Quadriceps EMG/force relationship in knee extension and leg press

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ABSTRACT

ALKNER, B. A., P. A. TESCH, and H. E. BERG. Quadriceps EMG/force relationship in knee extension and leg press. *Med. Sci. Sports Exerc.*, Vol. 32, No. 2, pp. 459–463, 2000. **Purpose:** This study compared the relationship between surface electromyographic (EMG) activity and isometric force of m. quadriceps femoris (QF) in the single-joint knee extension (KE) and the multi-joint leg press (LP) exercises. **Methods:** Nine healthy men performed unilateral actions at a knee angle of 90° at 20, 40, 60, 80, and 100% of maximal voluntary contraction (MVC). EMG was measured from m. vastus lateralis (VL), m. vastus medialis (VM), m. rectus femoris (RF), and m. biceps femoris (BF). **Results:** There were no differences in maximum EMG activity of individual muscles between KE and LP. The QF EMG/force relationship was nonlinear in each exercise modality. VL showed no deviation from linearity in neither exercise, whereas VM and RF did. BF activity increased linearly with increased loads. **Conclusions:** The EMG/force relationship of all quadricep muscles studied appears to be similar in isometric multi-joint LP and single-joint KE actions at a knee angle of 90°. This would indicate the strategy of reciprocal force increment among muscles involved is comparable in the two models. Furthermore, these data suggest a nonuniform recruitment pattern among the three superficial QF muscles and surface EMG recordings from VL to be most reliable in predicting force output. **Key Words:** ANTAGONIST ACTIVITY, ELECTROMYOGRAPHY, ISOMETRIC ACTION, MULTI- AND SINGLE- JOINT EXERCISE

The relationship between EMG activity and the generated force has been examined in several studies. While early reports (7,20) disclosed a linear relationship for the calf muscle, the results of recent studies of different muscles are equivocal (3). Although not a consistent finding (26), the EMG/force relationship for individual muscles of the quadriceps femoris muscle group (QF) in an isometric knee extension has been described as nonlinear, such that EMG amplitude increases out of proportion to force (4,10,14,17,18,24). Reported differences may reflect that individual QF muscles are not necessarily uniformly activated at increased loads in a specific action. Thus, the EMG/force-relationship may differ among QF muscles. Discrepancies in interpretation may arise from the fact that either the two-joint muscle rectus femoris or the single-joint muscles vastus lateralis or medialis have been chosen to reflect over-all QF activity. Moreover, some reports suggest that EMG activity of individual muscles is not uniform in multi-joint leg press compared with single-joint knee extension exercises (9,10,27). Thus, the EMG/force relationship might be different in multi-joint and single-joint actions. To our knowledge, no study has compared the EMG/force relationship for QF muscles during both multi-joint and single-joint exercise.

It has been put forth that antagonistic activity increases progressively at heavier loads to stabilize the knee joint and hence reduces the net force output of the QF muscle in the knee extension exercise (3). It follows that EMG signals would appear greater relative to external force at heavier loads.

Thus, the purpose of this study was to compare the EMG/force relationship of individual QF muscles in the single-joint knee extension and the multi-joint leg press. In an effort to assess the potential influence of antagonist activity on the EMG/force relationship of the knee extensor muscle group, EMG activity of m. biceps femoris was measured as well.

MATERIALS AND METHODS

General procedure. Nine men were acquainted with the equipment and protocol, and then performed a series of submaximal and maximal isometric actions in two exercise modalities 5–10 d before the experiments. Each session

0195-9131/00/3202-0459/0
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Submitted for publication July 1998.
Accepted for publication January 1999.

began with a 5-min warm-up on a cycle ergometer at about 100 W. Then they performed angle specific unilateral (right limb) isometric actions in the knee extension (KE) and the leg press (LP). After maximal voluntary isometric force had been assessed, submaximal actions were executed at four predetermined load settings. Force and surface electromyographic (EMG) activity of the three superficial quadriceps femoris muscles and m. biceps femoris were measured simultaneously. This protocol allowed us to study the EMG/force relationship in these two exercise modalities.

Subjects. Nine healthy and physically active men, their mean ($\pm$ SD) age, height, and weight were 24 $\pm$ 2 yr, 183 $\pm$ 7 cm, and 79 $\pm$ 6 kg, respectively, gave their informed consent to participate in this study. The experimental protocol was approved by the Ethics Committee at the Karolinska Institute.

