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EMG Biofeedback as a Tool for Simulating the Effects of Specific Leg Muscle Weakness on a Lifting Task

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This study investigated the use of EMG biofeedback to simulate weakened rectus femorii and gastrocnemii muscles during the performance of a lifting task. Eight healthy women performed 15 kg free-style lifts from floor level. Three conditions were tested: unconstrained lifting, lifting with rectus femorii activity volitionally limited bilaterally through EMG biofeedback to less than 45% of maximal EMG activity, and lifting with the gastrocnemii limited to a similar level. Limiting leg muscle activity through biofeedback led to an alteration of lifting strategy, with resulting performance variables (joint angles and torques, angular velocities, center of pressure excursion, and segment coordination) comparing favorably with those from lifting trials performed by six women with moderate leg muscle weaknesses. The data indicate that EMG biofeedback can be used to simulate the effects of leg muscle weakness during these lifts, providing a new tool to study the biomechanics of muscle weakness.

KEY WORDS: EMG; biofeedback; lifting; strength; muscle compensation.

INTRODUCTION

In a survey of 5,100 men and 4,705 women ages 55 to 74 years, up to 17% reported the inability to stoop, crouch, kneel, or lift or carry 25 pounds, and another 41% reported having difficulty when stooping, crouching, kneeling, or lifting or carrying 25 pounds (1). Survey respondents reported at least 10% greater difficulty with these tasks than with tasks such as walking, standing, sitting, reaching, or grasping. In addition, women reported up to 15% greater difficulty performing the tasks than men, which is of particular importance because the labor force participation rate of women over the age of 40 years has been increasing (2).

Leg muscle strength has been identified as a major factor affecting the performance of free-style and squat-style lifting tasks in women (3), a factor that can have serious

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consequences on lifting ability for older adults who often experience declines in muscular strength. Weaknesses in the knee extensors and ankle plantarflexors correlated with initial lifting postures better than forward balance and leg joint range of motion attributes in the study. However, using regression analyses in cross-sectional studies such as this one does not allow the direct determination of the effect of specific muscle group weaknesses on lifting task performance.

Current techniques for studying the effects of muscle weakness are inadequate. Analyzing specific strength effects on lifting performance in older individuals who may have such deficits is complicated by numerous confounding factors. Studies have shown functional declines with age for joint ranges of motion, proprioception, and postural balance as well as muscle strength (4,5). These functional abilities are further affected by an individual's experience with various daily exertions, medication, and disease processes (5). Computer simulations of muscle weakness have shown potential changes in lifting strategies, but are simplified representations depending on modeling assumptions that may be difficult to validate (3).

Ideally, the effects of individual leg muscle group weaknesses on the performance of lifting tasks would be directly examined by finding and testing healthy young female subjects with only one bilateral leg muscle strength deficit—if these individuals did not also experience additional changes in functional abilities as a result of compensatory movements. Because appropriate subject pools are not readily available, an alternative technique to allow the simulation of the effects of specific muscle deficits in normal, healthy young subjects is needed.

Electromyography (EMG) biofeedback has been used extensively to help individuals relax muscles or increase specific muscle strength (6–11). In one such study of trapezius muscle relaxation, researchers even noted changes in upper body postures and movements (12). Although Gowland *et al.* (13) noted that inadequate recruitment (low electromyographic values) of agonist muscles was a consistent finding in patients unable to perform upper-limb movement tasks, using EMG biofeedback as a way of simulating muscle weakness to study resulting changes in movement strategies has not been explored.

EMG signal amplitude generally decreases as the muscle force decreases (14,15). In a study of the gastrocnemius muscle, the relationship between isometric ankle plantarflexion tension and EMG has even been described as linear (16). The present study attempted to simulate muscle weakness by allowing the subject to utilize only a preset percentage of the maximal EMG signal in the targeted muscle during a common lifting task. Thus, the first aim of this study was to determine how healthy, physically active, young women would change their strategies of performing a lifting task beginning at floor level when EMG biofeedback was used to limit the maximal activity of the rectus femorii and the gastrocnemii muscles. Performance measures included: initial lifting postures, joint angular velocities, segment coordination, maximum torques about the leg joints, and maximum anterior excursion of the center of pressure. The second aim was to determine how these altered lifting strategies compared to those of individuals with demonstrated moderate declines in leg muscle strength. If EMG biofeedback can successfully simulate muscle weakness, then this technique can be used to explore the changes in movement strategies during the performance of a self-paced, free-style lifting task from floor level within individuals by comparing unconstrained trials to trials with muscles limited through EMG biofeedback.

Table I. Range of Subject Characteristics

		Validation groups	
Subject characteristics	Biofeedback group ($n = 8$)	Weak rectus femoris group ($n = 3$)	Weak gastrocnemius group ($n = 3$)
Ages (years)	21–28	27, 49, 69	61, 63, 68
Height (cm)	156–170	161–168	157–165
Mass (kg)	51–65	58–83	71–78

METHODS

Subjects

Normal Population

Eight healthy, physically active females ages 21 to 28 years volunteered for this study. Relevant subject anthropometric data are reported in Table I. Subjects were selected within a narrow height range to minimize stature effects. Subjects reported above average physical activity and good to excellent health, with no prior history of low-back pain, dizziness, recent surgeries, or current leg pain or numbness. Prior to participation in the study, each subject read and signed a university-approved consent form.

Symptomatic Population

Validation data were collected from six healthy, highly-motivated women of similar anthropometry (see Table I) identified in previous studies as having moderate declines in absolute leg muscle strength (over one standard deviation below the mean strength for healthy adult women measured in the study). Three of these women had moderate weakness localized in the quadriceps muscles and three of these women had moderate weakness in the gastrocnemii muscles. Strengths at the other leg joints were within one standard deviation above or below the group average. Strengths of the upper body were not measured, but subjects confirmed that they did not experience major limitations in these body segments. These subjects also reported good to excellent health and above average physical activity.

Data Calibration

Bipolar electrodes were placed bilaterally over the belly of the medial gastrocnemii and the rectus femorii. A prior lifting study has shown these muscles to play an important role in the distribution of the net moment over the joints they cross (17).

