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Reliability of electromyographic methods used for assessing hip and knee neuromuscular activity in females diagnosed with patellofemoral pain syndrome ☆

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ABSTRACT

Patellofemoral pain syndrome (PFPS) is one of the most common, yet misunderstood, knee pathologies. PFPS is thought to result from abnormal patella tracking caused from altered neuromuscular control. Researchers have investigated neuromuscular influences from the gluteus medius (GM), vastus medialis (VM), and vastus lateralis (VL) but with inconsistent findings. A reason for these discrepancies may be from varying methodology. The purpose of this study was to determine the reliability of electromyographic (EMG) methods used to assess amplitudes and timing differences of the GM, VM, and VL in subjects with PFPS. Seven females with PFPS participated. GM, VM, and VL activity was assessed during the stance phase of a stair descent task on two separate occasions. Amplitudes during the different intervals of stance were recorded and expressed as a percent of each muscle's maximum voluntary isometric contraction. Muscle onsets at the beginning of stair descent were also determined. VM–GM, VL–GM, and VL–VM onset timing differences were quantified. Intraclass correlation coefficients (ICCs) and standard errors of measurement (SEMs) were calculated to assess between-day reliability. Most EMG measures had acceptable reliability ($ICC_{3,5} \geqslant 0.70$). Although some measures had moderate reliability (ICC < 0.70), they had low SEMs, which suggested high measurement precision. These findings support using these methods for examining neuromuscular activity in subjects with PFPS.

1. Introduction

Patellofemoral pain syndrome (PFPS) represents a commonly seen and clinically challenging pathology (Wilk et al., 1998). Dye et al. (1999) described PFPS as the "Black Hole of Orthopaedics" because of its misunderstood etiology. Fulkerson (2002) has described abnormal patella tracking within the femoral trochlea as a possible cause of PFPS. Abnormal tracking may result from reduced vastus medialis (VM) muscle activity relative to the vastus lateralis (VL) as well as delayed onset of the VM relative to the VL (Cowan et al., 2002; Grabiner et al., 1994). More recent investigations (Brindle et al., 2003; Ireland et al., 2003; Powers et al., 2003; Boling et al., 2006) have focused on the influence of the hip on knee function. Brindle et al. (2003) have reported a delay in gluteus medius (GM) activation relative to the VM and VL and concluded that altered GM activity may adversely affect knee function.

A current review of the literature has shown discrepancies regarding VM and VL amplitudes and onset timing differences in subjects with and without PFPS during stair descent. One reason for such discrepancies may result from the way that data were expressed or analyzed. Powers et al. (1996) and Souza and Gross (1991) determined the average amplitude of the VM and VL throughout the entire cycle of stair descent for subjects with and without PFPS and did not report group differences. Alternatively, Mohr et al. (2003) assessed amplitudes for each 2% interval of stair descent. They reported greater VM and VL amplitudes in subjects with PFPS from patella instability, especially during the loading response interval of stair descent. This finding suggested that assessing amplitudes over discrete intervals may represent a more sensitive manner for identifying differences (Salsich et al., 2002).

Others have determined either the peak (Sheehy et al., 1998) or average (Souza and Gross, 1991) VM and VL activity during stair descent and expressed these values as a VM to VL ratio. Subjects with and without PFPS in these studies had similar ratios. The potential for not detecting group differences could have existed as subjects with PFPS could have exhibited lower VM and VL amplitudes but still have similar VM to VL ratios as healthy subjects. Therefore, expressing amplitudes as absolute values (not a ratio)

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and analyzing them over discrete intervals of stair descent may provide more conclusive information regarding neuromuscular activity in patients with PFPS.

Most prior works have examined onset timing differences between the VM and VL. Researchers (Voight and Wieder, 1991; Witvrouw et al., 1996) have reported delayed reflex response times of the VM compared to the VL during a patellar tendon tap. A potential limitation of these studies was the assessment of afferent pathways. Karst and Willett (1995) examined both reflex response times and VM–VL onsets during non-weight bearing and weight bearing voluntary knee extension exercise. Although they reported similar differences with reflex responses (Voight and Wieder, 1991; Witvrouw et al., 1996), they did not find VM–VL onset timing differences during voluntary exercise. This finding suggested that reflex testing was a poor indicator of muscle activity onsets during voluntary knee extension.

