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External biomechanical constraints impair maximal voluntary grip force stability post-stroke

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A R T I C L E I N F O

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A B S T R A C T

Background: Grip strength is frequently measured as a global indicator of motor function. In clinical populations, such as hemiparesis post-stroke, grip strength is associated with upper-extremity motor impairment, function, and ability to execute activities of daily living. However, biomechanical configuration of the distal arm and hand may influence the magnitude and stability of maximal voluntary grip force and varies across studies. The influence of distal arm/hand biomechanical configuration on grip force remains unclear. Here we investigated how biomechanical configuration of the distal arm/hand influence the magnitude and trial-to-trial variability of maximal grip force performed in similar positions with variations in external constraint.

Methods: We studied three groups of 20 individuals: healthy young, healthy older, and individuals post-stroke. We tested maximal voluntary grip force in 4 conditions: 1: self-determined/"free"; 2: standard; 3: fixed arm-rest; 4: gripper fixed to arm-rest, using an instrumented grip dynamometer in both dominant/non-dominant and non-paretic/paretic hands.

Findings: Regardless of hand or group, maximal voluntary grip force was highest when the distal limb was most constrained (i.e., Condition 4), followed by the least constrained (i.e., Condition 1) (Cohen's $f = 0.52$, *P*'s < 0.001). Coefficient of variation among three trials was greater in the paretic hand compared with healthy individuals, particularly in more (Conditions 3 and 4) compared to less (Conditions 1 and 2) constrained conditions (Cohen's $f = 0.29$, *P*'s < 0.05).

Interpretation: These findings have important implications for design of rehabilitation interventions and devices. Particularly in individuals post-stroke, external biomechanical constraints increase maximal voluntary grip force variability while fewer biomechanical constraints yield more stable performance.

1. Introduction

Grip force is a robust measure of normal human motor function (Nasreddine et al., 2005), only in part because the ability to generate adequate grip force is critical to performance of activities of daily living (ADL) (de Freitas and Lima, 2013). Due to its ubiquity, grip strength is a common clinical measurement, often used as a proxy for health status across the lifespan (Nasreddine et al., 2005; Shechtman, 2000). Even post-stroke, grip strength is strongly associated with overall upper extremity (UE) function (Boissy et al., 1999), independence in ADL (Bae et al., 2015), and has been suggested as a global representation of UE weakness (Ekstrand et al., 2016).

Production of maximal voluntary grip force (MVGF) is influenced by both neural and biomechanical factors. Due to stroke-related disruption of the corticospinal tract and indirect descending motor pathways, paretic hand MVGF tends to be reduced and less stable (Kang and Cauraugh, 2015). Stability of MVGF can be measured by motor output variability, including both variability within-a-trial and trial-to-trial variability (Christou and Tracy, 2006). Within-a-trial force variability has been widely studied during sustained submaximal power grip post-stroke, leading to the current assertion that paretic hand grip force is less stable than in healthy adults (Chang et al., 2013; Lindberg et al., 2012; Lodha et al., 2010). Related to within-a-trial variability, trial-to-trial variability is also an important component of motor output variability reflecting the ability to produce consistent, reproducible motor activity (Christou and Tracy, 2006; Shechtman, 2000). In older adults increased trial-to-trial variability of peak force is observed more frequently than within-a-trial variability (Christou and Tracy, 2006)

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suggesting it affords greater sensitivity for detecting age-related motor control deficits than within-a-trial variability. Observation of such differences with aging provides rationale for investigating trial-to-trial variability of maximal power grip to detect and understand motor control deficits post-stroke. Trial-to-trial variability of maximal power grip has not been systematically investigated in the post-stroke population.

Overall arm posture and biomechanical configuration of the distal arm/hand are two factors that influence MVGF production. Previous studies suggest that both proximal (Dominici et al., 2005; Ginanneschi et al., 2005, 2006; Su et al., 1994) and distal (Komi, 1974; Odriscoll et al., 1992) arm position can influence MVGF magnitude. To eliminate these biomechanical influences and enable generalizability of results across studies (Roberts et al., 2011), the American Society of Hand Therapists (ASHT) has recommended a 'standard position' (i.e., shoulder adducted and neutrally rotated, elbow flexed at 90°, forearm neutral, wrist held between 0°–30° dorsiflexion and 0°–15° ulnar deviation) for measurement of MVGF (Fess, 1992).

Different from relatively consistent arm posture, biomechanical configuration of the distal arm during MVGF measurement varies markedly (Brogardh et al., 2015; Choi et al., 2010; Ekstrand et al., 2015; Hamilton et al., 1992; Lariviere et al., 2010; Martins et al., 2015a, 2015b; Massy-Westropp et al., 2011; Mathiowetz et al., 1985; Motawar et al., 2016; Paclet et al., 2014; Persson et al., 2015; Shechtman et al., 2005; Ye et al., 2014). In most studies of healthy adults, participants are instructed to attain the standard arm position and maintain it voluntarily without external biomechanical constraints (Hamilton et al., 1992; Mathiowetz et al., 1985; Shechtman et al., 2005). Notably, many individuals post-stroke have difficulty coordinating the simultaneous tasks of maintaining the standard position, stabilizing the grip dynamometer, and producing MVGF. In addition, due to abnormal flexor synergy patterns (Brunnstrom, 1970; Dewald et al., 1995), individuals post-stroke are likely to produce off-axis movements with the arm and hand during grip (Brunnstrom, 1970; Chae et al., 2002). As a result, some investigators have used external biomechanical constraints to maintain the paretic limb position with the goal of preventing these off-axis movements (Ekstrand et al., 2015; Lodha et al., 2012, 2013; Martins et al., 2015a, 2015b; Persson et al., 2015; Ye et al., 2014). These external constraints take various forms, for example, manual arm stabilization by an experimenter during grip (Martins et al., 2015a, 2015b), placing or strapping the arm on a table or armrest (Ekstrand et al., 2015; Persson et al., 2015; Ye et al., 2014), or fixing the grip dynamometer to the table or apparatus (Lodha et al., 2012, 2013).

