RANGE OF MOTION AND LEG ROTATION AFFECT ELECTROMYOGRAPHY ACTIVATION LEVELS OF THE SUPERFICIAL QUADRICEPS MUSCLES DURING LEG EXTENSION

JOSEPH F. SIGNORILE,[1,2] KAREN M. LEW,[1] MARK STOUTENBERG,[3] ALESSANDRA PLUCHINO,[4] JOHN E. LEWIS,[5] AND JINRUN GAO[6]

[1]Department of Kinesiology and Sport Sciences, University of Miami, Coral Gables, Florida; [2]Associate Faculty, Center on Aging, Miller School of Medicine, University of Miami, Miami, Florida; Departments of [3]Epidemiology and Public Health; and [4]Family Medicine and Community Health, Miller School of Medicine, University of Miami, Miami, Florida; [5]Department of Psychiatry & Behavioral Sciences and Associate Director of the Medical Wellness Center, Miller School of Medicine, University of Miami, Miami, Florida; and [6]American International Group, New York, New York

ABSTRACT

Signorile, JF, Lew, KM, Stoutenberg, M, Pluchino, A, Lewis, JE, and Gao, J. Range of motion and leg rotation affect electromyography activation levels of the superficial quadriceps muscles during leg extension. *J Strength Cond Res* 28(9): 2536–2545, 2014—Leg extension (LE) is commonly used to strengthen the quadriceps muscles during training and rehabilitation. This study examined the effects of limb position (POS) and range of motion (ROM) on quadriceps electromyography (EMG) during 8 repetitions (REP) of LE. Twenty-four participants performed 8 LE REP at their 8 repetition maximum with lower limbs medially rotated (TI), laterally rotated (TO), and neutral (NEU). Each REP EMG was averaged over the first, middle, and final 0.524 rad ROM. For vastus medialis oblique (VMO), a REP × ROM interaction was detected ($p < 0.02$). The middle 0.524 rad produced significantly higher EMG than the initial 0.524 rad for REP 6–8 and the final 0.524 rad produced higher EMG than the initial 0.524 rad for REP 1, 2, 3, 4, 6, and 8 ($p \leq 0.05$). For rectus femoris (RF), EMG activity increased across REP with TO generating the greatest activity ($p < 0.001$). For vastus lateralis (VL), EMG increased across REP ($p < 0.001$) with NEU and TO EMG increasing linearly throughout ROM and TI activity greatest during the middle 0.524 rad. We conclude that to target the VMO, the optimal ROM is the final 1.047 rad regardless of POS, while maximum EMG for the RF is generated using TO regardless of ROM. In contrast, the VL is maximally activated using TI over the first 1.047 rad ROM or in NEU over the final 0.524 rad ROM.

KEY WORDS strength training, electromyographic activity, patellofemoral joint, vastus medialis, vastus lateralis

INTRODUCTION

Resistance exercises are commonly used to strengthen the muscles of the quadriceps group during training and rehabilitation. Among the major concerns faced by therapists, athletic trainers and strength coaches are low quadriceps strength and imbalances in strength and activation patterns between vastus medialis oblique (VMO) and vastus lateralis (VL) muscles, which may potentially lead to patellofemoral pain and dysfunction. Clinicians maintain that when the patella is surrounded by unbalanced forces that cause lateral patella tracking, the results are abnormal stresses on the subchondral bone resulting in pain and injury. These forces can be caused by poor coordination between the medial and lateral pull produced by the VMO and VL, respectively, combined with tightness of the lateral retinaculum and iliotibial band (12). Strengthening of the VMO is often considered an essential component of the treatment of anterior knee pain related to physical and biomechanical changes in the patellofemoral joint (12,24). Keeping this in mind, it may be desirable to selectively strengthen the vasti muscles, especially the VMO, to correct imbalances and re-establish or maintain normal patellofemoral tracking and reduce the likelihood or severity of irregular tracking patterns (7,35,36).

The benefits of closed chain kinetic exercises and open chain kinetic exercises (OKC) are well established in the literature (17,41,42). Traditionally, the leg extension (LE), the predominant OKC exercise, has been performed through the final 0.524 rad of extension if the specific objective was

Address correspondence to Joseph F. Signorile, jsignorile@miami.edu.

28(9)/2536–2545

Journal of Strength and Conditioning Research

Table 1. Physical characteristics of subjects.*

	N	Height (m)	Weight (kg)	Age (y)
Female	12	1.65 (0.09)	60.2 (7.3)	22.6 (2.2)
Male	12	1.84 (0.05)	84.9 (9.6)	24.8 (5.2)
Total sample	24	1.74 (0.12)	72.5 (15.1)	23.7 (4.0)

*Values represent mean (*SD*).

strengthening the VMO. Leg extension exercises in this end range of motion (ROM) have been encouraged because the overload on the VMO seems to be the greatest over this range (13,39); however, questions remain concerning the extent to which VMO recruitment and isolation are possible by limiting LE to the final 0.524 rad of extension (35). Additionally, some researchers contend that full extension may be ill-advised due to an increasing external moment arm, which creates large external and shearing forces, particularly over the final 0.785 rad of extension (19,21). These authors, therefore, advocate limiting the use of LE to the initial 0.785 rad of extension (0.785–1.571 rad of extension) to reduce these potentially damaging forces.

Given the discussions concerning the effectiveness and safety of using limited ROM to selectively target the VMO and VL, researchers have also examined the use of different foot positions during LE. These studies have included analyses during isometric (36–38), isokinetic (9,10,18), and isoinertial exercise (32).

To our knowledge, however, only 2 studies have used electromyographic (EMG) analyses to quantify VMO versus VL activity levels during isoinertial LE training. The initial study by Signorile et al. (32) examined the effect of 3 positions (POS): tibial internal rotation (toes in: TI); neutral rotation (toes neutral: NEU); and tibial external rotation (toes out: TO) during a single repetition through a constant ROM. The second study by Stoutenberg et al. (33) quantified levels of EMG activity of these muscles using the same 3 POS during a typical multirepetition, isoinertial training set. Finally, to date, only a single study has examined the combined effects of knee angle and ROM; however, the analysis was performed during isometric rather than isoinertial training (30). Our hypothesis is that the individual muscles of the quadriceps group can be selectively targeted during the LE exercise using knee angle and foot position, and that activity levels due to foot position will vary throughout the ROM of the exercise. Patella femoral pain (PFP) continues to be a concern when clinicians are working with LE injuries.

