Motor output is more variable during eccentric compared with concentric contractions

EVANGELOS A. CHRISTOU and LES G. CARLTON

Department of Kinesiology, University of Illinois at Urbana-Champaign, Urbana-Champaign, IL

ABSTRACT

CHRISTOU, E. A., and L. G. CARLTON. Motor output is more variable during eccentric compared with concentric contractions. *Med. Sci. Sports Exerc.*, Vol. 34, No. 11, pp. 1773–1778, 2002. **Purpose:** This study examined the ability of 10 young (25.3 ± 2.8 yr) healthy individuals to control knee-extension force during several discrete concentric and eccentric contractions. **Methods:** Subjects performed maximal and submaximal tasks on a KIN-COM isokinetic dynamometer. The submaximal tasks were to match a force-time parabola with a time to peak force of 200 ms at five target-forces (50, 100, 150, 200, and 250 N). **Results:** Mean peak force produced by the subjects at each target-force during concentric and eccentric contractions was similar. Mean time to peak force, however, was much shorter for eccentric contractions and was not influenced by increases in the level of force. The standard deviation (SD) and coefficient of variation (CV) of peak force was greater during eccentric compared with concentric contractions. The SD of time to peak force was greater for concentric contractions; however, when normalized to the mean time to peak force produced (CV), eccentric contractions were more variable. **Conclusions:** Results provide evidence that even in young adults the control of motor output is different for eccentric compared with concentric contractions. **Key Words:** SHORTENING, LENGTHENING, FORCE CONTROL, STEADINESS

Movements in daily living are produced by muscular contractions while the muscles shorten (concentric contraction) or lengthen (eccentric contractions). The accuracy of such movements frequently depends on the consistency of the muscular output from trial to trial. An example is ascending and descending stairs, where the consistent output by the quadriceps femoris is required for successful performance.

Several neural differences have been reported for eccentric contractions compared with concentric contractions and include a lower muscle activation (1,20), an alternative muscle activation of synergists (24), lower motor evoked potentials (2,26), higher cortical excitation as measured by electroencephalography (15), different force-velocity curves (30), and a decline in the rate of fatigue during eccentric contractions (5). Furthermore, two studies (19,23) suggest that the nervous system deviates from the size principle (17) during eccentric contractions and selectively recruits high threshold motor units. This finding has been refuted by a number of studies, which report that, although muscle activation is different during eccentric contractions, lower threshold motor units are also recruited (4,12,20,21). Based on the differences in muscle activation of the two contractions, researchers have hypothesized that the central nervous system may control muscle force differently during eccentric contractions (14).

Traditionally, variability of the motor output has been used as a window to understand the parameters that the central nervous system regulates to control a muscular contraction and thus perform an accurate movement (8,13). Variability in the motor output is typically measured as the within-subject standard deviation or coefficient of variation (CV, SD/mean × 100) of various parameters. In some experiments, the within-subject within-trial variability is measured (continuous contractions), whereas in other experiments numerous attempts or trials are generated (discrete contractions) and the within subject between-trial variability is measured for peak force and time to peak force produced (10). These discrete force pulses are commonly produced without visual information and at a very fast rate (200 ms time to peak force) to minimize the use of visual and sensory feedback (8,13). Variability of the motor output during rapid discrete tasks, therefore, has been linked primarily to variability of the motor program (descending command along with excitation of the motor neurons) (13).

Although several experiments have examined concentric and eccentric contraction differences, only a handful of studies have examined the ability of individuals to control muscle force during eccentric contractions. With the exception of one study that examined between trial variability of rapid quadriceps contractions (9), all other studies were concerned with the within-trial variability and the influence of the motor unit behavior on the steadiness of slow finger

0195-9131/02/3411-1773/$3.00/0
MEDICINE & SCIENCE IN SPORTS & EXERCISE®

Submitted for publication January 2002.
Accepted for publication June 2002.
Address for correspondence: Evangelos A. Christou, Ph.D., Neural Control of Movement Lab, Department of Kinesiology and Applied Physiology, University of Colorado at Boulder, Boulder, CO 80309-0354; E-mail: echristo@colorado.edu.
DOI: 10.1249/01.MSS.0000035201.21310.CC

movements in young and old adults (7,18,21,22). In the previous study (9), motor output variability from trial to trial was examined in young and old adults, and the level of force was expressed as a percentage of maximum (% MVC). The findings indicated that peak force variability was similar for the two anisometric contractions (both exhibited greater variability than isometric contractions), whereas the time to peak force variability was greater during eccentric compared with concentric contractions in old but not young adults. So far, however, no study has directly compared discrete concentric and eccentric contractions in young individuals over a range of absolute force levels.