Testing. First, subjects performed two maximal voluntary isometric contractions (MVC), and if force differed more than 5% between trials a third trial was allowed. To minimize potential influence of fatigue, KE and LP actions were performed in a random order on the same day. Two actions were subsequently performed at individual loads equal to 20, 40, 60, and 80% of MVC in each exercise modality. The order of different load settings was random. Subjects were required to increase force smoothly to the predetermined level, and once established that set force was sustained for 2–3 s. Visual feedback was provided such that the required force was displayed on a screen. If the subject failed to maintain the set level within a $\pm$ 5% margin off-set, a new trial was allowed. In addition, and following the KE, MVC was measured during knee flexion. One-minute rest was allowed between each action. Seated knee extensions and flexions were performed in a dynamometer described elsewhere (23) by applying force onto the lever arm pad attached to the lower leg. The leg press was performed in an ergometer designed for the seated leg press (5) by applying force onto a footplate. Fixation was ensured by strapping back (LP, KE), shoulders, and thigh (KE). In either modality, subjects held their arms crossed over their chest. Knee angle, measured using an electrogoniometer aligned with the rotation axis of the knee joint, was 90° (180° = fully extended) and hip angle was about 115° (180° = fully extended). The foot was always kept in a neutral position.

Force, subsequently corrected for limb weight, was measured using strain-gauge technique. EMG activity was measured from m. vastus lateralis (VL) just distal to mid-thigh, m. vastus medialis (VM) about 5 cm from patella, m. rectus femoris (RF) just proximal to mid-thigh and m. biceps femoris (BF) just proximal to mid-thigh. A reference electrode was placed on the proximal tibial bone. Disposable bipolar Ag-Ag/Cl surface electrodes (Multi Bio Sensors Inc., El Paso, TX) with a 25-mm interelectrode distance were applied, aligned with the fiber direction, after shaving the skin and cleansing with alcohol. Knee extension and flexion torque curves were produced on a strip-chart recorder (Gould 2400, Gould Inc., Cleveland, OH). All other data were collected using the Muscle-Lab (Langesund, Norway) recording and acquisition system, employing the accompanying software program on a lap-top computer.

The coefficient of variation (CV) between trials for force were 2.7 and 3.2% and EMG 4.7–9.2% and 5.8–8.8% for the KE and the LP, respectively.

Analyses. After being filtered with low and high cut-off frequencies of 9.5 and 510 Hz, respectively, the root mean square (RMS) of the raw EMG signal was passed through a smoothing window of 1000-ms time constant. Force and EMG values were averaged across the open 1000-ms time window showing the highest mean force value and then averaged across the two trials at each force level. Relative values (% of maximum values) were used when evaluating the EMG/force relationship as described below. EMG activity is graphically presented relative to maximal KE values.

To establish the EMG/force relationship the difference between the relative force and the corresponding relative EMG value was calculated for each submaximal level. The sum of these differences was subsequently formed for QF and each individual muscle, respectively.

Assuming a linear or close to linear relation between EMG activity of BF and knee flexor force (8,15), we estimated knee flexor force during knee extension by relating BF EMG activity measured in the KE to BF EMG activity and force recorded at knee flexion MVC. Two subjects were disregarded in data analyses of BF because of electrode failure.

Statistics. Analysis of variance (ANOVA) was employed to assess differences of the sums, as described above, between individual muscles or QF, respectively, from the line of identity, and differences in maximal EMG for each muscle between the two exercise modalities. Statistical significance was set at $P < 0.05$. Values given below are mean $\pm$ SD.

RESULTS

The QF EMG/force relationship in either KE or LP deviated from linearity ($P < 0.05$; Fig. 1A). Such a pattern was shown for VM and RF in either modality ($P < 0.05$; Figs. 1B and 1C). In contrast, VL showed a linear EMG/force relationship ($P > 0.05$; Figs. 1B and 1C).

In all four muscles examined, maximal EMG activity was comparable ($P > 0.05$) in KE and LP (Table 1). BF activity ($N = 7$) relative to EMG at knee flexion MVC averaged 17 $\pm$ 7% and 15 $\pm$ 6%, respectively, in KE and LP. Because knee flexion MVC averaged 42 $\pm$ 7% of KE MVC, the estimated force produced by the knee flexors regardless of force level was about 7–8% of the knee extensor force.