Conflicting results exist regarding VM and VL onsets during volitional tasks. Some investigators (Brindle et al., 2003; Powers et al., 1996; Sheehy et al., 1998) have reported simultaneous VM and VL activation whereas others (Cowan et al., 2002; Boling et al., 2006; Cowan et al., 2001) have found delayed VM activation. Reasons for discrepancies may result from differences with task performance, muscle onset identification, and signal processing (Cowan et al., 2000). Subjects in studies that did not find onset differences completed stair descent at a self-selected pace (Brindle et al., 2003; Powers et al., 1996; Sheehy et al., 1998) and the investigators identified muscle onsets using either visual analysis (Sheehy et al., 1998) or a computer algorithm (Brindle et al., 2003; Powers et al., 1996). Variations in signal processing also occurred as some researchers applied a 15 Hz low pass filter (Brindle et al., 2003) while others applied a 150–1000 Hz band pass filter (Powers et al., 1996).

Hodges and Bui (1996) recommended identifying muscle onsets using both visual inspection and a computer algorithm. They also recommended applying a low pass filter at 50 Hz because excessive signal smoothing can hinder proper determination of onsets. Based on these recommendations, Cowan et al. (2000) determined the reliability of a protocol to identify muscle onsets. In this study, healthy subjects completed a stair descent task at a standardized rate of 96 beats per minute. Electromyographic (EMG) signals were full wave rectified and low pass filtered at 50 Hz. They used an algorithm that defined an onset as the point in which a signal deviated by more than three standard deviations, for a minimum of 25 ms, over a baseline level taken 200 ms before a trial began. All muscle onsets were also visually confirmed. Using these procedures, Cowan et al. reported an intraclass correlation coefficient (ICC) equal to 0.96. More important, results from subsequent studies (Cowan et al., 2002; Boling et al., 2006; Cowan et al., 2001) that have incorporated these procedures have shown delayed VM onset relative to the VL during stair descent in subjects with PFPS. Therefore, these refinements may better identify differences in VM and VL onsets.

Recent attention has focused on the influence of the hip on PFPS (Ireland et al., 2003; Bolgla et al., 2008); however, limited information exists regarding neuromuscular activity of the hip in this patient population. To date, no study has examined hip muscle amplitudes and only two investigations (Brindle et al., 2003; Boling et al., 2006) have compared GM onsets to that of the VM and VL during stair descent. While Brindle et al. (2003) reported a greater delay in GM activation relative to the VM and VL in subjects with PFPS, Boling et al. (2006) did not corroborate this finding. Methodological difference most likely accounted for these discrepancies.

Inconclusive study results from prior research may reflect varying methodology instead of true differences in the observed parameter (Portney and Watkins, 2000). A limitation of prior works has been limited attention to measurement reliability. To our knowledge, no study has established measurement reliability for determining amplitudes during stair descent. Only Cowan et al. (2000) have specifically examined measurement reliability for identifying VM and VL onsets. Although they reported excellent measurement reliability in healthy subjects during stair descent, it has remained elusive if these methods would be equally reliable when assessing subjects with pathology. The identification and systematic use of reliable measures is paramount to better understand hip and knee neuromuscular activity for patients with PFPS.

Therefore, the purpose of this study was to establish measurement reliability for procedures designed to assess neuromuscular activity of the GM, VM, and VL during stair descent in subjects with PFPS. Specifically, we wanted to determine the reliability for quantifying amplitudes over discrete intervals of stair descent (Mohr et al., 2003) and identifying muscle onsets based on recommendations from Hodges and Bui (1996) and Cowan et al. (2000). We hypothesized that all measures would have an ICC greater than or equal to 0.70 (Portney and Watkins, 2000).