Because the excitation of muscle differs between the two muscular contractions, it is important to identify whether the motor program that controls muscle force and timing of concentric and eccentric contractions is similar. The purpose of this study, therefore, was to compare motor output variability exhibited by concentric and eccentric contractions of the quadriceps femoris muscle group at absolute levels of force.

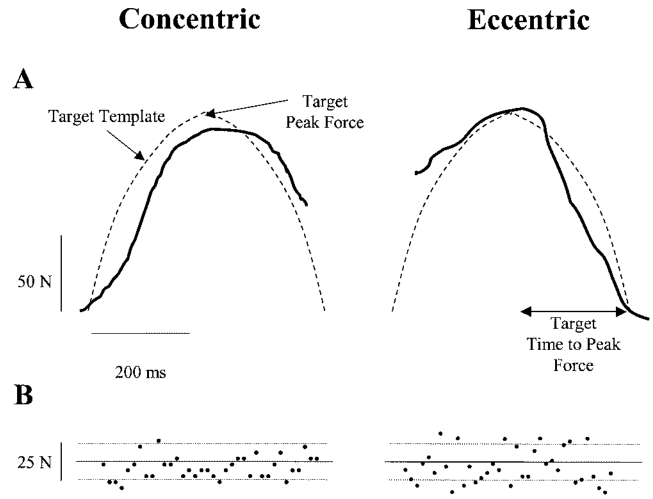

FIGURE 1—Panel A provides an example from a single trial during concentric (left) and eccentric (right) contractions at 150-N force level. The *thick solid line* is the actual force produced by the subject, whereas the *thin dashed line* is the targeted force-parabola. Panel B illustrates the variability in peak force from 36 experimental trials during concentric and eccentric contractions.

METHODS

Subjects. Ten active young adults (25.3 ± 2.8 yr old) volunteered for this experiment. All participants were healthy and had neither history of knee pathology nor any current knee injuries. After arriving at the laboratory, each volunteer was given a written summary and also received oral information about the testing procedures. Participants were required to sign the consent form indicating voluntary participation. The Institutional Review Board at the University of Illinois approved the procedures used in this study.

Experimental arrangement. To assess force production and motor output variability for a knee-extension task, a KIN-COM 500H isokinetic dynamometer (Chattanooga Corporation, Chattanooga TN) was used. The device allows for evaluation of force production during isokinetic, isometric, and isotonic actions. Force, velocity, and angle produced by each participant was displayed on the monitor (15 inch) of the isokinetic dynamometer and collected on a personal computer at a sampling rate of 100 Hz. The KIN-COM 500H has been shown to be a reliable way to assess force isometrically and isokinetically (3).

Each participant was seated for testing in the isokinetic dynamometer's chair with the backrest angle at 90°, and Velcro straps were placed over the pelvis and chest to stabilize the participant. Participants were required to cross their arms over their chest. The axis of rotation of the right knee was aligned with the axis of rotation of the dynamometer's armature, and the ankle cuff (load cell assembly) was attached one inch above the dorsal surface of the foot. Each participant removed the right shoe to eliminate any potential load differences to the quadriceps due to the weight of the shoe.

Experimental protocol. Each participant was required to attend two testing sessions of approximately 2 h each, and testing sessions were spaced at least 36 h from each other but no more than 72 h. In one of the testing sessions, each participant completed one of the two types of contractions (contraction-sessions). The order of the contraction-sessions was counterbalanced and randomly assigned to each participant. For each contraction-session, five absolute target-forces were given (50, 100, 150, 200, and 250 N), and the presentation of each target-force was randomly assigned. Before each contraction-session, participants warmed up by walking for 5 min and stretching their quadriceps femoris, hip flexors, and gastrocnemius muscles.

