Review

Bimanual Movements and Chronic Stroke Rehabilitation: Looking Back and Looking Forward

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Abstract: Executing voluntary motor actions in the upper extremities after a stroke is frequently challenging and frustrating. Although spontaneous motor recovery can occur, reorganizing the activation of the primary motor cortex and supplementary motor area takes a considerable amount of time involving effective rehabilitation interventions. Based on motor control theory and experience-dependent neural plasticity, stroke protocols centered on bimanual movement coordination are generating considerable evidence in overcoming dysfunctional movements. Looking backward and forward in this comprehensive review, we discuss noteworthy upper extremity improvements reported in bimanual movement coordination studies including force generation. Importantly, the effectiveness of chronic stroke rehabilitation approaches that involve voluntary interlimb coordination principles look promising.

Keywords: chronic stroke; bimanual movement; bimanual force control; rehabilitation

1. Introduction

Bimanual movement coordination has a long history and sound theoretical basis as an effective treatment to relearn dysfunctional motor actions caused by a stroke. Typical dysfunctional motor actions on the affected side of the body include weakness or partial paralysis. Planning and executing bimanual movements with an emphasis on simultaneously activating both limbs as a coordinative structure frequently facilitates progress toward motor recovery. Although the concept of bimanual movement coordination as a treatment for chronic stroke was first proposed over 60 years ago [1,2], the intervention has continued to develop, stimulating research and debate. This article will emphasize the rationale and evidence supporting bimanual movement coordination interventions as well as present persuasive arguments considering various rehabilitation treatment prescriptions.

When blood flow in the brain is disrupted by a focal neurological insult, mild to severe motor action dysfunctions become apparent on the contralateral side of the body. Granted, spontaneous motor action recovery can occur; however, a majority of the individuals (approximate 80–90%) who experienced a stroke must cope with hemiparesis [3]. Fortunately, dysfunctional motor actions are no longer viewed as permanent given the convincing neural plasticity evidence [4–8]. Even though Hebb postulated that synaptic plasticity was possible in 1949, the tendency of synapses and neuronal circuits to change because of activity took time to become accepted. Today, neural plasticity (i.e., brain changes that occur in response to experience-dependent challenges) and robust evidence supporting activity-based movements are primary components of multiple treatment protocols post-stroke [7–13]. Planning and executing simultaneous bimanual coordination actions are viable treatment protocols to minimize upper extremity motor dysfunctions post-stroke.

Recent studies on the contributions of the cerebral hemispheres involved in activity-based motor actions revealed focal areas active in excitation and inhibition [14]. Balancing activation of both hemispheres is still relevant to re-acquiring movements post-stroke.


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Moreover, in a discussion of non-invasive brain stimulation protocols, Bestmann and colleagues [15,16] stated that the premotor cortex and supplementary motor cortex readily interact with targeted primary motor cortex areas generating motor action improvements. Supporting evidence favoring this argument was reported by Byblow and colleagues when they tested stroke individuals and found increased corticomotor excitability post bimanual symmetrical (mirror) movements [17]. Further, Liao and colleagues revealed post-stroke bimanual coordination benefits for severely impaired individuals when stimulating the contralesional dorsal premotor cortex, whereas facilitating the ipsilesional motor cortex improved coordination for individuals with mildly impaired upper extremities [18]. In summary, post-stroke bimanual movements are less dysfunctional after receiving brain activity modulation in the primary motor cortex as well as the premotor and supplementary cortex areas of both hemispheres [19–23]. This conclusion is consistent with Carson’s comprehensive review article on neural control and bimanual arm interactions [24].

2. Chronic Stroke Rehabilitation

For chronic stroke rehabilitation, we are concerned with neural plasticity changes that occur during activity-based neural reorganization that occurs across time. The treatments are designed to re-acquire motor actions so that new and stable permanent memories for movements are created. Although there is consensus that intact brain areas may take over dysfunctional motor actions, specific details involving neural reorganization are still unclear. Granted, lesion location and extent contribute to reorganization, whereas rehabilitation frequency and intensity certainly facilitate the process. Rehabilitation specialists are experimenting with individually prescribed treatment protocols for focal neurological lesions of the motor system. An emerging theme is that neural networks closely aligned anatomically to the lesion site progressively adopt the functions of the damaged area over time and increased synaptic activity becomes apparent [7,8,10]. Indeed, Nudo [8] argued that recovering motor actions indicate waves of growth promotion and inhibition that modulate the adjacent intact tissue during the brain’s self-repair processes.