2. Methods

2.1. Subjects

Only female subjects participated since PFPS is more prevalent in this subject population (Thomee, 1997). They participated in a larger study that examined hip and knee function, strength, EMG activity, and kinematics in this patient population (Bolgla et al., 2008). Data from seven females with PFPS (age = 22.9 ± 2.7 years, height = 1.7 ± 0.1 m, body mass = 60.0 ± 5.6 kg, symptom duration = 11.6 ± 13.8 months) were included in the current analysis. Inclusion criteria included the following: (1) anterior knee pain during stair descent and (2) pain during at least two of the following provocative activities: (a) stair ascent, (b) squatting, (c) kneeling, or (d) prolonged sitting. Subjects also rated usual knee pain over the previous week at a minimum of three on a 10-cm visual analog scale (VAS) (Cowan et al., 2000). The most affected lower extremity was tested for subjects diagnosed with bilateral PFPS (Powers et al., 1996). One subject reported bilateral symptoms.

Subjects were excluded if they had: (1) previous knee surgery or significant injury; (2) traumatic patellar dislocation; (3) any neurologic involvement that would affect gait; or (4) previous hip surgery or significant injury (Brindle et al., 2003; Powers et al., 1996). All subjects signed an informed consent approved by the University of Kentucky Institutional Review Board and their rights protected.

2.2. Procedures

First, subjects completed the 10-cm VAS describing their usual pain over the previous week (Crossley et al., 2004). Next, they rode a stationary bike for 3 min in a pain-free range of motion at a submaximal speed.

Subjects' skin was prepared for EMG instrumentation in a standard fashion (Basmajian and De Luca, 1985). Bi-polar Ag–AgCl surface electrodes (Medicotest, Rolling Meadows, IL), measuring 5-mm in diameter and interelectrode distance of 20-mm, were placed in parallel arrangement over the GM, VM, and VL muscle bellies. The GM electrode was placed one-third the distance between the iliac crest and greater trochanter (Rainoldi et al., 2004). The VM electrode was placed approximately 4 cm superior and 3 cm medial to the superomedial border of the patella and oriented 55° to the vertical (Cowan et al., 2000). The VL electrode was placed 5–7 cm superior and 6–8 cm lateral to the superolateral border of the patella and oriented 15° to the vertical (Cram and Kasman, 1998). Adhesive tape was placed over the electrodes to prevent slippage during testing. Electrode placement sites (e.g.,

the distances from the specified landmarks) were recorded on a data collection sheet to facilitate duplicate replacement during repeat testing. A ground electrode was placed on the ipsilateral clavicle. Electrode placements were visually confirmed on an oscilloscope using manual muscle testing techniques. A 3-s standing "quiet" file was recorded to exclude background ambient noise (Mohr et al., 2003; Bolgla and Uhl, 2005).

A 16-channel Myosystem 1400 EMG system (Noraxon USA, Inc., Scottsdale, AZ) recorded GM, VM, and VL muscle activity during all testing. Unit specifications included a common mode rejection ratio exceeding 100 dB, amplifier gain of 1000, and input impedance exceeding 10 MΩ. EMG data were band pass filtered (10–1000 Hz) prior to sampling at 960 Hz (to allow for synchronous collection with video data that was sampled at 60 Hz) using a 12-bit analog-to-digital converter (National Instruments, Austin, TX) (Brindle et al., 2003).

Following EMG placement, maximum voluntary isometric contractions (MVIC) were taken for the GM, VM, and VL using procedures previously described (Bolgla et al., 2008; Bolgla and Uhl, 2007). For this purpose, we utilized immovable straps and the Commander PowerTrack II™ (J Tech Medical, Salt Lake City, UT) hand-held dynamometer (HHD). Immovable straps were used because lack of examiner strength can influence a subject's ability to generate a representative MVIC (Wikholm and Bohannon, 1991; Kramer et al., 1991; Agre et al., 1987). As described in further detail below, we used the HHD to simultaneously measure the force generated during each MVIC. Agre et al. (1987) stated that taking the average of three force values, with a coefficient of variation (CV) less than 10%, can improve measurement reliability when assessing a MVIC. Therefore, the HHD enabled us to quantify the amount of force generated during each trial.

All MVICs were taken in accordance with manual muscle testing techniques (Hislop and Montgomery, 2002). For the GM, subjects were positioned in sidelying (unaffected lower extremity directly on the table) with the test lower extremity in a neutral position by placing pillows between the lower extremities (Bolgla et al., 2008). The HHD was placed was placed over the lateral femoral condyle and secured with an immovable strap pulled around the table (Bolgla et al., 2008). For the VM and VL, subjects were positioned with the hip in 90° flexion and the knee in 60° flexion (Mohr et al., 2003; de Ruiter et al., 2004). The HHD was placed just proximal to the malleoli and secured with an immovable strap pulled through the HHD and around a stationary object (to resist knee extension).