To obtain a time to peak force of 200 ms, the range of motion was 20° at an isokinetic velocity of $50°\cdot s^{-1}$. Concentric contractions started with a knee angle of 90° and moved to 110° (180° was full extension). Eccentric contractions were produced in the opposite direction of the concentric contractions, thus knee joint angle ranged from 110° to 90°. The task was to produce peak force at 100° of knee flexion; however, each trial varied around that requirement depending on the force produced by each subject. During concentric contractions, each participant moved the dynamometer's armature by producing a knee-extension force. During eccentric contractions, however, participants resisted the movement of the dynamometer's armature by producing a knee-extension force. For both contraction types, movement of the armature was initiated when the participant exerted force approximately equal to his/her leg weight.

To familiarize the participants with the targeted-parabolas and each contraction type, participants completed 40 practice trials, followed by 36 experimental trials at each force level and contraction type. The target parabolas and example trials are shown in Figure 1. During the 40 practice trials, there was a slight and similar reduction in motor output variability for concentric and eccentric contractions. Both the force-time parabola and the force produced by the participant were displayed on the monitor during the task for the first 20 practice trials. During the last 20 practice trials and all experimental trials, the force-time parabola was hidden during the knee-extension force production. Immediately after each of these trials, visual feedback of the force-time curve produced and the force-time target parabola were shown to the participant. In addition, participants received verbal feedback regarding the amount of force and temporal characteristics they produced for each parabola. A brief rest period of 60 s was given to each participant between target level conditions. Criterion forces were randomly assigned for each participant and for the two contraction types. To examine whether fatigue occurred within a session, subjects produced three maximum voluntary isometric contractions before and after each session.

Data analysis. The dependent variables included the MVCs before and after each session, means, SD, and CV of peak force and time to peak force for each force level. The MVCs produced by each subject before and after the two contraction sessions were compared with a paired *t*-test. Each dependent variable was statistically analyzed with a two-factor ANOVA (2 contraction types × 5 levels of force) with repeated measures on contraction type and level of force (SPSS 9.0). When significant effects were found, Tukey-Kramer *post hoc* tests were performed to determine the location of the effect. The probability level for all statistical tests was 0.05.

RESULTS

The MVCs before (concentric, 642.8 ± 57.3 N; eccentric, 672.1 ± 59.3 N) and after (concentric, 650.5 ± 58.9 N; eccentric, 687.5 ± 61.2 N) each contraction session were not significantly different ($P > 0.05$), indicating that quadriceps fatigue did not occur. The mean peak force produced (including the leg weight) was similar for the two contractions (concentric: 124.6 ± 9.5 N −382.7 ± 23.4 N; eccentric: 135.4 ± 9.2 N −379.1 ± 27.2 N) for all levels of force ($P > 0.1$), and as expected, the mean peak force increased significantly as the level of force increased ($P < 0.01$). The mean time to peak force produced was significantly shorter for eccentric compared with concentric contractions ($P < 0.01$), especially at the light loads (Fig. 2). During concentric contractions, subjects matched the 200-ms goal for all target forces except at the lowest one, whereas during eccentric contractions subjects approximated the time to peak force goal only at the heaviest load.

Eccentric contractions produced greater overall variability (SD) compared with concentric contractions ($P < 0.01$); however, the interaction between contraction type and level of force was not significant ($P > 0.05$) (Fig. 3A). Similarly, eccentric contractions produced greater overall relative variability of peak force (CV) compared with concentric contractions ($P < 0.01$), and the interaction between contraction type and level of force was not significant ($P > 0.05$) (Fig. 3B). Because the mean forces produced for concentric and eccentric contractions were similar, the SD and CV results were expected to be similar.

