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Inter-joint synergies increase with motor task uncertainty in a whole-body pointing task

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ABSTRACT

The study investigates the effect of task uncertainty on motor synergies and movement time for a whole-body pointing task employing a Fitts' like paradigm. Thirty-three healthy, young adults were asked to hold a 1.5-m long stick and point it as quickly and accurately as possible to the unmarked center of fixed targets on the ceiling at 150% of the subject's height from the ground. Each subject performed fifteen continuous repetitions for each target size (1 cm, 2 cm, 3 cm, 5 cm, 8 cm, 13 cm and 21 cm diameters of circles). It was assumed that the task uncertainty increased as the target size increased. Motion capture was used to collect the data for joint angles in the sagittal plane and uncontrolled manifold (UCM) analysis was used in order to investigate synergistic actions of joints. Results from the study revealed that the movement time decreased as task uncertainty increased. The variability within the uncontrolled manifold (V_{UCM}) systematically increased with task uncertainty, resulting in an increase in the index of inter-joint synergies (ΔV), although the pointing task errors (V_{ORT}) were consistent across different target sizes. The results suggest that the central nervous system systematically modulates the inter-joint synergies with task uncertainty in the whole-body pointing task without affecting motor performance.

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The human body is a redundant system and the framework within which the central nervous system (CNS) manages this redundancy is a major topic of scientific investigation in human motor control [3]. The motor redundancy problem has also been called the degrees of freedom problem in the motor control literature. Although many previous studies have assumed that the redundant degrees of freedom pose a computational problem for the CNS, recent studies have suggested that this redundancy might provide a larger solution space for synergistic actions of motor effectors [11,14,17,18]. In these studies, the motor synergies have been considered task-specific neural organizations of individual effectors such as joints that stabilize the performance variables of multi-dimensional systems. It has been suggested that while performing a motor task such as reaching, pointing or sit-to-stand, the CNS increases synergistic actions of kinematically redundant joints when the task became more difficult so that the performance of the task can be accomplished successfully [17,18].

Many previous studies have employed the uncontrolled manifold (UCM) analysis as a method to investigate the redundancy in a motor system [11,16–18]. This method quantifies the total amounts of trial-to-trial variability in two components by projecting the total variability into independent vector sub-spaces [17]. The central tenet of the UCM hypothesis is that the multi degrees of freedom design of biological motor systems is not "redundant" (i.e., a source of computational problems) but "abundant" such that it provides flexible solutions [11,12,17,18]. The method involves taking two components of variability obtained from a motor task performed with several repetitions for a given condition. The component of variability (V_{UCM}), that does not affect the motor task performance is referred to as the variability within the null-space of the motor task, while the other component (V_{ORT}), that does affect the task performance is called the variability in the space orthogonal to the UCM space. A larger V_{UCM} may be interpreted as greater synergistic actions of motor elements (e.g., muscles, joint angles, finger forces) used by the CNS to successfully perform a specific motor task with redundancy/abundance while a larger V_{ORT} may be interpreted as increased errors while performing the motor task. For this reason, V_{UCM} and V_{ORT} have often been referred to as the "good variance" and "bad variance", respectively [13]. ΔV is calculated as the difference between V_{UCM} and V_{ORT} and has been used as an index of

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synergistic actions of motor elements in a redundant/abundant system. It is to be noted that the index of synergy increases with both, an increase in "good variance" and a decrease in "bad variance".

This methodological approach has provided insights into the control strategies used by the CNS during motor tasks involving mathematically redundant motor systems [2,9,13,17,19,20]. Whole body motor tasks such as standing or sit-to-stand have been adopted to investigate inter-joint synergies in the motor tasks and these studies have shown that synergistic actions are constrained by neural and biomechanical factors [1,9,16,17].