For testing, subjects produced a MVIC to a metronome set at 60 beats per minute. They generated maximum force over a 2-s period and maintained this force for another 5 s (Bohannon, 1997). Subjects performed one practice (Bolgla et al., 2008; Bolgla and Uhl, 2007; Bohannon, 1997) and three test trials, resting 30 s between trials (Bolgla et al., 2008; Bolgla and Uhl, 2007). A CV was calculated and another trial taken, if necessary, to ensure that subjects had three force measures with variability less than 10% (Agre et al., 1987). All subjects received strong verbal encouragement during testing (Campenella et al., 2000). The muscle testing order was randomized to account for ordering bias. All measures were recorded in newtons of force.

Next, retroreflective markers, with a 20-mm diameter, were placed on subjects using a standard Cleveland clinic marker setup. Video data were used to demarcate the start and end of stair descent and recorded using a seven camera motion capture system (Motion Analysis Corporation, Santa Rosa, CA) operating at 60 Hz. EMG and video data were collected synchronously using EVaRT 4.2 software (Motion Analysis Corporation) and stored on a personal computer.

After collecting an anatomic calibration file, subjects were shown the stair-stepping task and allowed five practice trials. They ascended and descended two 20-cm high steps (with 30-cm tread depth and 47-cm step width), ensuring that the test extremity lifted and lowered the body on the first and third steps. Subjects took at least three strides prior to and immediately following the stair-stepping task to maintain a continuous movement pattern. Because movement velocity may influence EMG activity, subjects performed the task at 96 beats per minute (Cowan et al., 2000). After demonstrating proficiency with the stair-stepping task, subjects performed 10 test trials. Data collected from the last five test trials were analyzed and used for statistical analysis to minimize any potential learning effects.

All subjects returned to the laboratory within 5–7 days for repeat testing. They performed all tests in an identical manner. Subjects completed another VAS as pain may represent a confounding variable. Loudon et al. (2002) recommended that repeat VAS scores be ±0.5 cm of the original score to prevent confounding of the pain variable. All subjects participated in the second part of this study.

2.3. Data processing

Raw EMG signals were further band pass filtered at 20–480 Hz using Datapac software (Run Technologies, Mission Viejo, CA). To determine muscle amplitudes, EMG data from the last five test trials were root-mean-square (RMS) smoothed using a 55-ms time constant (Sheehy et al., 1998), normalized to 100% of stair descent, and ensemble averaged.

Quiet file and MVIC data were band pass filtered and RMS smoothed in an identical manner and used to express activation amplitudes as a percent MVIC (% MVIC). A computer algorithm determined the maximum RMS amplitude recorded over a moving 500-ms average window across the MVICs. This amount represented 100% activity (Bamman et al., 1997). Ensemble averaged EMG data were then expressed as a % MVIC.

Mohr et al. (2003) reported varying muscle amplitudes throughout stair descent. To better identify differences (Salsich et al., 2002), we divided the stance phase of stair descent into three intervals: loading response (LR), single leg stance (SLS), and preswing (see Fig. 1). LR represented 0–7% of stair descent. SLS occurred from 8% to 46% and preswing from 47% to 58% of stair descent. The remaining 42% represented the swing phase. Average amplitudes for each stance interval were analyzed. Swing phase data were not analyzed since patients with PFPS typically demonstrate impairments during activities requiring loading on a flexed knee (e.g., the stance phase of stair descent).

Datapac software also determined muscle onsets at the beginning of stair descent. For this purpose, data were band pass filtered as above, full-wave rectified, and low-pass filtered at 50 Hz (Cowan et al., 2000). We defined an onset when the signal deviated by more than three standard deviations, for at least 25 ms, over the baseline taken 200 ms before the trial began (Cowan et al., 2000). All onsets were visually confirmed since movement artifact could be misconstrued as activity onset (Hodges and Bui, 1996). After identifying muscle onsets, Datapac software calculated timing differences. The GM onset was subtracted from the VM and VL onsets; therefore, a negative difference signified delayed GM activation while a positive difference meant GM preactivation. The software also subtracted the VM onset from the VL onset. A negative difference meant delayed VM activation and a positive difference signified VM preactivation. The average from the last five trials was used for statistical analysis (Cowan et al., 2001).