Providing clinicians, including therapists, strength coaches, or athletic trainers with the capacity to combine ROM and POS for more effective targeting of the vasti muscles may allow safer and more effective protocols for reducing and assessing anterior knee pain (11). Keeping this in mind, we investigated the EMG activity of the 3 superficial quadriceps muscles through 3 specific ROM during LE repetitions (REP) using TI, NEU, and TO. Increased activity of the VMO has been reported during the final 30° of knee extension in electromyographical and cadaver studies. Foot position can have a significant clinical implication if the emphasis is placed on proper positioning. End ROM should combine ROM and foot position to better target the vasti muscles.

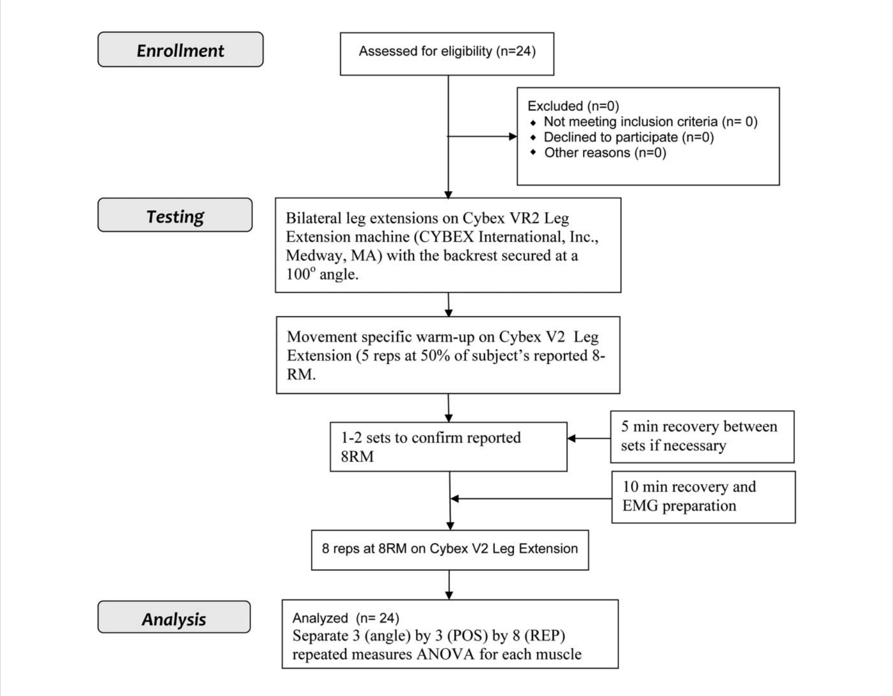

Figure 1. Study flow diagram.

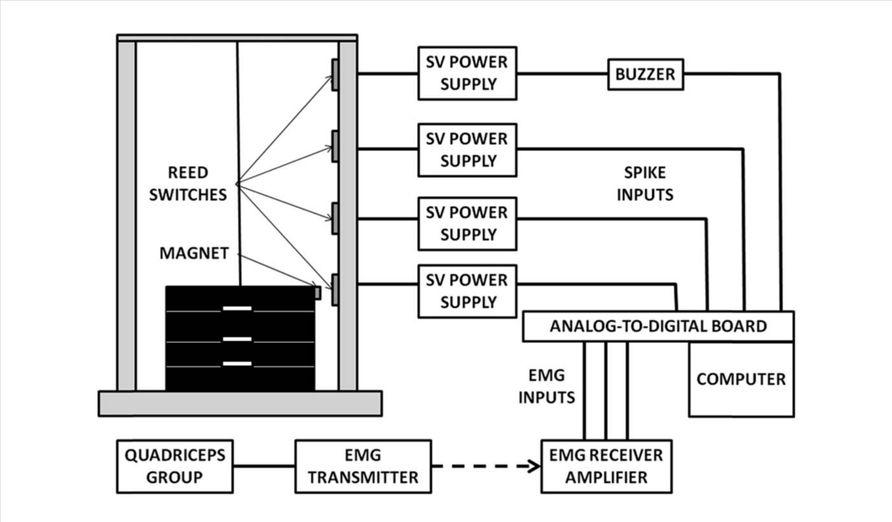

Figure 2. Schematic diagram of the collection system.

METHODS

Experimental Approach to the Problem

To investigate the impacts of foot position and ROM on the selected activities of the VL, vastus medialis, and rectus femoris (RF) during the LE exercise, participants performed three 8-repetition sets through their full ROM with their feet in the toes in, neutral, or toes in position. Each repetition was divided into three 0.524 rad segments marked by pulses resulting from closures of magnetic reed switches. Electromyographic activities of the RF and vasti muscles were collected throughout each set. The patterns of foot positions were randomly assigned, and recovery periods of 10 minutes were provided between sets. Separate 3 (ROM) by 3 (foot position) by 8 (repetition) repeated measures ANOVA were used to assess differences in the activities of the 3 superficial quadriceps muscles, and least square mean analyses with a Bonferroni adjustments were used to ascertain the source of those differences.

Subjects

Twelve men and 12 women (aged 18–40 years), who were currently training at least twice a week and had a minimum of 6 months of lifting experience, participated in the study. Physical characteristics of the subjects, who met these criteria and participated in the study, are presented in Table 1. Before admission into the study, all potential subjects completed a medical questionnaire form, which was used to screen for previous or preexisting injuries. To qualify for the study, applicants needed to be in good health with no knee problems, such as tendinitis, instability, or previous surgical repairs, which could have affected their performance or put them at undue risk for injury. The University of Miami Institutional Review Board for the Protection of Human Subjects approved all procedures before testing, and subjects were required to sign an informed consent before participation. The study complied with the principles laid down in the Declaration of Helsinki. A flow diagram illustrating the study design is presented in Figure 1.