DISCUSSION

This study addressed the issue of whether the increase in quadriceps EMG activity as a function of increased force differs in exercises involving either one or two joints. The protocol employed also allowed us to test the hypothesis that the EMG/force relationship is nonlinear. The results of this

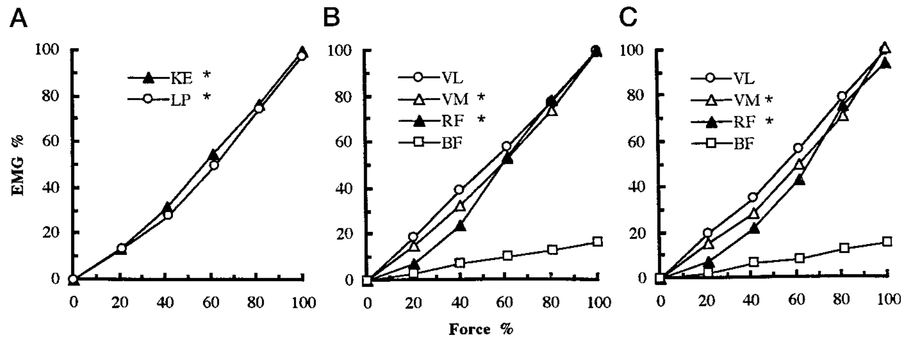

Figure 1—The EMG/force relationship for the mean values of the three superficial quadriceps muscles A) in knee extension and leg press, and B) for individual muscles in knee extension and C) leg press, respectively. EMG activity is expressed in percent of maximal values during KE, and force is expressed in percent of MVC in each exercise model. Values are mean ($N = 9$, except for BF; $N = 7$). KE, Knee extension; LP, Leg press; VL, vastus lateralis; VM, vastus medialis; RF, rectus femoris; BF, biceps femoris. * denotes a statistically significant deviation from linearity.

study suggest the EMG/force relationship is similar for the single-joint knee extension and the multi-joint leg press exercises for either quadriceps femoris (QF) or individual QF muscles. There were, however, differences in the EMG/force relationship among individual muscles, such that it was nonlinear for VM and RF, yet linear for VL.

The QF muscle group is the sole contributor to generate force in the KE. In the LP exercise additional muscles, including hip and ankle extensors, are brought into action and this might affect the QF EMG/force relationship. Moreover, the RF muscle may act as an antagonist by also flexing about the hip joint. It has been postulated that such a multiple function would reduce RF use in LP compared with that in KE (27). Our results are at variance and provide no evidence of failure of RF to be maximally activated because we observed no difference in maximal EMG activity between the two exercise modalities for any of the muscles, and the EMG/force relationship for QF or individual muscles was similar in LP and KE. This would imply that QF muscle use, at least in isometric actions performed at great flexion about the knee joint, is very similar in the multi-joint LP and the single-joint KE actions. In contrast to our findings, Eloranta (9,10) showed a linear relationship in the LP and a nonlinear relationship in the KE for all superficial QF muscles in two independent studies. His approach of averaging values compiled through the full range of motion, however, allows no comparison between exercises.

The nonlinear QF EMG/force relationship in the KE conforms with a previous study (14). Because individual muscles differ in size, e.g., RF cross-sectional area is only about one third of that of VL, and hence their relative contribution in generating force differ, averaged QF activity might not accurately reflect the EMG/force relationship of the entire muscle involved. Although it is unlikely, m. vastus intermedius (VI), which cannot be examined by surface EMG, may possess a markedly different EMG/force relationship, which in turn would impact the overall response. In either modality VL showed a linear relationship. Previous studies of KE showed either nonlinear (10,24) or linear (26) EMG/force relationships for VL. In contrast, VM displayed a nonlinear EMG/force relationship in this study and elsewhere (10). The nonlinear relationship found for RF in KE is consistent with previous observations (4,10,17,18,24). Differences in EMG/force relationship between muscles may indicate different recruitment patterns, such as a progressive relative use of RF and VM at higher loads. For the practical application of using surface EMG to estimate the force output of the entire QF muscle group, the present results favor the use of VL activity because of its linear relationship in both KE and LP exercise.

It has been put forth that a curvilinear EMG/force relationship in KE is caused by an unproportionally greater antagonist activation at heavier loads to stabilize the knee joint, concomitantly reducing the net force relative to EMG amplitude (3). The BF antagonist activity was minute and basically increased in proportion to increased loads. Therefore, and because it equalled only about 8% of knee extensor force as also shown elsewhere (8), it appears unlikely that antagonistic BF activity influenced the shape of the EMG/force curve. It has been suggested that such a co-activation in the KE is more pronounced at near extended knee (15), where the flexor to extensor force ratio is inherently

TABLE 1. Mean values (±SD) for knee extension, leg press, and knee flexion ($N = 9$, except for BF, N, 7).

