An Electromyographic Analysis of the Protonics™ Exercise System

Final Report

ASMI
American Sports Medicine Institute

Submitted to:
Inverse Technologies Incorporated

By:
The American Sports Medicine Institute (ASMI)

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Gene G. Jameson, B.S.
Glenn S. Fleisig, Ph.D.
Nigel Zheng, Ph.D.

INTRODUCTION

It is widely accepted that patellofemoral pain syndrome (PPS) is one of the most commonly diagnosed conditions in most orthopedic practices (Fox. 1975; Fulkerson & Hungerford. 1990). PPS has been suggested to indicate a number of conditions resulting in pain of the anterior aspect of the knee (Goodfellow, Hungerford, & Woods. 1976; Malek & Mangine. 1981). The underlying etiology behind PPS is still somewhat unclear; however, many researchers agree that malalignment of the patellofemoral joint is the cause (Fox. 1975; Ficat & Hungerford. 1977; Thomee, Renstrom, Karlsson, & Grimby. 1995). Malalignment of the patellofemoral joint can be the result of abnormal anatomy, malalignment of the quadriceps extensor mechanism, or a muscular imbalance (Ficat & Hungerford. 1977; Thomee, Renstrom, Karlsson, & Grimby. 1995; Garrick. 1989).

Some believe that pain occurs when the vastus medialis oblique (VMO) and the vastus lateralis (VL) are not synchronized or one is overpowering the other (Miller, J.P., Sedory, D., & Croce, R.V. 1997). When this occurs the patella translates onto the edges of its groove, causing pain.

The Protonics™ Exercise System (Protonics) is designed to resist knee flexion or extension and has been shown to cause increases in muscle activity as the brace resistance is increased (Diaz, G.Y., Averett, D.H., & Soderberg, G.L. 1997) . For patients with PPS, only flexion resistance is of interest. The theory is that if Protonics resists flexion controlled by eccentric quadriceps activity the hamstrings will co-contract to help produce the needed knee flexion and to help stabilize the knee joint. This in turn may reduce some of the tension of the quadriceps allowing the patella to be better aligned.

With this in mind our hypotheses for the current analysis were:

1) Muscular activity of the quadriceps muscles of a PPS patient wearing the Protonics device will more closely approximate the muscular activity of healthy control subjects than the PPS patients not wearing the device.

2) More hamstring activity will be produced by a PPS patient wearing the brace than when not wearing the brace.

3) The amount of knee flexion employed by PPS patients in completing the experimental tasks will be unchanged after introduction of the Protonics device.

4) The quadriceps to hamstring ratio during eccentrically controlled knee flexion will be less for the patients wearing the Protonics device than seen when they are not wearing the brace.

EXPERIMENTAL PROCEDURES:

Twenty-eight women ranging in age from 17 to 64 years of age were used as participants. Subjects were allowed to participate if they met all of the inclusion criteria (Tables 1 and 2). Ten control subjects and 18 PPS patients were tested after giving informed consent and completing a medical history. The control participants were free of knee disorders and chronic knee pain. The mean ages, heights and body masses of the subjects is shown in Table 3.

Table 1. List of the criteria to be satisfied in order for PPS participants to be included in current investigation.

No prior experience with the Protonics device.

Have not had knee surgery involving menisectomy

Have not had ACL surgery within the past 12 weeks

Must have been experiencing at least three (3) of the following symptoms at the time of testing:
a. Pain/crepitus during ascending or descending stairs
b. Pain/crepitus when rising from a seated position
c. Pain/crepitus during squatting movements
d. Swelling around the patellar fat pads after activity
e. Pain distal to the patella

Once the testing procedure was explained to the subject, reflective markers and electromyographic (EMG) electrodes were placed on her leg. The leg chosen for testing was the affected lower limb for the PPS participants, while the limb to be tested for the control subjects was randomly selected. Reflective markers were attached anteriorly to the subject's selected lower extremity at four points: proximal and distal thigh, and proximal and distal shank. The two thigh markers were placed in line with the femur; one placed approximately one-fourth the length of the femur inferior to the greater trochanter, while the other was placed superior to the knee and centered between the medial and lateral epicondyles. The two shank markers were placed in line with the tibia, one approximately one centimeter inferior to the tibial tuberosity and the other approximately 3 centimeters superior to the ankle joint and centered between the medial and lateral malleoli.

Table 2. List of the criteria to be satisfied in order for control participants to be included in current investigation.

Have never had knee surgery

No known medical problems that may affect their participation in the current study, including knee pain.

Be between the ages of 17 and 65

EMG surface electrodes (Medicotest Model N-00-S, Rugmarken, Denmark) were placed over five muscles of the affected lower extremity according to Perotto (1994) with a ground lead placed superficial to the patella. These muscles included the VMO, VL, rectus femoris, semitendinosus and biceps femoris. After the electrodes were attached, impedance measurements were taken. The electrodes were replaced if the measured impedance value exceeded 15 kΩ.

Table 3. Means and Standard Deviations (mean ± S.D.) for Age, Height and Weight for each of the two (2) test groups and the total population.

Group	Age (Years)	Height (M)	Mass (Kg)
Control	24.7 ± 5.7	1.64 ± 0.08	57.89 ± 7.9
PPS	35.0 ± 12.76	1.66 ± 5.3	76.11 ± 12.11
Total	31.32 ± 11.77	1.65 ± 0.07	69.6 ± 13.87

Data Collection

An automated motion analysis system (Motion Analysis, Inc., Santa Rosa, California) was used to quantify the three-dimensional movement of the reflective markers as the participant performed the required exercises. Video images of the reflective markers were transmitted from four 100-Hz charged coupled device cameras to a video processor. Synchronized EMG data from the five muscles were recorded at 1000-Hz using a Noraxon Myosystem 2000 (Noraxon USA, Inc., Scottsdale, Arizona) and converted to a digital signal for storage and subsequent analysis (Figure 1).

All of the data for each subject were collected during a single session. At the beginning of each data collection session, the subject completed two randomly ordered isometric exercises (2 trials each) to obtain maximum voluntary isometric contractions (MVIC) and the corresponding muscle activity elicited during each. The exercises consisted of a seated leg extension with the knee at 70° flexion, and a seated leg curl with the knee at 90° flexion and the foot 10º plantar flexed (Figures 2 and 3). The leg extension was used to establish the MVIC of the three quadriceps muscles, VMO, VL, and rectus femoris. The leg curl provided the MVIC for the hamstring muscles, semitendinosus and biceps femoris.