To determine maximum torque and maximum root-mean square (RMS) EMG of the leg muscles, subjects sat in a Biodex™ dynamometer to isokinetically and isometrically test these values for knee extension and ankle plantarflexion exertions. For the rectus femorii, isokinetic knee extension strength was recorded at 60°/sec for five extension cycles and then repeated for the opposite leg. Maximum torque was determined as the peak torque value from this testing. Similarly, maximum EMG was determined from its peak value during this testing. For intra-subject calibration of the relationship between torque and EMG, isometric testing was then conducted on the stronger of the two legs. Five-second recordings of both torque and EMG were taken at included knee angles of 160°, 130°, and 100° (flexion angles of 20°, 50°, and 80°, measured from full extension). First, subjects were asked to demonstrate their maximum strength ability for the given angle. The maximum isometric values were determined from the average values of the last three seconds of testing. Then, while being provided visual feedback on joint torque exertion, subjects were asked to exert 65% of their maximum torque while EMG signals were recorded for five seconds. Isometric values for torque and EMG were again averaged over the last three seconds of testing. Similar testing was completed for the gastrocnemii. For these muscles, isokinetic testing for maximum torque took place at 30°/sec, and isometric testing for EMG calibration took place at both 90° included angle and 80° included angle (10° dorsiflexion).

Active joint ranges of motion of the hips, knees, and ankles were measured with a goniometer. Angles were determined using the Neutral Zero Method defined by the American Academy of Orthopaedic Surgeons (18).

Selection of EMG Biofeedback Levels

Isokinetic extension strengths of young (ages 20–39 years) and older (ages 60–79 years) females indicate older subjects have quadriceps muscle strength ranging from 44–75% as strong as that in young subjects, depending on the isokinetic testing speed (19–21). For ankle isokinetic plantarflexion strengths, published values report older subjects being 52–72% as strong as young subjects (22–24). To reflect this wide range of estimates in strength declines, the generally linear but inexact relationship between muscle force and surface EMG, and the variability in such relationships associated with dynamic movement, this study utilized two biofeedback levels for each muscle group (rectus femoris and gastrocnemius). Selected biofeedback levels were 65% and 45% of demonstrated maximum isokinetic EMG. Pilot work supported the viability of these selected levels.

Procedure

Initial Set-up

A small box (16 cm × 21 cm × 20 cm) was placed on the floor in the mid-sagittal plane in front of the subject, with the center of the box located 40 cm anterior to the malleoli. Because subjects were of similar anthropometry, this location was not adjusted for body size. This box contained an evenly distributed load of 15 kg, which was determined in prior studies to be sufficiently challenging for young females, but still within safe handling limits (3). Standing on a force platform with feet spaced shoulder-width apart, the subject lifted the box vertically from the ground to waist height, keeping the box at a constant horizontal distance of 40 cm anterior to the malleoli, to simulate the lifting of bulky loads or the lifting of objects over a barrier. A string was attached vertically between the ceiling and the floor and was threaded through an eye screw attached to the front of the box to provide visual cues about the horizontal location of the box during the lift. All subjects were provided with a standard pair of comfortable walking shoes to control for possible footwear effects.

Lifting Tasks

Ten lifting trials were recorded for each subject. As a baseline, the subject first performed two unconstrained free-style lifting trials. Then, the subject performed lifting trials with real-time EMG biofeedback from the rectus femorii. The biofeedback level was first set at 65% of the subject's demonstrated maximum EMG from the isokinetic strength testing. The subject was asked to perform the lift without exceeding this level and repeated the task until this goal was achieved. If one of the EMG signals exceeded the preset level (65% of maximum), the biofeedback system emitted a short tone and the subject was instructed to stop the movement and return the box to the ground. Two minutes were given to rest and then the subject was asked to repeat the lifting task in a manner that used the selected muscle group to a lesser extent. The subject tried different lifting strategies (approximately five on average) until she was able to lift the box without exceeding the preset EMG level. When a successful lifting strategy was found, the subject was given two minutes to rest and then asked to repeat the lifting task without exceeding the preset EMG level. Upon demonstrating the ability to successfully repeat this task as requested, the subject was asked to perform two lifting trials while data were collected, with two minutes of rest between trials. Then, the biofeedback level was decreased to 45% of maximum EMG and the process was repeated. This entire process was repeated with biofeedback from the electrodes on the gastrocnemius of each leg, again with feedback levels of 65% and 45%. Subjects were instructed to maintain a consistent, comfortable lifting speed throughout the experiment.

Movement Recording

All lifting trials were recorded on video at 60 Hz with a video-based passive marker tracking system (ExpertVision™ system from MotionAnalysis™ Corp.). Reflective markers were placed on the left side of the subject at the lateral malleolus, the lateral femoral condyle, the center of the greater trochanter, the acromion process, the lateral epicondyle of the humerus, and the head of the styloid process of the ulna. Recording started with the subject in the standing position and ended with the subject in the standing position after completion of the lifting task. An AcqKnowledge® software program (from BIOPAC Systems, Inc.) was used to record EMG and force plate signals.

Data Conditioning

Only the rising portion of the lift was analyzed. This was defined as the portion of the lift from when the box left the ground to the point at which the subject's wrists reached their greatest vertical distance from the ground. Calculations of relative joint positions were completed by MotionAnalysis™ software. Joint torques were estimated with a ten-link 3 D inverse dynamic calculation computer program, similar to one described by Chaffin and Erig (25) with dynamic inertial properties added to each segment. This program also low-pass filtered the input motion data using a moving Hanning-weighted window averaging method. Joint angular velocities were calculated through numerical differentiation using the three-point central difference technique. Maximal anterior center of pressure excursion was calculated from the force plate voltages and normalized to foot length.

Movement coordination of the body segments was compared through analyses of the hip and knee joint angles. Angle-angle plots compared the included angle at the hip to the included angle at the knee throughout the lifting trial. For the initial and final 25% of each lifting trial, the ratio of the change in included angle at the hip joint to the change in included angle at the knee joint was calculated. (This corresponds to the generalized slope of the angle-angle plot for the respective time period.)