Force Load (%)	F	VL (μV)	VM (μV)	RF (μV)	BF (μV)	QF (μV)
Knee extension	(Nm)					
20	42 ± 7	53 ± 18	63 ± 17	19 ± 10	9 ± 9	45 ± 6
40	84 ± 12	109 ± 38	138 ± 44	59 ± 17	19 ± 9	102 ± 19
60	126 ± 21	169 ± 65	223 ± 51	140 ± 41	26 ± 12	177 ± 28
80	168 ± 27	228 ± 92	321 ± 103	206 ± 60	34 ± 10	251 ± 49
100	208 ± 37	311 ± 182	452 ± 186	268 ± 80	44 ± 20	344 ± 102
Leg press	(N)					
20	163 ± 19	54 ± 17	61 ± 15	17 ± 8	6 ± 5	44 ± 8
40	324 ± 39	97 ± 34	118 ± 43	53 ± 23	16 ± 5	89 ± 26
60	483 ± 62	162 ± 66	216 ± 88	108 ± 40	21 ± 11	162 ± 49
80	640 ± 82	237 ± 119	303 ± 114	193 ± 65	33 ± 11	244 ± 65
100	787 ± 106	307 ± 169	443 ± 177	245 ± 72	40 ± 18	332 ± 102
Knee flexion	(Nm)					
100	85 ± 11	17 ± 7	28 ± 17	17 ± 7	283 ± 138	27 ± 14

F, force; VL, vastus lateralis; VM, vastus medialis; RF, rectus femoris; BF, biceps femoris; QF, quadriceps femoris (VL + VM + RF averaged).

increased (25), and the potential for knee stabilization in that position cannot be extrapolated from these data. Although BF is considered an agonist muscle in LP by extending at the hip joint, the results of this and a recent study, reporting on EMG activity in dynamic actions (12), showed no differences in maximal BF activity between KE and LP. Likewise, by studying the exercise-induced contrast shift of MR-images, Ploutz-Snyder et al. (22) showed almost no BF involvement in parallel barbell squat.

The present study reports on joint angle-specific EMG activity. It appears, however, that reciprocal EMG activity among the three superficial quadriceps muscles does not vary throughout the range of motion in the single-joint knee extension (13,19). Whereas RF activity at knee angle 90° is similar in LP and KE, it seems less used near full extension in LP and other multi-joint knee extensor activities (2,11). This is compatible with the finding of lower overall RF activity in LP and the squat compared with that in KE (12), and moreover, by the observation of modest RF use, as studied by magnetic resonance imaging (MRI) in the barbell squat executed through the full range of motion (22).

The reproducibility of surface EMG measurements across trials was quite similar for the two exercise modalities and the three muscles studied and of similar reasonable magnitude to what has been reported elsewhere (1,6). Yet there are certainly inherent methodological problems associated with use of the surface EMG technique (16,21,26), e.g., cross-talk between adjacent muscles, inaccessibility to certain muscles or portions of muscles, or lack of linearity in signal output from the recorded pick-up area. These limitations should not be neglected when interpreting the results of this study. We believe, however, that the study design employed allowed us to assess and compare the EMG/force relationship of individual quadriceps muscles in the knee extension and the leg press, where the results suggest muscle use to be very similar. Our findings, however, are restricted to angle-specific isometric actions and extrapolation of these observations to dynamic actions, for example, those performed in devices using cam or lever systems and producing variable external resistance through the arc of motion, should be exercised with caution.

The relationship between EMG activity of the three superficial quadricep muscles and force shows a striking similarity in multi-joint leg press and single-joint knee extension actions. It seems, however, that there are differences in the EMG/force relationship among the three superficial muscles, such that VL shows linear and VM and RF curvilinear responses in isometric actions at a knee angle of 90°. Regardless of the exercise model this suggests the increased demand of involvement may not be equally shared among muscles possessing different anatomical origin and insertion. Despite the slight deviation from linearity of quadriceps EMG when averaged across the three muscles, it appears that it can be used as a rough estimate of force. In this context VL seems to be the most valid individual muscle because EMG activity increases linearly with increased force.

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