For the time to peak force, concentric contractions produced greater overall variability (SD) compared with eccentric contractions ($P < 0.01$), and the interaction between contraction type and level of force was significant ($P > 0.01$). During concentric contractions, the SD of time to peak force decreased as the level of force increased, whereas during eccentric contractions, the SD of time to peak force

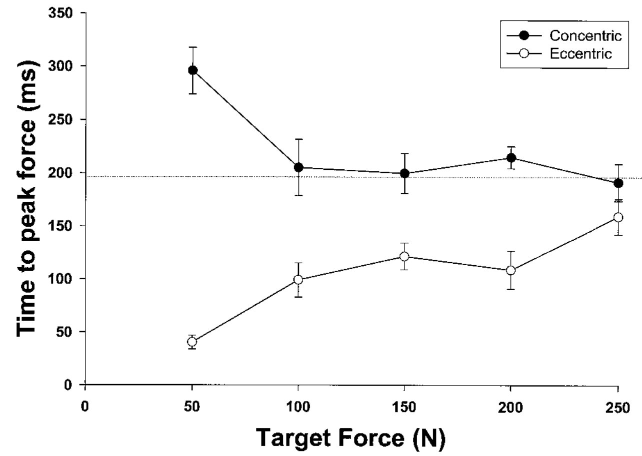

FIGURE 2—Time to peak force was faster for eccentric compared with concentric contractions at all force levels except at 250 N. During concentric contractions the subjects matched the target for time to peak force (200 ms) at all force levels except at the lowest force level. In contrast, during eccentric contractions, the subjects approached the target for time to peak force only at the highest force level.

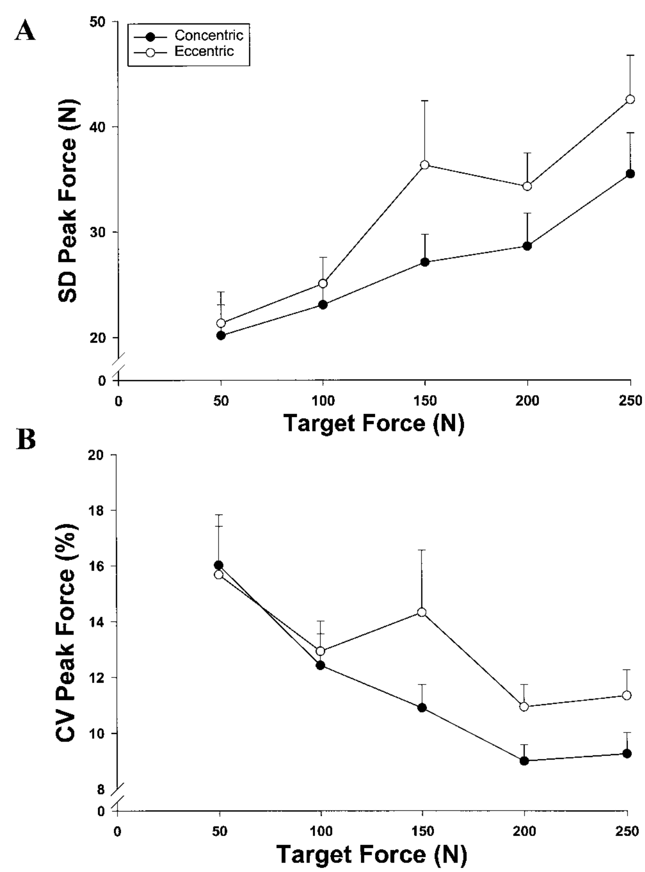

FIGURE 3—Overall, the SD (A) and CV (B) of peak force were greater during eccentric compared with concentric contractions. Although the differences were greater at the highest force levels, the interaction was not significant.

