Maximal voluntary force of bilateral and unilateral leg extension

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The aims were: (1) to investigate whether the 10–20% lower force during bilateral (BL) as compared to unilateral (UL) leg extension could be due to a general inability to activate fully a large number of muscles simultaneously, (2) to analyse the EMG signal of the quadriceps femoris during leg extensions, (3) to study the BL/UL force ratio in extension of the knee, and (4) to study the BL/UL leg extension force ratio in untrained and trained subjects. A 10% lower maximal voluntary isometric force was demonstrated during BL as compared to UL leg extension. This force discrepancy did not change when a total arm load of 250 N was applied simultaneously. Nor did the absolute force levels change, which indicates that the lower BL leg extension force is not due to a general mechanism of reduced activation with an increased number of muscles recruited in maximal voluntary contractions. Integrated EMG activity, mean power frequency and root mean square value of the EMG amplitude did not differ between UL and BL leg extensions. The knee extension force was slightly greater (4%) during BL than UL contractions. These findings are arguments against a reduced activation of the knee extensor muscles being the cause of the lower bilateral leg extension force. No differences in BL/UL force ratio were noted between groups of untrained and trained subjects despite the fact that several of the trained groups do different forms of BL leg extensions regularly. Thus, it does not appear that training readily affects the BL/UL leg extension force ratio.

Key words: EMG, human, muscle strength, physical training.

Since the study by Asmussen & Heebøll-Nielsen in 1961, it has been known that the maximal voluntary force during bilateral (BL) isometric attempted leg extension is lower than the sum of the maximal unilateral (UL) forces, i.e. the forces recorded during separate left and right leg contractions. This phenomenon was demonstrated in both sexes and in all age groups (15–55 years) investigated. Later, Vandervoort et al.

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(1984) extended these observations to include concentric leg extensions.

The cause is not known, however. It has been suggested that it depends on a restricted type I (Secher et al. 1978) or type II (Vandervoort et al. 1984) recruitment. The latter authors also reported a markedly lower EMG activity of the quadriceps femoris during BL leg extension.

A conceivable origin of the force reduction could be that the CNS is incapable of maximal activation of a large number of muscles simultaneously. In such a case, the BL leg extension force could be expected to decrease if an arm load was applied simultaneously. To investigate this matter, subjects performed UL and BL leg extensions with or without an arm load (a 125-N

dumb-bell in each hand). The same procedures were also undertaken with knee extensions. The purpose of this was to see whether a lower BL force and any effect of adding an arm load could be generalized with regard to another form of attempted movement partly involving the same muscles.

To investigate further the suggested differences in the activation patterns during UL and BL leg extensions, the myoelectric signal characteristics of the vastus lateralis were subjected to a computer-aided power spectrum analysis. The force was recorded simultaneously.

Secher (1975) reported that the BL/UL force discrepancy was smaller for competitive oarsmen than for untrained subjects. The paucity of data on the influence of physical training prompted a comparison of untrained and trained subjects including several groups (ballet dancers, volleyball players, and strength-trained subjects) that often execute maximal bilateral leg extensions.

MATERIALS AND METHODS

The different parts of this study stated in the Introduction will be referred to as (1) bilateral/unilateral leg and knee extensions with or without an arm load (BL/UL ± arm load), (2) EMG study, and (3) cross-sectional study.

Subjects

Different subjects were recruited for the different parts of the study. Six male and eight female physical education students participated in '*BL/UL ± arm load*'. Their age, height, and weight were 23 ± 2 years, 1.71 ± 0.02 m, and 64 ± 2 kg (mean ± SE). Nine male physical education students participated in the *EMG study* (28 ± 2 years, 1.82 ± 0.02 m, 78 ± 3 kg). The *cross-sectional study* included several groups, each consisting of five subjects. These were: untrained female (23 ± 1 years, 1.72 ± 0.03 m, 59 ± 2 kg) and male subjects (26 ± 2 years, 1.79 ± 0.03 m, 71 ± 1 kg), female (24 ± 1 years, 1.70 ± 0.01 m, 64 ± 2 kg) and male physical education students (25 ± 2 years, 1.84 ± 0.03 m, 77 ± 3 kg), female (27 ± 4 years, 1.65 ± 0.02 m, 51 ± 2 kg) and male professional ballet dancers (26 ± 2 years, 1.81 ± 0.02 m, 70 ± 2 kg), male volleyball players (national elite, 22 ± 1 years, 1.91 ± 0.03 m, 84 ± 2 kg) and male strength-trained subjects (national elite, 28 ± 1 years, 1.76 ± 0.03 m, 91 ± 5 kg).