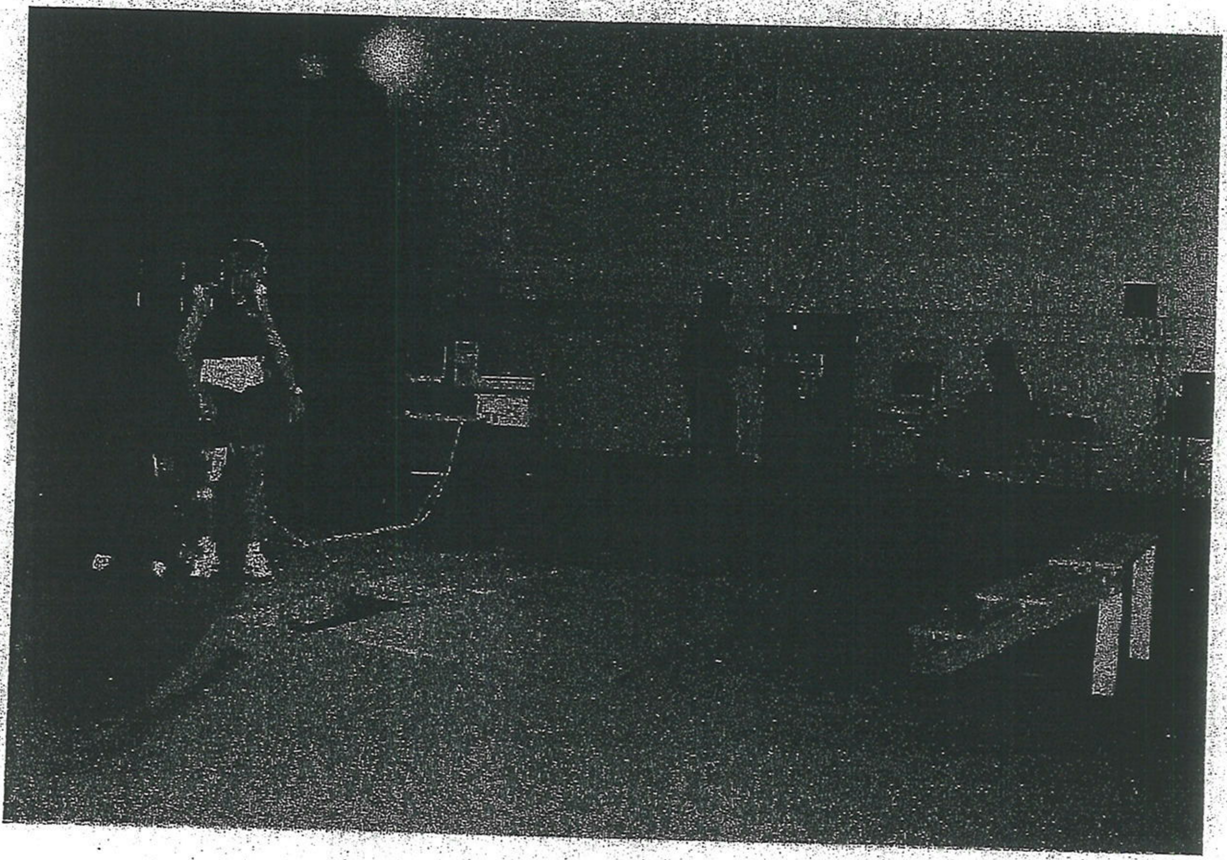

Figure 1. Photograph of the laboratory setup at the American Sports Medicine Institute.

After the MVIC exercises were completed, testing commenced. Each of the participants performed five randomly ordered exercises. These consisted of ascending and descending stairs, squatting, level walking and lunging. Two successful five second trials were completed for each of the exercises and each trial typically included two or three repetitions or gait cycles (two cycles was the minimum acceptable) which were averaged. The following sections list the parameters established for the successful completion of each of the exercises.

Figure 2. Seated isometric leg extension exercise used to obtain MVIC for the quadriceps.

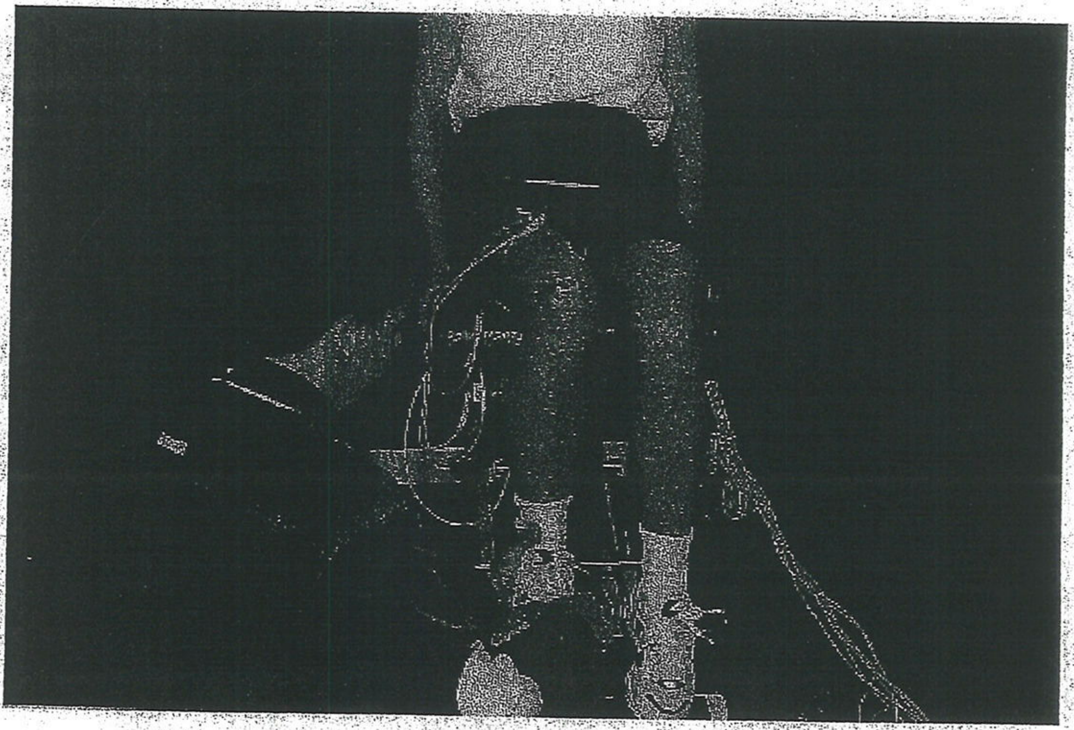

Figure 3. Seated isometric leg curl used to establish MVIC for the hamstrings.

Ascending Stairs:

The participant was instructed to walk up a set of four steps leading with her affected leg on each step. The other leg was lifted to the same step. This method ensured that a concentric quadriceps contraction of the affected limb would be used to elevate the body to each step. Data for three to four steps were collected then averaged for each trial based on knee flexion angle.