For the muscle strength/EMG signal comparisons, the EMG voltage from the last three seconds of the submaximal (65% torque level) isometric exertion was averaged and then normalized to the average EMG signal recorded in the last three seconds of the maximum isometric exertion:

$$\mathrm{NEMG}_i = (O_i - \mathrm{min}_i)/(\mathrm{MVC}_i - \mathrm{min}_i)$$

In this equation, i represents the rectus femoris or gastrocnemius muscles, O_i is the three-second average RMS EMG value for muscle i, min_i is the minimum EMG value observed in motionless sitting for muscle i, and MVC_i is the maximum EMG value observed for muscle i in isometric testing.

Data Analysis

To examine the effects of muscle weakness on lifting behavior, changes in the dependent variables (initial joint flexion angles, peak joint angular velocities, peak torques at the joints, and maximum anterior center of pressure excursion) were compared between the unconstrained trials and each EMG biofeedback-limited trial using two-sided paired t-tests.

An analysis of variance (ANOVA) was used to compare initial joint flexion angles and peak torques at the joints between lifting trials where EMG biofeedback was used on young subjects and lifting trials performed by individuals with identified deficits in muscle strength, to evaluate the ability of biofeedback to simulate leg muscle weakness. The Tukey-Kramer test identified any significant differences between each group.

RESULTS

The eight normal young women in this study displayed leg strengths and joint ranges of motion comparable to other women their age (see Table II). Although the average isokinetic knee extension strength was below that reported in other studies, it was within the range (average of 133 Nm ± 33) collected on the same machine for another group of young, healthy women of similar anthropometry in an earlier study by these authors (3). These strength abilities were sufficient to enable the subjects to perform the 15 kg lifting task under unconstrained conditions.

In the controlled testing of isometric muscle strength and EMG signals, EMG signal decreased as muscle force production decreased (Figs. 1 and 2). When subjects exerted 65% of their maximum voluntary isometric contractions for knee extension, the three-second average EMG for the rectus femoris averaged 50–67% (range: 42–83%) of the three-second average EMG recorded during the maximum isometric exertions, depending on the angle at which the knee was tested. (See Fig. 1). When subjects exerted 65% of

Table II. Comparison of Functional Abilities Between the Eight Young Female Subjects in This Study and Those Reported in the Literature for Females Ages 20–39 Years

Functional ability	Study group	Literature group	Citation source
Isokinetic strength (Nm)			
knee extension, 60°/s	107.6 (19.6)	147 (26)	20
		158 (11)	26
ankle plantarflexion, 30°/s	94.6 (34.0)	85 (27)	22
		67 (12)	23
Isometric strength (Nm)			
knee extension, 80°[a]	137.6 (12.9)	169 (34)	19 (at 90°)
knee extension, 50°	122.6 (21.8)		
knee extension, 20°	46.2 (24.8)		
ankle plantarflexion, 0°	108.5 (31.6)	130 (27)	22
ankle plantarflexion, −10°	131.0 (29.8)		
Range of motion (°)			
maximum hip flexion	123.8[a] (3.9)	123 (12)	27
maximum knee flexion	149.5 (3.1)	134 (9)	27
maximum ankle dorsiflexion	26.8 (8.6)	26 (6.4)	28

[a]Angles are reported as degrees flexion from a neutral standing posture.

their maximum voluntary isometric contractions for ankle plantarflexion, EMG voltages for the gastrocnemius averaged 40–43% (range: 12–63%) of the EMG recorded during the maximum isometric plantarflexion exertions, again depending on the angle at which the ankle was tested. (See Fig. 2).

Analyses of Lifting Trials

Subjects demonstrated repeatable lifting strategies, as determined by the lift kinematics. During unconstrained lifting trials, the within-subject variation in the initial joint angles ranged from 4°(±2) at the hip, to 5°(±3) at the knee, to 1°(±2) at the ankle. Similarly, in trials with rectus femorii activity limited to 45%, within-subject variations in initial joint angle ranged from 1°(±1) at the hip, to 7°(±5) at the knee, to 2°(±1) at the ankle, and for trials with gastrocnemii activity limited to 45%, initial within-subject joint angle variations ranged from 1°(±1) at the hip, to 6°(±5) at the knee, to 2°(±2) at the ankle. Variations in peak torques exhibited similar statistically insignificant changes. Because the trials were repeatable and a few of the first trials had some missing EMG data files, the second of the two trials was chosen for analysis.

Although pilot subjects repeatedly exceeded 65% of their maximum leg muscle EMG during lifting trials, the 65% level was not sufficiently challenging for most experimental subjects for either muscle group. On average, unconstrained lifting trials required less than 65% of maximum EMG for the rectus femorii and gastrocnemii, with the exceptions that one subject used 83% of her maximum EMG in her rectus femoris and two subjects used 71% and 86% of their maximum gastrocnemii EMG. It was concluded, therefore, that a constraint of 65% of maximum EMG was not sufficient to significantly affect lifting behavior, so all remaining analyses were limited to those trials conducted with the 45% biofeedback level constraint.

In addition, it was found that the two subjects who used the most stoop-like initial lifting posture (using 35°–47° less knee flexion than the other subjects) never exceeded