TABLE 2. Beginning and ending knee angles of subjects.*

	N	Beginning (rad)	Ending (rad)
Female	12	1.950 (0.075)	0.209 (0.070)
Male	12	1.941 (0.099)	0.180 (0.069)
Total sample	24	1.941 (0.091)	0.201 (0.070)

*Values represent mean (*SD*).

Lifting Protocols

Bilateral LEs were performed on a Cybex VR LE machine (CYBEX International, Inc., Medway, MA, USA) with the backrest secured at 1.75 rad. The bilateral LE was chosen over the single leg movement because it provided a more comfortable position for varying foot positions and is a more commonly used exercise than the unilateral LE. Subject testing and data collection occurred during a single laboratory session. This ensured that the collected EMG data were not affected by electrode placement or preparation or environmental variations. All exercises were preceded by a movement-specific warm-up on the Cybex machine consisting of 5 repetitions (REP) at 50% of the subject's reported 8RM. After the warm-up set, each subject performed 1 or 2 additional sets to establish his or her 8RM. Because subjects were experienced weight-trainers, they were able to establish their 8RM within 2 testing sets. Subjects were provided a 5-minute recovery period between 8RM attempts and received a minimum of 10 minutes of additional recovery before the start of testing. During this time, the subject was prepared for EMG data collection.

Electromyography

Because the purpose of the study was to examine the level of EMG activity in the 3 large superficial quadriceps muscles (VL, RF, and VMO), a bipolar surface electrode configuration was chosen to maximize the reception area, while controlling the potential for cross talk among the muscles examined. Surface electrodes have been specifically

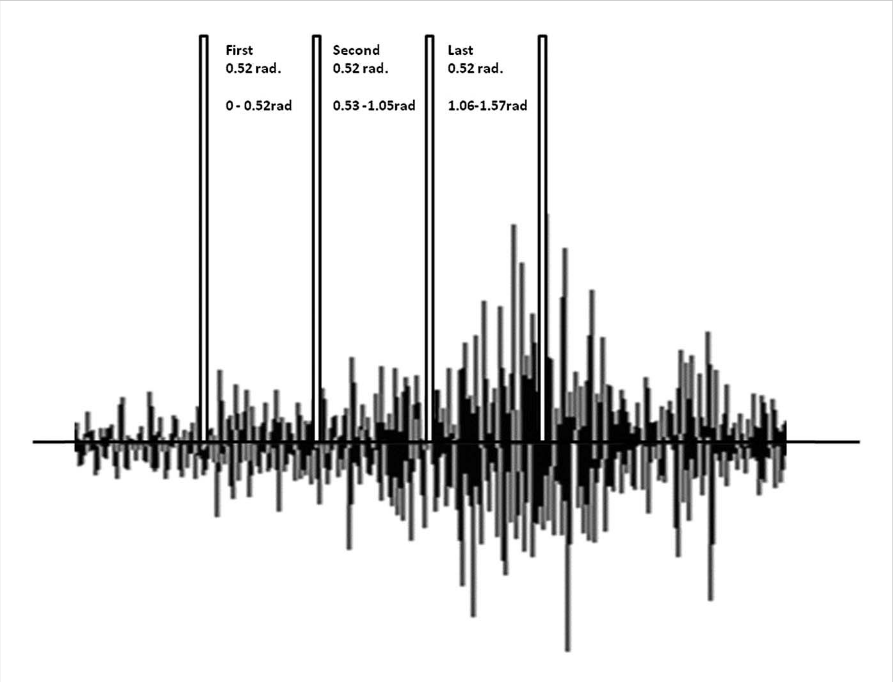

Figure 3. Illustration of a raw electromyography signal with 5-V spikes used to delineate specific ranges of motion.

recommended for this application. Andreassen and Rosenfalck (2) have reported that a bipolar configuration set parallel to the active fibers of the muscle is the most selective surface configuration to control for cross talk. In addition, Lynn et al. (22) estimated that the area of detection using a bipolar surface configuration was equal to the interelectrode distance. Because the girth of the muscles examined in this study was considerably greater than the 1.5-cm interelectrode distance used, the likelihood of cross talk was minimal.

The location of each muscle's motor point was determined using a low-voltage stimulator delivering a series of 5-millisecond pulses at 5 pulses per second. Voltage was progressively reduced from approximately 50 V until only 1 point elicited a response. This point was then used as the motor point for that muscle. After motor points were located, the skin surface distal to each point was shaved, lightly abraded, and cleaned with alcohol to remove dead surface tissues and oils, which might reduce signal fidelity. Disposable Ag/AgCl pregelled disk surface electrode pairs (Marquette Medical Systems, Jupiter, FL, USA) were positioned immediately distal to each motor point, 1.5 cm apart and parallel with the underlying muscle fibers as determined by the pennation of the muscle. EMG data were collected from the quadriceps muscles of each subject's right leg, and a reference electrode was placed on the head of the fibula of the same leg.

Raw EMG signals were recorded using a wireless telemetry system (Noraxon USA, Inc., Scottsdale, AZ, USA), and the quality of the signals was visibly assessed for each muscle before data collection. The Noraxon system used to collect the EMG data had an input impedance of 2 Megaohms (MΩ) and a common mode rejection ratio of 100 db. The gain was set at 2000 with band pass filtering set between 5 and 500 Hz. Signals were sampled at a speed of 1024 Hz, digitized using

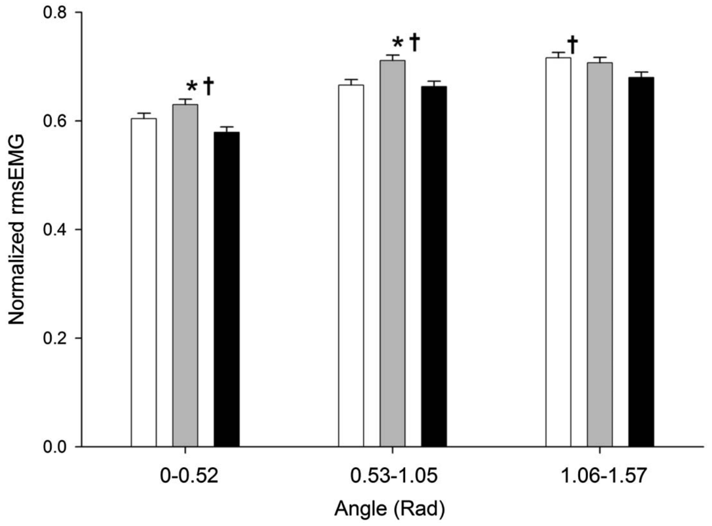

Figure 4. Normalized vastus lateralis rms electromyography for the neutral, toe in, and toe out positions across designated ranges of motion. *Significantly different than the neutral position ($p \leq 0.05$). †Significantly different than toe out position ($p \leq 0.05$).

