SHORT REPORT

ABSTRACT: We examined the influence of varying stimulation frequency on muscle output during isometric and dynamic contractions. Our findings demonstrate that the predictability of the force– and excursion–frequency relationships is extremely strong across stimulation intensities. There were no differences in the frequency which elicited 50% of peak or peak muscle output. We conclude that the impact of varying stimulation frequency is consistent between isometric and dynamic contractions.

Muscle Nerve **38:** 1627–1629, 2008

COMPARING THE FORCE– AND EXCURSION–FREQUENCY RELATIONSHIPS IN HUMAN SKELETAL MUSCLE

CHRIS M. GREGORY, PhD, PT,[1,2] C. SCOTT BICKEL, PhD, PT,[3] NITIN SHARMA, BS,[4] and WARREN E. DIXON, PhD[4]

[1] Brain Rehabilitation Research Center, Malcom Randall VAMC, Gainesville, Florida, USA
[2] Department of Physical Therapy, P.O. Box 100154, University of Florida, Gainesville, Florida 32610, USA
[3] Department of Physical Therapy, University of Alabama at Birmingham, Birmingham, Alabama, USA
[4] Department of Mechanical and Aerospace Engineering, University of Florida, Gainesville, Florida, USA

Accepted 8 August 2008

Functional electrical stimulation (FES) of skeletal muscle is intended to facilitate purposeful movements in persons following various injuries or disease states. Previous studies have described several characteristic relationships within skeletal muscle in response to electrical stimuli. Most notably, there is a highly predictable relationship between stimulation frequency and muscle output (i.e., force–frequency relationship).[2,6] Although this relationship is quite strong between subjects, the use of isometric contractions as the primary model in examining this relationship potentially limits its applicability to FES. Given that facilitating purposeful movements is fundamental to the design of efficacious FES protocols, an understanding of how joint motion impacts responses to electrical stimulation is critical. The purpose of this study was to compare the force– and excursion–frequency relationships in the m. quadriceps femoris to determine whether eliciting limb motion alters the relationship between muscle output and stimulation frequency. We hypothesized that this relationship would differ between conditions, with differences attributable to various contractile and mechanical properties of skeletal muscle that likely alter limb dynamics.

METHODS

Ten subjects (29.9 ± 6.7 years, 174.2 ± 7.4 cm, 72.7 ± 11.6 kg; 8 men, 2 women) participated in two data collection sessions separated by a minimum of 72 hours. Criteria for participation included: (1) 18–50 years of age; (2) recreationally active; (3) no history of orthopedic or neurological injury that might affect lower extremity muscle function; and (4) no known contraindications to electrical stimulation. Prior to participation, written informed consent was obtained from all subjects as approved by the institutional review board at the University of Florida.

The m. quadriceps femoris muscle group in the dominant limb of each subject was tested using a Biodex isokinetic dynamometer (isometric) or a commercially available plate-loaded leg-extension machine (dynamic). All measures were obtained with subjects seated with hips and knees flexed 90°, the axis of rotation aligned with the knee joint and the leg secured to the lever arm. Prior to isometric

Abbreviations: FES, functional electrical stimulation; MVIC, maximum voluntary isometric contraction
Key words: electrical stimulation; force; muscle
Correspondence to: C.M. Gregory; e-mail: drewgreg@phhp.ufl.edu

Published online 24 November 2008 in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/mus.21161

data collection, a value for maximum voluntary isometric contraction (MVIC) was determined as previously described.[3]

Electrical Stimulation. Bipolar self-adhesive neuromuscular stimulation electrodes were placed over the distal–medial and proximal–lateral portion of the quadriceps femoris muscle group. Current voltage for each session was determined using a 1000-ms pulse train (100-Hz/700-μs pulse duration) that elicited 25% of MVIC during isometric contractions or a 50° excursion during dynamic actions. Prior to data collection, five additional trains (500-ms duration) were delivered at the aforementioned settings to verify that the quadriceps femoris muscle group was fully potentiated (i.e., no increase in torque or excursion in subsequent trains). Previous work has shown that the total number of pulses, independent of pulse frequency, is the determining factor in potentiation of this muscle group,[1] and our protocol delivered more than the minimum necessary to account for this phenomenon. Stimulation pulses were delivered via a computer-controlled stimulator (Model S8800; Grass Instruments), and data were digitized at 1000 Hz. Next, 500-ms pulse trains were delivered in random order using all possible combinations of frequencies (20, 30, 40, 50, 60, 70, and 100 Hz) and pulse durations (200, 300, 400, 500, 600, and 700 μs) at the predetermined voltage. Muscle output during isometric (torque, in foot-pounds) and dynamic (excursion, in degrees) contractions was used to determine the torque– and excursion–frequency relationships, respectively.

Data Analysis. Data were normalized to 100-Hz values and plotted over the range of frequencies. Curves were then collapsed across pulse widths and fit to a second-order polynomial curve. Paired-sample *t*-tests were used to test for differences across frequencies as well as between conditions (i.e., isometric vs. dynamic). Level of significance was set at $\alpha = 0.05$.