Experimental protocol

(1) 'BL/UL ± arm load'. Force was measured during maximal bilateral (BL) and unilateral (UL, left and right leg separately) isometric attempted leg and knee extensions (for a description of the force measurement device and body positions, see below). These contractions were performed with or without a simultaneous arm load: a 125-N dumb-bell in each hand. The weights were held with an elbow angle of about 90° with the upper arm supported against the trunk and/or the back of the experimental chair. During leg and knee extensions without an arm load, the arms were held in the same positions but as relaxed as possible. The rest periods between and within the four sets of BL and UL contractions (leg and knee extensions with or without arm load) were 1.5 min and 10 s respectively. The peak value of two attempts per condition were used in the calculations.

(2) EMG study. Force and EMG (for details on EMG analysis, see below) were recorded during two sets of maximal BL and UL leg extensions, one attempt for each type of contraction per set. The rest period between and within the sets of contractions was 2 min and 30 s respectively. Mean values from the two sets were used for the calculations.

(3) Cross-sectional study. Force was measured during maximal UL and BL leg extensions, with two attempts per condition. The contractions were interspersed with approximately 10 s of rest, and peak values were used in the calculations.

During the two latter studies, the arms were crossed with the hands resting on the opposite shoulder.

Features common to all experiments were a randomized order and a warming-up period on a cycle ergometer (5 min, 100 watt) prior to the measurements.

Force measurements

Maximal isometric leg extension force was measured with a strain-gauge dynamometer originally described by Asmussen et al. (1959). The subject sat in a chair with a support for the back and pressed the feet against a foot-plate attached to a steel rod mounted in bearings on an iron frame. The foot-plate was placed at about the same level as the seat of the chair (Fig. 1).

Maximal isometric knee extension force was measured with the subject seated in a fixed position with his legs attached to the lever arms of two isokinetic dynamometers (Cybex II, Lumex Inc., New York). The experimental set-up was a dual arrangement of one used and described by Thorstensson (1976) (Fig. 2). Both leg and knee extensions were performed with the knee joint at a 90° angle: the trochanter major, rotation axis of the knee joint and lateral malleolus were used as reference points.
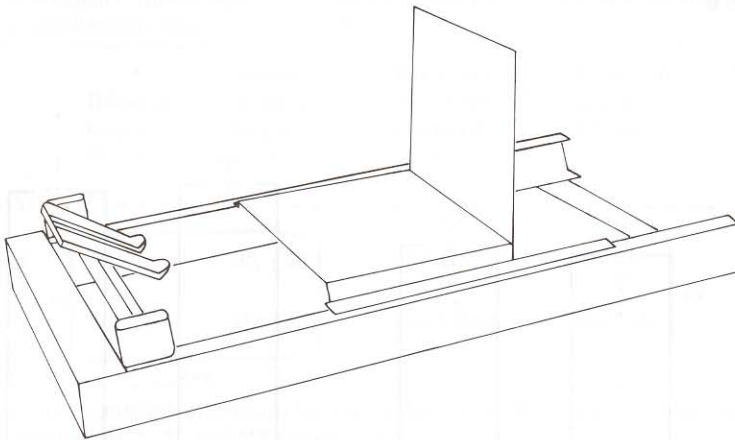
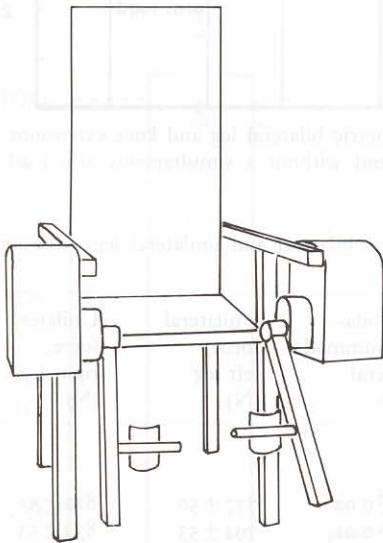Fig. 1. Force measurement apparatus used in leg extension experiments.

Fig. 2. Force measurement apparatus used in knee extension experiments.

electrode distance) similar to those used by Petrofsky & Lind (1980) were also used. The myoelectric signal was amplified by a system described by Halbertsma (1983).