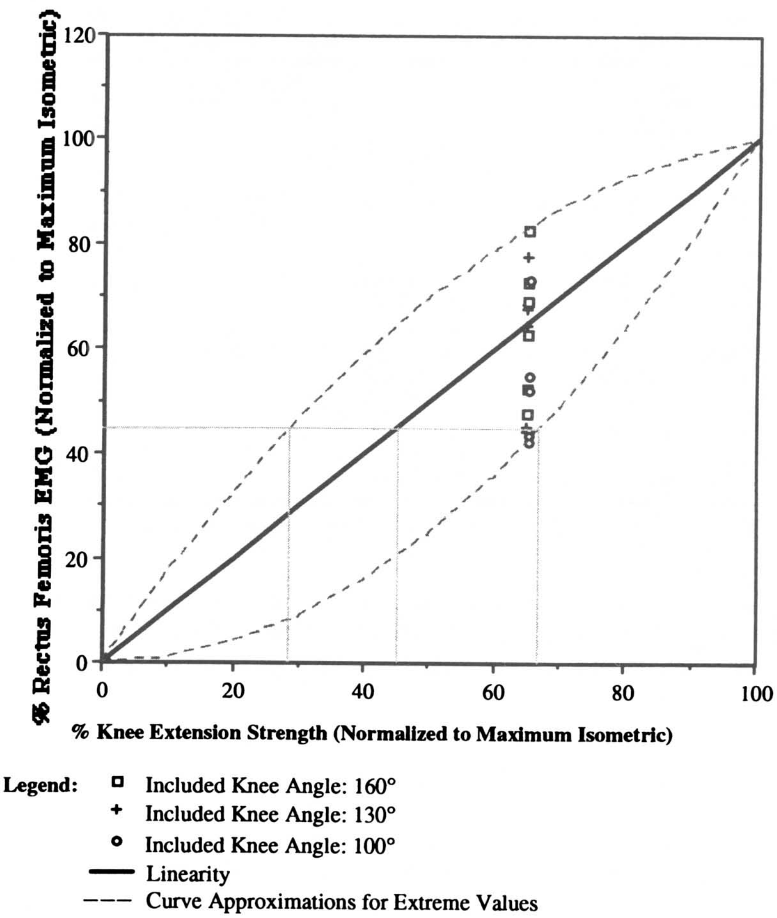


Fig. 1. Percentage of maximum isometric rectus femoris EMG voltages (averaged over a 3-second period) for subjects exerting 65% of maximum isometric knee extension strength.

45% of their maximum EMG for either muscle group studied. During the unconstrained free-style lifts they employed 15–45% of their maximum rectus femorii EMG and 21–34% of their maximum gastrocnemii EMG. Because changes in their lifting postures could not be studied by imposing the 45% maximum EMG constraint with the biofeedback system, their data were not used in the final analyses.

Effect of Rectus Femoris 45% EMG Level Constraint

Subjects changed movement strategies for the lifting task when their rectus femoris muscle activity was limited to the 45% EMG level, as outlined in Table III. A two-sided paired t-test showed that subjects significantly decreased ($p < 0.0008$) the maximum amount of knee flexion they used in the EMG biofeedback limited condition by an average of 61°(41%), as illustrated in Figs. 3a and 3b. In addition, maximum knee extension

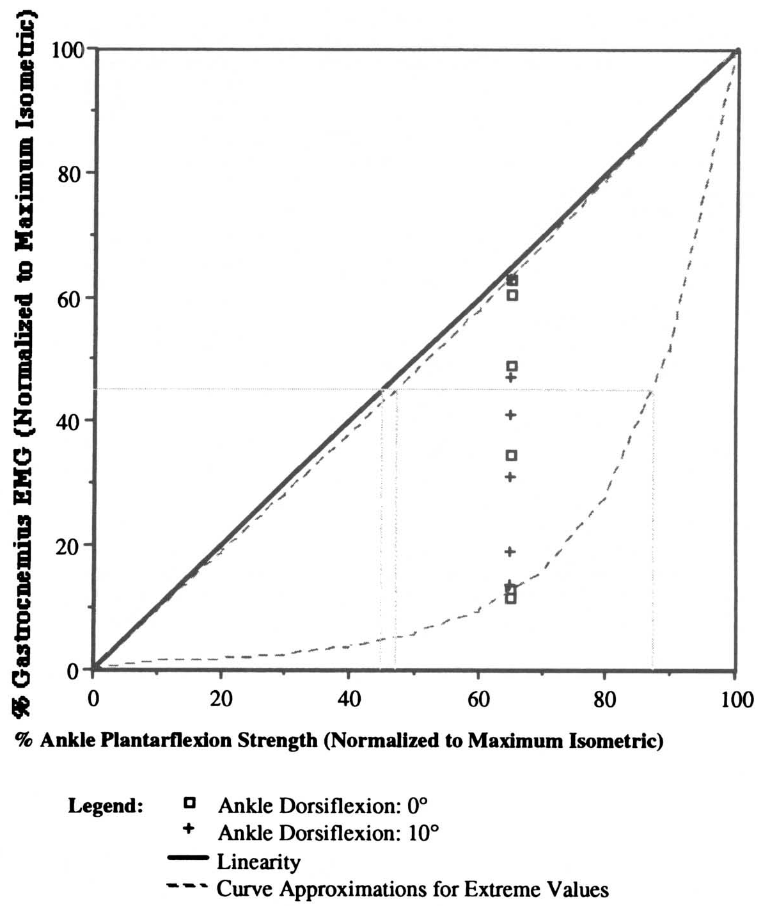


Fig. 2. Percentage of maximum isometric gastrocnemius EMG voltages (averaged over a 3-second period) for subjects exerting 65% of maximum ankle plantarflexion strength.

velocity significantly decreased ($p < 0.03$) an average of 48°/s (32%). Maximum anterior center of pressure excursion did not differ from those in the unconstrained lifts. Subject lifting speeds also were not significantly different, with the lift completed only 0.05 seconds faster for trials with limited rectus femorii activity.

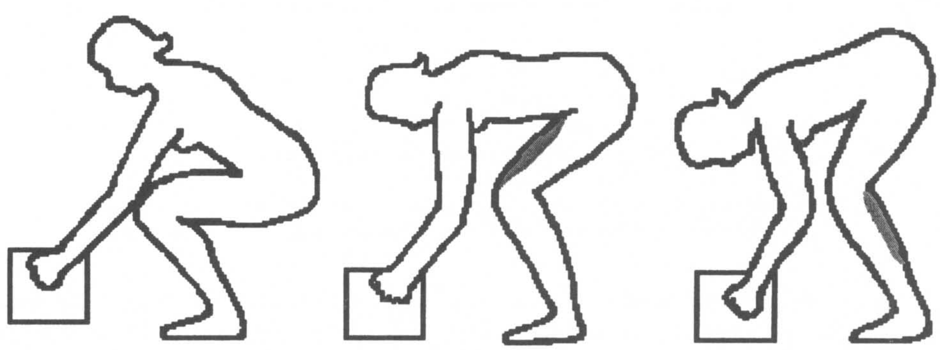
Effect of Gastrocnemius 45% EMG Level Constraint

Subjects also changed movement strategies for the lifting task when their gastrocnemius muscle activity was limited to the 45% EMG level (Table III). They significantly decreased ($p < 0.009$) the amount of knee flexion by an average of 61°(49%), as illustrated by the changes between Figs. 3a and 3c. Rising from this more stoop-like posture, subjects decreased ($p < 0.03$) the peak hip extension velocity by an average of 40°/s (20%), and decreased ($p < 0.007$) their peak knee extension velocity by an average of 80°/s (53%), but

