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An Electromyographical Comparison of the Squat and Knee Extension Exercises

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Reference Data

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ABSTRACT

The seated knee extension is commonly used with the parallel squat to promote balance between the vastus medialis (VM) and vastus lateralis (VL). No controlled studies have examined the relative contributions of each muscle during these exercises, so this study employed EMG analysis to determine their contributions. Ten experienced lifters performed squats and knee extensions at their 10-RM. Sets were separated by 15 min rest and the order of performance was reversed between sessions, which were 1 week apart. EMG was collected on the VL and VM of the dominant leg during the first and last repetition of each exercise. Since EMG activity differed significantly between the two testing days, each was analyzed separately. No significant differences were found between the root mean square of the amplitude of the EMG for the VL and VM during either exercise. The parallel squat elicited more electrical activity than the knee extension in both muscles, and the downward shift in frequency of the EMG signal was greater for both the VM and VL during the parallel squat. The results question the value of the knee extension as a supplemental exercise in this case.

Key Words: muscle activity, vastus lateralis, vastus medialis, rmsEMG, mean power frequency

Introduction

Many coaches, trainers, and therapists believe that if the parallel squat is used exclusively for quadriceps development, it can cause a significant imbalance between the vastus lateralis (VL) and vastus medialis (VM) muscles. They usually recommend the seated knee extension, commonly called the leg extension, as a necessary exercise to reduce this imbalance. However, an exhaustive search of the literature produced no controlled studies confirming the imbalance between the VM and VL that is thought to occur with the exclusive use of the parallel squat. In addition, no studies could be found to indicate that the leg extension can correct this proposed imbalance. Thus it appears that this precept is based on a coupling of the data produced by a number of unrelated studies and some long-standing beliefs about the relative activity levels of the various quadriceps muscles.

In 1866 Duchenne used a localized faradization technique to analyze the relative contributions of the quadriceps muscles during knee extension (8). He reported that the VM had slightly greater activity during extension than the VL. Both Nicoll (19) and Steindler (26) expressed the belief that the leg could not complete its final 15° of extension without the vasti muscles, especially the VM. Smillie (25) stated that the VM is the "key to the knee" since it is the only component needed for the final 10 to 15° of knee extension, which was, in his estimation, the most important region in the knee's entire range of motion.

The selective function of the VM during the final phase of knee extension was first disputed by Brewerton (5). Using palpation, surface EMG, and saline infusion, he found no selective reductions, respectively, in muscle firmness, electrical activity, or measured pain response among these muscles during the final 15° of extension. Wheatley and Jahnke (28), using surface electrodes, also reported that the higher level of electrical activity seen during the final phase of the knee extension was present in both the VM and VL.

These conclusions were confirmed by the electromyographical studies of Pocock (21), using indwelling wire electrodes, and by Lieb and Perry (13), using needle electrodes. The latter study did report a higher degree of electrical activity for the oblique portion of VM throughout the entire range of motion, however, most probably due to the inefficient angle of pull of these fibers during the activity. In fact, an earlier study by Lieb and Perry (12) using amputated limbs concluded that the only selective function of the VM that could be found was patellar alignment. They also found that the increased activity of the VM during the final phase of knee extension was a function of the inefficiency of all the quadriceps muscles at this angle of pull.

Finally, in a comparative study of the electrical activities of the quadriceps muscles using fine wire electrodes during an unweighted and weighted knee extension compared with an unweighted parallel squat, Basmajian et al. (4) found that weighted knee extension elicited the greatest electrical activity in all muscles. In addition, they stated that the VM appeared to increase its electrical activity more rapidly during the final stages of the knee extension, but not during the squat. It should be recognized, however, that the squat exercise used in this study was without resistance.

The results of such studies appear to have been used to develop the hypotheses that (a) the VM can only be optimally strengthened by performing the knee extension during its final 15° of motion, and (b) performing the squat alone will cause an imbalance between the VM and VL and the related patellar misalignment that accompanies it. These hypotheses are questionable, however, since none of the studies attempted to use the functional loads commonly employed during training, making relative comparisons of the two exercises inappropriate.

Given this lack of information on the relative levels of electrical activity of the VL and VM during the parallel squat and knee extension at the resistance levels used during training, it was the purpose of this study to compare both the level of activation and amount of fatigue of the VM and VL muscles during such activity.

Materials and Methods

The subjects, 9 University of Miami football players and a strength training coach, were experienced lifters who performed both the parallel squat and knee extension exercises regularly. Physical characteristics of the group are presented in Table 1. All procedures were approved by the University of Miami's medical science subcommittee for the protection of human subjects, and informed consent was obtained prior to testing.

