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VARIABILITY, FREQUENCY COMPOSITION, AND COMPLEXITY OF SUBMAXIMAL ISOMETRIC KNEE EXTENSION FORCE FROM SUBACUTE TO CHRONIC STROKE

J. W. CHOW * AND D. S. STOKIC

Center for Neuroscience and Neurological Recovery, Methodist Rehabilitation Center, Jackson, MS, USA

Abstract—We examined changes in the variability, frequency composition, and complexity of force signal from subacute to chronic stage of stroke during maintenance of isometric knee extension and compared these parameters between chronic stroke and healthy subjects. The sample included 15 healthy (65 ± 8 years) and 23 chronic stroke subjects (65 ± 14 years, 6–112 months post-stroke) of whom 10 (64 ± 15 years) were also examined 11–22 days post-stroke (subacute stage). The subjects performed isometric knee extension at 10%, 20%, 30%, and 50% of peak torque for 10 s (two trials each). Coefficient of variation (CV) was used as a measure of force variability. The median frequency and relative power in the 0–3, 4–6, and 8–12 Hz bands were obtained through a power spectrum analysis of the force signal. The signal complexity was quantified using the sample entropy (SampEn). The longitudinal analysis revealed a significant decrease in CV from subacute to chronic stage across all contraction levels ($P < 0.001$) but no significant changes in the frequency and entropy parameters. Comparison between the chronic stroke and control subjects revealed no significant difference in CV across the force levels ($P > 0.05$) but significantly decreased median frequency ($P < 0.01$), with the relative power increased in 0–3 Hz band and decreased in 4–6 and 8–12 Hz bands in both paretic and non-paretic legs ($P < 0.001$). SampEn was also significantly decreased in chronic stroke, bilaterally ($P < 0.001$). These results indicate a shift toward lower frequencies and a less complex physiological process underlying force control in chronic stroke. The overall results suggest the improvement in force variability from subacute to chronic stroke but without normalization in the frequency composition and complexity of the force signal. Thus, disordered structure of the force signal remains a marker of impaired motor control long after stroke occurrence despite apparent recovery in force variability.

Key words: force steadiness, spectral analysis, sample entropy, knee extensors, hemiparesis.

*Corresponding author. Address: Methodist Rehabilitation Center, 1350 East Woodrow Wilson Drive, Jackson, MS 39216, USA. Tel: +1-601-364-3402; fax: +1-601-364-3305.
E-mail address: jchow@mmrcrehab.org (J. W. Chow).
Abbreviations: ANOVA, analysis of variance; CV, coefficient of variation; FFT, Fast Fourier Transform; FM, Fugl-Meyer scale; MVC, maximum voluntary contraction; RMI, Rivermead Mobility Index; SampEn, Sample entropy; SD, standard deviation.

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INTRODUCTION

The ability to produce a steady force is impaired in stroke patients. Lodha et al. (2010) reported a significantly greater force variability (coefficient of variation (CV)) in the paretic wrist/finger extensors for nine stroke subjects (4 months to 12 years post-onset) compared to nine controls at 5%, 25%, and 50% of the maximum voluntary contraction (MVC). The greatest difference between stroke and control subjects was found for bilateral tasks at 5% and 50% of MVC (Lodha et al., 2012). Chow and Stokic (2011) examined 33 subjects within a month of stroke on the isometric knee extension task at 10%, 20%, 30%, and 50% of MVC and reported significantly increased CV in both paretic and non-paretic legs of stroke subjects compared to controls across all force levels.

In addition to simple measures of force variability (CV), nonlinear analytic approaches allow examination of the structure of force signal and provide an insight into underlying physiological processes (Schiffman et al., 2006). The structure of a time series includes both time (complexity analysis) and frequency (power spectrum analysis) domains. Approximate entropy, a measure of complexity structure of the force signal, was significantly decreased in stroke subjects during a constant wrist/finger extension task, particularly at higher force levels (Lodha et al., 2010). These investigators ascribed the less complex force signal to the lack of motor adaptability associated with relatively fixed or stereotypic patterns in motor coordination and abnormal movement synergies in chronic stroke.

Chow and Stokic (2013) performed a power spectrum analysis on force signals during a constant knee extension task in subacute stroke and reported a shift from 4–12 Hz to 0–3 Hz. A shift toward lower frequencies within the 0–1 Hz band has also been reported in chronic stroke in an isometric grip task (Lodha et al., 2013). The predominance of lower frequencies in the power spectrum and decreased entropy during constant-force tasks have been found in Down syndrome (Heffernan et al., 2009) and Parkinson's disease (Vaillancourt et al., 2001), suggesting disordered structure of the force signal across different neurological disorders. In healthy subjects, 0–3 Hz band during a constant-force task has been associated with visuomotor processing (Freund and Hefter, 1993; Slifkin et al., 2000; Vaillancourt et al., 2001), 4–6 Hz band with long-latency stretch reflexes (Marsden, 1978; McAuley and Marsden, 2000), and 8–12 Hz band with short-latency stretch reflexes (Marsden, 1978; McAuley and Marsden, 2000).