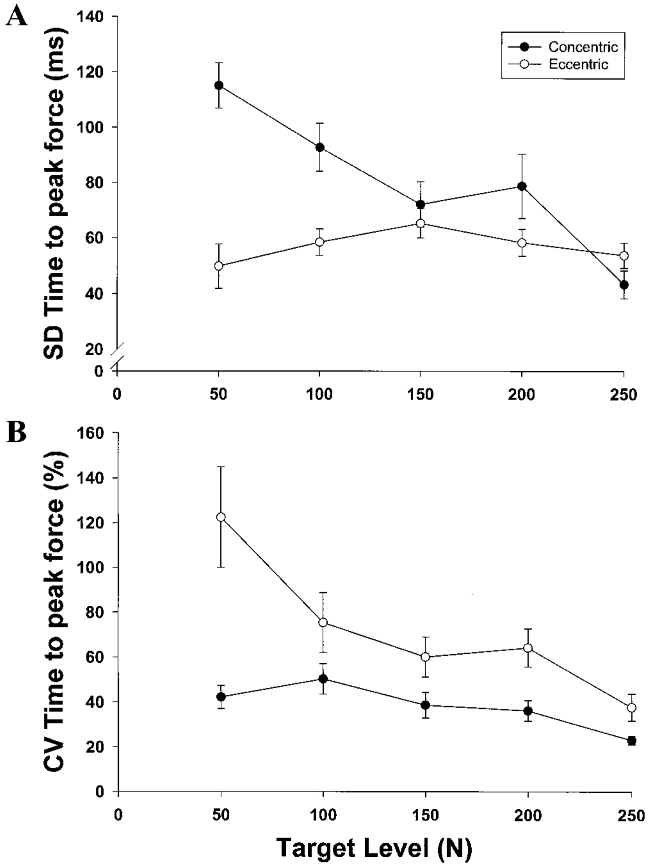

FIGURE 4—Overall, the SD of time to peak force was greater during concentric compared with eccentric contractions (A). The differences were significant only at the force targets of 50 and 100 N. The SD of time to peak force decreased with increases in the force level for concentric contractions but remained relatively consistent for eccentric contractions. In contrast, when the variability of time to peak force was normalized to the mean time to peak force (CV; B) the variability was greater during eccentric contractions. The differences were greater at the 50-N force levels. The CV of time to peak force decreased with increases in the force level for eccentric contractions but remained relatively consistent for concentric contractions.

did not systematically vary with changes in level of force produced (Fig. 4A). When the variability of time to peak force was normalized to the mean time to peak force produced, however, eccentric contractions produced greater overall relative variability of time to peak force (CV) compared with concentric contractions ($P < 0.01$). The greatest differences occurred at the lightest load ($P < 0.01$) (Fig. 4B).

DISCUSSION

The present experiment demonstrated that peak force variability was greater during rapid eccentric compared with rapid concentric contractions. The variability of time to peak force was also significantly greater during eccentric contractions but only at low levels of force. These results contradict findings from a previous study (9), which indicated that peak force variability was similar between the two anisometric contractions and time to peak force was more variable during eccentric compared with concentric contractions only in old adults. The novel findings of this study are that young individuals also exhibit greater motor output variability during eccentric compared with concentric contractions performed at the same absolute level of force.

The greater force variability observed in young individuals during eccentric contractions is in contrast to the findings of a previous study that found nonsignificant increases in variability for eccentric contractions (9). The difference in results may be related to task differences. For example, the isokinetic movement velocity was faster ($50°\cdot s^{-1}$ vs $25°\cdot s^{-1}$), and the range of motion for the knee extension movement was greater (20° vs 10°). Another important difference is that in the previous study the target forces were relative to the maximum force produced (%MVC), whereas in this study the target forces were absolute force levels (N). Furthermore, the findings of this study indicate that eccentric compared with concentric contractions appear to be more variable in the timing of the contraction (CV of time-to-peak force) particularly at low levels of force. This finding suggests that there is a differential control for the timing of the contraction with the level of force.

There is evidence that the sensory feedback differs between concentric and eccentric contractions during slow movements (6); nonetheless, a number of studies have demonstrated that the descending command and excitability of motor neurons may be different during eccentric contractions. For example, magnetic and electrical stimulation of the motor cortex at various intensities evoked lower motor responses in the biceps brachii during eccentric compared with concentric contractions (2,26). Movement-related cortical potentials, as measured by electroencephalography, were greater during eccentric contractions (15). In addition, synchronization of motor units, an index of the strength of common input to the motor neurons, was greater during eccentric contractions (27).

Although this study did not specifically examine neural mechanisms that can alter the control of muscular contractions during eccentric contractions, it provides support that the motor program is different during eccentric contractions. Traditionally, rapid contractions eliminate the use of sensory and visual feedback and evaluate variability in the motor program (descending motor command and excitability of motor neurons) (8,13). The organization of the motor program is evaluated in several parameters of the contraction, which include the peak force and time to peak force (8,25). Because the motor output variability was greater during eccentric contractions and, more importantly, there was an interaction with force level for the timing of the contraction (time to peak force), the findings suggests that the motor program may be organized differently for eccentric compared with concentric contractions.