2.4. Statistical analysis

ICCs (Shrout and Fleiss, 1979) were used to determine between-day intrarater reliability; standard errors of measurement (SEMs) were used to determine measurement precision (Denegar and Ball,

Fig. 1. The stair platform and intervals of the stance phase during stair descent. (A) Loading response began when the test extremity's foot initially contacted the third step and ended when the contralateral foot was lifted off the second step (e.g., initial double leg stance); (B) single leg stance began when the contralateral foot was lifted off the second step and ended when the contralateral foot touched the floor; and (C) preswing began when the contralateral foot contacted the ground and ended when the test extremity's foot was lifted off the third step (e.g., terminal double leg stance).

1993). $ICC_{3,5}$ was calculated for all EMG values since they represented the average of five trials. Statistical analyses were performed using SPSS version 12.0 (SPSS, Inc., Chicago, IL). Level of significance was established at the 0.05 level.

3. Results

Subjects rated usual pain over the previous week an average of 4.8 ± 1.9 cm on the VAS. Tables 1 and 2 summarize means, standard deviations, ICCs, and SEMs for all dependent measures. Amplitudes during the LR and SLS intervals for all the muscles had an $ICC_{3,5}$ greater than 0.70. During the preswing interval, $ICC_{3,5}$ for the GM (0.95) was higher than the VM (0.40) and VL (0.53). Regarding timing differences, $ICC_{3,5}$ for the VM–GM (0.83) and VL–GM (0.91) were higher than the VL–VM (0.70). Although the VL–VM timing difference had a lower ICC, its relatively small SEM (4.0 ms) implied greater measurement precision.

4. Discussion

Measurement reliability is critical for data analysis. It ensures that changes in a specific measure represent a true change in performance and not one from chance alone (Loudon et al., 2002). Overall, our results suggested that the methods used in the current study provided reliable measures for determining GM, VM, and VL amplitudes and onset timing differences in females with PFPS during a stair descent task.

Table 1
Summary of means, standard deviations (SD), and standard errors of measurement (SEM), all expressed as a percent of maximum voluntary isometric contraction, and intraclass correlation coefficients (ICC) for the electromyographic amplitude measures during each interval of the stance phase of stair descent.

	Day 1		Day 2		$ICC_{3,5}$	SEM
	Mean	SD	Mean	SD		
Loading response						
Gluteus medius	40	20	42	34	.77	10
Vastus medialis	59	30	59	28	.95	7
Vastus lateralis	41	21	50	35	.87	8
Single leg stance						
Gluteus medius	30	20	28	16	.73	10
Vastus medialis	50	23	55	20	.91	7
Vastus lateralis	40	14	42	18	.87	5
Preswing						
Gluteus medius	8	5	7	6	.95	1
Vastus medialis	13	15	4	3	.40	12
Vastus lateralis	9	13	3	3	.53	8

Table 2
Summary of means, standard deviations (SD), and standard errors of measurement (SEM), all expressed in milliseconds, and intraclass correlation coefficients (ICC) for the electromyographic onset timing differences at the beginning of stair descent for the gluteus medius (GM), vastus medialis (VM), and vastus lateralis (VL).

	Day 1		Day 2		$ICC_{3,5}$	SEM
	Mean	SD	Mean	SD		
VM–GM[a]	−60.9	28.7	−72.1	38.7	.83	14
VL–GM[a]	−56.4	32.4	−71.4	42.0	.91	12
VL–VM[b]	−6.7	8.3	−4.4	4.1	.70	4

[a] A negative value represents a delay in GM activation.
[b] A negative value represents a delay in VM activation.