Several previous studies have adopted Fitts' Law paradigm (i.e., speed-accuracy trade off) to investigate the relationship between the variability and the movement time (MT) using the index of difficulty [5,7,9,10]. Fitts' Law refers to a linear relationship between the movement time (MT) and the index of difficulty (ID), where the ID incorporates the target size and the target distance from a start position. Many human movement tasks involving reaching to a target with a certain size at a certain distance are known to follow the Fitts' Law [8]. The ID has been shown to be proportional to the target distance and inversely proportional to the target size [8,15]. Previous studies have shown that when ID increase, MT increases not only in simple and classical motor tasks such as reaching, but also in more complex motor tasks involving a whole body [4–7,9].

This study investigated how the inter-joint synergies in the UCM framework changed with IDs in Fitts' paradigm, where the task difficulty was manipulated by changing the target size. We hypothesized that the MT would decrease with the target size as shown in previous motor tasks similar to the Fitts' paradigm (Hypothesis 1), and inter-joint synergies would increase with the target size because it was assumed that the uncertainty of the task increased with the target size (Hypothesis 2).

Thirty-three healthy adults (28.3 ± 6.5 years old, 179.2 ± 9.0 cm, 87.6 ± 21.6 kg), without any history of neurological disorders or musculoskeletal injuries participated in this study. All subjects signed the informed consent approved by the Institutional Review Board (IRB) at the University of Maryland before participating in the experiments. Seven reflective markers, 1 cm diameter each, were attached on the right side of each subject's body (toe, ankle, knee, hip, shoulder, elbow, and wrist) and one marker was attached at the distal end of a wooden stick (150 cm in length and 1 cm in diameter) (Fig. 1). Each subject was instructed to stand on the rigid plate with their feet, shoulder-width apart and hold the stick with two hands. A wooden panel ($100\,\text{cm} \times 100\,\text{cm}$) was installed on the ceiling. The distance of the target from the ground was adjusted at 150% of subject's height. The target size was systematically varied for each of seven different target conditions: 1 cm, 2 cm, 3 cm, 5 cm, 8 cm, 13 cm and 21 cm diameters of circle. The center position of the target remained unchanged and unmarked. Since the circle center remained at the same position and only the diameter of the circle systematically changed for different target size conditions, it was assumed that the uncertainty of the task to identify the circle center increased with the circle size. For each target size condition, subjects were asked to point at the unmarked center of the circles with the distal end of the stick as quickly and accurately as possible. Subjects were instructed to perform fifteen continuous repetitions of squatting at a comfortable level and pointing to the target with the stick. Subjects were given five minutes of rest between target conditions to reduce fatigue. The order of the target conditions was balanced across subjects. The positions of the reflective markers were recorded and digitized using the Kwon3D system (VISOL Inc, Seoul, Korea). Joint angles in the sagittal plane were identified at the time instant when the end point marker of the stick contacted the wooden panel.

It is to be noted that the motor task occurred in three-dimensional space while our analysis was limited to two-dimensional space in the sagittal plane. The position of the tip of the stick $P(x, y)$, when it was in contact with the target, was measured in the sagittal plane. The two-dimensional coordinates of the stick tip position had the following relationship with the angular positions of each joint (Eq. (1)). This geometric model was constructed from the positions of the markers attached to the sagittal plane of the subjects (Fig. 1).