The signal was digitized and stored on a floppy disk at a sampling rate of 1024 Hz, with band-pass filtering at between 5 Hz and 1 kHz using an HP 9836 desk-top computer. The digitized data from two separate trials were processed with the Hamming window function and 512-point fast Fourier transform to obtain mean power frequency (MPF) and the root mean square value of the EMG amplitude (RMS) (Moritani *et al.* 1986). MPF was defined as the ratio between spectral moments of orders one and zero (Moritani *et al.* 1982). For quantitative comparisons, the MPF and RMS were calculated during 512 ms around the peak force. The EMG activity was also integrated during the period when force output reached 90% of peak value until peak force was reached. Force values used for calculations of the EMG/force ratios were integrated over the same time-period as the EMG.

Surface EMG analysis

For the surface EMG frequency power spectral analysis, bipolar silver/silver chloride electrodes (9 mm pick-up diameter, 2 cm inter-midelectrode distance) were applied over the left and right vastus lateralis, at a point 20 cm above the knee joint on the line between the rotation axis of the knee joint and the trochanter major. The reference electrode was attached to the iliac crest. For comparison (*n* = 2), larger electrodes (10 mm pick-up diameter, 4 cm inter-

Statistics

Results are presented as means and individual values or ± standard error of mean (SE). The one-way analysis of variance (ANOVA) was used to test the significance of differences between conditions or groups when the same values were used in more than one comparison. Student's paired *t*-test was used when the same values were used in only one comparison. Differences with a probability level of *P* < 0.05 will be designated in the text as significant.
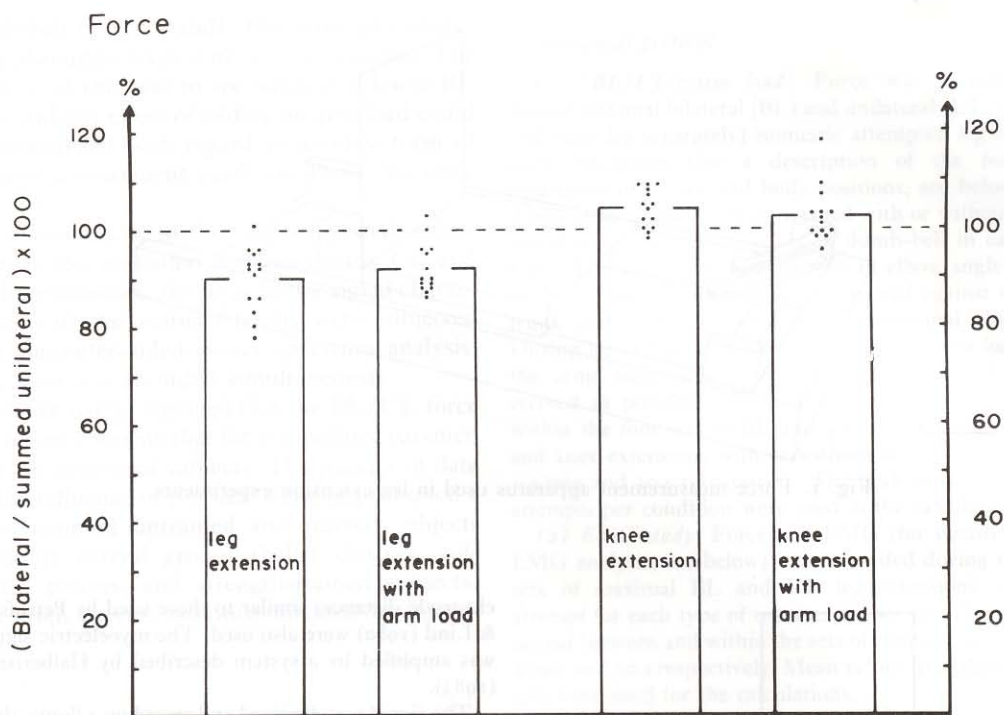
Force

Fig. 3. Maximal voluntary contraction force during isometric bilateral leg and knee extensions in per cent of the sum of the unilateral forces with and without a simultaneous arm load $(2 \times 125 \text{ N})$. Mean and individual values.

Table 1. Maximal voluntary contraction force during isometric bilateral and unilateral leg extension with and without a simultaneous arm load $(2 \times 125 \text{ N})$

	Bilateral force (N)	Summed unilateral force (N)	Ratio bilateral/summed unilateral force	Unilateral force, left leg (N)	Unilateral force, right leg (N)
Leg extension MVC					
Without arm load	1432 ± 80	1599 ± 100	0.90 ± 0.02	777 ± 50	822 ± 51
With arm load	1490 ± 84	1627 ± 104	0.92 ± 0.01	794 ± 53	833 ± 53

Means $\pm$ SE $(n = 14)$. A significant difference between values at the $P < 0.001$ probability level is indicated by *.