4.1. EMG amplitudes

Conflicting results exist regarding EMG amplitudes during stair descent in subjects diagnosed with PFPS. Some researchers (Mohr et al., 2003) have reported different quadriceps amplitudes while others (Powers et al., 1996; Souza and Gross, 1991; Sheehy et al., 1998) have not. A limitation of prior studies has been averaging the EMG signal over the entire stance phase of stair descent (Powers et al., 1996; Souza and Gross, 1991) or assessing the peak amplitude at a single point in time of stair descent (Sheehy et al., 1998). Averaging the EMG signal at designated intervals of stance might improve the ability to identify discrete activity differences (Salsich et al., 2002). We accounted for this limitation by dividing stance into intervals that corresponded to LR, SLS, and preswing.

Sheehy et al. (1998) identified two peaks of eccentric VM and VL EMG activity during the stance phase of stair descent. The first peak occurred during weight acceptance where subjects decelerated and controlled forward and downward body motion onto the step. They stated that this interval was the most demanding portion of stance and resulted in greater EMG activity. For the current study, the LR and SLS intervals occurred during this first activity peak. Like prior works (Mohr et al., 2003; McFadyen and Winter, 1988; Lyons et al., 1983), our subjects generated relatively greater EMG amplitudes during these intervals compared to the preswing interval.

Sheehy et al. (1998) also identified a second peak of EMG activity as subjects lowered their body toward the ground (center of

mass movement past the stance lower extremity). Amplitudes during this interval were less compared to the first peak and occurred during preswing in the current study. Like Sheehy et al., our subjects generated lower amplitudes compared to the LR and SLS intervals.

LR and SLS ICCs exceeded 0.70 for all muscles. These findings suggested that subjects used similar motor patterns during the more demanding intervals. Conversely, ICCs for the VM and VL during preswing were substantially lower and data more variable. This finding suggested that subjects used different activation patterns during this less demanding interval.

The GM had acceptable reliability during all stance intervals. Neumann and Hase (1994) demonstrated the importance of the GM for frontal plane stability. Our subjects might have stabilized the hip and pelvis using consistent GM activation throughout all stance intervals.

4.2. EMG onset timing differences

Cowan et al. (2000) examined reliability for VM and VL timing differences in healthy subjects for the parameters used in the current study. They reported $ICC_{3,5}$ of 0.96 during stair descent. Our findings inferred acceptable reproducibility of VL–VM timing differences at the onset of stair descent for subjects with PFPS. Although a higher ICC was desirable, the associated SEM (4.0 ms) was small. A relatively lower ICC, but a small SEM, suggested measurement inconsistency in an acceptably small range (Denegar and Ball, 1993).

Brindle et al. (2003) first reported delayed GM activation relative to the quadriceps during stair descent for subjects with PFPS. Conversely, Boling et al. (2006) did not corroborate this finding. Conflicting results likely reflected varying methodology. Boling et al. used a standardized rate while subjects in the Brindle et al. study used a self-selected pace. Differing cadence might explain conflicting results.

We used the same methods as Boling et al. (2006). Our study revealed acceptable reliability for the VM–GM and VL–GM timing differences. In summary, continued debate has existed regarding GM and quadriceps timing differences. Future studies using methods from the current study might provide more conclusive data.

4.3. Limitations

The current study has certain limitations. The primary examiner collected and analyzed all data and might have unintentionally introduced bias. We minimized potential bias as all measures were taken in accordance with standardized procedures. It should also be noted that intrarater reliability generally is greater compared to interrater reliability. Therefore, findings from the current study may only apply to a single examiner. Another potential limitation associated with EMG studies has been signal cross-talk. Other muscles, like the gluteus minimus, tensor fascia lata, and rectus femoris, might have influenced the signals. We minimized this influence by donning electrodes over the belly of the muscles tested as recommended by previous researchers (Basmajian and De Luca, 1985; Cram and Kasman, 1998).

5. Conclusion

Results from this study indicated acceptable reliability for most of our EMG measures used to assess the GM, VM, and VL. Overall, surface EMG provided reliable measures of amplitudes and timing differences for the GM, VM, and VL. Subjects completed the stair-stepping task at a standard rate; it is unknown if similar ICCs would be calculated using other cadences.

These findings have important implications from both a research and clinical standpoint. Researchers have reported different findings for this patient population (Brindle et al., 2003; Boling et al., 2006; Cowan et al., 2001). Use of standardized techniques might provide more conclusive data regarding neuromuscular activity in patients with PFPS.

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