The alternative neural output during eccentric compared with concentric and isometric contractions is evident from lower muscle activation (7,11,20,21), reduced H-reflexes (23,24), and alternative synergistic activation of muscles (24). The substantial decrease in muscle activation has been shown to be due to a decreased discharge rate of the motor units during eccentric compared with concentric contractions, and this difference becomes greater with movement speed (11,20,21,30). Furthermore, the discharge rate of motor units is not only lower during eccentric contractions but also more variable (20,21). Increases in the discharge rate variability of the motor units have been shown to induce greater variability of the motor output for isometric (29) and anisometric contractions (21). Thus, the differences in motor output variability between concentric and eccentric contractions found in this study may relate to the lower and more variable discharge of motor units during eccentric contractions.

Another mechanism that can increase the motor output variability is the selective recruitment of a fewer number of high threshold motor units and derecruitment of low threshold motor units during eccentric contractions (19,23). At low forces, the contribution of unfused high threshold motor units to the total force will be greater compared with low threshold motor units; therefore, the fluctuations in muscle force will be greater (16). Although this mechanism remains a possibility, a number of studies reported recruitment of low and similar threshold motor units during both eccentric and concentric contractions (4,12,20,21,28). Thus, selective recruitment of motor units may indeed occur, but it is believed to be more of an occasional exception than the rule.

In summary, the results of this study provide further evidence to the hypothesis that eccentric contractions might be uniquely controlled by the central nervous system (14). This differential control of force levels between the two anisometric contractions is most evident for the timing of the contraction. These findings are limited to rapid movements that are repeated over a number of trials using an isokinetic dynamometer and a limited knee range of motion. Nonetheless, these findings suggest that even in young adults the motor output is different between concentric and eccentric contractions, which can have functional implications for the control of movement.

The authors would like to thank Dr. Jennifer Jakobi for comments on a draft of this paper.