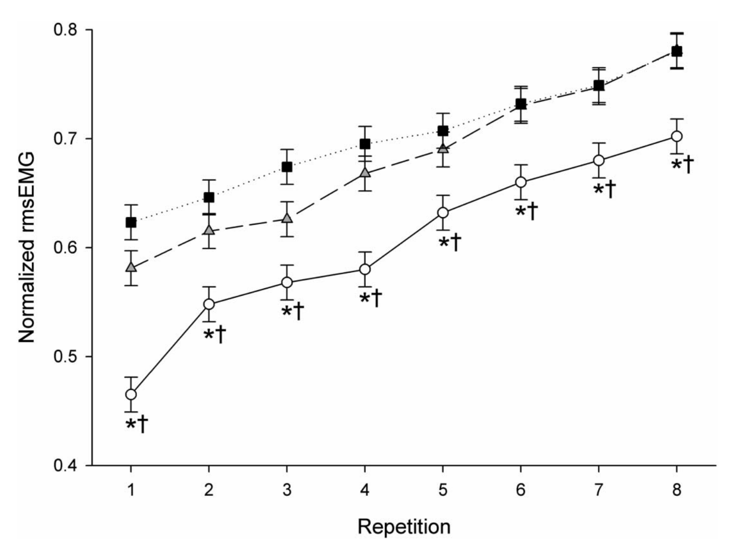

Figure 5. Normalized vastus lateralis rms electromyography for the 0–0.524 rad, 0.525–1.047 rad, and 1.047–1.570 rad positions across repetitions. *Significantly different than 1.047–1.570 rad ($p \leq 0.05$). †Significantly different than 0.525–1.047 rad ($p \leq 0.05$).

a 16-bit A/D converter (DataPac, Laguna Beach, CA, USA) and stored on a laboratory computer.

Data Collection

After electrode preparation, each subject performed bilateral LE at 70% of his or her 8RM. The ROM for the LE movement was individually established for each subject. A magnet was attached to the upper edge of the top plate on the moving weight stack. Two magnetic closure (reed) switches, interfaced with 5 V power sources, were placed on the frame of the LE machine at each end of the subject's ROM. One reed switch was placed on the frame of the LE machine directly across from the magnet, when the subject was seated in the machine with the weight plates resting on one another. The angle of knee flexion was measured at this point using a mechanical 12-inch International Standards of Measurement goniometer. The subject was then asked to maximally extend his or her legs, and a second reed switch was placed on the machine frame at this position to mark the upper end of the subject's ROM. Two additional reed switches were placed on the LE machine at 0.524 rad and 1.047 rad of knee flexion from the horizontal plane. A schematic diagram of the LE data collection is presented in Figure 2. Mean values for the knee angle corresponding to the beginning and end points of ROM for the male and female subjects and the entire sample are presented in Table 2.

During each REP, whenever the magnet passed a reed switch, a 5-V spike was produced and sent to the analog-to-digital board of the EMG collection system. These spikes were used to separate the different angles at which EMG data were collected throughout the concentric portion of the LE (Figure 3). The reed switch marking the end ROM was interfaced with a second 5-v power source and a buzzer, so an audible signal was produced. This signal indicated to the subject that he or she had reached the end of the concentric ROM. The spikes collected at the beginning and end of each concentric contraction allowed us to accurately mark the concentric portion of the event for EMG analysis.

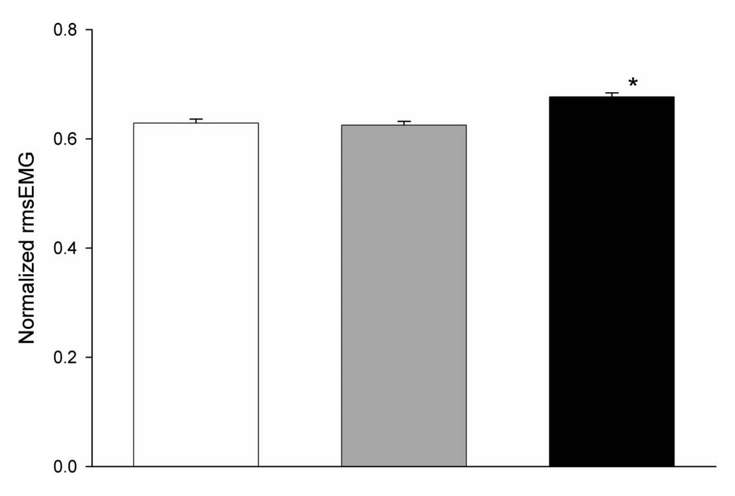

Figure 6. Normalized rectus femoris root mean square electromyography for the toe in, neutral, and toe out positions. *Significantly different than the neutral and toe in positions ($p < 0.0001$).