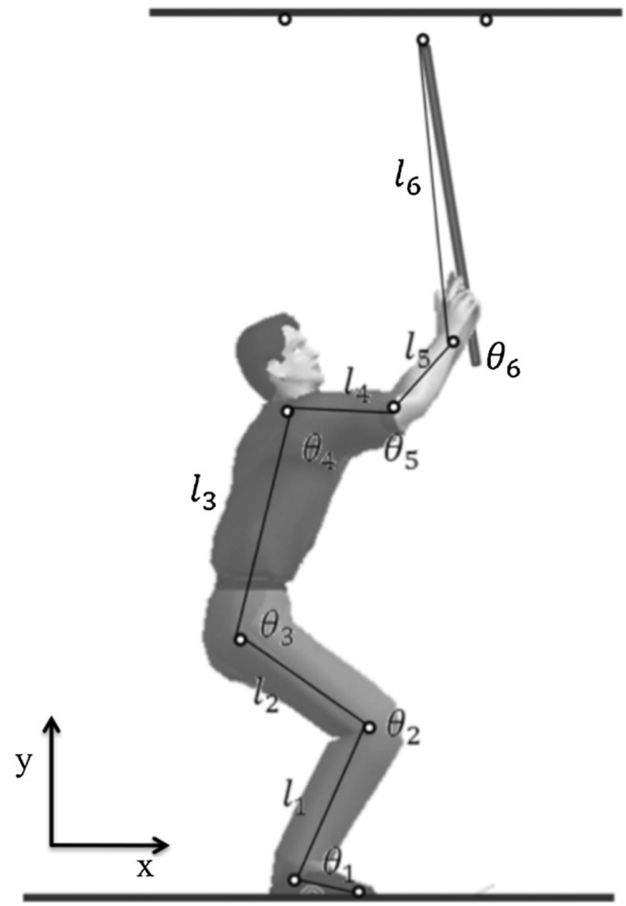

Fig. 1. Schematic diagram of the experimental setup: reflective markers (white circles) were attached at the toe, major joints, and distal tip of the stick, $P(x, y)$, held by subjects. Two markers were attached on the ceiling to define the diameter of the targets.

$$\begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} \sum l_n \cos(\theta_n) \\ \sum l_n \sin(\theta_n) \end{bmatrix} \tag{1}$$

where n represents different joints and varies from 1 to 6. θ and l represent joint angles and body segment lengths, respectively.

The relation between inter-joint variability and the variability of the end point of the stick was established using the framework of UCM [17]. A Jacobian matrix, connecting the changes in joint angles and changes in stick tip position was formed (Eq. (2)). The joint angle variance (V_{TOT}) from the mean angles across the trials for each target size was calculated. V_{TOT} was then partitioned into two components: the component of variance within the null space of the Jacobian (V_{UCM}) (Eq. (3)) and the component of variance orthogonal to the null space (V_{ORT}) (Eq. (4)). The index of synergy (ΔV) was calculated as the difference between V_{UCM} and V_{ORT}, normalized by the total variability per total degrees of freedom (Eq. (5)). Details of this computational approach have been described in previous studies [13,17].