2.1. Activity-Based Movements (Experience-Dependent Movements)

For maximum and lasting motor action benefits, stroke protocols should be founded on a sound theoretical framework based on motor learning and control principles [25,26]. Importantly, activity-based movements or experienced-dependent movements are sound stroke rehabilitation treatment protocols that have consistently expedited progress toward stroke recovery in the upper extremities [27–29]. Persuasive evidence comes from Sheahan, Franklin, and Wolpert [30] in a motor planning and execution experiment. Participants performed reaching movements through a force-field that perturbed movements. They found that motor planning and neural control enhanced movement learning by forming motor memories.

An implication for stroke interventions is that individuals should be actively involved in planning motor actions [31], and this includes both arms intentionally moving simultaneously. Combining motor planning and performing bimanual upper extremity movements highlights the basis for conducting activity-dependent movements to create new neural connections. Specifically, neural plasticity changes evolve from the Hebbian synapse rule that states that individual synaptic junctions respond to activity/use and inactivity/disuse [32–34]. Experience-dependent long-term modification of synaptic efficacy underlies motor memories in neural networks [30,35–37].

2.2. Bimanual Movement Interventions

Compelling evidence suggests that assimilation occurs between the left and right arms during neural control of symmetrical bimanual motor actions [24,38]. Promising findings on chronic stroke interventions have been identified when participants perform the same movement with both limbs. Further, producing the same forces on both arms with homologous muscles firing simultaneously post-stroke assists in
making progress toward motor recovery. Early bimanual coordination or bimanual coordination studies consistently reported synchronization among effectors in concurrently performed movements [24,39–51]. Importantly, Bernstein’s classic argument that both arms are centrally linked as a coordinative structure holds, and upper extremities function in a homologous coupling of muscle groups on both sides of the body [52].

A series of chronic stroke studies focused on bimanual movements executed concurrently and supplemented with neuromuscular-triggered electrical stimulation revealed consistent motor improvement findings. Manipulating treatment protocols centered on bimanual movements as well as EMG-triggered stimulation generates progress toward motor recovery in the upper extremities [21,38,53–58]. Positive experience-dependent and active stimulation findings include increased motor capabilities in short-term and longitudinal post-testing. Moreover, adding a proportional load to the non-paretic arm while requiring bimanual movements produced less dysfunctional motor actions in the impaired arm/hand. In a systematic review and meta-analysis on bimanual movement coordination (i.e., interlimb coordination) protocols post-stroke indicated that the chronic stroke groups improved performance while executing both synchronous and asynchronous bimanual movements [54]. Further, Whitall and colleagues found asynchronous support when they strapped the paretic and non-paretic arms to cars attached to a trackway and required participants to perform rhythmic alternating (asynchronous) bimanual movements [59].

3. Bimanual Kinematic and Kinetic Functions in Chronic Stroke

Motor impairments on one side of the upper body such as muscle weakness, spasticity, and loss of motor skills in the affected arm typically appear in patients with stroke [3]. Further, the increased asymmetrical motor functions between paretic and non-paretic arms interfere with bimanual movement control capabilities (e.g., bimanual performances and coordination) required for successful execution of activities of daily living [60,61]. For example, common post-stroke motor impairments include movement initiation and control on command as well as coordination problems during bimanual arm/hand reaching, moving objects, hand drawing, and finger tapping tasks [62–66]. According to motor control theory, movement kinetics are the primary components involved in activating motor actions [67–70]. As individuals post-stroke initiate or attempt to initiate arm movements, generating forces in the paretic arm are imperative. One way to facilitate this process or system is to require the non-paretic arm to initiate the same movement. Symmetrical motor performances are easier to execute than asymmetrical movements.

Kantak and colleagues suggested that estimating interlimb coordination is crucial for stroke motor rehabilitation because less cooperative upper limb movements post-stroke can increase motor reliance on the non-paretic arm compromising the efficiency of motor actions requiring both arms (e.g., opening the drawer with the non-paretic arm) [66]. Thus, investigating potential motor rehabilitation protocols for improving bimanual coordination functions is useful for facilitating progress toward motor recovery.