How biomechanical configurations of distal arm influence magnitude or between-trial stability of MVGF has not been investigated in healthy individuals or individuals post-stroke. External constraint of the distal arm reduces the degrees of freedom (DoF) (Bernstein, 1967; Bober et al., 1982; Fischer et al., 2009; Kornecki et al., 2001; Seo and Armstrong, 2009), which has been associated with reduced activity in wrist stabilizing muscles (Fischer et al., 2009; Kornecki et al., 2001) and increased activity in primary movers (Kornecki et al., 2001), thus potentially contributing to increased MVGF magnitude. While it is recognized that trial-to-trial variability can be influenced by the presence of neuromuscular impairment and motor task (i.e., task difficulty, the number of joints involved, etc.) (Lechner et al., 1998; Simonsen, 1995; Tornvall, 1963), it remains unclear whether trial-to-trial variability can be influenced by biomechanical configurations of distal arm.

Beyond straightforward variations in MVGF magnitude and between-trial stability, differences in biomechanical configuration alter the motor task (e.g., external constraints requiring the person to adjust to the task vs. unconstrained movements allowing the task to be adjusted to the person). As popular rehabilitation devices, end-effector based robots provide external constraints to the arm, ostensibly to promote focus on training hand function (Dovat et al., 2008; Masia et al., 2007; Oblak et al., 2010). In contrast, exoskeleton robots do not constrain natural joint movements to fixed positions (Balasubramanian et al., 2010). It remains unclear how the contrasting biomechanical configurations of these designs influence neural control of movements performed as part of rehabilitation and which might lead to greater rehabilitation efficacy. Therefore, understanding the influence of biomechanical configurations on motor performance, particularly in the post-stroke population, would inform the design of rehabilitation interventions and devices.

Here we investigated the magnitude and stability of MVGF across four biomechanical configurations with different levels of external constraint in healthy young and older adults, and individuals post-stroke. We hypothesized: (1) MVGF magnitude varies as a function of biomechanical constraint with higher MVGF observed in more constrained conditions; (2) paretic hand MVGF stability is reduced independent of condition; and (3) biomechanical configuration does not influence MVGF stability.

2. Methods

2.1. Subjects

Twenty individuals in the chronic phase post-stroke, twenty young, and twenty older healthy adults participated. Individuals post-stroke meeting the following criteria were included: clinical presentation of a single, mono-hemispheric stroke with resulting hemiparesis of at least 6 months duration able to perform power-grip in the 'standard position' (Fess, 1992), unaccompanied by significant UE joint pain, severe osteoarthritis or prior pathological fracture, or significant cardiovascular impairments contraindicative to exertion. Inclusion criteria for healthy adults were absence of: disease, injury, or prior surgery that could affect UE strength, or presence of UE pain. Demographic characteristics are reported in Table 1.

Each subject provided written, informed consent prior to enrollment and participation. Approval for all procedures was attained from University of Florida Health Science Center Institutional Review Board (IRB-01) and carried out in conformity with the standards set by the Declaration of Helsinki.

2.2. Instrumentation

MVGF was assessed during isometric power grip using a custom grip dynamometer instrumented with a capacitive load cell (iLoad Mini MFD-200 & DQ-1000A, Loadstar Sensors, Fremont, California). Transducer calibration using weights of known mass was linear under both loading and unloading conditions. The grip dynamometer could be adjusted to three positions (i.e., apertures) consistent with standard dimensions of commercially available grip dynamometers; all participants were tested in Position 2 (i.e., aperture length 4.76 cm (Mathiowetz et al., 1985; Trampisch et al., 2012)). Analog signals were sampled (2000 Hz) and processed online (100 ms moving-window median) using Signal (Version 6.0, Cambridge Electronic Designs, Cambridge, UK). Real-time feedback was provided by displaying the processed force signal on a television screen (Samsung, TruSurround HD, Dolby Digital, 48 in.). The maximal value of each filtered force trace was identified in software and recorded as MVGF for statistical analysis.

2.3. Experimental protocol

2.3.1. Clinical assessments

The Edinburgh Handedness Inventory (Oldfield, 1971) was used to determine laterality and the Montreal Cognitive Assessment (MoCA) to characterize cognitive function in all participants (Rossetti et al., 2011). Motor impairment was assessed in individuals post-stroke using the upper-extremity component of the Fugl-Meyer Motor Function Assessment (UE FMA) (Fugl-Meyer et al., 1975) and the Modified Ashworth Scale (Bohannon and Smith, 1987).