Descending Stairs:

The instructions for descending were similar to the ones given for ascending. The difference was that the participant started with her unaffected leg and then stopped on the same step with their affected limb. This was done so that eccentric activity of the quadriceps from the affected side would control the descent of the lead leg on to the lower step. As during ascending, data for three to four steps was collected and averaged based on knee flexion angle.

Squatting

The squatting task was similar to squatting and wall squatting exercises used in rehabilitation settings. The participant placed her hands on her hips and completed two squats. She was instructed to descend as far as she could without experiencing pain. The data from the two squats completed for each trial were averaged based on knee flexion angle.

Level Walking:

For the level walking portion of the testing the subject was instructed to simply walk across the floor. Each was told to look straight ahead and to walk without changing their stride. For each trial approximately two or three steps of the affected limb were collected then averaged based on knee flexion angle.

Lunging:

The lunge, also a rehabilitation type exercise, was done with the subject lunging onto a step that was 18 cm high. The subject was asked to lunge until her knee was flexed approximately 90°. Several practice trials were completed so the subject could become familiarized with this degree of knee flexion. One lunge was completed for each trial.

Once all of the exercises were completed successfully without the Protonics device, each PPS participant was fitted with the device. During the brace fitting process the PPS subject performed various exercises, including stair climbing and descending and level walking so that a Functional Resistance Setting (FRS) could be established. The FRS is a number corresponding to the amount of resistance that the brace provides. Generally, more resistance is needed for activities consisting of larger amounts of knee flexion (i.e. squats, lunges and stair climbing) and less is needed for ambulation. The personnel fitting the brace took care ensuring the subject was comfortable and was assigned the proper FRS for the activities performed. The participant was allowed as much time as needed to become familiar with and accustomed to the

Protonics device. Once the PPS subject was comfortable with the brace, testing proceeded and concluded upon successful completion of all the exercises listed above.

After all testing was completed, the motion analysis markers and EMG electrodes were removed from the subject and all of her questions regarding the study and her participation were addressed. The Protonics personnel then returned to complete the normal paperwork and description of the device and its instructions.

DATA ANALYSIS

The EMG data were full-wave rectified, filtered, integrated and normalized to the MVIC. The EMG was then averaged for the repetitions completed during each trial, relative to knee flexion angle during each of the exercises. In order to determine knee flexion the two segments defined by the four leg markers were used. The segment created by the proximal and distal thigh markers was used to define the femoral segment, while the proximal and distal shank markers defined the tibial segment. Once the two segments were established, the angle between the two was calculated three dimensionally. Because this angle was the three-dimensional angle between these two segments, care was taken to place the markers so that the two segments were coplanar.

During this study two proprietary Protonics devices (Inverse Technology Corporation and Professional Products Incorporated) were used on nine subjects each. The EMG of subjects using each of the two Protonics braces were compared for the exercises completed. No significant differences were observed between the two braces. Because no statistical differences were found the data from the two proprietary braces were pooled to form one PPS group so that statistical power would be improved. The statistical analysis compared the EMG activity of the control group, PPS group with the Protonics device (PPS-B), and the PPS group without the Protonics device (PPS-NB) at each degree interval of knee flexion. A One-way analysis of variance was performed for each dependent variable (each muscle or muscle ratio) at each degree of knee flexion to determine the statistical differences elicited by the brace based on knee flexion angle. An alpha level of 0.05 was used for all statistical tests.

RESULTS

The results will be reported for each exercise completed. Graphs illustrating all of the results for each exercise follow the written results for each exercise. To allow greater ease in making comparisons between the test groups muscle activity levels during the exercises that were less than 20% MVIC were considered to be low muscle activity; 21 to 45%, moderate activity; 46 to 65% MVIC, high activity; and greater than 65% MVIC, very high activity.

Knee range of motion during two of the five exercises was significantly decreased upon introduction of the brace (Table 4). The control group exhibited significantly greater knee flexion than the PPS-B group during three of the five exercises. The control participants showed the greatest amount of total knee motion for all exercises followed by the PPS-NB group.

The following sections describe and list the results for each exercise performed by the participants. Appendix A lists the statistically significant knee flexion ranges for each of the variables during each exercise.

Ascending Stairs

During stair ascending, the quadriceps were active primarily during the knee extension phase. Their concentric activity during this phase allowed the subjects to lift their body weight upward to the level of the next step. The quadriceps' activity remained less than 30% MVIC during knee flexion. The PPS-B group showed the greatest level of quadriceps activity during flexion followed by the PPS-NB group, then the control group (Figure 5a, 5b and 5c).

During the knee extension phase, the PPS-NB group showed the most quadricep activity. When the brace was introduced, the PPS group's quadriceps activity was lowered. The PPS-NB VMO peaked at 95% MVIC and was lowered to 70% with the brace's introduction. The control group's VMO activity peaked at 60% MVIC. The VL activity showed similar responses to the presence of the brace. The VL activity for the PPS-NB was lowered from 100% to 80% MVIC when the Protonics device was worn. The VL level for the controls peaked at 65% MVIC. Rectus femoris activity behaved the same, decreasing from 50% to 30% MVIC when the brace was worn, while the control subjects peaked at 35%.

As expected during stair ascending, the hamstring muscles showed low levels of muscle activity (Figures 5d and 5e). Hamstring activity hardly rose above 30% MVIC throughout stair climbing, with the control subjects showing less semitendinosus and biceps femoris activity than the other two groups through both flexion and extension. During the last half of the knee flexion phase the semitendinosus and biceps femoris muscle activities for the PPS-B group increased and were greater than both of the other groups, indicating an increase in their recruitment during non weight bearing knee flexion.

There were no discernable patterns noted for either the VMO:VL ratio or the Quadriceps:Hamstring ratio during stair ascending (Figures 5f and 5g).

Table 4. Means and Standard Deviations (mean ± S.D.) for knee range of motion variables for each of the three (3) test conditions five (5) exercises.

Exercise / Group	Control Group	PPS-NB Group	PPS-B Group
Ascending			
Minimum Knee Angle	6.80°	8.10°	7.30°
Maximum Knee Angle	105.20°♣	99.30°♣	84.50°
Total Knee Motion	98.40°♣	91.20°♣	77.20°
Descending			
Minimum Knee Angle	7.80°	7.11°	6.82°
Maximum Knee Angle	99.40°♣	94.22°	88.11°
Total Knee Motion	91.60°♣	87.11°	81.29°
Squat			
Minimum Knee Angle	8.00°	7.67°	7.63°
Maximum Knee Angle	76.80°	73.56°	73.75°
Total Knee Motion	68.80°	65.89°	65.13°
Walk			
Minimum Knee Angle	4.60°	6.44°	5.65°
Maximum Knee Angle	70.00°♣	64.89°♣	52.00°
Total Knee Motion	65.40°♣	58.44°♣	46.35°
Lunge			
Minimum Knee Angle	7.40°	8.59°	6.24°
Maximum Knee Angle	95.40°	93.41°	87.29°
Total Knee Motion	88.00°	84.82°	81.06°

♥ *significantly different from PPS-NB group*
♣ *significantly different from PPS-B group*

Figure 4: PPS subject shown during stair ascending.

