Journal of Motor Behavior, 2003, Vol. 35, No. 4, 322–324

Force Control Is Greater in the Upper Compared With the Lower Extremity

Evangelos A. Christou
Department of Integrative Physiology
University of Colorado, Boulder

Mark Zelent
Les G. Carlton
Department of Kinesiology
University of Illinois at Urbana-Champaign

ABSTRACT. The authors investigated whether force control is similar between the upper and lower limbs and between contractions that involve 1 or 2 joints. Six volunteers (27.5 ± 11.2 years of age) attempted to produce consistent discrete rapid force responses of 30, 60, and 90 N by using 6 different body postures, 3 with the upper and 3 with the lower limb. One of the postures for each limb involved 2 joints. The standard deviation of peak force and impulse (aggregate of the force–time curve) was significantly greater (~25%) for the lower limb than for the upper limb ($p < .01$). Contractions that involved 1 or 2 joints within a limb had similar variability. Therefore, the upper limb might have better control of force than the lower limb because of its extensive use in fine motor tasks in daily activities.

Key words: accuracy, arm, force variability, isometric contractions, leg, motor output variability

Accurate force production from muscular contractions is essential for the control of movement. Although most movements in both the upper and lower limbs involve more than a single joint, nearly all investigators of the accurate control of force have focused on single-joint movements in the upper limb (Carlton & Newell, 1993). The findings from the limited number of comparisons of the ability of individuals to control motor output with different joints and limbs have been controversial. For example, individuals exhibited similar force variability with the index finger, forearm, and foot during low-force (4–11 N) isometric contractions (Keele, Ivry, & Pokorny, 1987). In contrast, when participants performed rapid aiming movements, the fingers were more accurate than the wrist, and the wrist was more accurate than the elbow (Langolf, Chaffin, & Foulke, 1976). Because that issue has both theoretical and functional significance, our purpose in this experiment was to determine whether force control was similar between the upper and lower limbs and between contractions that involved one or two joints.

Method

Participants

Six adults (4 men and 2 women, 27.5 ± 11.2 years of age) volunteered for this study. All participants were healthy, physically active, and reported being right hand and leg dominant. The institutional review board for research approved the protocol, and all participants gave written informed consent.

Apparatus and Procedure

We used a KIN-COM 500H isokinetic dynamometer (Chattanooga Corp., Chattanooga, TN) to measure and record forces during discrete isometric contractions. Force was sampled at 100 Hz. For the upper limb, the postures and activities were shoulder flexion, elbow extension, and a two-joint movement that combined shoulder flexion and elbow extension (similar to the bench press; Figure 1). For the lower limb, the postures and activities were hip flexion, knee extension, and a two-joint movement that combined hip and knee extension (similar to a leg press).

Testing was conducted over two testing sessions within a 1-week period. In each posture, participants were instructed to produce rapid discrete isometric forces with peak forces of 30, 60, and 90 N, depending on the condition, with a time to peak force of 200 ms and a force duration of 400 ms. An example trial and the criterion force template are provided in Figure 1G. Following each trial, we gave visual feedback to the participants to aid them in producing the appropriate

---

Correspondence address: Evangelos A. Christou, Neural Control of Movement Laboratory, Department of Integrative Physiology, University of Colorado at Boulder, Boulder, CO 80309-0354, USA. E-mail address: echristo@colorado.edu

