

Acknowledgments We would like to thank At Hof, Bert Otten, and Dirk-Jan Veeger for their help with the computations of the angles, Henry van de Crommert and Emyl Smid for technical support, and Frank Zaal for helpful discussions. We thank also two anonymous reviewers for the helpful suggestions.

Open Access This article is distributed under the terms of the Creative Commons Attribution Noncommercial License which permits any noncommercial use, distribution, and reproduction in any medium, provided the original author(s) and source are credited.

References

- Arbib MA, Bonaiuto JB, Jacobs S, Frey SH (2009) Tool use and the distalization of the end-effector. *Psychol Res* 73:441–462
- Baird KM, Hoffmann ER, Drury CG (2002) The effects of probe length on Fitts' law. *Appl Ergonomics* 3:9–14
- Bakeman R (2005) Recommended effect size statistics for repeated measures designs. *Behav Res Methods* 37:379–384
- Bernstein NA (1967) *The coordination and regulation of movements*. Pergamon Press, New York
- Bongers RM, Michaels CF, Smitsman AW (2004) Variations of tool and task characteristics reveal that tool-use postures are anticipated. *J Motor Behav* 36:305–315
- Cardinali L, Frassinetti F, Brozzoli C, Urquizar C, Roy AC, Farnè A (2009) Tool-use induces morphological updating of the body schema. *Curr Biol* 19:1157–1158
- Cohen J (1988) *Statistical power analysis for the behavioral sciences*, 2nd edn. Erlbaum, Hillsdale
- De Freitas SM, Scholz JP, Stehman AJ (2007) Effect of motor planning on use of motor abundance. *Neurosci Lett* 417:66–71
- Domkin D, Laczko J, Jaric S, Johansson H, Latash ML (2002) Structure of joint variability in bimanual pointing tasks. *Exp Brain Res* 143:11–23
- Domkin D, Laczko J, Djupsjöbacka M, Jaric S, Latash ML (2005) Joint angle variability in 3D bimanual pointing: uncontrolled manifold analysis. *Exp Brain Res* 163:44–57
- Gelfand IM, Latash ML (1998) On the problem of adequate language in movement science. *Mot Control* 2:306–313
- Heuer H, Sülzenbrück S (2009) Trajectories in operating a handheld tool. *J Exp Psychol Hum Percept Perform* 35:375–389
- Jacobs S, Bussel B, Combeaud M, Roby-Brami A (2009) The use of a tool requires its incorporation into the movement: evidence from stick-pointing in apraxia. *Cortex* 45:444–455
- Jacquier-Bret J, Rezzoug N, Gorce P (2008) Synergies during reach-to-grasp: a comparative study between healthy and C6-C7 quadriplegic subjects. In: *Conference Proceedings of the IEEE Engineering in Medicine and Biology Society*, pp 5366–5369
- Jacquier-Bret J, Rezzoug N, Gorce P (2009) Adaptation of joint flexibility during a reach-to-grasp movement. *Mot Control* 13:342–361
- Klous M, Danna-dos-Santos A, Latash ML (2010) Multi-muscle synergies in a dual postural task: evidence for the principle of superposition. *Exp Brain Res* 202:457–471
- Latash ML (2008) *Synergy*. Oxford University Press, New York
- Latash ML, Scholz JP, Schönner G (2007) Toward a new theory of motor synergies. *Mot Control* 11:267–308
- Maravita A, Iriki A (2004) Tools for the body (schema). *Trends Cogn Sci* 8:79–86
- Olejnik S, Algina J (2003) Generalized eta and omega squared statistics: measures of effect size for some common research designs. *Psychol Methods* 8:343–447
- Scholz JP, Schönner G (1999) The uncontrolled manifold concept: identifying control variables for a functional task. *Exp Brain Res* 126:289–306
- Scholz JP, Schönner G, Latash ML (2000) Identifying the control structure of multijoint coordination during pistol shooting. *Exp Brain Res* 135:382–404
- Schönner G (1995) Recent development and problems in human movement science and their conceptual implications. *Ecol Psychol* 8:291–314
- Tseng Y, Scholz JP, Schönner G (2002) Goal-equivalent joint coordination in pointing: affect of vision and arm dominance. *Mot Control* 6:183–207
- Tseng Y, Scholz JP, Schönner G, Hotchkiss L (2003) Effect of accuracy constraint on the underlying joint coordination of pointing movements. *Exp Brain Res* 149:276–288
- Turvey MT (2007) Action and perception at the level of synergies. *Hum Mov Sci* 26:657–697
- van Andel CJ, Wolterbeek N, Doorenbosch CAM, Veeger HEJ, Harlaar J (2008) Complete 3D kinematics of upper extremity functional tasks. *Gait Posture* 27:120–127
- Wu G, van der Helm FCT, Veeger HEJ, Makhsous M, van Roy P, Anglin C, Nagels J, Karduna AR, McQuide K, Wang X, Werner FW, Buchholz B (2005) ISB recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion—Part II: shoulder, elbow, wrist and hand. *J Biomech* 38:981–992
- Zhang W, Scholz JP, Zatsiorsky VM, Latash ML (2008) What do synergies do? Effects of secondary constraints on multidigit synergies in accurate force-production tasks. *J Neurophysiol* 99:500–513
- Zhang W, Olafsdottir HB, Zatsiorsky VM, Latash ML (2009) Mechanical analysis and hierarchies of multidigit synergies during accurate object rotation. *Mot Control* 13:251–279