EMG Activity During Ascending

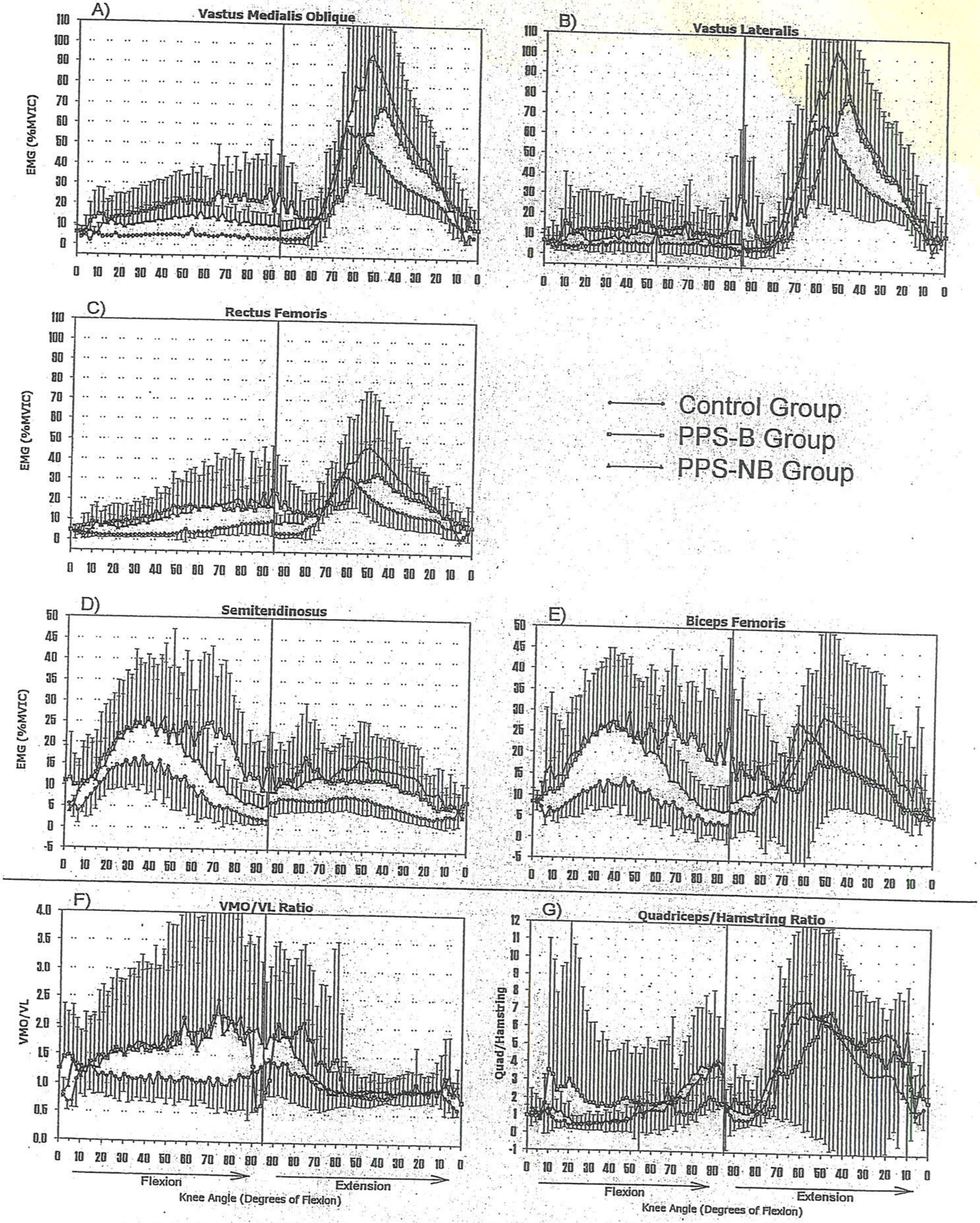

Figure 5: Graphs of EMG actvity and ratios during stair climbing versus knee flexion angle. Note, the first half of the graph represents knee flexion and the last half represents knee extension

Descending Stairs

During stair descending, the quadriceps control the downward movement of the body eccentrically. Therefore, the phase during which most quadriceps activity was noted was the knee flexion phase. The control group consistently showed the least amount of activity during knee flexion followed by the PPS-B group, then the PPS-NB group. The peak level of activity produced by the quadriceps muscles ranged from 30 to 65% MVIC (Figure 7a, 7b and 7c). During the last half of flexion the graphs indicate the PPS-B group's quadriceps activity was lower than the PPS-NB group.

The hamstrings again showed low levels of activity during stair descending (Figures 7d and 7e). The control group showed the least amount of activity while the two PPS groups showed significantly more activity. The brace group, however, showed no significant changes from their pre-brace results. No significant differences were noted for either the VMO:VL or the Quadriceps:Hamstring ratios (Figures 7f and 7g).

Figure 6: PPS subject shown during the stair descending activity.