Three foot positions (POS) were tested during each testing session: (a) toes neutral (NEU) with no medial or lateral

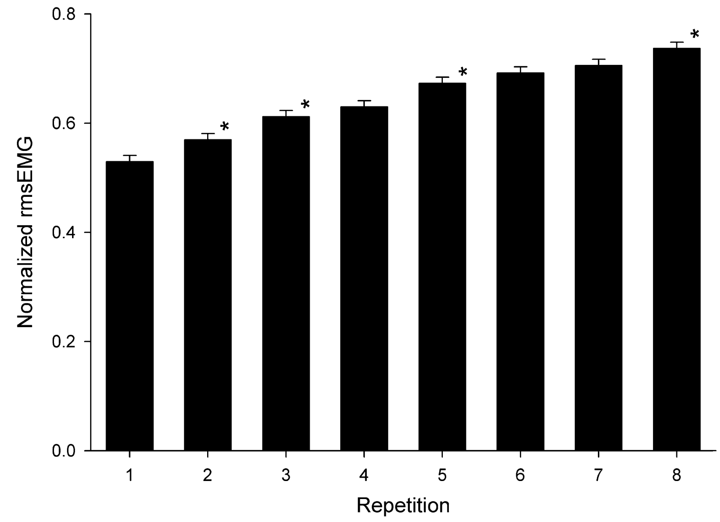

Figure 7. Normalized rectus femoris root mean square electromyography across repetitions. *Significantly higher than the preceding repetition ($p \leq 0.05$).

rotation, (b) toes in (TI) with toes internally or medial rotated as far as the subject could comfortably be maintained by the subject throughout all REP, and (c) toes out (TO) with toes externally or laterally rotated as far as the subject could comfortably be maintained throughout all REP. No attempt was made to dictate a specific foot angle for the TI or TO POS because this would be dependent on each individual's ROM and his or her ability to maintain that position during performance of the LE. The order of the POS was randomly selected to reduce the impact of any order effect. One set of 8 REP was performed for each POS. A REP was not counted unless it was performed throughout the individual's full ROM. An acceptable REP began with a momentary resting of the weight plates and ended, when the magnet affixed to the weight stack passed the reed switch eliciting an audible signal. Subjects were instructed not to reverse the direction of movement at the top of the ROM until the audible signal was heard and to provide a momentary stop at the bottom of the ROM. Subjects were given a 5-minute recovery period between sets. Consistent instructions were used to motivate the subjects during testing. Data were collected throughout the entire ROM and later divided into the concentric and eccentric portions of each REP for analysis.

Electromyographic Analysis Procedures

Recorded EMG signals from each muscle were analyzed using DATAPAC 2K2 software (Run Technologies, Mission Viejo, CA, USA). The root mean square of the EMG signal (rmsEMG) was used as a measure of average muscle activity for each muscle throughout the concentric phase of each REP under each testing POS. The rmsEMG signal was normalized (NrmsEMG) using the highest recorded value seen for each individual muscle during any of the 3 testing POS, and all comparisons were made using NrmsEMG.

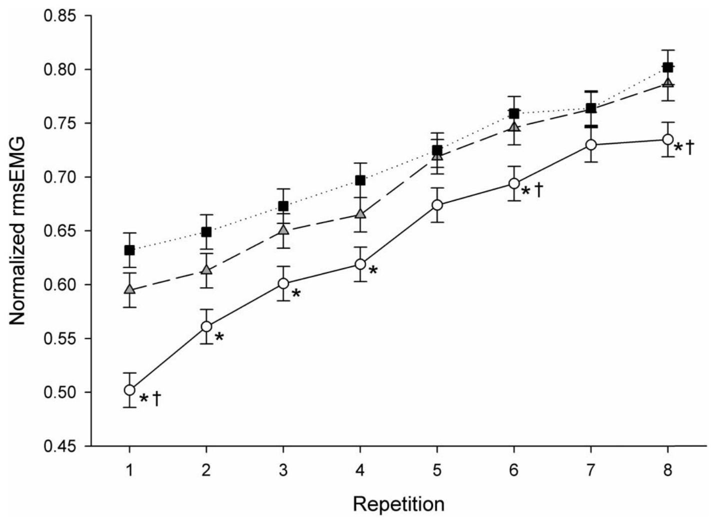

Figure 8. Normalized vastus medialis root mean square electromyography for 0–0.524 rad, 0.525–1.047 rad, and 1.047–1.570 rad across repetitions. *Significantly different than 1.047–1.570 rad ($p \leq 0.05$). †Significantly different than 0.525–1.047 rad ($p \leq 0.05$).

Statistical Analyses

Data analyses included separate 3 (ROM) by 3 (POS) by 8 (REP) repeated measures ANOVA to examine differences in NrmsEMG within each of the 3 superficial quadriceps muscles. When statistically significant differences were detected, individual least square means (LS means) analyses with a Bonferroni adjustment were used to ascertain the source of those differences. All analyses were performed using the SAS 8.0 statistical package (SAS Institute Inc., Cary, NC, USA).

RESULTS

Vastus Lateralis

For the VL, significant POS by ROM ($p < 0.001$) and REP by ROM ($p = 0.007$) interactions were detected. A post-hoc analysis of the POS by ROM interaction revealed that the EMG activity produced during the NEU and TO positions increased linearly across knee angles, while the EMG activity for the TI position was the greatest in the middle 0.524 rad ROM. The electrical activity produced in the TI position was significantly greater than the TO and NEU positions during the first 0.524 rad and middle 0.524 rad ROM. Additionally, over the final 0.524 rad ROM, only the NEU position was significantly different than the TO position (Figure 4). The post-hoc analysis of the REP by ROM interaction revealed that no significant differences existed between the middle and final 0.524 rad ROM over the course of the 8 REP. However, the first 0.524 rad ROM was significantly lower than the middle and final 0.524 rad ROM during each REP (Figure 5).

Rectus Femoris

For the RF, significant main effects were observed for REP ($p < 0.0001$) and POS ($p = 0.0009$). Mean EMG activity of the RF progressively increased across REP (Figure 6). For POS, the TO position generated significantly higher electrical activity than either the NEU ($p < 0.001$) or TI ($p < 0.001$) positions (Figure 7).

Vastus Medialis

A significant REP by ROM interaction ($p = 0.02$) was found for the VMO. A post-hoc analysis revealed that no significant differences existed between the middle and final 0.524 rad ROM over the course of the 8 REP; however, the electrical activity during the first 0.524 rad ROM was significantly lower than that of the middle 0.524 rad for REP 6 and 8 and the final 0.524 rad for REP 1, 2, 3, 4, 6, and 8 (Figure 8).