Table III. Dependent Variables (Mean and Standard Deviation) Measured in Subjects Constrained to 45% of Maximal Muscle Activity Level Through EMG Biofeedback

		EMG biofeedback-limited	
	Unconstrained ($n = 6$)	Rectus femoris ($n = 6$)	Gastrocnemius ($n = 6$)
Included angles at Initiation of Lift			
hip (°)	36 (7)	40 (6)	40 (7)
knee (°)	56 (10)	113 (16)[b]	117 (33)[b]
ankle (°)	82 (3)	79 (5)	81 (3)
Peak joint angular velocities			
hip (°/s)	185 (35)	180 (37)	145 (23)[a]
knee (°/s)	145 (29)	96 (25)[a]	65 (29)[b]
ankle (°/s)	45 (16)	60 (21)	60 (19)
Peak extension torque			
hip (Nm)	115 (17)	113 (8)	111 (14)
knee (Nm)	53 (17)	55 (15)	54 (15)
ankle (Nm)	104 (21)	103 (28)	90 (29)
Center of pressure excursion (% of foot length)	64 (5)	63 (4)	62 (4)

Significant differences between unconstrained trials and biofeedback-limited trials for within-subject comparisons (using two-sided paired *t*-tests) are indicated by asterisks.
[a] $p < 0.05$.
[b] $p < 0.01$.



a.) b.) c.)

Fig. 3. Examples of initial lifting postures for the vertical lifting task, with shaded areas highlighting the biofeedback-constrained muscle groups, (a) unconstrained free-style lifts, (b) rectus femorii muscles constrained, and (c) gastrocnemii constrained. Box trajectory remained at a constant horizontal distance anterior to the ankles throughout the lifting task.

no significant changes in their maximum anterior center of pressure excursion occurred. Subjects also did not significantly change the speed of their lifts when compared to the unconstrained lifts, completing their lifts an average of 0.046 seconds slower than during the EMG biofeedback constrained tasks.

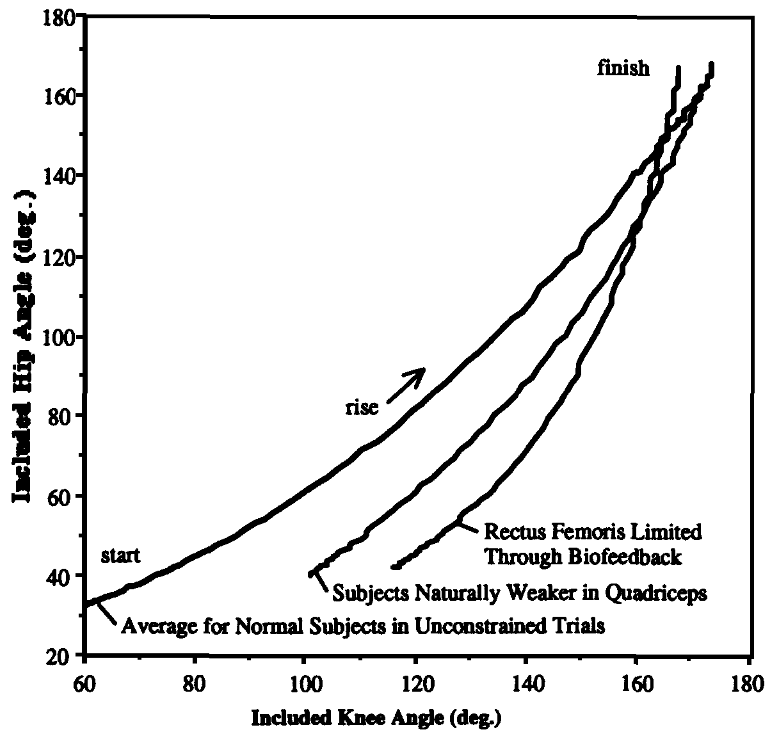


Fig. 4. Averaged hip angle-knee angle plot for duration of lifting task, comparing coordination of unconstrained trials by strong subjects to trials by the subjects naturally weaker in the quadriceps muscles and trials by the subjects with the rectus femorii limited through EMG biofeedback.

Segment Coordination

Angle-angle plots for the hip and knee provide insight into the coordination of the lifting tasks. Figures 4 and 5 show the coordination of hip and knee extension during unconstrained and constrained trials, averaged across all subjects within subject group. The deviation of the plot from straight lines indicates some decoupling between hip extension and knee extension, as described by Winstein and Garfinkel (29). The shape of these curves suggests more knee extension occurs earlier in the lift while the completion of the lift utilizes more hip extension.

Because of the large differences in initial knee angles, it is difficult to directly compare the curves in Figs. 4 and 5. To obtain a better comparison of coordination between the different lifting trials, the ratio of the change in hip angle to the change in knee angle was computed for the initial 25% (displayed in Fig. 6a) and the final 25% (displayed in Fig. 6b) of the lifting trials. In the initial phase of the lifts, ratios near 1.0 indicate that the hips and knees extended similar amounts. For the unconstrained trials, ratios <1.0 suggest that the knees extended more degrees than the hips during this phase. During the final 25% of the lift, ratios >3.0 show that hip angles changed considerably more than knee angles, particularly for trials with the rectus femorii limited through EMG biofeedback. These larger ratios would occur in lifting trials with hip extension completed mostly by torso