Our previous findings (Chow and Stokic, 2013) raise a question whether the increased force variability and altered force frequency characteristics observed in the subacute stage of stroke carry over into the chronic stage. Also it is unknown whether decreased complexity of the force signal in chronic stroke reported for the wrist/finger extensors (Lodha et al., 2010) also applies to the knee extensors. Therefore, the first aim of this study was to examine changes in the variability, frequency composition, and complexity of the force signal from the subacute (within the first month of stroke) to the chronic stage of stroke (at least 6 months post-stroke) during an isometric knee extension task. We hypothesized some degree of normalization of CV, frequency composition, and complexity of the force signal over time (hypothesis 1). Because the force structure of an isometric knee extension has not been previously investigated in chronic stroke, our second aim was to compare variability, frequency composition, and complexity of the force signal between persons with chronic stroke and healthy controls. Based on the previous findings (Lodha et al., 2010, 2013; Chow and Stokic, 2013), we hypothesized that chronic stroke subjects would show an increase in force variability, a shift toward lower frequencies in the power spectrum, and a decrease in complexity of the force signal in both the paretic and non-paretic legs compared to controls (hypothesis 2). Since the associations between force parameters and clinical measures of motor recovery were not directly related to the tested hypotheses, these correlations were explored in secondary analyses.

EXPERIMENTAL PROCEDURES

Subjects

Twenty-three community-dwelling persons with chronic stroke were included in this study (Table 1). The inclusion criteria were at least 6 months post-stroke, single unilateral stroke or multiple strokes on the same side, unimpaired vision (able to see a line on a monitor), able to extend both knees against gravity in the seated position, and able to follow simple instructions. Those with clinical evidence of visual (hemianopia) or perceptual (neglect) deficits, heart diseases, uncontrolled hypertension, normal pressure hydrocephalus, knee pain, or artificial knee replacement were excluded. The control group included 15 subjects (age 65 ± 8 years, height 177 ± 11 cm, body mass 82 ± 14 kg, 11 men) with normal or corrected-to-normal vision and no reported orthopedic or neurological disorders at the time of testing. The age difference between the two groups was not significant (unpaired *t*-test, $P = 0.63$). All subjects signed the informed consent approved by the institutional review board. Prior to force tasks, stroke subjects were assessed by the same physical therapist on the lower extremity motor section of the Fugl-Meyer (FM) scale (range 0–34, Fugl-Meyer et al., 1975), modified Ashworth scale (range 1–5, Bohannon and Smith, 1987), and Rivermead Mobility Index (RMI) (maximum 15, Collen et al., 1991; Hsieh et al., 2000) (not collected in two subjects because the therapist was not available).

Ten stroke subjects were tested twice – within the first month of stroke just prior to discharge from in-patient rehabilitation and then at 6–8 months post-stroke (Table 1). They received outpatient physical and occupational therapy for up to 3 months after the in-patient discharge.

Experimental setup and protocol

With the subject in a seated position, knee extension torques were collected using a Biodex System 3 isokinetic dynamometer (Biodex Medical Systems, Inc., New York, NY, USA) and a custom-built amplifier connected directly to the torque sensor of the dynamometer (overall sensitivity 57.5 mV/Nm). Torque signals from the dynamometer were fed to a 17-in. LCD monitor that was mounted on a swing arm and an EvaRT data acquisition system (Motion Analysis Corp., Santa Rosa, CA, USA, sample rate 1200 Hz, 12-bit analog-to-digital resolution). Before practice trials, the monitor was positioned according to individual preferences, usually 40–50 cm directly in front of the head.

Both legs of stroke patients were tested in a random order and only the self-reported dominant (preferred ball kicking) leg in controls. The warm-up included five repetitions of maximum isokinetic knee extension-flexion at 210°/s and 60°/s. The subject then performed three to four trials of maximum isometric knee extension (90° angle, 3–4 s each, 1-min pause). The largest force (proportional to the largest torque because of the constant moment arm) was used as the MVC.

After several practice trials, the subject was asked to extend the knee, match the displayed torque signal (a horizontal line) with a designated target force marked on the monitor (10%, 20%, 30%, or 50% of MVC), and maintain the force for 10 s, as accurately and steadily as possible. The four force levels were presented in a random order and two trials per level were completed with a 30–60-s rest in between.

Data analyses

MVC torques were smoothed using a sliding average of 600 data points (0.5-s window). Torques during constant-force trials were filtered using a second-order Butterworth low-pass filter with 30-Hz cutoff. The CV, calculated as the ratio between standard deviation (SD) and mean torque (CV = SD/mean × 100%), was used to quantify force variability (steadiness). Only the middle 8 s of each 10-s trial were analyzed to exclude the ramp up and down portions of the force signal. Out of two trials collected at each force level, the one with a lower CV was used for statistical analysis. The ratio of paretic