Table 1
Physical Characteristics and 10-RM Figures for All Subjects

Subj.	Height (cm)	Weight (kg)	Age (yrs)	Squat (10-RM) (kg)	Leg ext. (10-RM) (kg)
1	185.4	104.6	22	125.0	31.8
2	195.6	125.0	19	113.6	31.8
3	190.5	125.0	22	113.6	25.0
4	180.3	81.8	20	113.6	27.3
5	190.5	115.9	20	143.2	40.9
6	198.1	104.6	19	102.3	27.3
7	177.8	102.3	30	152.3	36.4
8	193.0	111.4	21	143.2	36.4
9	193.0	95.5	19	93.2	29.6
10	177.8	95.5	19	143.2	27.3

The subjects performed both the parallel squat and knee extension exercises. For the squat they used free weights placed on an Olympic-style bar. Knee extensions were performed on a Hammer knee extension machine (Hammer Strength, Cincinnati). Since a number of studies have shown greater muscle activity during a unilateral versus a bilateral movement (2, 22, 27), knee extension data were collected only on the dominant leg during alternating single knee extensions. Given that the squat is by definition a bilateral exercise, while the knee extension as performed in this study was unilateral, the implications of superior results produced during the squat would have even greater relevance. The strength and conditioning coach provided 10 repetition maximum (10-RM) figures for each exercise using data collected during regular training sessions.

Bipolar surface electromyography (EMG) was used to assess both the levels of electrical activity and degree of fatigue during each 10-RM set. Silver/silver chloride electrodes (1.2 cm diameter) were placed on the longitudinal axis of the vastus lateralis muscle and the oblique head of the vastus medialis muscles of the dominant leg at an interelectrode distance of 1.5 cm.

Surface electrodes were chosen for a number of reasons. First, this collection system is noninvasive and painless. Since the study was performed under the typical nonsterile environment of a college athletic department weight room, the noninvasive nature of the data collection system was considered important. Second, most subjects were reluctant to participate in the study if it involved invasive procedures. Third, the purpose of the study was to examine the level of EMG activity in two very large superficial muscles that could be easily evaluated using surface EMG. In fact, Basmajian and DeLuca (3) specifically recommend surface electrodes for this application. Fourth, the large movements involved in this study, as opposed to those in research studies using isometric contractions, can result in considerable movement and dislodging of indwelling electrodes due to the contraction of the muscle. Since it may take a number of contractions for this condition to stabilize, and this study measured fatigue as well as muscle activity, the use of indwelling electrodes was not considered feasible (10).

To ensure that the placement of the electrodes was the same across the 2 days of testing, a measurement was made along the longitudinal axes of each muscle from the superior rim of the patella to the lower rim of the most distal electrode on the first day. The electrode placement was then held constant for the second day of testing. For the VL, the proximal electrode was placed midway between the superior rim of the patella and the pelvic fold. For the VM, the proximal electrode was placed on the oblique fibers 5 cm superior to the superior rim of the patella.

The skin over each muscle was prepared by shaving, abrasion, and cleansing with alcohol to reduce impedance at the electrode/skin interface to a resistance of less than 5,000 ohms. Signals were amplified using a Grass P511k differential AC amplifier (Grass Corp., Quincy, MA). The gain was set at 2,000 with a band pass between 3 Hz and 3 kHz. Signals were digitized using a Metrobyte DAS16G analog-to-digital conversion board (Keithley/Metrobyte, Taunton, MA) at a collection speed of 1,024 samples/sec.

Although there is a possibility of cross talk among the three muscles tested, the bipolar configuration used during this study minimizes any such problems. As Andreassen and Rosenfalck (1) have reported, a bipolar configuration set parallel to the active fibers of the muscle is the most selective surface configuration. In addition, Lynn et al. (15) estimated that the area of detection using a bipolar surface configuration was equal to the interelectrode distance. Therefore the depth of the detection area is defined by a semicircle with a radius equal to approximately that same interelectrode distance. Since the girth of the muscles tested was substantially greater than 1.5 cm, the likelihood of cross talk was minimal. In addition, the high input impedance of the differential amplifier that was used (2×10^{10} ohms) and its high common mode rejection ratio (1,000:1 independent of frequency) further reduced the chance of cross talk using this bipolar configuration.

Subjects attended two sessions 1 week apart. During the first session they performed a set of 10 parallel squats at the 10-RM figure. This set was followed by a 15-min rest period and a set of 10 knee extensions at the subject's 10-RM figure. The same protocol was followed during the second session, with the exercises performed in the reverse order.