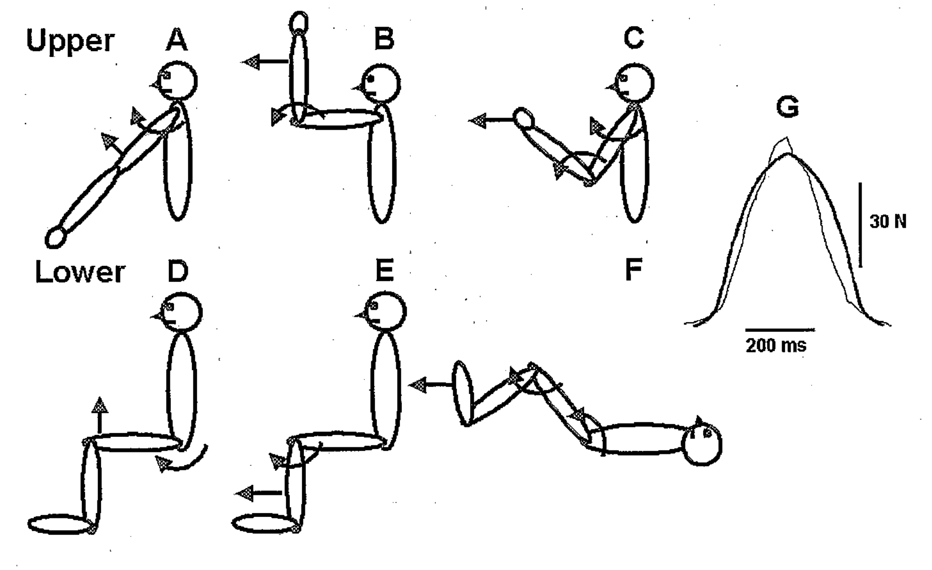

FIGURE 1. The six force-production conditions (postures) compared in the study. The top row represents the upper limb postures, whereas the bottom row represents the lower limb postures. Straight arrows represent the transducer location and the direction of force application. Curved arrows indicate the torque applied to the involved joints. Panel G shows a comparison between a single representative trial (thin line) and the force criterion (thick line), which was parabolic.

force–time response. Participants performed 80 trials at each posture and force level combination. Trials were blocked within force levels, and force levels were blocked within postures. The order of postures and the order of forces within a posture were random. Before testing at each condition, the resting force exerted by the participant on the isokinetic arm was recorded. The target force was defined as the resting force plus the goal target force. A 1-min rest was given to participants between each force condition and a 3-min rest between different postures.

Statistical Analysis

The dependent variables were the intertrial mean, the within-participant standard deviation (*SD*) of peak force, and the within-participant *SD* of impulse (aggregate of force–time curve). Analyses were completed over the last 50 trials at each condition. A small number of trials ($< 1\%$) were eliminated on the basis of highly deviant force characteristics (outliers). Those responses were random across limbs, postures, and force levels. A three-factor analysis of variance (ANOVA)—2 Limbs × 3 Postures × 3 Target Forces—with repeated measures on limb, posture, and target force was used. The probability level was set at .05.

Results

As expected, the mean peak force and impulse increased significantly with force level, $F(2, 10) > 100, p < .001$. Participants exerted similar peak forces and impulses for the upper and lower limbs, $F(1, 5) < 3, p > .1$, and for the different postures within a limb, $F(2, 10) < 2, p > .1$. The *SD* of peak force and the *SD* of impulse increased significantly with force level, $F(2, 10) > 30, p < .001$. Both peak force *SD* and impulse *SD* were significantly greater for the lower limb compared with the upper limb, $F(1, 5) > 9, p < .01$ (Table 1). There were no significant differences among postures within a limb for either *SD* of peak force or *SD* of impulse, $F(2, 10) < 2.5, p > .05$.

Discussion

The findings of the present study are the first to indicate that force control is greater in the upper than in the lower limb and that force control is similar between different articulars of the same limb, including biarticular contractions. The results contradicted previous findings that participants exhibited similar force control with the upper (fingers and forearm) and the lower limb (foot; Keele et al., 1987). The discrepancy might have been caused by the wider range of force levels used in the current study (30–90 N) compared with the previous experiment (4–11 N). The present findings supported those of previous studies in which similar force control among articulars was demonstrated within the upper limb or within the lower limb (Carlton & Medow, 1995; Keele et al., 1987) but contrasted with the findings of Langolf et al. (1976) for aimed movements to a target.

