Neuroscience 319 (2016) 194–205

EFFECTS OF UNILATERAL STROKE ON MULTI-FINGER SYNERGIES AND THEIR FEED-FORWARD ADJUSTMENTS

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Abstract—We explored the changes in multi-finger synergies in patients after a single cortical stroke with mild motor impairments. We hypothesized that both synergy indices and anticipatory synergy adjustments prior to the initiation of a self-paced quick action would be diminished in the patients compared to age-matched controls. The patients with history of cortical stroke, and age-matched controls ($n = 12$ in each group) performed one-finger and multi-finger accurate force production tasks involving both steady-state and quick force pulse production. Finger interdependence (enslaving) and multi-finger synergies stabilizing total force were quantified. The stroke patients showed lower maximal finger forces, in particular in the contralesional hand, which also showed increased enslaving indices. Multi-finger synergies during steady-state force production were, however, unchanged after stroke. In contrast, a drop in the synergy index prior to the force pulse generation was significantly delayed in the stroke patients. Our results show that mild cortical stroke leads to no significant changes in multifinger synergies, but there is impairment in feed-forward adjustments of the synergies prior to a quick action, a drop in the maximal force production, and an increase in enslaving. We conclude that studies of synergies reveal two aspects of synergic control differentially affected by cortical stroke.

Key words: stroke, hand, synergy, feed-forward control, anticipatory synergy adjustments.

INTRODUCTION

Sensorimotor impairment of the hand happens commonly after a unilateral cortical stroke affecting a range of activities of daily living. Typical consequences of stroke that affect the extremities contralateral to the lesion include weakness, predominance of fixed patterns of muscle activations (abnormal synergies, resulting in losses of independent joint control, Bobath, 1978; Dewald et al., 1995), spasticity, and intersegmental coordination deficits (Wyke, 1967; Beer et al., 2000). In cases of mild stroke, impairments in the coordination among motor elements, such as arm joints and digits, become important factors affecting functional independence, even in the ipsilesional arm (Wetter et al., 2005; Rinehart et al., 2009; Schaefer et al., 2009a,b).

Recently, an approach to the neural coordination of multiple effectors has been developed based on the principle of abundance (Gelfand and Latash, 1998; Latash, 2012). According to this principle, the apparently redundant design of the human body is not a source of computational problems for the central nervous system (CNS), but a rich and flexible apparatus that allows the CNS to organize stable performance in the varying and unpredictable environment. Neural organizations that ensure stable performance by co-varied contributions of elements (muscles, joints, digits, etc.) have been referred to as ‘‘synergies” (Latash et al., 2007). This term has been used in the literature in different meanings. As mentioned, abnormal synergies describe stereotypic pattern of muscle activations that interfere with intentional movements (Twitchell, 1951; Brunnström, 1970). This term has also been used to imply parallel changes in variables produced by effectors, kinetic, kinematic, or electromyographic, across task parameters or over the time course of movement execution (d’Avella et al., 2003; Ivanenko et al., 2004; Ting and Macpherson, 2005). We use this term to reflect stability of natural movements with respect to salient variables, which is crucial for success given the natural variability in body states and unpredictable changes in external forces (reviewed in Latash et al., 2007; Latash, 2008).

This important aspect of coordination can be quantified using a method that has been developed within the uncontrolled manifold (UCM) hypothesis (Scholz and Schöner, 1999). This analysis is based on

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Abbreviations: ASAs, anticipatory synergy adjustments; CNS, central nervous system; CS, control subject; LHD, left-hemisphere damage; MVC, maximal voluntary contraction; ORT, orthogonal to the UCM subspace; PD, Parkinson’s disease; RHD, right-hemisphere damage; SD, standard deviation; SE, standard error; UCM, uncontrolled manifold.

http://dx.doi.org/10.1016/j.neuroscience.2016.01.054
0306-4522/

the idea that repeating actions from slightly different initial conditions is expected to lead to diverging trajectories in unstable directions and converging trajectories in stable directions. Hence, analysis of inter-trial variance in different directions in the space of elemental variables (those produced by elements involved in the action) provides an index that can be used as a proxy of stability in those directions within the multi-dimensional space of elemental variables. The analysis quantifies inter-trial variance in directions that lead to no changes in a potentially important performance variable (along the UCM for that variable, V_{UCM}) and in directions orthogonal to the UCM sub-space (V_{ORT}). If $V_{UCM} > V_{ORT}$, quantified per degree of freedom in the corresponding sub-spaces, a conclusion is drawn that a synergy stabilizes that performance variable. A synergy index, ΔV, reflecting relative amount of V_{UCM} in total variance has been used as a metric reflecting stability of the performance variable (reviewed in Latash, 2008). Recently, relations of the ΔV index to stability have been studied in a number of experiments with controlled perturbations of ongoing actions (Yang et al., 2007; Wilhelm et al., 2013; Reschechtko et al., 2014; Zhou et al., 2015).

