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Review

# Force control in chronic stroke

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ABSTRACT

Force control deficits are common dysfunctions after a stroke. This review concentrates on various force control variables associated with motor impairments and suggests new approaches to quantifying force control production and modulation. Moreover, related neurophysiological mechanisms were addressed to determine variables that affect force control capabilities. Typically, post stroke force control impairments include: (a) decreased force magnitude and asymmetrical forces between hands, (b) higher task error, (c) greater force variability, (d) increased force regularity, and (e) greater time-lag between muscular forces. Recent advances in force control analyses post stroke indicated less bimanual motor synergies and impaired low-force frequency structure. Brain imaging studies demonstrate possible neurophysiological mechanisms underlying force control impairments: (a) decreased activation in motor areas of the ipsilesional hemisphere, (b) increased activation in secondary motor areas between hemispheres, (c) cerebellum involvement absence, and (d) relatively greater interhemispheric inhibition from the contralesional hemisphere. Consistent with identifying neurophysiological mechanisms, analyzing bimanual motor synergies as well as low-force frequency structure will advance our understanding of post stroke force control.



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## 1. Introduction

Motor dysfunctions in the upper extremities are common disabilities post stroke. Specifically, paresis or weakness on one side of the body appears as a motor impairment because neurological deficits interfered with the brain's blood flow (Hallett, 2002, 2007). Given that hemiparesis is a disability in arm functions that affects both unimanual as well as bimanual movements (Carson, 2005; Cauraugh and Summers, 2005), functional recovery in both unimanual and bimanual motor control is a primary goal of stroke rehabilitation protocols.

Stroke rehabilitation investigators have examined motor control abilities during various upper extremity movement tasks. Studies revealed deficits in movement control (e.g., kinematic variables) such as trajectory, velocity, and acceleration during reaching movements (Mani et al., 2013; Schaefer et al., 2009). Force control is defined as a capability to generate accurate and steady force output that matches a target goal including timing of muscular force production (Corcos et al., 1992; Elliott et al., 2010; Naik et al., 2011; Patten, 2000). In addition, successful bimanual force control involves well-coordinated individual forces from each limb and relatively symmetrical force production between limbs (Hu and Newell, 2011). Conventional perspectives on the relationship between force and dynamic movement control such as the impulse-timing and optimized submovement models indicate that fast movements cause higher variability in primary movement endpoints than slow movements because greater forces are necessary to produce rapid movements (Meyer et al., 1988; Schmidt and Lee, 2011; Schmidt et al., 1979). While producing greater forces required for more challenging tasks with longer reaching distance and higher movement speed, controlling magnitude and timing of force production is most important for successful performances. Based on the multiple-process model of limb control (Elliott et al., 2010), the magnitude and timing of muscular forces contributing to accelerating and decelerating limbs are specified before movement initiation. After practice, planned forces appear to reduce endpoint variability (Elliott et al., 2010; Khan et al., 1998). Consequently, a failure to plan and control force outputs (i.e., kinetic variables) before and during dynamic movement may cause abnormal movement patterns (e.g., higher movement variability or task error) (Cruz et al., 2005).

Concerning force control stroke studies, movement control deficits have been attributed to impaired force control capability. That is, deficits in isometric force control capabilities characterized as less mean force production were associated with movement control impairments such as reduced range of motion, involuntary movements, greater movement variability, or more stereotyped movement as indicated by less approximate entropy (ApEn) values (Cruz et al., 2005; Miller and Dewald, 2012; Mukherjee et al., 2013). These findings indicate that investigating kinetic performance changes over time provides a window to study force production and modulation strategies required for generating successful movements (Lodha et al., 2010). As Murgia and colleagues noted, force control impairments, viewed as deficits in dexterously manipulating objects, may compromise activities of daily living such as buttoning a shirt or blouse, holding a cup, or pouring water into a pitcher (Murgia et al., 2004). Importantly, force control capabilities post stroke were significantly associated with findings from conventional clinical assessments such as the upper extremity Fugl-Meyer Assessment (FMA) (DeJong and Lang, 2012; Hermsdorfer et al., 2003; Lindberg et al., 2012; Lodha et al., 2012a, 2010; Naik et al., 2011). Consequently, force control capabilities are frequently used to determine the magnitude of motor impairments post stroke as well as an indication of progress toward motor recovery after rehabilitation.

Earlier force control studies reported that stroke survivors revealed more deficits in force control than age-matched control groups (Lodha et al., 2010; Naik et al., 2011). Specifically, force control capabilities were estimated using linear (e.g., root mean square error, standard deviation, or coefficient of variation) and nonlinear (e.g., approximate entropy) analyses as well as timing of muscular forces. Moreover, the force production magnitude and variability between the paretic and non-paretic hands were more asymmetrical in comparison to control groups (Kang and Cauraugh, 2014a; Lindberg et al., 2012; Lodha et al., 2012a). These asymmetrical force control capabilities between hands may be attributed to an unbalanced level of excitatory and inhibitory activation between hemispheres post stroke (Nowak et al., 2009; Stinear et al., 2014). Recently, stroke researchers discovered an unusual low-frequency pattern (e.g., below 1 Hz) in force production (Lodha et al., 2013). These findings indicate that force control capabilities can effectively reflect abnormal motor functions post stroke, and investigating new force control variables may demonstrate fine motor control changes not detected by conventional measurements in motor control. Synthesizing evidence on force control deficits allows stroke researchers to better understand the characteristics of behavioral impairments post stroke. Consequently, our purpose was to (a) summarize variables that influence force control capabilities post stroke and (b) identify new robust analyses on functional recovery involving the upper extremities. Further, this review includes studies that investigated brain activation patterns post stroke to elaborate on the neurophysiological mechanisms involved in force control.

## 2. Force control impairments in the upper extremities

### 2.1. Conventional force control approaches

#### 2.1.1. Force production and asymmetry between hands

When producing maximal and submaximal force outputs by unimanual paretic arms, chronic stroke individuals have more difficulty than with their non-paretic arms. Specifically, paretic arms usually produce less unimanual maximal force than non-paretic arms (Lindberg et al., 2012; Ye et al., 2014). Further, maximal force produced by paretic arms was less than each arm in age-matched controls (Kim et al., 2014; Li et al., 2003; Lindberg et al., 2012; Ye et al., 2014). During two tasks, gripping and wrist and fingers extension, maximal combined bimanual forces produced by two arms decreased in comparison to age-matched control groups implicating an impaired maximal force production capability in the paretic arms (Lodha et al., 2012a; Naik et al., 2011). Indeed, greater maximal force production in the paretic arms was associated with improved motor function estimated by three clinical assessment measures: (a) Frenchay Arm Test, (b) FMA, and (c) Box and Block Test (Boissy et al., 1999; Lindberg et al., 2012).

During bimanual force production at submaximal force levels (e.g., 5%, 25%, and 50% of maximum voluntary contraction: MVC), stroke groups revealed more asymmetrical force production than



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