EMG Activity During Descending

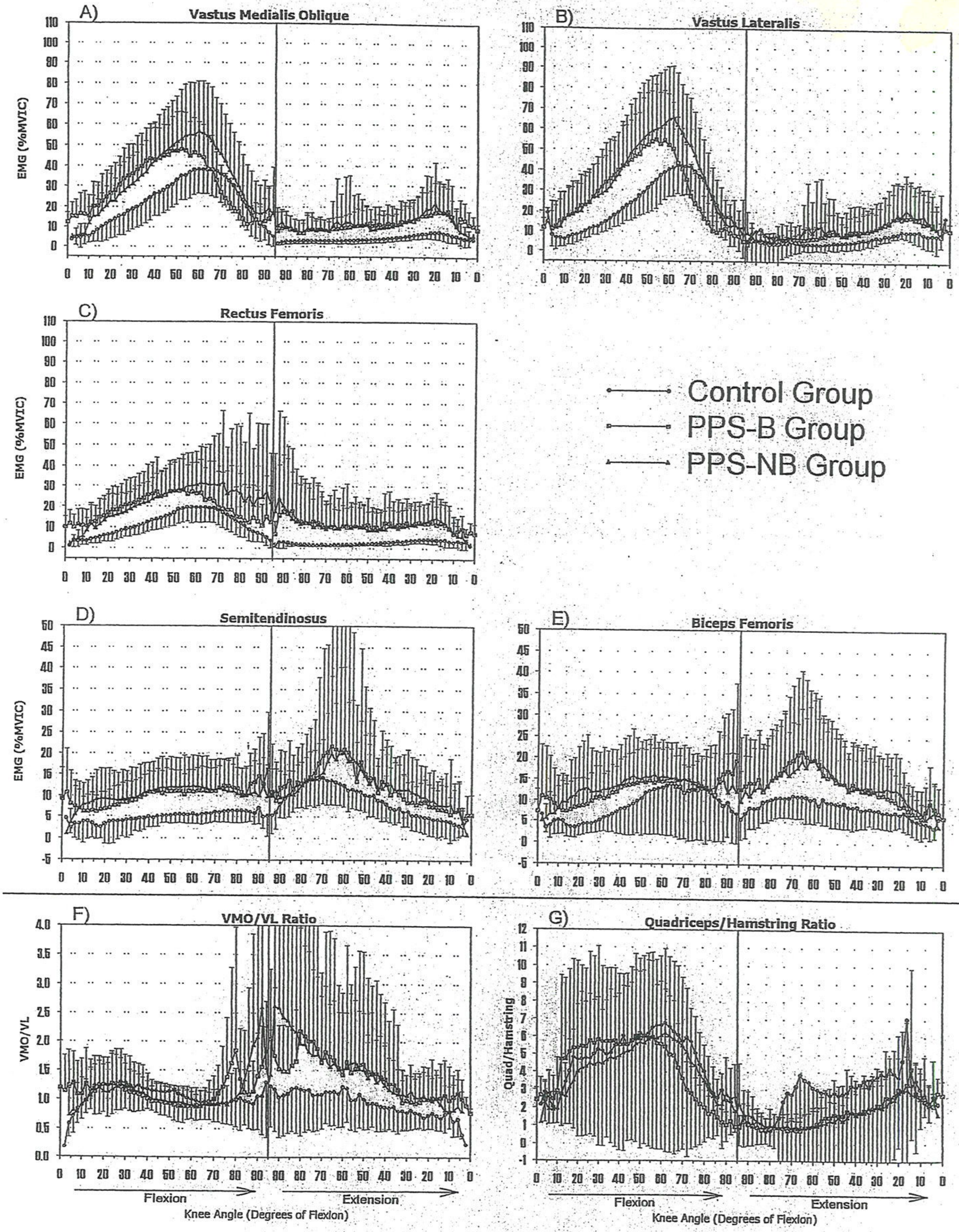

Figure 7: Graphs of EMG actvity and ratios during stair descending versus knee flexion angle. Note, the first half of the graph represents knee flexion and the last half represents knee extension

Squatting

The quadriceps muscles during knee flexion and extension showed similar patterns for each muscle (Figures 9a, 9b and 9c). Through the entire range of knee flexion the control group showed the least amount of muscle activity for all quadriceps muscles. The PPS-NB group showed significantly greater levels of quadriceps activity through the middle ranges of flexion and extension than the controls. The control and PPS-B groups, however, were not found to be different, indicating a lowering of quadriceps muscle activity as a result of the brace's introduction. During the knee extension phase of squatting the quadriceps showed no differences between the two PPS groups and both were significantly greater than the control group through the middle range of extension.

The hamstring muscles showed very low levels of muscle activation during both flexion and extension (Figures 9d and 9e). The semitendinosus reached its maximum of 10% MVIC late in the flexion range of motion. The Biceps femoris reached higher levels of activation; however, no significant differences were seen between any of the groups. As with the other activities, there were no observed differences between any of the groups for either the VMO:VL or Quadriceps:Hamstring ratios (Figures 9f and 9g).

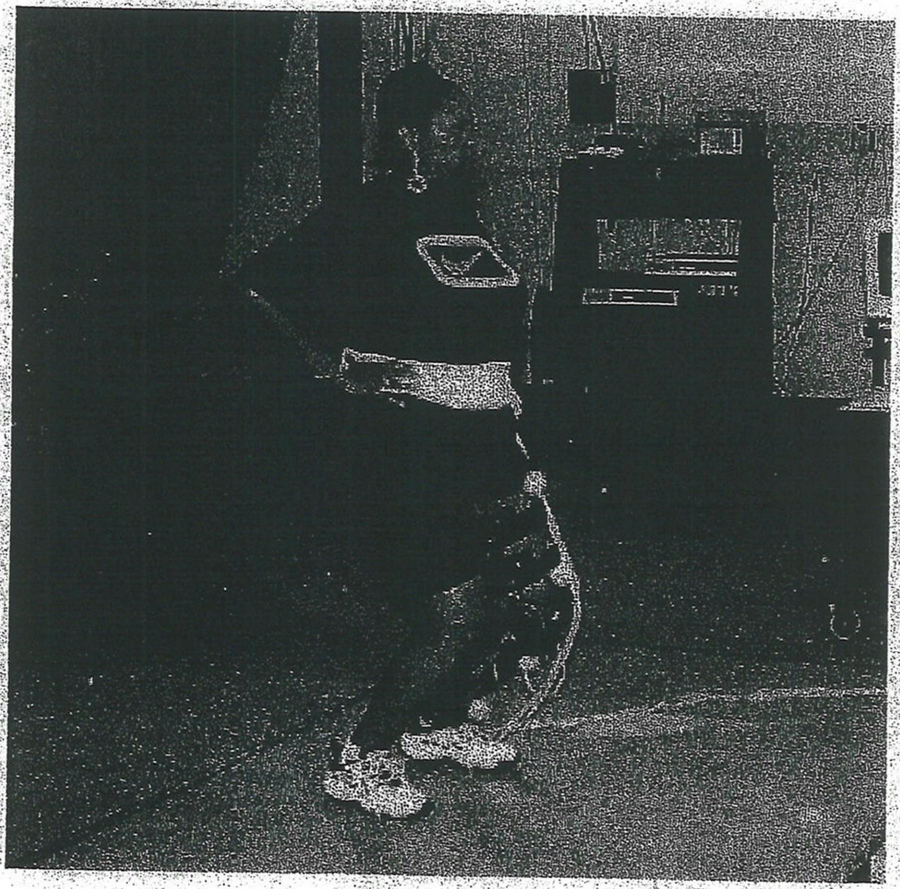

Figure 8: PPS subject demonstrating the squatting exercise.