Since it was the purpose of this study to compare the muscular activity elicited by each exercise through its entire range of motion, rather than to evaluate specific segments of either movement, the EMG recorded for the entire repetition was used for the analysis. The data collected through the entire range of motion (ROM) of each exercise allowed direct comparisons, since questions of selective activation at specific points in the ROM were no longer pertinent. EMG was collected during the first and last repetition of each set. The raw EMG was plotted and examined for visual artifacts.

No trials were found to have prolonged delays between the concentric and eccentric portions of the movement. The root mean square (rmsEMG) of the EMG was used to evaluate the amplitude of the signal as a measure of muscle activity (3). Fast Fourier analysis was used to analyze the frequency power spectrum of the signal. Frequency changes were evaluated by differences in the mean of the power frequency spectrum (MPF) as an indication of fatigue (3, 11, 15, 16, 18).

A 2 × 2 × 2 × 2 (daily order × exercise × repetition × muscle) repeated measures ANOVA was used to analyze differences in the rmsEMG. Since the MPF analysis is based on a shift in frequency between the first and last repetition, a 2 × 2 × 2 (daily order × exercise × muscle) ANOVA was used to analyze these data.

Results

Since each session required a new preparation, differences in EMG values within individuals between the 2 days were expected due to variations in surface impedance or environmental variables across sessions. Given that the weight room was kept at an ambient temperature of between 24 and 26°C, electrode placement and interelectrode distance were held constant, and impedance was kept below 5,000 ohms, these effects should have been minimized. However, significant differences between sessions ($p < 0.05$) were detected for the first and last repetitions for each muscle during each exercise except for the first repetition of the knee extension ($p = 0.079$) and squat ($p = 0.090$) for the vastus lateralis.

These differences may have been due to levels of exercise performed by the athletes prior to the testing sessions, variations in body temperature at the time of collection, or differences in the levels of hydration at the time of testing. It should be noted, however, that the daily pattern of change that occurred across repetitions for each exercise was the same. Given the significant difference in raw EMG values across days, amplitude and frequency analyses for each day were reported separately.

No significant differences were found between muscles on any day within repetition or exercise. However, significant differences were detected between exercises for each muscle, on each day, during both the first and last repetitions, the only exception being for the VL during the first repetition on the first day of testing ($p = 0.073$). Figure 1 illustrates the difference in rmsEMG of the VL for the first and last repetitions during each session for each exercise. Figure 2 presents the same information for the VM. As can be seen, the

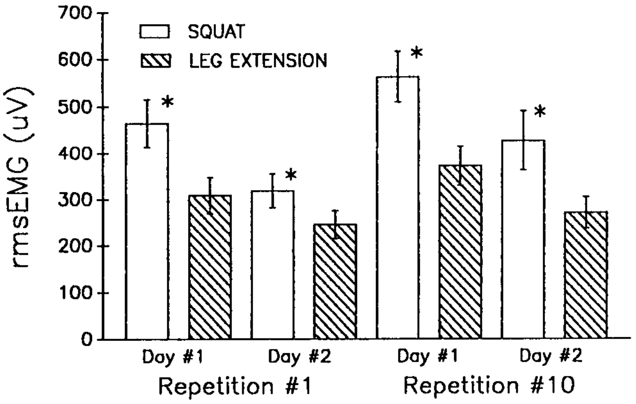

Figure 1. Vastus lateralis: rmsEMG for the first and last repetition of each exercise for each testing session. *Significantly higher value between exercises for the indicated muscle and session, $p < 0.05$.

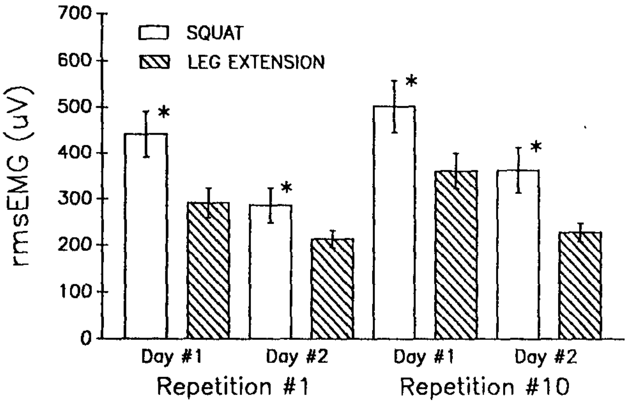

Figure 2. Vastus medialis: rmsEMG for the first and last repetition of each exercise for each testing session. *Significantly higher value between exercises for the indicated muscle and session, $p < 0.05$.

parallel squat evoked greater electrical activity than the knee extension across both muscles during each repetition on both testing days.