RESULTS

The relationship between muscle output and stimulation frequency across stimulation intensities was extremely strong, as indicated by the force–frequency ($y = -0.0001x^2 + 0.0215x + 0.1913$; $R^2 = 0.9426$) and excursion–frequency ($y = -0.0046x^2 + 0.8066x + 12.561$; $R^2 = 0.9738$) relationships (Fig. 1). When the normalized muscle output at each frequency was compared, the only difference found was a greater muscle output during isometric actions at the 10-Hz frequency ($P = 0.03$). Otherwise, no differences were found in the stimulation frequency that elicited 50% of peak output (17.4 Hz) or peak muscle output (60 Hz) during either isometric or dynamic muscle actions.

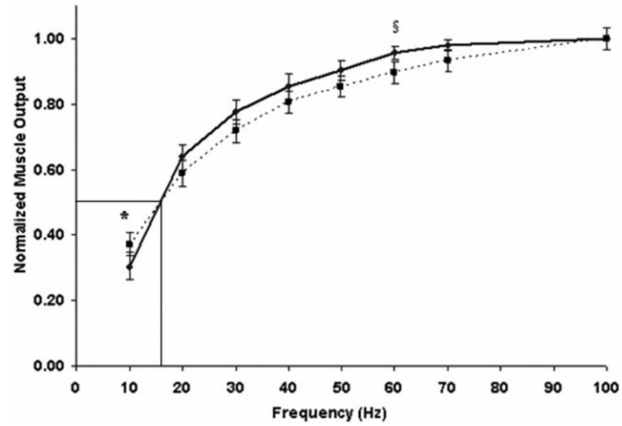

FIGURE 1. Force–frequency relationship normalized across stimulation intensities during isometric (dashed line) and dynamic contractions (solid line). The vertical line represents the frequency that elicited 50% of peak output. Section symbol (§) indicates frequency at which maximum muscle output was achieved. Asterisk (*) denotes a significant difference between isometric and dynamic values ($P < 0.05$). Values represent mean ± SEM.

DISCUSSION

Given that predictable muscle output is essential to human movement, translation of findings from studies that incorporate isometric contractions to FES requires a fundamental understanding of how contraction type may alter muscle responses to electrical stimulation. We found that the impact of varying stimulation frequency is consistent between isometric and dynamic contractions. This finding is contrary to our original hypothesis but it is encouraging for the application of findings from previous studies to FES. We recognize that we are not the first to apply electrical stimulation to elicit dynamic actions. Recently, Binder-Macleod et al. translated findings from their isometric studies to dynamic contractions by examining the impact of different stimulation train characteristics on muscle output and fatigability.[4,7,8] In fact, our data are consistent with their previously described excursion–frequency relationship.[7] The novelty of the present work lies in the detailed comparisons made between the force– and excursion–frequency curves so as to make conclusions about the translation of findings from isometric to dynamic muscle actions. It should be noted that the relationships described in the present work may be unique to the train characteristics as well as the range of motion prescribed, as the impact of these and other factors (i.e., muscle contractile and mechanical properties, joint angular velocity, and gravitational influences) on limb dynamics may alter this relationship should these characteristics be changed.

In conclusion, these data demonstrate the inherent stability of the force– and excursion–frequency relationships and suggest the ability to accurately predict muscle responses to changes in stimulation frequency. Given that no differences were found between normalized isometric and dynamic muscle actions, the force–frequency relationship described previously during isometric contractions may well be translated to elicit limb movements within the context described herein. These findings are important, because they directly address application of results to FES development. Future studies aimed at optimizing FES design should focus on dynamic contractions. There should be an emphasis on predicting the stimuli necessary to elicit predictable excursions at desired velocities in an effort to meet the contractile demands necessary for functional movement.

This work was funded in part by a Center of Excellence Grant F2182C (Brain Rehabilitation Research Center) from the Rehabilitation Research and Development Service of the Department of Veterans Affairs and is the result of work supported by the Office or Research and Development, Rehabilitation R & D Service, Department of Veterans Affairs, and the Malcom Randall VA Medical Center, Gainesville, FL. In addition, support was provided by NIH HD055929 (to C.G.) and NSF CAREER award CMS-0547448 (to W.D.).

REFERENCES

1. Binder-Macleod SA, Dean JC, Ding J. Electrical stimulation factors in potentiation of human quadriceps femoris. Muscle Nerve 2002;25:271–279.
2. Cooper S. The isometric responses of mammalian muscles. J Physiol 1930;27:69:377–385.
3. Gregory CM, Dixon W, Bickel CS. Impact of varying pulse frequency and duration on muscle torque production and fatigue. Muscle Nerve 2007;35:504–509.
4. Kebaetse MB, Binder-Macleod SA. Strategies that improve human skeletal muscle performance during repetitive, non-isometric contractions. Pflugers Arch 2004;448:525–32.
5. Kebaetse MB, Lee SC, Johnston TE, Binder-Macleod SA. Strategies that improve paralyzed human quadriceps femoris muscle performance during repetitive, nonisometric contractions. Arch Phys Med Rehabil 2005;86:2157–2164.
6. Kernell D. Neuromuscular frequency-coding and fatigue. Adv Exp Med Biol 1995;384:135–145.
7. Maladen R, Perumal R, Wexler AS, Binder-Macleod SA. Relationship between stimulation train characteristics and dynamic human skeletal muscle performance. Acta Physiol (Oxf) 2007;189:337–346.
8. Maladen RD, Perumal R, Wexler AS, Binder-Macleod SA. Effects of activation pattern on nonisometric human skeletal muscle performance. J Appl Physiol 2007;102:1985–1991.