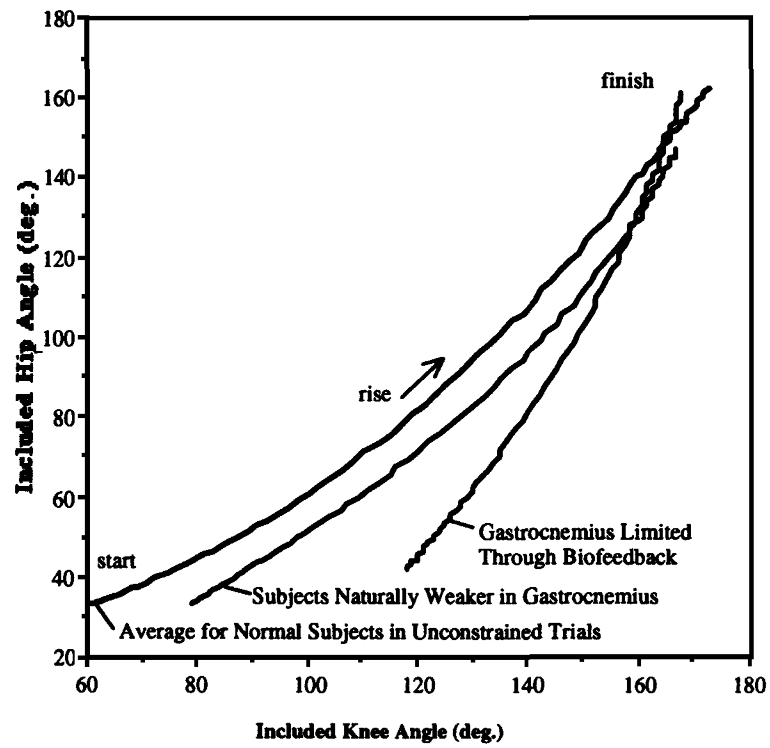


Fig. 5. Averaged hip angle-knee angle plot for duration of lifting task, comparing coordination of unconstrained trials by strong subjects to trials by the subjects naturally weaker in the gastrocnemii and trials by the subjects with the gastrocnemii limited through EMG biofeedback.

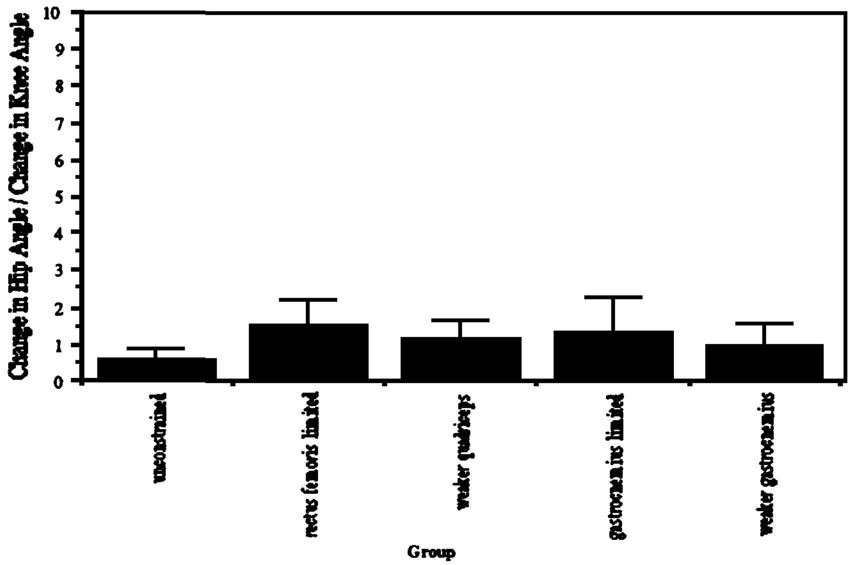
motion. The large error bars in Fig. 6b demonstrate the large variability in coordination techniques during this final quarter phase.

Extension Velocities

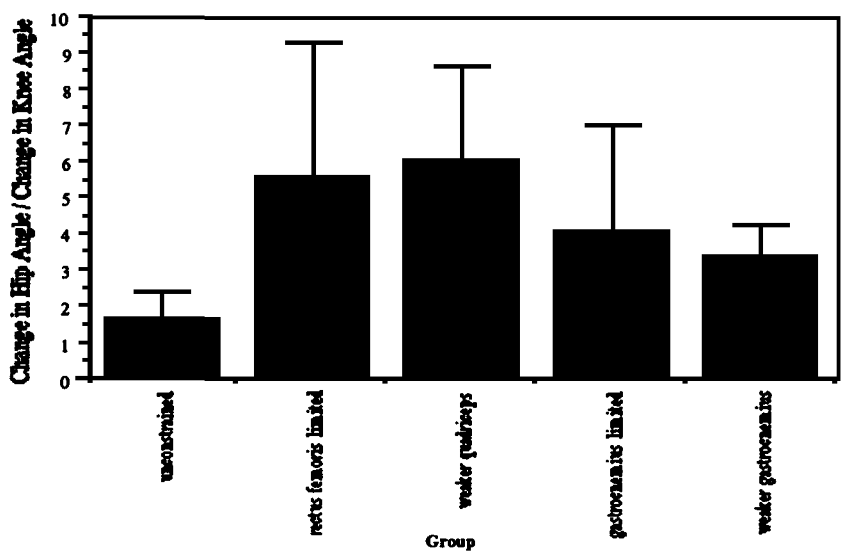
Average hip and knee joint angular extension exhibited a trend of lower angular velocities during the middle of the lifting tasks for individuals with extensor muscles limited through EMG biofeedback. This was evident in trials focusing on the rectus femoris of the quadriceps as well as for trials focusing on the gastrocnemius, which are presented in Figs. 7 and 8. In all instances, women performing biofeedback-limited trials had the lowest peak knee extension angular velocities.

Evaluation of EMG Biofeedback as a Tool to Simulate Muscle Weakness

Healthy young subjects with muscle activity constrained through EMG biofeedback altered their lifting strategies toward movements that resembled lifting movements



a.)



b.)

Fig. 6. Ratio of change in hip angle to change in knee angle for (a) the initial 25% of the lifting task and (b) the final 25% of the lifting task.

demonstrated by naturally weak individuals. Subjects limited to the 45% EMG biofeedback level used similar maximum joint angles and peak joint torques as subjects with the respective identified muscle weakness (outlined in Table IV). A review of Figs. 7 and 8 shows trends of lowered joint angular velocities during the lifts in both cases.