A recent meta-analysis study summarized specific patterns of bimanual movement and coordination deficits post-stroke [71]. Patients with stroke showed more interlimb kinematic and kinetic coordination impairments than age-matched healthy controls while executing asymmetrical movements with more difficult task goals such as asymmetric movement with independent goals and asymmetric parallel movements with a common goal for each hand [63,72]. These impairments were additionally observed in symmetric movement tasks when two hands targeted a common task goal. Bimanual movement tasks consisting of more challenging task constraints typically require more interactive behavioral communications between two arms with increased motor-related cortical activation across the primary motor area and supplementary motor areas [73,74]. Thus, unbalanced cortical activation and interhemispheric inhibition levels between hemispheres post-stroke may cause more impairments in bimanual movement and coordination with more difficult task goals [75]. Interestingly, meta-regression results indicated that deficits in bimanual coordination were significantly associated with increased time since stroke onset [71].
These findings indicate that despite relatively rapid recovery progress within six months post-stroke [76], bimanual movement control capabilities continue to be compromised in the chronic stage of motor recovery.

In addition to bimanual kinematic dysfunctions post-stroke, impairments in bimanual kinetic functions often appeared in patients with stroke. Kang and Cauraugh [77] conducted a comprehensive literature review that demonstrated potential deficits in bimanual force control capabilities in post-stroke individuals. While processing visual feedback displaying isometric forces produced by both hands and a targeted submaximal force level, stroke groups revealed less force accuracy (e.g., root mean squared error) and variability (e.g., coefficient of variation), indicating more erroneous and inconsistent force generation patterns during bimanual wrist extension and gripping force tasks [78–81]. Moreover, bimanual forces produced by participants post-stroke tended to be more regular (i.e., greater force regularity) as indicated by higher values of approximate entropy [79,82,83], and these patterns indicated decreased motor adaptability during force control tasks [84]. Asymmetrical muscular functions between the paretic and non-paretic hands as well as impaired sensorimotor processing may be responsible for lower submaximal bimanual force control performances from 5% to 50% of maximum voluntary contraction (MVC) [78,83].

Importantly, interlimb force coordination patterns were additionally impaired after stroke onset. Lodha and colleagues reported lower values of cross-correlation strength with increased time-lag as compared with age-matched controls during bimanual isometric wrist and fingers extension tasks [83]. These findings suggested that stroke may interfere with temporal coordination between paretic and non-paretic hands, and further non-paretic hands presumably modulated their forces to compensate for lacking forces generated by paretic hands during bimanual force control [81,85]. These deficits in interlimb coordination in individuals with stroke were additionally observed in dynamical force control tasks (e.g., force increment and decrement phases) [86]. Moreover, altered bimanual force coordination in patients with stroke were significantly associated with motor impairments as indicated by various clinical assessments (e.g., the Fugl–Meyer assessment and Pegboard assembly score) [81,82,86]. Proposed neurophysiological mechanisms underlying impairments abound for bimanual movements and bimanual coordination [39,40], including altered sensorimotor integration capabilities post-stroke such as online motor correction using simultaneous visual information [87]. Further, increased interhemispheric inhibition from the contralesional hemisphere typically suppresses cortical activation of the ipsilesional hemisphere, which may send biased efferent signals to the paretic and non-paretic arms, causing impaired interlimb coordination functions [73,88]. Indeed, changes in somatosensory feedback influenced by stroke appear to be a crucial reason in weakening interlimb coordination because prior studies showed more deficits in force coordination without a visual feedback condition for chronic stroke patients [79,89].