The rmsEMG values for the VL during the first repetition of the squat on the first and second test days averaged 464.4 ± 50.9 μV and 318.8 ± 36.1 μV, respectively. For the same repetition, the knee extension produced significantly less electrical activity on the first day of testing, yielding 308.5 ± 38.9 μV (p = 0.037), and showed a similar trend on the second testing day, producing 245.5 ± 30.1 μV (p = 0.032). The VM produced rmsEMG values of 441.0 ± 50.0 μV and 286.2 ± 37.7 μV for the first repetition of the squat on the first and second days, respectively. As with the VL, the knee extension yielded significantly lower rmsEMG values than the squat at 291.5 ± 32.4 μV (p = 0.014) and 213.0 ± 18.4 μV (p = 0.040) for the first and second testing days, respectively.

Similar differences were detected for the last repetition across both muscles for both testing sessions. On the preliminary testing day, the VL produced 536.0 ± 53.3 μV and 372.5 ± 42.6 μV for the squat and knee extension, respectively. This constituted a significant difference (p = 0.002). The squat also produced significantly greater VL activity during the final testing session, producing 427.0 ± 63.7 μV compared to 271.2 ± 33.9 μV for the knee extension (p = 0.029).

The pattern of the squat producing greater electrical activity than the knee extension held true for the VM across days during the 10th repetition. On Day 1 the squat produced greater electrical activity at 501.5 ± 55.9 μV than the knee extension at 361.5 ± 38.1 μV (p = 0.042). On Day 2, values of 363.3 ± 49.5 were recorded from the VM for the squat and 228.0 ± 20.1 for the knee extension (p = 0.026). Finally, the differences in rmsEMG values for the first versus the last repetition within exercise conditions and testing days were not statistically significant.

Figure 3 presents a sample illustration of the raw EMG and frequency power spectrum for one subject.

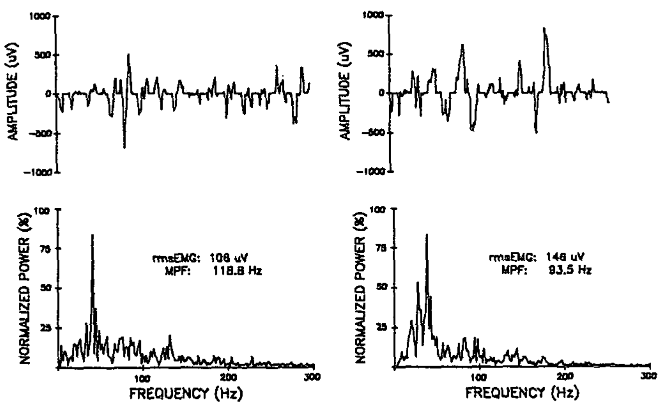

Figure 3. Raw EMG and frequency power spectra of the first and last repetitions for Subject 1. Note the decline in MPF and increased rmsEMG characteristic of fatigue.

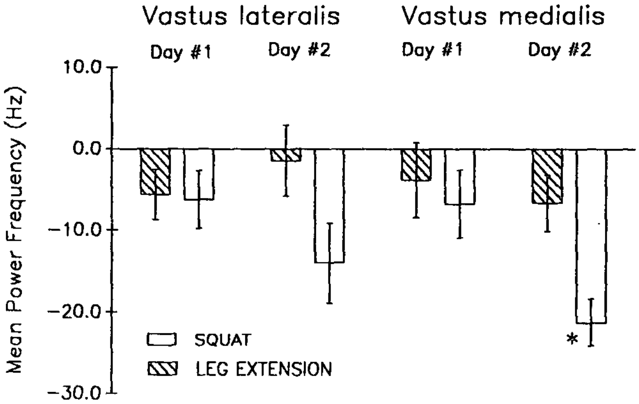

Figure 4. Changes in MPF between the first and last repetition of each muscle on each day during each exercise. *Significantly greater drop in MPF, $p < 0.05$.

This subject shows a typical fatigue response to submaximal exercise: a drop in MPF and an increase in rmsEMG. This response is notably small compared to that elicited by a static contraction. This is typical of a dynamic contraction when increased metabolite washout occurs due to the pumping action of the lengthening and shortening musculature (17, 22, 24).