Table IV. Dependent Variables (Mean and Standard Deviation) Measured in Subjects Constrained to 45% of Maximal Muscle Activity Through EMG Biofeedback as well as Naturally Weaker Individuals

	Weak quadriceps		Weak gastrocnemius	
	Biofeedback ($n = 6$)	Natural ($n = 3$)	Biofeedback ($n = 6$)	Natural ($n = 3$)
Included angles at Initiation of lift				
hip (°)	40 (6)	37 (1)	40 (7)	35 (4)
knee (°)	113 (16)	98 (10)	117 (33)	85 (18)
ankle (°)	79 (5)	83 (5)	81 (3)	87 (4)
Peak extension torque				
hip (Nm)	113 (8)	119 (33)	111 (14)	120 (5)
knee (Nm)	55 (15)	32 (9)	54 (15)	46 (28)
ankle (Nm)	103 (28)	92 (19)	90 (29)	102 (7)

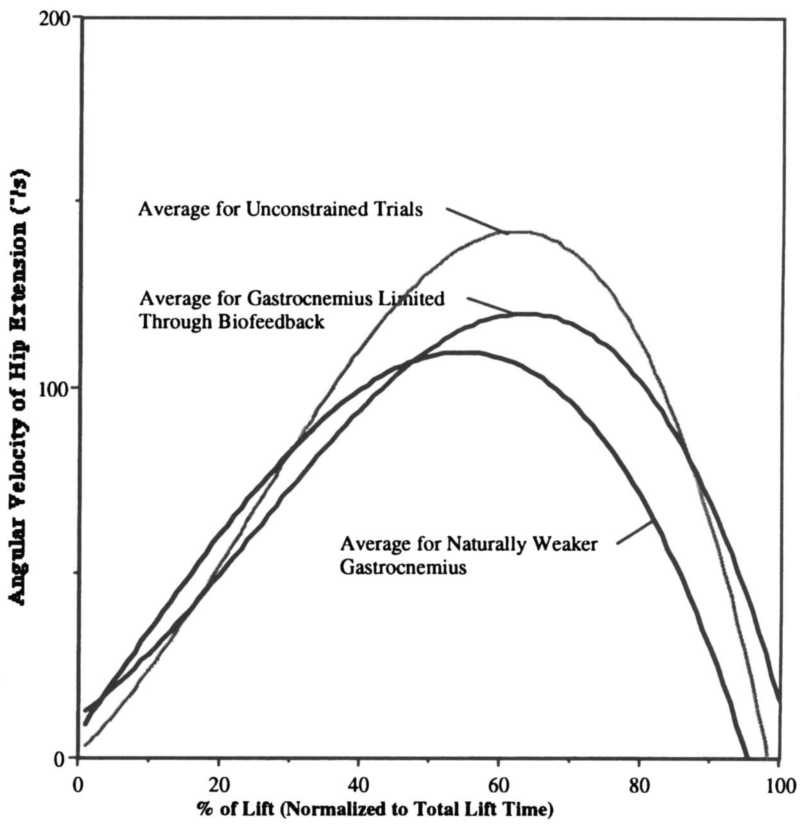


Fig. 7. Comparison of averaged hip extension angular velocity in trials by all subjects naturally weaker in the gastrocnemii to trials by all the healthy, strong subjects in unconstrained testing and in testing with the gastrocnemii limited through EMG biofeedback.

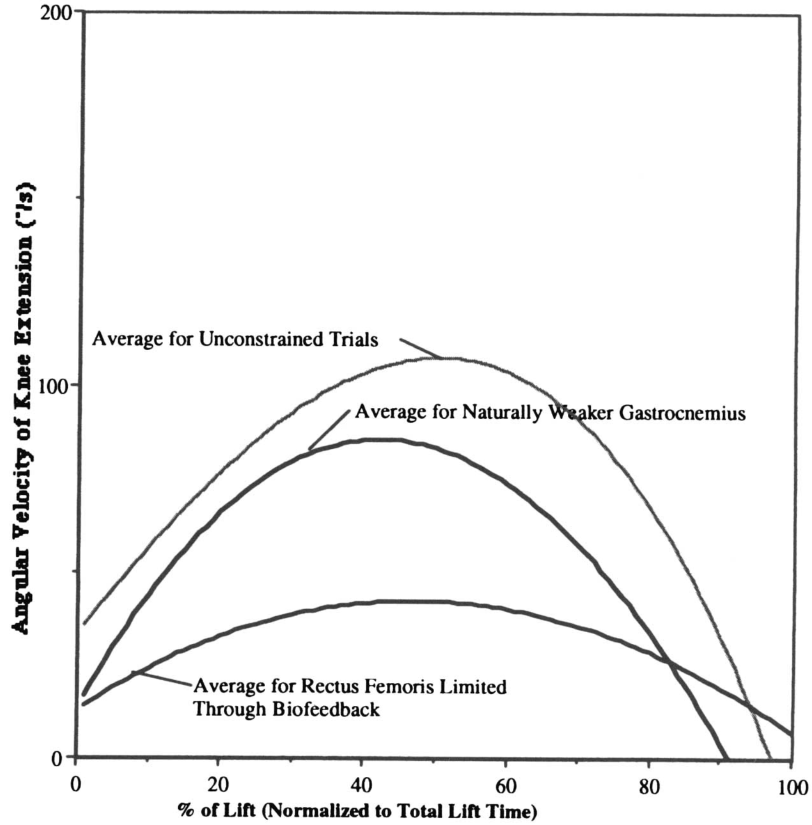


Fig. 8. Comparison of averaged knee extension angular velocity in trials by all subjects naturally weaker in the gastrocnemii to trials by all the healthy, strong subjects in unconstrained testing and in testing with the gastrocnemii limited through EMG biofeedback.

DISCUSSION

During the lifting trials, subjects with leg muscle activity limited through EMG biofeedback changed their performance of the lifting task, most notably in initial lifting posture, subsequent limb segment coordination, and joint extension velocities. Previous literature in the biofeedback arena supports these results, with studies that have noted general changes in arm coordination (movements and postures) utilized by subjects when EMG feedback was used to decrease the tension of the trapezius muscles (12).

Changes in the coordination of the lifting task have important biomechanical consequences. It is well-established that body postures during lifting tasks affect reaction forces at joints such as the knee and low-back (e.g., 30,31). When a lift is performed mostly by the back, as done by the biofeedback-limited and naturally weaker subjects, more work is done in the L5/S1 joint (17). Because altered movement coordination results in a reallocation of forces to the joints of the body, different body structures will have to withstand increased forces. Because age can affect the biomechanical properties of body structures (32), this altered coordination in older individuals could change their risk for injury or pain.