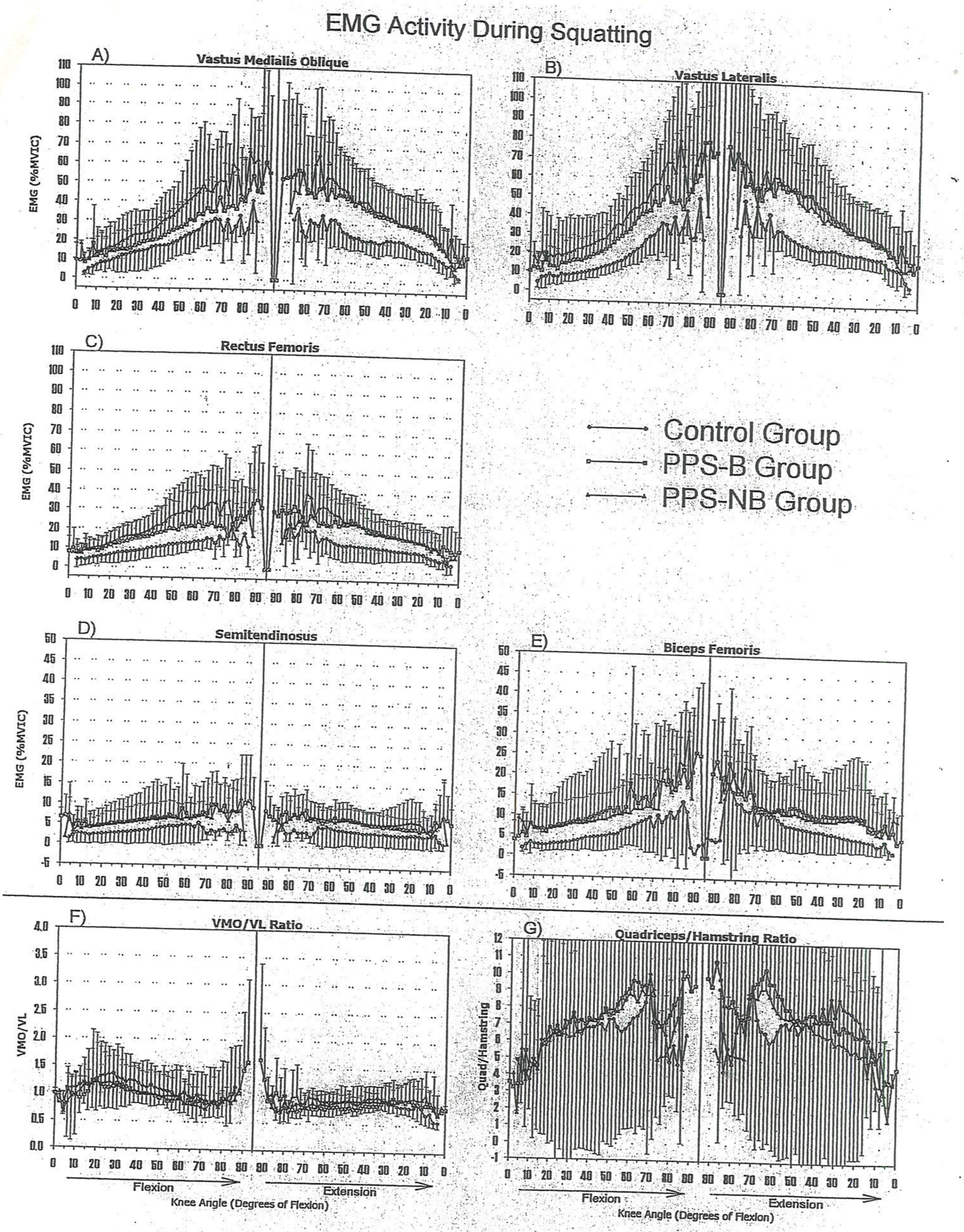

Figure 9: Graphs of EMG actvity and ratios during squatting versus knee flexion angle. Note, the first half of the graph represents knee flexion and the last half represents knee extension

Walking

During walking the control group was found to show significantly less VMO and rectus femoris muscle activity during knee flexion than both of the PPS groups (Figures 11a, 11b and 11c). These muscles, however, showed only low levels of activation. The control group's VL activity was significantly less than the PPS-NB groups for most of the flexion range, but was only significantly different from the PPS-B group for a few degrees. During the extension phase of level walking, the quadriceps showed few significant differences between the groups. The VL was the only quadriceps muscle to show significant differences between the PPS-NB and control groups while showing no differences between the PPS-B and control groups.

The hamstrings displayed low levels of myoelectric activity through knee flexion and extension (Figures 11d and 11e). The biceps femoris showed significantly greater activity for the PPS-B group than the control group through the latter two-thirds of the flexion range of motion, while the semitendinosus showed similar significant differences between the control and both of the PPS groups. No significant group differences were observed for either the VMO:VL ratio or the Quadricep:Hamstring ratio (Figures 11f and 11g).

Figure 10: PPS subject during level walking.