Figure 4 shows the changes in MPF between the first and last repetition for each muscle during each exercise on each day of testing. As would be expected, the MPF values for the first repetition between muscle groups for each exercise did not differ significantly. However, the drop in MPF was significantly greater ($p < 0.011$) for the VM during the last repetition of the squat (21.1 ± 2.8 Hz) versus the knee extension (6.6 ± 3.5 Hz) on the second day of testing. This same trend held true for the VL (squat = 14.0 ± 4.9 Hz, knee extension = 1.4 ± 4.3 Hz), but the difference was not statistically significant ($p < 0.137$).

Discussion

The results of this study raise doubts about the need to supplement the parallel squat with the knee extension in order to balance VM activity with VL activity. The data from our laboratory question the need to use the knee extension as a supplemental exercise for two reasons. First, no significant differences were found in electrical activity between the VL and VM for either the first or last repetition of the squat during either testing session. These data cast doubt on the assumption that there is a disproportionate amount of activity, which would cause unequal development, between these muscles during the squat. These results are in agreement with a number of studies reporting equal contributions of the VM and VL during the knee extension (5, 9, 13, 21) and unweighted squat (3).

The second reason is based on the differences between the two exercises. When the two exercises were compared at the same relative intensity, 10-RM, the squat produced greater electrical activity than the knee extension in the VM as well as in the VL during all repetitions on all testing days. These results are not surprising since, at the same relative load (10-RM), the absolute load for the squat far exceeded that of the knee extension. In addition, the significant drop in the MPF of the frequency power spectrum for the VM during the last repetition of the squat, compared to the knee extension during the second day of testing, reflects the greater fatigue that results from its repeated execution. It is therefore a further indication of increased effort during the parallel squat.

Although it may be argued that these shifts were most prominent during the testing session when the squat followed the leg extension in order of execution (Day 2), this same significant shift did not occur during the leg extension on Day 1 when it was the second exercise performed. Thus it is doubtful that the results recorded on Day 2 are based on residual fatigue from doing the leg extension prior to the squat, although some residual fatigue might be hypothesized during both performance sessions. The downward shift of the EMG signal in both the VM and VL is even more striking since dynamic exercise does not produce the same sustained occlusion characteristic of isometric exercise, and therefore the shift in MPF would not be expected to be as pronounced (23, 24).

Practical Applications

While a single study should not be the basis for immediately changing practices that have served athletes well over the years, these data do raise questions about the rationale on which the practices are based. The questions are important both in the weight room and during rehabilitative therapy.

The practical implications in the weight room are quite obvious. The mandatory prescription of the leg extension, during lifting sessions that are already lengthy, appears to be unwarranted. This does not mean the knee extension is ineffectual as a supplemental exercise for the quadriceps group, but the data do suggest that its touted role in maintaining muscular balance and preventing injury is tenuous at best. It should also be noted that the squat elicited greater muscle activity than the seated knee extension in both muscles, making it a logical choice for increasing strength.

Possibly as important if not more so are the implications for rehabilitation. Seated knee extensions have been the primary quadriceps rehabilitative exercise for decades. Recently, however, concerns have been raised about the increased stress that develops during knee extensions compared to the parallel squat. For example, Palmitier et al. (20) reported greater stresses on the anterior cruciate ligament during the knee extension versus the squat. In addition, Lutz et al. (14) reported that shear forces during the leg press were significantly lower than those experienced during leg extensions or leg curls at comparative knee angles. Finally, Brownstein et al. (6) concluded there is less patellofemoral contact during the final 30° of leg extension than during the initial 30°.

This reduced contact, which is obviously part of every full-range knee extension, leads to greater tensile stress on the patella. Due to the closed-chain nature of the squat and the reduced forces at the terminal angles of extension, these stresses are greatly reduced. As stated in a roundtable discussion (7) on the subject of rehabilitation, "knee extension exercises may place greater anterior/posterior forces on the joint than closed kinetic chain exercises [squats, leg presses]."

Further studies should be done to confirm these results and examine specific changes in activity in the entire quadriceps group throughout the ROM of each exercise at normal training intensities. Given the emphasis on quality of training and the time commitment already demanded of amateur, professional, and student athletes, workouts must be designed to produce optimal results with minimal time requirements. Therefore, unnecessary or redundant activities that reduce the time and energy the athlete can apply to sport-specific skill training should be eliminated. In addition, rehabilitation exercises that reduce compression and subluxation while promoting balance and maximal strength development are of utmost importance. It may be beneficial to examine the use of pressing exercises, such as the squat, during knee rehabilitation.

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