RESULTS

Maximal bilateral and unilateral isometric leg extension force with and without an arm load

The bilateral (BL) leg extension force was significantly lower than the summed unilateral (UL) force both with $(8 \pm 1\%, n = 14,$ mean $\pm$ SE) and without $(10 \pm 1\%)$ a simul-taneous arm load. The absolute force values did not change on adding the arm load (Table 1, Fig. 3).

Maximal bilateral and unilateral isometric knee extension force with and without an arm load

The BL knee extension force tended to be greater (with arm load; $2.6 \pm 1.6\%, n = 14,$

Table 2. Maximal voluntary contraction torque during isometric bilateral and unilateral knee extension with and without a simultaneous arm load (2 × 125 N)

	Bilateral torque (N m)	Summed unilateral torque (N m)	Ratio bilateral/summed unilateral torque	Unilateral torque, left leg (N m)	Unilateral torque, right leg (N m)
Knee extension MVC					
Without arm load	381 ± 31	364 ± 28	1.04 ± 0.01	180 ± 16	184 ± 13
With arm load	392 ± 30	382 ± 28	1.03 ± 0.02	189 ± 16	193 ± 13

Means ± SE (n = 14). Significant differences between values at the P < 0.01, P < 0.05, and P < 0.1 levels of probability are indicated by *, ** and *** respectively.
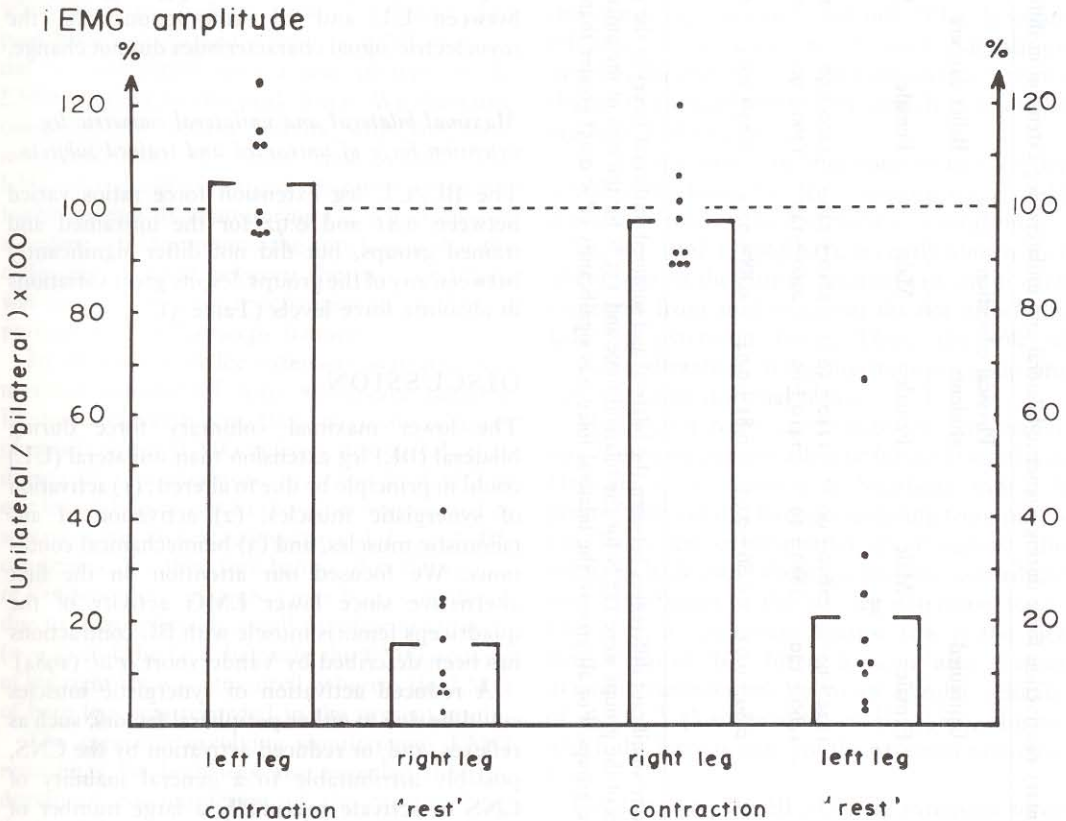

Fig. 4. Integrated EMG activity of the lateral portion of the quadriceps femoris (vastus lateralis) in contracting and 'resting' legs during unilateral (UL) contractions in per cent of the values at maximal bilateral (BL) contraction. Mean and individual values.