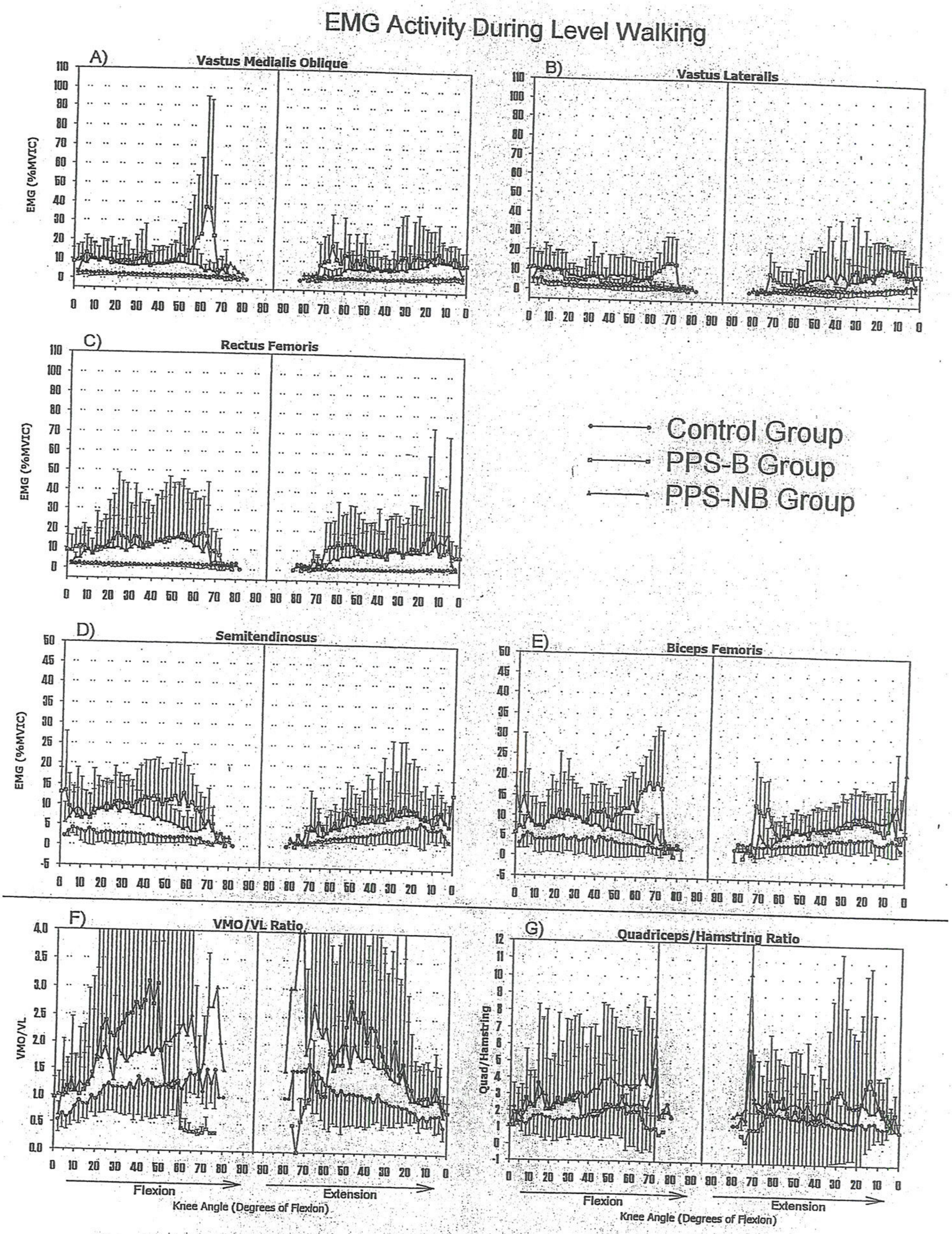

Figure 11: Graphs of EMG actvity and ratios during level walking versus knee flexion angle. Note, the first half of the graph represents knee flexion and the last half represents knee extension

Lunging

During the lunge, quadriceps activity showed moderate to high levels of muscle activity at the deeper angles of knee flexion and exhibited erratic differences between the control group and the two PPS groups (Figures 13a, 13b and 13c). The VMO activity, for instance, was significantly greater for the PPS-B groups than for the control group through most of the flexion range of motion. There were no differences between the control and the PPS-NB groups during this same range exhibiting an increase in VMO activation resulting from the Protonics device. Similar findings were noted for the VL activity, however, the significant differences were found at the deeper flexion angles. The rectus femoris showed some significant differences between the PPS groups and the control group, however, unlike the VMO and VL activity patterns, there were no visible differences between the two PPS groups. During the knee extension phase of lunging few significant differences existed between the control group and either of the two PPS groups.

The hamstrings showed low to moderate activity that was fairly constant through the ranges of flexion and extension (Figures 13d and 13e). The semitendinosus never reached muscle activation greater than 15% MVIC, while the biceps femoris only exceeded15% at the deeper knee angles. Significant differences were noted, however, between the PPS-B group and the control groups for most of the flexion range of motion for both hamstring muscles. Fewer statistical and observational differences were noted during the knee extension portion of the lunge. As with the other activities, no differences were observed for either of the two muscle ratio variables (Figures 13f and 13g).

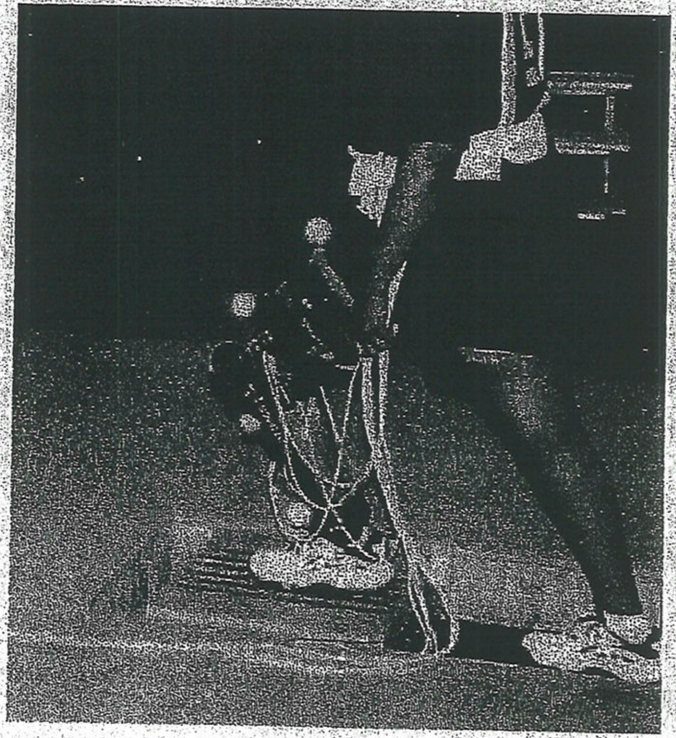

Figure 12: PPS subject performing the lunge exercise.

