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Diminished joint coordination with aging leads to more variable hand paths

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ABSTRACT

Differences in joint coordination between arms and due to aging were studied in healthy young and older adults reaching to either a fixed, central target or to the same target when it could unexpectedly change location after reach initiation. Joint coordination was investigated by artificially removing the covariation of each joint's motions with other joints' motions. Uncontrolled manifold analysis was used to partition joint configuration variance into variance reflecting motor abundance (V_{UCM}) and variance causing hand path variability (V_{ORT}). The extent to which V_{ORT}, related to the consistency of the hand path, increased after removing a joint's covariation indicated the strength of its coordination with other joints. Young adults exhibited stronger indices of joint coordination, evidenced by a larger increase in V_{ORT} after removing joint covariation than for older adults. This effect was more striking for the dominant right compared to the left arm for young adults, but not for older adults, especially with target uncertainty. The results indicate that interjoint coordination in young adults leads to less hand path variability compared to older adults.

1. Introduction

The coordination of tasks like reaching, postural control, and force production has been shown to involve the use of motor abundance by the central nervous system (CNS) (de Freitas, Scholz, &

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Stehman, 2007; Gera et al., 2010; Hsu, Scholz, Schöner, Jeka, & Kiemel, 2007; Krishnamoorthy, Scholz, & Latash, 2007; Latash, Scholz, Danion, & Schoner, 2001; Latash, Scholz, Danion, & Schöner, 2002; Scholz & Schöner, 1999; Scholz et al., 2007; Tseng & Scholz, 2005; Zhang, Scholz, Zatsiorsky, & Latash, 2008). These studies suggest that the CNS stabilizes variables most related to task success by allowing for flexible combinations of redundant degrees of freedom. A functional synergy in this context is defined as having two features, namely, (1) a neural organization that determines the division of labor among elemental variables (i.e., how much each variable contributes, on average, to the value of a performance variable) and (2) their covariation to stabilize the values of important performance variables (Latash, Scholz, & Schöner, 2007). Covariation between elemental variables could either be negative or positive. However, negative covariation has a greater probability of stabilizing the task (Latash et al., 2007). For example, a task requiring generation of a total of 10-N force by pressing with two fingers can be accomplished by attempting to produce exactly 5-N by each finger on every attempt. Successful performance then requires near perfect control. A more realistic approach involves the negative covariation of finger forces, i.e., an increase in one finger's force is accompanied by an equal reduction in the other's force, thus providing more flexibility to stabilize the 10-N total force.

The second feature of functional synergies has been quantified using the uncontrolled manifold approach (UCM) to separate the across-trials or across time (depending on the task) variance of elemental variables into a component that reflects flexibility in stabilizing a performance variable (variance within the UCM subspace) from a component that leads to variability of the same variable (orthogonal subspace) (Latash et al., 2007; Schöner & Scholz, 2007). In this study, we used the framework of UCM to investigate the extent to which covariation of individual joints with other joints of the arm stabilizes the hand's three-dimensional path during reaching. Some of the UCM variance could reflect the fact that the axis of a particular joint's motion lies geometrically parallel to a dimension of the UCM in joint space. To the extent that this is true, its variance has no effect on the performance variable under consideration. Thus, even if such a joint's motion did not co-vary with that of other joints, it would contribute to UCM variance. For example, during a pointing task when the elbow is extended fully forward and shoulder flexed to 90°, rotation of forearm has a minimal to no effect on the three dimensional position of the hand. That is, the hand position considered as the performance variable would have low sensitivity to this rotation.

In addition, it has been observed that proximal and distal joints play different roles in the control of reaching. Proximal joints appear to be most important for arm transport, whereas distal joints are more important for positioning and orienting the hand near the target (Jeannerod, 1999; Marotta, Medendorp, & Crawford, 2003; Wang, 1999). Differences in the role of proximal and distal joints have also been proposed by the leading joint hypothesis (Dounskaia, 2005). This hypothesis postulates that the leading joint, generally proposed to be the shoulder joint, generates the muscle torques to accelerate the limb, whereas the subordinate joints (usually wrist and elbow) regulate interaction torques produced by the leading joint and create net torque resulting in motion of the end-effector (Galloway & Koshland, 2002). The effectiveness of this proposed strategy should be reflected by coordination of proximal and distal joint motion to stabilize the hands' path to a target. This hypothesis can be tested by artificially removing the covariation, a measure of coordination, between various joint motions to determine its effect on hand path stability compared to what is observed experimentally. That is, lack of coordination of proximal joint motions with those of other joints might be expected to have a greater effect on the transport phase of reaching, whereas poor coordination of distal joint motions with more proximal joints could have a greater effect as the hand approaches the target. To our knowledge, the role of covariation of different joints with others in stabilization of the hand position has not been investigated previously. Recently, the UCM approach has been used to distinguish between joint covariation and individual variation of joint motions whose axes are nearly parallel to one dimension of the UCM subspace of joint space as the source of UCM variance (Verrel, 2011; Yen & Chang, 2011).

The UCM approach has been used to show that motor abundance provides the ability to resolve multiple task constraints simultaneously (Gera et al., 2010; Zhang et al., 2008) and to overcome unexpected perturbations (de Freitas et al., 2007; Scholz et al., 2007). The double step paradigm has been used to investigate the effect of target uncertainty on movement planning and the control of arm movements (Freitas & Scholz, 2009; Georgopoulos, Kalaska, & Massey, 1981; Pelisson, Prablanc, Goodale, & Jeannerod, 1986; Robertson & Miall, 1997; Soechting & Lacquaniti, 1983). Soechting and