DISCUSSION

This is the first study, to our knowledge, examining levels of EMG activity of the superficial quadriceps muscles using specific ROM and POS during a set of isoinertial bilateral LE; however, the combined effects of ROM and POS have been examined in one other study by Signorile et al. (30) using isometric contractions at 3 set knee angles, 90° (1.571 rad), 150° (2.620 rad), and 175° (3.054 rad). Given that these are the only studies that evaluated the concurrent influences of these 2 factors on quadriceps' activity levels, we will begin our discussion with a comparison between the findings from this study and those presented by Signorile et al. (30).

The results of this study show that to maximally activate the VL, both ROM and POS must be considered. When the LE was performed with the ROM limited to the initial 1.047 rad, TI produced the highest electrical activity levels. As we noted in an earlier article (31), the increased muscle activity may have been due to the medial rotation of the leg causing an increase in tension along the fibers that run obliquely downward from the VL lateral to the medial side. These results differ from those reported by Signorile et al. (30) for the VL during isometric LE testing, where NEU produced greater electrical activity than TI at 90° (1.571 rad) and greater than TO at 150° (2.620 rad) knee angles. These knee angles are within the first and second 0.524 ROM used during this study. Our results showing that NEU produced greater activity than TO during the final 0.524 rad agree with their results, which noted that NEU produced greater electrical activity than TI or TO at a 175° (3.054 rad) knee angle.

Our results indicating that for targeting the RF, ROM was not a consideration and that TO generated the highest activity also differs considerably from those reported by Signorile et al. (31). They reported that 90° produced greater activity than 175° (3.054 rad) during NEU and TO and greater activity than 150° (2.620 rad) in neutral POS. They also stated that in the NEU and TO POS, 150° (2.620 rad) produced higher activity than 175° (3.054 rad). They noted that no differences were seen due to POS for any knee angle with the exception of 150° (2.620) rad, which generated a higher rmsEMG at NEU versus TI, but did not differ from TO.

Finally, when comparing our results for the VMO to those of Signorile et al. (30), our finding that, across a set of exercise, the rmsEMG for the second and third 0.524 rad ROM was greater than for the initial 0.524 rad ROM regardless of POS, once again differs from their findings. Signorile et al. (30) reported that at 90° (1.571 rad) and 150° (2.620 rad), NEU produce greater EMG activity than TI and TO, respectively, and that for the 175° (3.054 rad) knee angle, TI activity was greater than that for TO. Additionally, these researchers also reported for the TO position that the 90° (1.571 rad) knee angle produced greater activity than either the 150° (2.620 rad) or 175° (3.054 rad) knee angle.

The differences between the results reported by Signorile et al. (30) and those of this study may be explained by a number of factors. The fact that their study used a single isometric contraction at isolated knee angles, rather than isoinertial contractions throughout each subject's identified ROM is the most obvious explanation. A number of researchers have reported weak relationships between EMG activities during maximum dynamic versus isometric performances (4,8). These differences may be the result of the type of contraction (3), the load or tension produced (1,15), changing angles throughout each individual's ROM (14), the speed of movement and momentum (29), and incorporation of elastic energy from the stretch-shortening cycle (23,28). Therefore, comparisons between these studies, although both examined the interactive effects of knee and foot positions on quadriceps activities, are tenuous.

Comparisons of our results to other studies that have examined POS during dynamic contractions are feasible, but cannot address the potential interactions that are evidenced by our results. For the VL, our results showing that the TI POS produced the highest activity levels during the initial 1.047 rad are in agreement with the results reported by Stoutenberg et al. (33) who stated that this POS produced the highest electrical activity levels for the VL throughout participants' full ROM. However, our results differ from those reported by Signorile et al. (32) who reported no impact on EMG activity due to POS. The stronger agreement between the results reported by Stoutenberg et al. (33) compared with the earlier study by Signorile et al. (32) may have been the result of the use of a similar number of repetitions by thsi study and that of Stoutenberg et al. (33) compared with the 3 repetitions used in the earlier study (32). Additionally, the subjects in the study by Signorile et al. (32) were Division 1 competitive athletes, whereas this study included participants between the ages of 18 and 40 years, and the study by Stoutenberg et al. (33) used college-aged subjects, engaged in recreational resistance training. Our results also agree with the findings of Wheatley and Jahnke (38) who reported that the greatest level of activation of the VL was during medial rotation of the tibia when the knee was held at 1.57 rad and the isometric contraction was performed with the subject in a seated position. For the RF, our results indicating that the TO POS produces the highest level of activity among the 3 foot positions tested and is in agreement with the 2 previous studies that have examined the impact of POS on EMG activity during dynamic isoinertial exercise (30,33). Finally, our finding that POS had no impact on VM activity is in agreement with the results reported by Signorile et al. (30), but conflicts with the results reported by Stoutenberg et al. (33) indicating that the TI position produced significantly greater muscle activity than NEU.

The impact of knee angle alone on the EMG activities of the superficial quadriceps during this study can also be examined relative to results reported in previous studies; however, these comparisons must be considered recognizing the influence of foot position on muscle activity at specific knee angles. For example, considering the VL, no definitive statement can be made because optimal knee angles cannot be determined without considering foot position. On examining the impact of knee angle on RF activity, comparisons are also difficult because this study detected no impact of ROM on EMG activity. These results differ from those of Wheatley and Jahnke (38) and Browstein et al. (6) who indicated that the highest activity levels for this muscle were elicited between 90° (1.570 rad) and 100° (1.745 rad). Our results for the VM do support the contention that the levels of activity of this muscle should be greater at larger knee angles (13,39); however, the results of a number of studies argue against this hypothesis (1,34), and the studies that have provided direct electromyographic evidence are limited (5,20,38).

Finally, the patterns of increasing activity seen across repetitions regardless of knee angle or foot position are to be expected given the correlation between increasing levels of fatigue and EMG amplitude increases reported during repeated submaximal contractions (27).

When considering the use of LE to balance VM and VL forces, based on structural kinematics, researchers have advocated movement in the final 0.524 rad because in this position, the patella rests completely above the intercondylar groove against a suprapatellar fat pad resulting in little or no contact forces (16,35). In fact, the greatest contact forces at the patellofemoral joint have been shown to occur between 1.047 and 1.571 rad of flexion, when only 30% of total patella area is in contact with the femur leading to excessive contact pressure (25). In addition, the greatest patellofemoral joint stress is between 0 and 0.524 rad, plateauing between 0.524 and 1.047 rad, and steeply declining from 1.047 to 1.571 rad. These findings, in conjunction with our results, provide evidence that if targeting the VMO for reduction of patellar dysfunction, the optimal benefit would occur over the final 1.047 rad ROM and that the POS is not a factor. However, if the objective is to reduce the activity of the VL during this training, the TO POS should be used.