REFERENCES

1. Aagaard, P., E. B. Simonsen, J. L. Andersen, S. P. Magnusson, J. Halkjaer-Kristensen, and P. Dyhre-Poulsen. Neural inhibition during maximal eccentric and concentric quadriceps contraction: effects of resistance training. *J. Appl. Physiol.* 89:2249–2257, 2000.
2. Abbruzzese, G., M. Morena, L. Spadavecchia, and M. Schieppati. Response of arm flexor muscles to magnetic and electrical brain stimulation during shortening and lengthening tasks in man. *J. Physiol. (Lond.)* 481:499–507, 1994.
3. Arnold, B., and D. Perrin. The reliability of four different methods of calculating quadriceps peak torque and angle specific torques at 30°, 60°, and 75°. *J. Sport Rehabil.* 2:243–250, 1993.
4. Bawa, P., and K. E. Jones. Do lengthening contractions represent a case of reversal in recruitment order? *Prog. Brain Res.* 123:215–220, 1999.
5. Binder-Macleod, S. A., and S. C. Lee. Catchlike property of human muscle during isovelocity movements. *J. Appl. Physiol.* 80:2051–2059, 1996.
6. Burke, D., K. E. Hagbarth, and L. Lofstedt. Muscle spindle activity in man during shortening and lengthening contractions. *J. Physiol. (Lond.)* 277:131–142, 1978.
7. Burnett, R. A., D. H. Laidlaw, and R. M. Enoka. Coactivation of the antagonist muscle does not covary with steadiness in old adults. *J. Appl. Physiol.* 89:61–71, 2000.
8. Carlton, L. G., and K. M. Newell. Force variability and characteristics of force production. In: *Force Variability*, K. M. Newell and P. Cordo (Eds.). Champaign, IL: Human Kinetics, 1993, pp. 128–132.
9. Christou, E. A., and L. G. Carlton. Age and contraction type influence motor output variability in rapid discrete tasks. *J Appl Physiol*. 93:489–498, 2002.
10. Christou, E. A., and L. G. Carlton. Old adults exhibit greater motor output variability than young adults only during rapid discrete isometric contractions. *J. Gerontol. A Biol. Sci. Med. Sci.* 56:B524–B532, 2001.
11. Christou, E. A., M. Shinohara, and R. M. Enoka. The changes in EMG and steadiness with variation in movement speed differ for concentric and eccentric contractions. In: *Proceedings of the 25th Annual Meeting of the American Society of Biomechanics*, San Diego, CA, 2001, pp. 333–334.
12. Christova, P., and A. Kossev. Human motor unit activity during concentric and eccentric movements. *Electromyogr. Clin. Neurophysiol.* 40:331–338, 2000.
13. Cordo, P., L. Carlton, L. Bevan, M. Carlton, and G. K. Kerr. Proprioceptive coordination of movement sequences: role of velocity and position information. *J. Neurophysiol.* 71:1848–1861, 1994.
14. Enoka, R. M. Eccentric contractions require unique activation strategies by the nervous system. *J. Appl. Physiol.* 81:2339–2346, 1996.
15. Fang, Y., V. Siemionow, V. Sahgal, F. Xiong, and G. H. Yue. Greater movement-related cortical potential during human eccentric versus concentric muscle contractions. *J. Neurophysiol.* 86: 1764–1772, 2001.
16. Fuglevand, A. J., D. A. Winter, and A. E. Patla. Models of recruitment and rate coding organization in motor-unit pools. *J. Neurophysiol.* 70:2470–2488, 1993.
17. Henneman, E. Relation between size of neurons and their susceptibility to discharge. *Science* 126:1345–1347, 1957.
18. Hortobagyi, T., D. Tunnel, J. Moody, S. Beam, and P. Devita. Low- or high-intensity strength training partially restores impaired quadriceps force accuracy and steadiness in aged adults. *J. Gerontol. A Biol. Sci. Med. Sci.* 56:B38–B47, 2001.
19. Howell, J. N., A. J. Fuglevand, M. L. Walsh, and B. Bigland-Ritchie. Motor unit activity during isometric and concentric-eccentric contractions of the human first dorsal interosseus muscle. *J. Neurophysiol.* 74:901–904, 1995.
20. Kossev, A., and P. Christova. Discharge pattern of human motor units during dynamic concentric and eccentric contractions. *Electroencephalogr. Clin. Neurophysiol.* 109:245–255, 1998.
21. Laidlaw, D. H., M. Bilodeau, and R. M. Enoka. Steadiness is reduced and motor unit discharge is more variable in old adults. *Muscle Nerve* 23:600–612, 2000.
22. Laidlaw, D. H., K. W. Kornatz, D. A. Keen, S. Suzuki, and R. M. Enoka. Strength training improves the steadiness of slow lengthening contractions performed by old adults. *J. Appl. Physiol.* 87:1786–1795, 1999.
23. Nardone, A., C. Romano, and M. Schieppati. Selective recruitment of high-threshold human motor units during voluntary isotonic lengthening of active muscles. *J. Physiol. (Lond.)* 409:451–471, 1989.
24. Nardone, A., and M. Schieppati. Shift of activity from slow to fast muscle during voluntary lengthening contractions of the triceps surae muscles in humans. *J. Physiol. (Lond.)* 395:363–381, 1988.

25. Plamondon, R., and A. M. Alimi. Speed/accuracy trade-offs in target-directed movements. *Behav. Brain Sci*. 20:279–303; discussion 303–349, 1997.
26. Sekiguchi, H., T. Kimura, K. Yamanaka, and K. Nakazawa. Lower excitability of the corticospinal tract to transcranial magnetic stimulation during lengthening contractions in human elbow flexors. *Neurosci. Lett.* 312:83–86, 2001.
27. Semmler, J. G., D. V. Kutzscher, S. Zhou, and R. M. Enoka. Motor unit synchronization is enhanced during slow shortening and lengthening contractions of the first dorsal interosseus muscle. In: *Society for Neuroscience Abstracts*, New Orleans, LA, 2000, p. 446.
28. Sogaard, K., H. Christensen, B. R. Jensen, L. Finsen, and G. Sjogaard. Motor control and kinetics during low level concentric and eccentric contractions in man. *Electroencephalogr. Clin. Neurophysiol.* 101:453–460, 1996.
29. Taylor, A., J. Steege, and R. Enoka. Increased variability of motor unit discharge rate decreases the steadiness of simulated isometric contractions. *The Physiologist* 43:321, 2000.
30. Westing, S. H., J. Y. Seger, and A. Thorstensson. Effects of electrical stimulation on eccentric and concentric torque- velocity relationships during knee extension in man. *Acta Physiol. Scand.* 140:17–22, 1990.