There are at least two possible explanations for the differences in variability between the upper and lower limbs. First, muscles of the lower limb have, on average, larger motor units (more fibers innervated by a single motor neuron). Thus, for a given absolute force (30–90 N), fewer motor units might have been recruited for the lower limb,

TABLE 1. Standard Deviations ± *SEM* for Peak Force and Impulse

	Peak force (N)			Impulse (Ns)		
Limb activity	30 N	60 N	90 N	30 N	60 N	90 N
Shoulder flexion	3.89 ± 0.45	5.36 ± 0.51	8.61 ± 1.25	2.34 ± 0.50	3.31 ± 0.44	3.70 ± 0.71
Elbow extension	3.80 ± 0.75	5.35 ± 0.88	6.53 ± 0.73	1.34 ± 0.22	2.25 ± 0.30	3.76 ± 0.63
Arm extension	3.58 ± 0.72	6.50 ± 0.47	8.45 ± 0.93	1.23 ± 0.11	2.35 ± 0.29	4.32 ± 0.71
Hip flexion	6.14 ± 0.67	6.95 ± 0.69	9.47 ± 0.95	2.13 ± 0.31	4.53 ± 1.37	5.77 ± 1.42
Knee extension	4.68 ± 0.52	7.75 ± 0.76	8.78 ± 0.56	2.20 ± 0.48	3.26 ± 0.60	4.74 ± 0.85
Leg extension	4.72 ± 0.38	5.84 ± 0.34	8.00 ± 0.61	3.10 ± 0.74	3.76 ± 0.54	5.15 ± 0.94

Note. SEM = standard error of measurement.

which contributed to the greater fluctuations in the force trajectory (Enoka et al., 2003) and consequently impaired force accuracy (Christou, Shinohara, & Enoka, in press). Second, precise movements such as drawing, typing, grasping, and manipulating objects are practiced more with the upper compared with the lower limbs. For example, humans appear to use the upper limb muscles approximately twice as much as the lower limb muscles within their normal daily routines (Kern, Semmler, & Enoka, 2001). There is also evidence that practiced movements are represented more extensively in the primary motor cortex (Karni et al., 1995).

In conclusion, the findings of this study indicated that force control is greater with the upper than with the lower limb; however, articulars within a limb exhibited similar variability.

The greater force control in the upper limb might have been caused by the greater number of motor units involved and by the enhanced ability of the motor cortex to coordinate muscle activity in the upper limb as a result of that limb's extensive practice.

REFERENCES

Carlton, L. G., & Medow, J. E. (1995). Accuracy of force production for forces produced by proximal and distal muscles of the upper limb [Abstract]. *Journal of Sport & Exercise Psychology, 17,* S37.

Carlton, L. G., & Newell, K. M. (1993). Force variability and characteristics of force production. In K. M. Newell & P. Cordo (Eds.), *Force variability* (pp. 128–132). Champaign, IL: Human Kinetics.

Christou, E. A., Shinohara, M., & Enoka, R. M. (in press). Fluctuations in acceleration during voluntary contractions lead to greater impairment of movement accuracy in old adults. *Journal of Applied Physiology.*

Enoka, R. M., Christou, E. A., Hunter, S. K., Kornatz, K. W., Semmler, J. G., Taylor, A. M., et al. (2003). Mechanisms that contribute to differences in motor performance between young and old adults. *Journal of Electromyography and Kinesiology, 13,* 1–12.

Karni, A., Meyer, G., Jezzard, P., Adams, M. M., Turner, R., & Ungerlieder, L. G. (1995). Functional MRI evidence for adult motor cortex plasticity during motor skill learning. *Nature, 377,* 155–158.

Keele, S. W., Ivry, R. B., & Pokorny, R. A. (1987). Force control and its relation to timing. *Journal of Motor Behavior, 19,* 96–114.

Kern, D. S., Semmler, J. G., & Enoka, R. M. (2001). Long-term activity in upper- and lower-limb muscles of humans. *Journal of Applied Physiology, 91,* 2224–2232.

Langolf, G., Chaffin, D. B., & Foulke, J. A. (1976). An investigation of Fitts' law using a wide range of movement amplitudes. *Journal of Motor Behavior, 8,* 113–128.

Submitted April 4, 2003
Revised May 25, 2003

TITLE: Force Control Is Greater in the Upper Compared With the Lower Extremity
SOURCE: J Mot Behav 35 no4 D 2003
WN: 0333507509001