$$P = J \cdot \theta \tag{2}$$

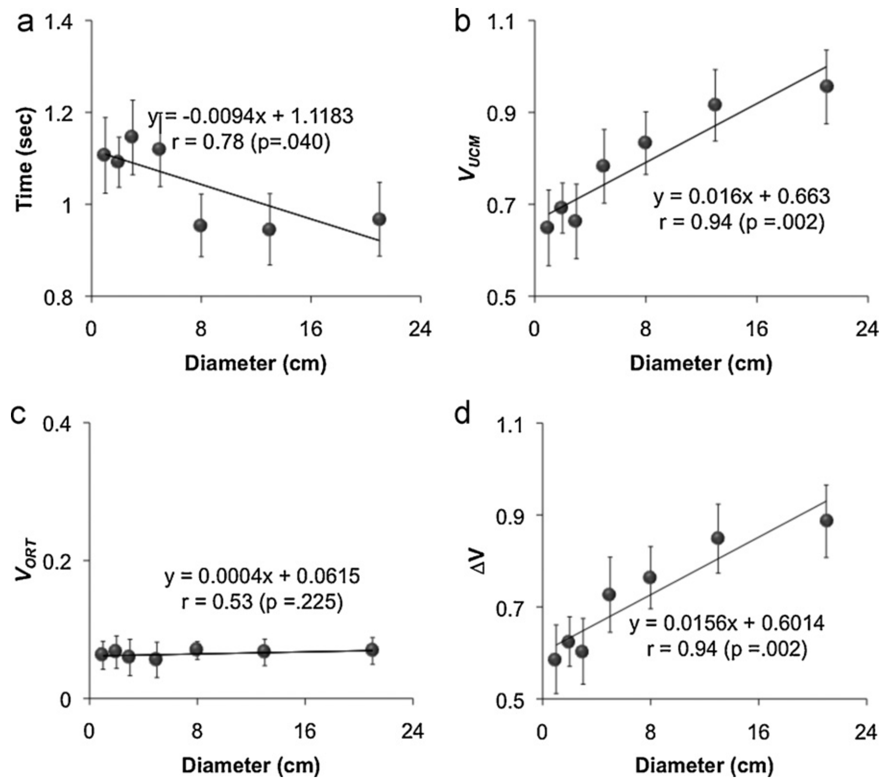

Fig. 2. Relationships between target size and (a) movement time, (b) V_{UCM}, (c) V_{ORT}, and (d) ΔV during the whole body pointing task. Circles represent average values calculated across participants with standard deviation bars. Note that the slopes of the regression lines for ΔV and (a) movement time, (b) V_{UCM}, and (d) ΔV are statistically significant ($p<.05$).

where $P=[x, y]^{-1}$ and $\theta=[\theta_1 \cdots \theta_6]$

$$V_{\mathrm{UCM}} = \frac{\sum (\theta_{\parallel})^2/N_{trials}}{n-1} \tag{3}$$

$$V_{\mathrm{ORT}} = \frac{\sum (\theta_{\perp})^2/N_{trails}}{DoF_{task}} \tag{4}$$

$$\Delta V = \frac{V_{\mathrm{UCM}} - V_{\mathrm{ORT}}}{V_{\mathrm{TOT}}/n} \tag{5}$$

where N_{trials} is the total number of trials per subject, n is the total number of degree-of-freedom of the system, and DoF_{task} is the degrees-of-freedom of the task.

Linear regression analysis was performed to investigate the relationship of the target size to the MT, V_{UCM}, V_{ORT}, and ΔV. The level of significance for all statistical tests was set at $p<.05$.

The results of the study showed that the MT decreased with increase in the target size ($r=0.78$, $p=.04$) (Fig. 2a) and V_{UCM} also increased with increase in the target size ($r=0.94$, $p=.002$) (Fig. 2b). However, V_{ORT} was consistent regardless of the target size ($r=0.53$, $p>.05$) (Fig. 2c). The increase in V_{UCM} and the consistent V_{ORT} with the target size resulted in an increase in ΔV with the target size ($r=0.94$, $p=.002$) (Fig. 2d).

In agreement with the Fitts' paradigm, MT decreased with an increase in the target size, thus confirming the first hypothesis. This result was in line with previous studies that used similar motor task paradigms [6,10,13]. The UCM analysis revealed that inter-joint synergies became greater when task uncertainty increased, thus confirming the second hypothesis. The components of variability under the UCM framework showed that the variability within the UCM (V_{UCM}) increased with the increase in task uncertainty. This result is consistent with the previous study that showed an increase in V_{UCM} with decrease in ID in another whole body movement task [9]. However, a few previous studies showed that the CNS produces enhanced synergistic actions between the joints when task difficulty increased [16–18]. If it is assumed that the task difficulty increases with the task uncertainty, the current study is not consistent with those studies in this regard. The present study demanded touching at the center of the circle regardless of the size of the target, which is different from the Fitts' paradigm. Also, the Fitts' paradigm is based on the successful trials achieved by pointing anywhere in the target range while the current study does not have a range and demands motor performance as accurate as possible by pointing as close to the circle center as possible. An increase in the size of the target makes a motor task easier with respect to Fitts' Law paradigm. However, the motor task used in this study could become more challenging with the increase in the target size because the uncertainty of the task could increase with the target size. In this context, the present study was in line with previous studies that used similar motor paradigms [5,7].

These results suggest that increases in task uncertainty cause systematic changes in the synergistic control of multiple joints employed by the CNS. While the whole-body pointing system follows the Fitts' paradigm, increases in V_{UCM} and ΔV values also suggest that the CNS utilizes systematically changing solutions in the abundant multi-joint system in order to complete the motor task. Since multiple muscle groups are involved in the production of the whole-body movement employed in this study, one may interpret the results as an indirect indication of synergistic actions of those muscles although the mapping between the muscular activities and joint angles are currently unknown.