Beyond the altered bimanual motor control functions within a trial, recent studies explored changes in bimanual coordination strategies across multiple trials for post-stroke individuals. Sainburg and colleagues proposed the importance of bimanual motor synergies reflecting different cooperative behaviors between hands across multiple trials in stroke motor rehabilitation [43]. According to the uncontrolled manifold hypothesis [90–92], motor variability consists of two components: good and bad variability. During multiple trials of a bimanual force control task, the fundamental elements can include pairs of left and right mean forces within a trial. Good variability is the variance of fundamental elements projected on the uncontrolled manifold line that does not influence the stability of task performance (e.g., overall force accuracy across multiple trials). However, greater good variability indicates that the motor system produces more possible motor solutions (i.e., motor flexibility), whereas less good variability denotes that the motor system selects a more consistent motor solution (i.e., motor optimality). Bad variability is the variance of fundamental elements projected on the line orthogonal to the uncontrolled manifold line that does influence the stability of task performance. Increased bad variability impairs the stabilization of task performance across multiple trials. Taken together, given that the
index of bimanual motor synergies is the proportion of good variability relative to bad variability, increased values of bimanual motor synergies across bimanual force control trials indicate better bimanual coordination strategies across trials contributing to overall task stabilization. In fact, Kang and Cauraugh [38] examined bimanual motor synergies in chronic stroke patients during bimanual force control tasks. The stroke group revealed less bimanual motor synergies than age-matched controls at 50% of MVC, and chronic stroke patients increased bad variability levels from 5% to 50% of MVC. These findings indicated that an impaired motor system post-stroke may compromise motor functions at the execution level (i.e., within a trial) as well as planning level (i.e., between trials). Thus, future stroke motor interventions should examine the effects of interactive motor actions between the paretic and non-paretic arms.

4. Looking Forward

What is on the horizon for bimanual movement interventions and chronic stroke rehabilitation? Rehabilitation interventions should aim for maximum recovery of function through motor learning improvements on the hemiplegic side [22]. Applying non-invasive brain stimulation (NIBS) in addition to motor training may be an attractive treatment protocol for improving bimanual coordination function post-stroke. Pixa and Pollak [93] suggested potential effects of transcranial direct current stimulation (tDCS), one of the NIBS protocols, on bimanual motor skills in healthy individuals. Two tDCS stimulations consist of anodal tDCS that may potentially increase cortical excitability and cathodal tDCS that may potentially suppress cortical excitability. Specific tDCS protocols for facilitating bimanual motor function improvements involved (a) anodal tDCS on the primary motor cortex (M1) of the ipsilesional hemisphere and cathodal tDCS on M1 of the contralesional hemisphere and (b) anodal tDCS on M1 of bimanual hemispheres [94–96]. Theoretically, these tDCS protocols are expected to be effective for re-balancing brain activations between affected and unaffected hemispheres, contributing to functional improvements in bimanual actions (e.g., bimanual typing performance and Perdue pegboard test). In testing chronic stroke patients, many prior studies reported transient and sustained treatment effects of tDCS protocols on unilateral paretic arm functions [22,97,98], whereas potential tDCS effects on bimanual motor functions are still insufficient. A limited number of studies revealed that bihemispheric tDCS in addition to conventional physical therapy improved interlimb coordinative skills in patients with stroke [99,100].

Beyond the interhemispheric competition model emphasizing the balanced excitatory and inhibitory activations between hemispheres post-stroke via tDCS [20,101], a recent approach proposed the bimodal balance-recovery model integrating both vicariation and interhemispheric competition approaches [75]. Intriguingly, this model posited that the vicariation model, assuming the important role of the unaffected hemisphere for functional recovery of the paretic limbs, may be beneficial for stroke patients with lower structure reserve (e.g., more severe and wide ranges of brain lesion), whereas the interhemispheric competition model may be effective for stroke patients with higher structure reserve (e.g., more recovered brain regions). Based on this model, applying cathodal tDCS suppressing the contralesional hemisphere may decrease treatment effects on motor recovery of patients with severe brain damages and less recovered brain functions (e.g., acute and subacute phases). In fact, several meta-analytic findings evidenced that tDCS protocols including cathodal tDCS on the contralesional hemisphere revealed overall significant positive effects on motor recovery, whereas this protocol failed to show functional improvements in the paretic arms of the acute and subacute patients with stroke [102,103]. These findings support a proposition that bihemispheric tDCS protocols should be individualized based on either the severity or the recovery state of affected brain regions. For example, applying anodal tDCS on the primary motor cortex of bimanual hemispheres may be more effective for improving bimanual motor functions in patients with acute and subacute patients [104].

One caveat about tDCS protocols concerns the general brain assumptions necessary to ensure individual treatment benefits. That is, tDCS stimulation effects that are dose-
controlled according to electrode size, location placement, and stimulus intensity will minimize the trial-and-error effect frequently seen with so many stroke-rehabilitation protocols [105]. Establishing accepted procedures in administering tDCS should lead to individualized dose-controlled treatments [98]. Further, standardizing tDCS protocols for chronic stroke intervention must include when and duration of the anodal and cathodal stimulation combinations [106]. Questions on the optimal stimulation time are still being debated. Should chronic stroke individuals receive 20–30 min of tDCS before performing bimanual movement training or should 20–30 min of stimulation occur simultaneously with bimanual movements?