Subjects also demonstrated that the presence of small strength deficits (as simulated through EMG biofeedback) does not always require the alteration of lifting strategy for a successful lift completion. Most subjects performed the unconstrained lifting tasks utilizing less than 65% of their maximal isokinetic EMG. Two subjects even chose unconstrained lifting strategies that did not require more than 45% of their maximal isokinetic EMG. Thus, the presence of small strength deficits in the rectus femorii or gastrocnemii muscles does not necessarily require alterations in lifting strategy when loads are at or below 15 kg and placed at a nominal distance in front of the feet.

Alternative lifting strategies selected by subjects using biofeedback to limit leg muscle strength exhibited similar trends to individuals with moderate leg muscle weaknesses. Subjects limited to the 45% EMG biofeedback level used larger initial included knee angles, completed the lifts with more hip extension than knee extension, and tended to decrease mid-lift joint extension velocities just as those subjects with the respective (quadriceps or gastrocnemius muscle) strength decrement. These alterations in lifting postures also resemble postural changes exhibited in young males performing lifts with fatigued quadriceps muscles (33). The ability of EMG biofeedback to simulate the effects of muscle fatigue deserves further study.

There were some differences between the biofeedback and naturally weaker groups. Joint torques did not appear to exhibit similar trends between biofeedback-limited individuals and naturally weak individuals. Although ANOVA analyses did not determine any statistical differences, this could be attributed to poor statistical power because of a small number of subjects. If the trends are indeed different, there are several possible explanations for such differences. First, naturally weaker individuals have fully adapted to their condition while the biofeedback group had just the short laboratory time to explore the boundaries of their limitation. Second, there is the potential for artifacts resulting from such a small sample size of naturally weaker individuals. Additionally, anthropometric differences between the naturally weak subject group and the biofeedback group could have an influence which would not exist for the within-subject comparisons. Furthermore, it is possible that the naturally weaker individuals had some strength declines at other joints. Most of the validation subjects were older, and physiologic changes in muscles (which would affect all muscles of the body) have been associated with increasing age (34–36). Although these validation subjects were not *significantly* weaker statistically (more than one standard deviation below average) for the other leg extension strengths, a combination of below average strengths at the other leg joints could affect their lifting performance. Finally, because of the inherent limitations of the EMG biofeedback technique, the decline in strength induced by biofeedback could only be matched within a range to strength deficits calculated for the naturally weaker individuals. The inexact relationship between EMG and muscle force production due to changing muscle length and muscle shortening velocities made it impossible to exactly match biofeedback levels to weakness levels present in the naturally weak validation subjects. This difficulty could also explain why initial lifting postures were not exactly the same, although the two groups showed similar postural trends. The fact that the initial lifting postures were not identical would also influence the recorded joint torques. An expanded subject pool could help clarify some of these issues.

Three potential difficulties exist with the use of EMG biofeedback for simulating muscle weakness. First, there is no simple relationship between anisometric muscle force production and muscle EMG (37, for example), making it difficult to select appropriate biofeedback levels, as evident in the present experiment. Although pilot work indicated muscle activity in unconstrained 15 kg lifts exceeding 65% of maximum EMG, this biofeedback threshold level was not low enough to challenge a majority of the subjects in the full experiment. Reviewing Fig. 2, it appears that at least for the gastrocnemii, the biofeedback levels were much less challenging than their percentage description would indicate. EMG levels as low as 13% corresponded to isometric strength decrements of just 35% while the 45% EMG level could represent strength decrements of only 13–53%. Thus, the biofeedback threshold of 45% was still not low enough to challenge two subjects who utilized the most stoop-like initial lifting postures for the unconstrained trials, yet was nearly impossibly low for two other subjects who required approximately ten additional practice trials before they were able to achieve successful lifts without exceeding the threshold. This also indicates a second potential problem: practice and learning. Physically active subjects were specifically recruited for this study because they had a greater awareness of their body movement. It still took several trials for them to find alternative lifting techniques to consistently activate the target muscles below the biofeedback threshold levels. Individuals with less awareness of their physical movement may require considerably more practice. Finally, the third potential difficulty with the use of EMG biofeedback for simulating muscle weakness arises from the fact that EMG for submaximal tension is different between miometric and pliometric contractions (38). During pliometric contractions, greater muscle force may be produced while EMG signals remain low. Thus, EMG biofeedback-limited muscles in pliometric contractions may not be limited much, as the biofeedback technique relies on the subjecting lowering the EMG signal to lower muscle force production. Observing these precautions, it is concluded that EMG biofeedback techniques may be a useful tool for simulating weak muscle affects on whole-body exertions.

The purpose for utilizing EMG biofeedback was to effectively simulate weakness in selected muscle groups in otherwise strong, healthy individuals. As shown in the results, use of EMG biofeedback to limit muscle activity yields changes in lifting performance similar to those exhibited by naturally weaker individuals. This allows the effect of each particular weakness to be studied in within-subject comparisons in individuals who have not experienced disuse atrophy of other muscles or other physiologic changes resulting from altered movement. The electromyographic biofeedback technique also has a major benefit over potential real-time kinetic feedback techniques in that it works at the muscle level and can account for any extra muscle force needed to overcome co-contraction by antagonistic muscles, forces that could be overlooked in kinetic techniques (17).

These EMG biofeedback techniques could be applied to other muscles of the legs. It is expected that synergists to the muscles examined in this study would produce similar results, as quadriceps muscles have been shown to produce comparable peak amplitudes and time to peak amplitudes during lifting studies (39). Examination of muscles in antagonistic muscle groups such as the hamstrings would provide additional information on the lifting performance effects resulting from leg muscle weakness, because these muscles work against the agonists to stabilize the joints.

Two important conclusions emerge from this study. First, individuals can successfully alter their lifting movement strategies (including altered initial postures, peak joint angular velocities, and body segment coordination) to overcome enforced changes in muscle recruitment abilities. From comparisons of these altered movement strategies to lifting movements demonstrated by naturally weaker individuals, it was determined that EMG biofeedback is a novel technique that may be used to simulate specific muscle group weakness in otherwise strong, healthy adults performing lifting tasks from floor level. It is proposed that this EMG biofeedback method be used for further studies of the effects of leg muscle weakness on lifting performance to develop solutions to aid workers experiencing difficulty performing lifting tasks as a result of leg muscle weaknesses.

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