P < 0.1) or was significantly greater (without arm load; 4.2 ± 1.0 %, P < 0.05) than the UL force. Absolute force levels during BL and UL knee extensions were 4–5 % greater (P < 0.05) with than without an arm load. The BL/UL knee extension force ratios with or without an arm load were significantly higher than those during leg extension (Table 2, Fig. 3).

Table 3. *Maximal voluntary contraction force during isometric bilateral and unilateral leg extension in different groups* (n = 5)

	Untrained		Physical education students		Ballet dancers		Volleyball players	Heavy-resistance trained
	Female	Male	Female	Male	Female	Male	Male	Male
Leg extension MVC								
Bilateral force (N)	1120±90	1610±90	1140±50	1810±140	1200±90	2020±130	2120±220	2700±110
Summed unilateral force (N)	1260±120	1880±70	1410±90	2060±140	1360±90	2350±180	2400±190	2930±120
Ratio bilateral/ summed unilateral force	0.89±0.03	0.86±0.03	0.81±0.04	0.88±0.03	0.87±0.03	0.86±0.03	0.88±0.02	0.92±0.02

Means±SE. There were significant differences between the bilateral and summed unilateral forces in the groups. The least significant differences ($P < 0.05$) between the mean values of the groups were 127 N for the bilateral force and 133 N for the sum of the unilateral forces. The BL/UL force ratio did not differ significantly between the groups. For all groups, the bilateral force was significantly ($P < 0.05$) greater than the sum of the unilateral forces.

EMG during maximal bilateral and unilateral isometric leg extension

The BL leg extension force was significantly lower (13±2%, n = 9) than the UL force. However, the muscle activation level, as estimated by the integrated EMG activity, did not reveal any systematic difference (BL/UL ratio 0.99±0.03) (Fig. 4). The iEMG activity of the 'resting' leg during UL contractions amounted to about 20% of that during maximal BL contractions (Fig. 4). The ratio of integrated EMG/integrated force was 12±3% higher ($P < 0.01$) during BL than UL. Neither the mean power frequency (BL/UL ratio 1.00± 0.03) nor the root mean square value of the EMG amplitude (BL/UL ratio 1.04±0.05) differed between UL and BL contractions, i.e. the myoelectric signal characteristics did not change.

Maximal bilateral and unilateral isometric leg extension force of untrained and trained subjects

The BL/UL leg extension force ratios varied between 0.81 and 0.92 for the untrained and trained groups, but did not differ significantly between any of the groups despite great variations in absolute force levels (Table 3).

DISCUSSION

The lower maximal voluntary force during bilateral (BL) leg extension than unilateral (UL) could in principle be due to altered: (1) activation of synergistic muscles, (2) activation of antagonistic muscles, and (3) biomechanical conditions. We focused our attention on the first alternative since lower EMG activity of the quadriceps femoris muscle with BL contractions has been described by Vandervoort et al. (1984).

A reduced activation of synergistic muscles could be due to either peripheral factors, such as reflexes, and/or reduced activation by the CNS, possibly attributable to a general inability of CNS to activate maximally a large number of muscles simultaneously. The approach used to test the latter alternative was to add arm loads during leg extension. This affected neither the BL nor UL force levels, which suggests another origin of the lower force during BL leg extension.

The report by Vandervoort et al. (1984) of halved iEMG activity of the quadriceps femoris, in combination with pharmacologically based

suggestions by Secher *et al.* (1978) of a reduced fibre type I recruitment of synergistic muscles during BL leg extension, prompted a more detailed analysis of the myoelectric signal characteristics during BL and UL leg extension.

The fact that we were unable to demonstrate altered iEMG activity of the lateral portion of the quadriceps femoris during BL contractions is intriguing (the BL/UL iEMG activity ratio was 0.99 ± 0.03, $n = 9$). In a control experiment we could rule out that the opposite results were due to differences in electrode pick-up diameter and inter-electrode distance between our study and that by Vandervoort *et al.* (1984).