Moreover, developing isometric rehabilitation programs may be a viable option for facilitating functional recovery of the paretic arm. Given that isometric contraction requires no dynamic movements, patients with stroke can safely participate in the isometric training regardless of their muscle weakness and spasticity in the paretic arms as prior findings suggested [107–109]. Moreover, Kang and colleagues raised a possibility that bimanual actions transiently increased motor functions in the paretic arms by demonstrating greater maximal and submaximal mean forces and less force variability and regularity produced by the paretic arm during bimanual force control tasks than those during unimanual force control tasks [110,111]. These findings indicated that applying bimanual isometric training protocols can be an additional effective approach to improvements in acquiring coordinative motor skills post-stroke.

To facilitate motor recovery progress post-stroke, pharmacological therapies can be viable alternatives [13,112]. For example, a meta-analysis study reported that the serotonin reuptake inhibitor (SSRI) fluoxetine improved motor recovery in acute and subacute patients (less than 3 months since stroke) [113]. Potentially, the SSRI fluoxetine may be beneficial for motor improvements via the facilitation of neurogenesis and anti-inflammatory neuroprotection and enhancing cerebral blood flow according to the findings from animal models [114]. Importantly, the appropriate timing of these pharmacological treatments would be within first three months since the stroke because this period presumably increases a possibility of interactive effects between pharmacological treatments and spontaneous recovery maximizing motor rehabilitation. Despite controversial treatment effects on stroke patients with increased time since the stroke (e.g., >6 months), pharmacological interventions would be an additional option for improving bimanual motor functions in chronic patients.

5. Summary

The current evidence on experience-dependent neural changes is becoming integrated in rehabilitation protocols focused on individuals in the chronic stroke stage of recovery (Figure 1). Indeed, accumulated findings on bimanual movements training indicate an effective and efficient intervention to address post-stroke motor dysfunctions. Practicing bimanual coordination movements improves the motor capabilities on the impaired side of the upper extremity. Specifically, four sets of evidence form a converging operations conclusion that bimanual coordination movement training treatments are positive: (a) a primer for a typical treatment protocol, which includes activating the muscles involved in the treatment before beginning the stroke protocol; (b) in conjunction with neuromuscular-triggered electrical stimulation; (c) while executing rhythmic alternating movements; and (d) robotic guided rehabilitation [20,53,115–117].

Concerning the neural networks and brain areas involved in changing the severity of motor dysfunctions, science has made important advances in understanding the interactions among brain areas [118–121]. However, exact details on the distributed neural networks connecting the cortical and subcortical brain areas active during voluntary motor actions are still being explored. Consistent with Baddeley’s elegant discussion of the concept of working memory evolving with the addition of new empirical findings, neural plasticity and distributed networks interacting with various brain mechanisms are still evolving [122,123].
Figure 1. Progress toward stroke motor recovery using bimanual motor training.

Together, the current empirical bimanual movement training findings present a persuasive alternative to unilateral rehabilitation post-stroke. The time has come to select bimanual coordination as a sound theoretical basis for making progress toward motor recovery post-stroke and abandon one arm protocols. Logical and convincing arguments on motor actions involved in planning and executing challenging bimanual movements, perhaps with an assistive device (e.g., neuromuscular electrical stimulation or robotic manipulandum) included in the intervention, will advance our understanding of effective and efficient interventions. Based on the accumulated evidence [54,77,86,124,125], chronic post-stroke individuals who are prescribed experience-dependent treatments that include bimanual coordinated movements will display fewer impaired motor actions.

Granted, comprehensive post-stroke rehabilitation protocols with the explicit intention of making progress toward motor recovery should closely follow the guidelines recommended by the American Heart Association [32] as well as England’s Queen Square Upper Limb Neurorehabilitation Program [126]. As Cauraugh and Summers stated in 2005, the efficacy and effectiveness of post-stroke bimanual movement interventions will advance rapidly when groups of individuals are matched according to lesion location, lesion size, and impairment severity [50]. Individualized post-stroke rehabilitation prescriptions are steps in the right direction.

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