EMG Activity During Lunging

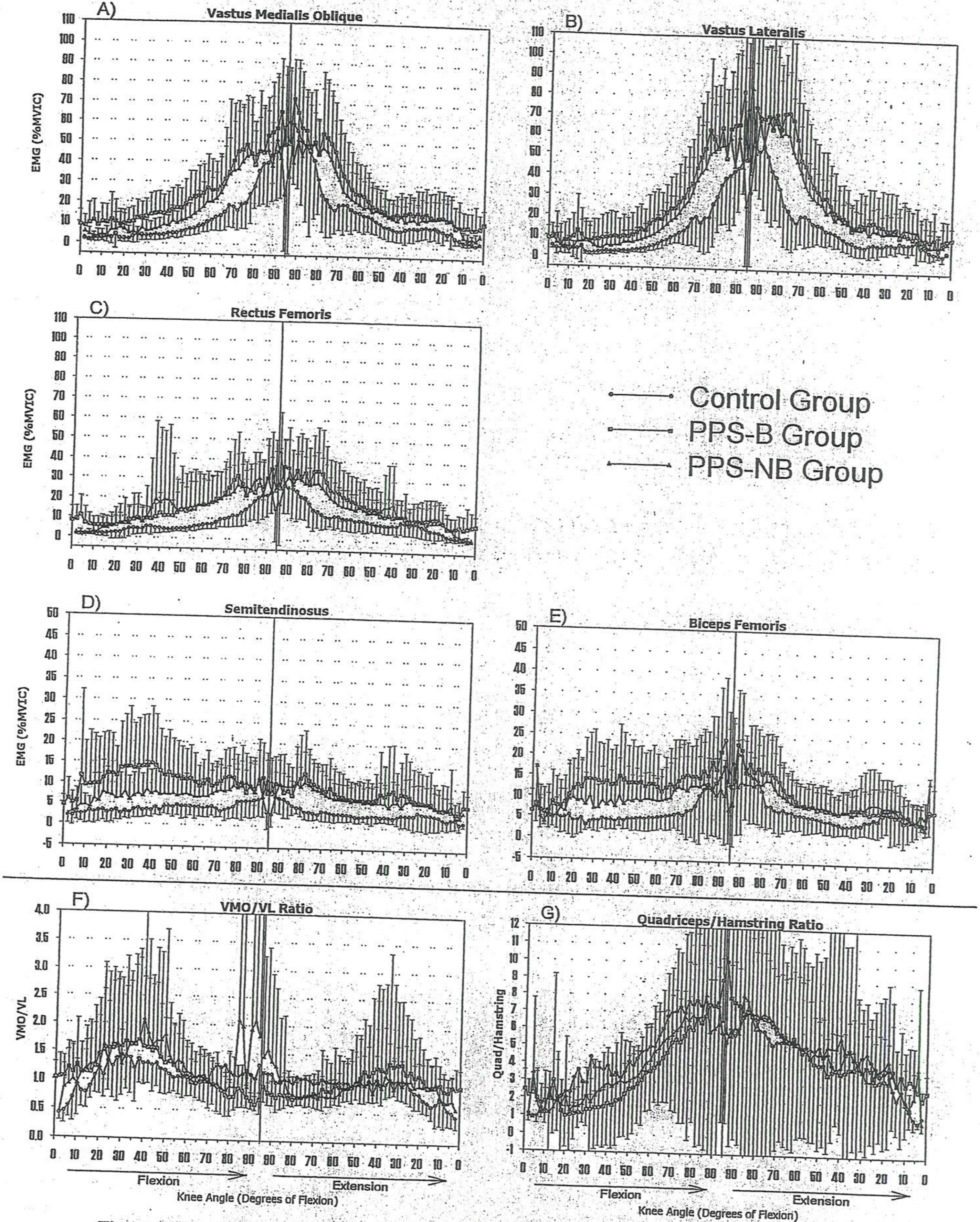

Figure 13: Graphs of EMG actvity and ratios during lunging versus knee flexion angle. Note, the first half of the graph represents knee flexion and the last half represents knee extension

DISCUSSION

Perhaps the greatest asset of a device such as the Protonics device is that it reduces pain. All subjects who wore the device commented on a reduction in the amount of pain that they were experiencing prior to using the brace.

During stair ascending and descending, squatting and lunging the brace group showed differences in quadriceps activity from the no-brace groups. During ascending these differences were seen during the knee extension movement when the quadriceps were contracting to elevate the body to the next step. In all three quadriceps muscles the PPS-NB group showed higher levels of activity than the other two groups. While wearing the brace the quadriceps activity of the PPS group was decreased to levels approaching that of the healthy control group. Similar findings were seen during stair descending. The quadriceps were most active for the PPS-NB group during knee flexion. When the brace was worn the group's muscle activity decreased. This decrease was noted to be during the latter half of knee flexion where it neared the control group's level of quadriceps activity. During squatting the quadriceps are used during both knee flexion and extension. More quadriceps changes resulting from the presence of the Protonics device occurred during the flexion movements of squatting and lunging. The changes seen as a result of wearing the device came at the beginning of knee flexion during lunging and throughout knee flexion during squatting. The PPS-NB group showed the greatest levels of quadriceps activity, in most cases more than twice the activity of the control group. The PPS-B group showed less quadriceps activity than the PPS-NB group but remained greater than the controls. These differences were greater at the deeper knee flexion angles. It appears that the resistance of the Protonics device during exercises controlled by eccentric quadriceps activity works against gravity just as the quadriceps do. This in turn lessens the demand on those muscles resulting in less patellofemoral compressive force and, therefore, pain. This is supported by the PPS participants reporting less pain while performing the exercises with the brace in place.

The changes in hamstring activity seen after the brace's introduction were mixed but the amount of myoelectric activity in the hamstrings was generally quite low. During stair ascending and level walking the hamstrings seemed to increase during the latter portions of knee flexion. No hamstring changes resulting from the introduction of the brace were observed during stair descending or squatting. During lunging the brace group showed greater hamstring activity than both of the other groups through much of knee flexion, however, these differences were not statistically significant through the entire range. Therefore, during stair ascending, level walking and lunging the hamstring activity increased when the Protonics device was worn. Despite the low magnitude of EMG activity, these differences may have clinical significance. The location within the knee flexion range where the differences occurred changed from one activity to another.

The amount of knee flexion employed significantly decreased during stair ascending and level walking when the Protonics device was worn. The knee ranges of motion for the other three exercises were unaffected by the introduction of the Protonics device.

Contrary to what was expected, the quadriceps:hamstring ratio seemed to be erratic and inexplicable. There were times when the brace seemed to lower this ratio supporting the notion that the quadriceps activity was decreased and/or the hamstrings activity increased. The knee flexion ranges during which this difference was present was usually short in duration, and seldom statistically significant. VMO:VL ratio reacted similarly and showed no statistical significance, and provided little insight as to the relative contributions of the VMO and VL. One probable contributor to this lack of statistical significance is the inherently high variability seen in EMG output.

In conclusion, the results indicate an advantage associated with wearing the brace. This was shown in decreases in quadriceps activity as well as increases in hamstring activity for various exercises. The high variability seen in pathological EMG data is most likely the primary reason for a lack in statistical significance.

Another possible limitation of this study is the seemingly unmatched subject groups. The control subject's mass was approximately 20 kg less than the PPS subjects. It was unexpected to see that the PPS group was predominately comprised of women whose weights were greater than 160 pounds. Because of this difference correlation coefficients were calculated for two muscles and two exercises chosen randomly. When body mass was correlated to maximum VMO activity during stair climbing the coefficients for the control and PPS groups were -0.1247 and 0.0605, respectively. Similarly, the correlation between mass and maximum VL activity during squatting showed coefficients of -0.4555 for the control group and -0.2390 for the PPS group. Because these correlation coefficients were low (all below 0.5), the subjects' body mass was determined to have no significant effect on EMG signal detection.

This study only investigated the immediate myoelectrical changes associated with the introduction of the Protonics device. Neuromechanical changes must be made in order for long-term, permanent changes to occur. A follow-up study examining the same participants and their long-term changes associated with their use of the Protonics device would be useful in understanding more completely the device and its benefits.

Future investigations should be concentrated on the long term effects of the brace on the muscle activity changes. Discovering whether the brace permanently changes muscle firing patterns and therefore halts PPS symptoms, or if the changes seen here disappear once the Protonics device is removed is essential for physicians and therapists to be able to accurately prescribe the device.

ACKNOWLEGEMENTS

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