In more intuitive terms, this definition of synergy is related to inter-compensation of errors among the contributions of elements to a salient performance variable (cf. principle of error compensation, Latash et al., 1998). For example, carrying a cup of coffee while walking requires co-variation of joint rotations to keep the cup vertical. A strong joint configuration synergy implies that spontaneous variations in joint angles or a perturbation applied to the arm would lead to changes in joint configuration primarily within the UCM for the vertical cup orientation, i.e., cup orientation would show dynamic stability. This is expected to lead to relatively high V_{UCM} values and positive ΔV values.

In patients with mild-to-severe contralesional impairment, deficits in intersegmental coordination during reaching movements of the contralesional arm have been documented (Beer et al., 2000), and have been shown to vary with the side of the lesion. In addition, coordination deficits in the ipsilesional arm have been documented as early as 1967 (Wyke, 1967), and have been shown to differ, depending on the side of the lesion (Winstein et al., 1999; Haaland et al., 2004). While these studies have addressed the coordination of joint motions to produce a given trajectory within a reaching trial, they have not addressed the ability to stabilize performance as reflected in the two aforementioned indices of inter-trial variance, V_{UCM} and V_{ORT}, and in the synergy index ΔV.

Only one group has so far applied this method of analysis to arm movements of post-stroke patients (Reisman and Scholz, 2003, 2006). The results of the first study were surprising: While the patients with mild-to-moderate hemiparesis displayed abnormal patterns of coordination in the contralesional arm that were notably more deficient than those of the ipsilesional arm, the relative amount of V_{UCM} and V_{ORT} computed in the joint configuration space (these are addressed as goal-equivalent and non-goal-equivalent solutions in the Reisman and Scholz studies) was about the same in the contralesional and ipsilesional arms and also similar to the data in age-matched controls. This was accompanied by a proportional increase in both variance components, V_{UCM} and V_{ORT}, in the contralesional arms of the patients. The follow-up study (Reisman and Scholz, 2006) confirmed these findings for reaches of the paretic hand to contralateral targets, while during reaches to ipsilateral targets V_{ORT} showed a disproportional increase. These findings suggest that the pronounced effects of stroke on reaching movements, which are seen in the averaged across-trial kinematics, are not necessarily reflected in patterns of joint movement covariation across trials. The small number of subjects in the two studies (eight and seven per group, respectively) makes these conclusions tentative.

In contrast, studies of finger coordination in patients with subcortical disorders (Parkinson's disease, PD, and multi-system atrophy, Park et al., 2012, 2013a,b; Jo et al., 2015) have shown a consistent, significant drop in the synergy index during accurate steady-state multi-finger force production and prehensile tasks. These changes were significant in both hands, even in patients with Hoehn–Yahr stage-I of PD who showed clinical symptoms on one side of the body only. The contrast between the findings in PD and stroke patients suggests that subcortical loops, rather than cortical structures, might be crucial for synergic control. However, since the stroke study quantified arm reaching movements, and the PD studies quantified finger coordination, a comparison of the results cannot differentiate between the effect of the disorder (PD or stroke) and the limb effectors (proximal joint coordination vs. finger coordination).

In order to directly address this ambiguity, we quantified multi-finger synergies in a group of stroke survivors with unilateral hemisphere damage and mild contralesional impairment, using the same procedure as that of several earlier studies of PD patients (Park et al., 2012, 2014). Based on the mentioned earlier study (Reisman and Scholz, 2003), we hypothesize that the stroke group should show differences from control subjects (CSs) and between the ipsilesional and contralesional hands in overall performance indices, but not in the multi-finger synergy index computed with respect to the salient performance task variable, namely total force (Hypothesis-1). As in many earlier studies (Latash et al., 2001; Scholz et al., 2002; reviewed in Latash et al., 2007), we analyzed multi-finger synergies in the space of finger modes as elemental variables. Finger modes are defined as commands to individual fingers that can be modified by the subject one at a time; each mode, however, leads to force production by all the fingers of the hand because of the phenomenon of enslaving (Zatsiorsky et al., 2000; Danion et al., 2003b). Due to enslaving, finger forces are expected to co-vary across tasks, and the amount of co-variation may differ across groups. Therefore, analysis of synergies in a finger force space can potentially lead to false conclusions on stronger or weaker synergies stabilizing specific performance variables. Analysis in the mode space eliminates this confound.