Another conceivable erroneous factor was that, for methodological reasons, our iEMG values were integrated over the time-period when force reached 90% of peak value until peak force was attained. Thus, the iEMG activity did not necessarily give a true picture of the EMG coupled to the peak force. We therefore compared the iEMG activity with the force integrated over the same time-period. The EMG/force ratio attained thereby was 12% higher during BL than during UL leg extension, a finding which supports the conclusion that the difference in force between the two conditions was not due to altered activation of the lateral portion of the quadriceps femoris.

In all trials with leg extensors activated, the maximal summed UL force was greater than the BL force. Nevertheless, there were several cases of clearly lower iEMG activity during UL than during BL. Furthermore, increases in iEMG of one leg and decreases in the other were noted in several cases when comparing UL and BL conditions. We therefore believe that the results of Vandervoort *et al.* (1984) may be a coincidence due to their relatively small number of subjects ($n = 4$) and the fact that only the EMG activity of the right leg was measured, whereas the EMG of both legs was recorded in the present study.

The approach involving simultaneous EMG recordings for both legs also revealed that the degree of co-contraction of the 'resting' leg during UL contractions was low. Thus, there was a clear difference in the muscular activation pattern of the contralateral leg between BL and UL contractions.

With the EMG frequency spectral analyses used in this study, it has been shown that changes in MPF can reflect relative changes in motor unit recruitment observed intramuscularly under a variety of conditions (Moritani *et al.* 1985, 1986, Moritani & Muro 1987). Thus, the absence of change in MPF may indicate that there is no shift in involvement of the slow and fast motor units during BL and UL leg extensor activation.

Hip extensor and knee extensor muscles are synergists in the attempted leg extensions studied. The finding that the force during isolated knee extension was slightly higher (4%) during BL contractions, in combination with a previous report of slightly lower (3%) (Coyle *et al.* 1981) BL knee extension force, is an argument against altered activation of these muscles being responsible for the lower BL leg extension force. This is further supported by the fact that iEMG activity of the lateral portion of the quadriceps femoris did not differ between BL and UL leg extensions. An altered activation of either the hip extensors or antagonistic muscles therefore appears more likely, and deserves to be studied in the future.

It is appropriate in this context to consider whether the lower BL leg extension force could merely be due to the experimental conditions.

Secher *et al.* (1988) have recently shown that alterations in the sitting position (10 cm in each direction from mid-position) do not affect the UL leg extension force. Thus, the role of possible alterations in biomechanical conditions appears to be minimal if any.

Motor unit recruitment patterns can change due to proprioceptive afferent inputs (Grimby & Hannerz 1976, Garnett & Stephens 1981). A greater afferent discharge originating from pressure from the experimental chair against the subject's back could therefore possibly contribute to an inhibition of the BL leg extension force. However, an argument against this is the fact that a lower BL force is seen also during dynamic contractions up to an angular velocity of $450° \text{ s}^{-1}$ (Vandervoort *et al.* 1984), during which the force is only $\frac{1}{4}$ of the maximal isometric force.

Furthermore, the BL/UL leg extension force ratio did not differ between the presently studied subjects despite their great differences in absolute force and thereby pressure against the back.

Finally, the noted lower BL force during elbow flexion and extension (Ohtsuki 1983) lends further support to the assumption that the lower BL leg extension force can be a characteristic of normal motor control.

The present data suggest that non-specific BL exercises (by strength-trained subjects, volleyball players, ballet dancers) have no effect on the BL/UL leg extension force ratio. This is in accordance with a recent comparison of 38 weight-lifters with 90 untrained male subjects (Secher *et al.* 1988).

More movement-specific training might, however, produce an effect. Secher (1975) demonstrated a BL/UL leg extension force ratio ranging from 0.92 in club oarsmen to 1.04 in international caliber oarsmen. These values should be compared with a ratio of 0.80 normally noted when subjects are tested under the same experimental conditions as the rowers, i.e. with a 150° knee angle (Secher *et al.* 1988). Selection factors may, however, explain these differences. There is an obvious need for a longitudinal study to clarify these matters.

It is concluded that the lower bilateral leg extension force is not a simple effect of a general inability of the CNS to activate maximally a large number of muscles simultaneously. The smaller force cannot be explained by a lower activation level of the lateral portion of the quadriceps femoris. The finding that the force during bilateral knee extension was slightly greater than the unilateral force also argues against a reduced activation of the knee extensor muscles being the cause of the lower bilateral leg extension force. Finally, non-specific bilateral leg extension training does not appear to affect the difference in bilateral and unilateral leg extension force.

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