PRACTICAL APPLICATIONS

Open chain kinetic exercises exercises are used in physical therapy clinics and athletic training facilities during the late phases of rehabilitation after major reconstructive surgery of the anterior cruciate ligament (ACL) and to address patellar malalignment that may lead to patellofemoral pain and dysfunction. Several studies have shown the efficacy of using OKC, such as the LE, as a part of this rehabilitation process (i.e., ACL reconstruction) (26,33). However, in ACL rehabilitation, therapists using the LE exercise may choose to avoid the final 0.524 rad ROM, where anterior shearing forces are the greatest and can lead to increased graft strain and disruption (13,39). Additionally, when addressing PFP, targeting selected superficial quadriceps muscles using different knee angles, foot positions, or combinations of the 2 can increase the effectiveness of the intervention. Our results indicate that for targeting the VMO when addressing PFP, the final 1.047 rad of LE is most effective regardless of foot position; however, when addressing imbalances between the vasti muscles, the relative training effect on the VL can be reduced using the TO position. Our results indicate that, given the data indicating that the final 0.524 rad ROM should be avoided during ACL rehabilitation, using the middle 0.524 rad ROM and alternating between the TI and TO positions will allow the greatest activation of the superficial quadriceps, while minimizing anterior shearing forces.

In conclusion, clinicians, with the use of the proper combination of ROM and POS, can apply our results to design exercise OKC protocols specifically for patients with either PFP or in the late stages of rehabilitation after ACL reconstruction surgery. The results from this study will allow clinicians to use suggested TI or TO positions to selectively activate the vasti muscles. In many OKC protocols, the focus on individual muscle activation of the superficial quadriceps muscles could be improved. The ability to target these muscles using a combination of ROM and varying foot positions supports our hypothesis. The generalizability of our results may be limited by the use of a young, healthy sample with no history of knee or ankle injury. This may affect both the exercise patterns and the EMG responses during LE. We suggest a similar study be conducted with patients presenting PFP. Finally, these results are specific to the LE exercise and may not be applicable to other open or closed kinetic chain knee exercises (40).

Acknowledgments

The authors would like to thank A. Cole Meyers and Hyung-pil Jun, Research Assistants at the Department of Kinesiology and Sport Sciences of the University of Miami, for their help in preparing the Introduction and Discussion sections of this article.

References

1. Alkner, BA, Tesch, PA, and Berg, HE. Quadriceps EMG/force relationship in knee extension and leg press. *Med Sci Sports Exerc* 32: 459–463, 2000.
2. Andreassen, S and Rosenfalck, A. Recording from a single motor unit during strong effort. *IEEE Trans Biomed Eng* 25: 501–508, 1978.
3. Babault, N. Activation of human quadriceps femoris during isometric, concentric, and eccentric contractions. *J Appl Physiol (1985)* 91: 2628–2634, 2001.
4. Ball, N and Scurr, J. Electromyography normalization methods for high velocity muscle actions: Review and recommendations. *J Appl Biomech* 29: 600–608, 2013.
5. Basmajian, JV, Harden, TP, and Regenos, EM. Integrated actions of the four heads of quadriceps femoris: An electromyographic study. *Anat Rec* 172: 15–20, 1972.
6. Brownstein, BA, Lamb, RL, and Mangine, RE. Quadriceps torque and integrated electromyography. *J Orthop Sports Phys Ther* 6: 309–314, 1985.
7. Callaghan, MJ and Oldham, JA. The role of quadriceps exercise in the treatment of patellofemoral pain syndrome. *Sports Med* 21: 384–391, 1996.
8. Comfort, P, Pearson, SJ, and Mather, D. An electromyographical comparison of trunk muscle activity during isometric trunk and dynamic strengthening exercises. *J Strength Cond Res* 25: 149–154, 2011.
9. Cresswell, AG and Ovendal, AH. Muscle activation and torque development during maximal unilateral and bilateral isokinetic knee extensions. *J Sports Med Phys Fitness* 42: 19–25, 2002.
10. Croce, RV, Miller, JP, and St Pierre, P. Effect of ankle position fixation on peak torque and electromyographic activity of the knee flexors and extensors. *Electromyogr Clin Neurophys* 40: 365–373, 2000.
11. Cutbill, JW, Ladly, KO, Bray, RC, Thorne, P, and Verhoef, M. Anterior knee pain: A review. *Clin J Sport Med* 7: 40–45, 1997.
12. Dye, SF. The pathophysiology of patellofemoral pain: A tissue homeostasis perspective. *Clin Orthop Relat Res* 100–110, 2005.
13. Escamilla, RF, Fleisig, GS, Zheng, N, Barrentine, SW, Wilk, KE, and Andrews, JR. Biomechanics of the knee during closed kinetic chain and open kinetic chain exercises. *Med Sci Sports Exerc* 30: 556–569, 1998.
14. Ferber, R, Osternig, LR, and Gravelle, DC. Effect of PNF stretch techniques on knee flexor muscle EMG activity in older adults. *J Electromyogr Kinesiol* 12: 391–397, 2002.
15. Fiebert, IM, Spielholz, NI, Applegate, NI, Applegate, EB, Carbone, M, Gonzalez, G, and Gorack, WM. Integrated EMG study of the medial and lateral heads of the gastrocnemius during isometric plantar flexion with varying cuff weight loads. *J Back Musculoskelet Rehabil* 8: 145–150, 2001.
16. Fitzgerald, GK. Open versus closed kinetic chain exercise: Issues in rehabilitation after anterior cruciate ligament reconstructive surgery. *Phys Ther* 77: 1747–1754, 1997.
17. Heintjes, E, Berger, MY, Bierma-Zeinstra, SM, Bernsen, RM, Verhaar, JA, and Koes, BW. Exercise therapy for patellofemoral pain syndrome. *Cochrane Database Syst Rev* CD003472, 2003.
18. Holm, I, Hammer, S, Larsen, S, Nordsletten, L, and Steen, H. Can a regular leg extension bench be used in testing deficits of the quadriceps muscle during rehabilitation? *Scand J Med Sci Sports* 5: 29–35, 1995.
19. Hungerford, DS and Barry, M. Biomechanics of the patellofemoral joint. *Clin Orthop Relat Res* 9–15, 1979.
20. Lieb, FJ and Perry, J. Quadriceps function: An electromyographic study under isometric conditions. *J Bone Joint Surg Am* 53: 749–758, 1971.
21. Lutz, GE, Palmitier, RA, An, KN, and Chao, EY. Comparison of tibiofemoral joint forces during open-kinetic-chain and closed-kinetic-chain exercises. *J Bone Joint Surg Am* 75: 732–739, 1993.
22. Lynn, PA, Bettles, ND, Hughes, AD, and Johnson, SW. The influence of electrode geometry on bipolar recordings of the surface electromyogram. *Med Biol Eng Comput* 16: 651–660, 1978.
23. McBride, JJM. Comparison of kinetic variables and muscle activity during a squat vs. a box squat. *J Strength Cond Res* 24: 3195–3199, 2010.
24. McConnell, J. Rehabilitation and nonoperative treatment of patellar instability. *Sports Med Arthrosc* 15: 95–104, 2007.
25. Mesfar, W and Shirazi-Adl, A. Biomechanics of the knee joint in flexion under various quadriceps forces. *Knee* 12: 424–434, 2005.
26. Mikkelsen, C, Werner, S, and Eriksson, E. Closed kinetic chain alone compared to combined open and closed kinetic chain exercises for quadriceps strengthening after anterior cruciate ligament reconstruction with respect to return to sports: A prospective matched follow-up study. *Knee Surg Sports Traumatol Arthrosc* 8: 337–342, 2000.
27. Moritani, T, Muro, M, and Nagata, A. Intramuscular and surface electromyogram changes during muscle fatigue. *J Appl Physiol (1985)* 60: 1179–1185, 1986.
28. Newton, RU, Murphy, AJ, Humphries, BJ, Wilson, GJ, Kraemer, WJ, and Hakkinen, A. Influence of load and stretch shortening cycle on the kinematics, kinetics and muscle activation that occurs during explosive upper-body movements. *Eur J Appl Physiol Occup Physiol* 75: 333–342, 1997.
29. Sakamoto, A and Sinclair, PJ. Muscle activations under varying lifting speeds and intensities during bench press. *Eur J Appl Physiol* 112: 1015–1025, 2012.
30. Signorile, JF, Kascik, D, Perry, A, Robertson, B, Williams, R, Lowensteyn, I, Digel, S, and Caruso, J. The effect of knee and foot position on the electrical activity of the superficial quadriceps. *J Orthop Sports Phys Ther* 22: 2–9, 1995.
31. Signorile, JF, Kacsik, D, Perry, A, Robertson, B, Williams, R, Lowensteyn, I, Digel, S, Caruso, J, and LeBlanc, WG. The effect of knee and foot position on the electromyographical activity of the superficial quadriceps. *J Orthop Sports Phys Ther* 22: 2–9, 1995.