Conflict of interest

No author has any financial or personal relationship that could inappropriately influence the work submitted for publication.

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References

[1] T. Asaka, Y. Wang, J. Fukushima, M. Latash, Learning effects on muscle modes and multi-mode postural synergies, Exp. Brain Res. 184 (2008) 323–338.
[2] A.G. Auyang, J.T. Yen, Y.H. Chang, Neuromechanical stabilization of leg length and orientation through interjoint compensation during human hopping, Exp. Brain Res. 192 (2009) 253–264.
[3] N.A. Bernstein, The Co-ordination and Regulation of Movements, Pergamon Press, Oxford, New York, 1967.
[4] F. Berrigan, M. Simoneau, O. Martin, N. Teasdale, Coordination between posture and movement: interaction between postural and accuracy constraints, Exp. Brain Res. 170 (2006) 255–264.
[5] F. Danion, M. Duarte, M. Grosjean, Fitts' law in human standing: the effect of scaling, Neurosci. Lett. 277 (1999) 131–133.
[6] M. Duarte, S.M. Freitas, Speed–accuracy trade-off in voluntary postural movements, Motor Control 9 (2005) 180–196.
[7] M. Duarte, M.L. Latash, Effects of postural task requirements on the speed–accuracy trade-off, Exp. Brain Res. 180 (2007) 457–467.
[8] P.M. Fitts, The information capacity of the human motor system in controlling the amplitude of movement, J. Exp. Psychol. 47 (1954) 381–391.
[9] S.M. Freitas, M. Duarte, M.L. Latash, Two kinematic synergies in voluntary whole-body movements during standing, J. Neurophysiol. 95 (2006) 636–645.
[10] S.M. Freitas, J.P. Scholz, M.L. Latash, Analyses of joint variance related to voluntary whole-body movements performed in standing, J. Neurosci. Methods 188 (2010) 89–96.
[11] S. Karol, Y.S. Kim, J. Huang, Y.H. Kim, K. Koh, B.C. Yoon, J.K. Shim, Multi-finger pressing synergies change with the level of extra degrees of freedom, Exp. Brain Res. 208 (2011) 359–367.
[12] M. Latash, There is no motor redundancy in human movements. There is motor abundance, Motor Control 4 (2000) 259–260.
[13] M.L. Latash, V. Krishnamoorthy, J.P. Scholz, V.M. Zatsiorsky, Postural synergies and their development, Neural Plast. 12 (2005) 119–130 (discussion 263–172).
[14] M.L. Latash, J.P. Scholz, G. Schöner, Motor control strategies revealed in the structure of motor variability, Exerc. Sport Sci. Rev. 30 (2002) 26–31.
[15] G.H. Robinson, R.P. Leifer, Generality of Fitts' law under differential error instruction, Percept. Mot. Skills 25 (1967) 901–904.
[16] J.P. Scholz, D. Reisman, G. Schöner, Effects of varying task constraints on solutions to joint coordination in a sit-to-stand task, Exp. Brain Res. 141 (2001) 485–500.
[17] J.P. Scholz, G. Schöner, The uncontrolled manifold concept: identifying control variables for a functional task, Exp. Brain Res. 126 (1999) 289–306.
[18] J.P. Scholz, G. Schöner, M.L. Latash, Identifying the control structure of multijoint coordination during pistol shooting, Exp. Brain Res. 135 (2000) 382–404.
[19] K. Shim, J. Huang, M.L. Latash, V.M. Zatsiorsky, Multi-digit maximum voluntary torque production on a circular object, J. Biomech. 39 (2006) S166.
[20] Y. Wang, T. Asaka, V.M. Zatsiorsky, M.L. Latash, Muscle synergies during voluntary body sway: combining across-trials and within-a-trial analyses, Exp. Brain Res. 174 (2006) 679–693.