32. Signorile, JF, Kwiatkowski, K, Caruso, JF, and Robinson, B. Effect of foot positon on the electromyographical activity of the superficial quadriceps muscles during the parallel squat and knee extension. *J Strength Cond Res* 9: 182–187, 1995.
33. Stoutenberg, M, Pluchino, A, Ma, F, Hoctor, J, and Signorile, JF. The impact of foot position on electromyographical activity of the superficial quadriceps muscles during leg extension. *J Strength Cond Res* 19: 931–938, 2005.
34. Tagesson, S, Oberg, B, Good, L, and Kvist, J. A comprehensive rehabilitation program with quadriceps strengthening in closed versus open kinetic chain exercise in patients with anterior cruciate ligament deficiency: A randomized clinical trial evaluating dynamic tibial translation and muscle function. *Am J Sports Med* 36: 298–307, 2008.
35. Tang, SF, Chen, CK, Hsu, R, Chou, SW, Hong, WH, and Lew, HL. Vastus medialis obliquus and vastus lateralis activity in open and closed kinetic chain exercises in patients with patellofemoral pain syndrome: An electromyographic study. *Arch Phys Med Rehabil* 82: 1441–1445, 2001.
36. Taskiran, E, Dinedurga, Z, Yagiz, A, Uludag, B, Ertekin, C, and Lok, V. Effect of the vastus medialis obliquus on the patellofemoral joint. *Knee Surg Sports Traumatol Arthrosc* 6: 173–180, 1998.
37. Tepperman, PS, Mazliah, J, Naumann, S, and Delmore, T. Effect of ankle position on isometric quadriceps strengthening. *Am J Phys Med* 65: 69–74, 1986.
38. Wheatley, MD and Jahnke, WD. Electromyographic study of the superficial thigh and hip muscles in normal individuals. *Arch Phys Med Rehabil* 32: 508–515, 1951.
39. Wild, JJ Jr, Franklin, TD, and Woods, GW. Patellar pain and quadriceps rehabilitation. An EMG study. *Am J Sports Med* 10: 12–15, 1982.
40. Wilk, KE, Escamilla, RF, Fleisig, GS, Barrentine, SW, Andrews, JR, and Boyd, ML. A comparison of tibiofemoral joint forces and electromyographic activity during open and closed kinetic chain exercises. *Am J Sports Med* 24: 518–527, 1996.
41. Witvrouw, E, Danneels, L, Van Tiggelen, D, Willems, TM, and Cambier, D. Open versus closed kinetic chain exercises in patellofemoral pain: A 5-year prospective randomized study. *Am J Sports Med* 32: 1122–1130, 2004.
42. Witvrouw, E, Lysens, R, Bellemans, J, Cambier, D, and Vanderstraeten, G. Intrinsic risk factors for the development of anterior knee pain in an athletic population. A two-year prospective study. *Am J Sports Med* 28: 480–489, 2000.