Muscle Activation Patterns and Patellofemoral Pain in Cyclists

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ABSTRACT

DIETER, B. P., C. P. MCGOWAN, S. K. STOLL, and C. A. VELLA. Muscle Activation Patterns and Patellofemoral Pain in Cyclists. *Med. Sci. Sports Exerc.*, Vol. 46, No. 4, pp. 753–761, 2014. **Introduction**: Patellofemoral pain syndrome (PFPS) is pervasive and debilitating in the sport of cycling. Currently, little is known about the underlying mechanism causing patellofemoral pain in cyclists. **Purpose**: The purpose of this study was to determine whether temporal differences in the muscle activity of the vastus medialis (VM), vastus lateralis (VL), semitendinosus (ST), and biceps femoris (BF) were correlated to patellofemoral pain in cycling. **Methods**: Ten healthy cyclists (six women and four men, height = 1.74 ± 0.10 cm, weight = 71.9 ± 16.5 kg, cycling experience = 199.5 ± 82 miles·wk^{-1}) and seven cyclists with PFPS (one woman and six men, height = 1.84 ± 0.08 cm, weight = 89.8 ± 9.4 kg, cycling experience = 228 ± 51 miles·wk^{-1}) volunteered to participate in this study. Each participant completed a 10-min cycling trial during which surface EMG was recorded for the VM, VL, ST, and BF muscles. Sagittal plane knee kinematic data were recorded using an electrogoniometer. **Results**: An ANOVA revealed no significant difference between groups for the differences in onset times of the VM and VL ($P = 0.805$). There were significant differences between groups for the differences in offset time of the VM and VL ($P = 0.032$), the differences in onset time of BF and ST ($P < 0.001$), and the differences in offset time of the ST and BF ($P = 0.024$). Root mean square values for BF activity were significantly higher in the PFPS group compared with the control (CTL) group ($P < 0.01$), and ST values were significantly lower in the PFPS group compared with the CTL group ($P < 0.01$). Root mean square values for BF were significantly greater than ST activity in the PFPS group ($P < 0.01$) but not in the CTL group ($P > 0.05$). **Conclusion**: The results of this study indicate that trained cyclists with PFPS exhibit altered temporal characteristics in muscle activation patterns compared with trained cyclists without PFPS.
Key Words: ANTERIOR KNEE PAIN, SURFACE EMG, NEUROMUSCULAR, CYCLING

Patellofemoral pain syndrome (PFPS) describes anterior or retropatellar knee pain in the absence of other clinically diagnosed pathology and presents as diffuse anterior or retropatellar knee pain exacerbated by physical activity requiring deep knee flexion (3,10). In the sport of cycling, PFPS is especially pervasive and debilitating. Thirty-six percent of professional cyclists experience PFPS, and it accounts for more than 57% of all time-loss injuries (8). Despite the literature relating to patellofemoral pain and the high rate of occurrence, little is known about the underlying mechanism causing patellofemoral pain in cyclists. To prevent and treat PFPS in the sport of cycling, a clear understanding of the mechanism responsible for causing the pathology needs to be developed.

PFPS commonly develops on the lateral aspect of the patella (40), suggesting that frontal plane loads may play a large role in the development of PFPS. The abnormal frontal plane motion of the patella during flexion and extension of the knee, known as patellar maltracking, has been shown to be a contributing factor to this pathology (4,26,28,32,40). A mechanism hypothesized to cause patellar maltracking is an imbalance in the temporal component of the muscle activity of the vastus medialis (VM) relative to the vastus lateralis (VL) (10,30,31,40) and an imbalance in the temporal component of the muscle activity of the semitendinosus (ST) relative to the biceps femoris (BF) (31). However, this has not been investigated in a cyclist population to date.

Trained cyclists adopt highly specialized activation patterns when cycling as compared with untrained cyclists (50). Chapman et al. (5) found that novice cyclists display greater individual variance, population variance, longer duration of

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muscle activity, and more variable coactivation than trained cyclists. The sterotypical activation patterns adopted by trained cyclists may result in imbalances in temporal component of the muscle activation strategies (6,33,34). These may be an adaption to increase the mechanical advantage of the knee extensor mechanism through lateralization of the patella (29,39).

Temporal imbalances in muscle activation patterns have been associated with the malalignment of the knee extensor mechanism and PFPS in noncycling populations (32). High-frequency loading delivered to a malaligned extensor mechanism yield persistent, debilitating pain in some athletes (15); thus, muscle activation imbalances that result in a malaligned extensor mechanism may be one reason for the high occurrence of patellofemoral pain in the cycling population.

Previous research in non–cycling-specific studies have found a delay in the VM onset relative to VL onset in PFPS populations compared with a healthy control group during functional movements (10,39). Researchers have also shown a delay in the ST and semimembranosus muscle (ST/SM) onset relative to the BF onset during isometric contractions when comparing a PFPS population with a healthy control population. Furthermore, although researchers have demonstrated no temporal delay in quadriceps and hamstring activation patterns in healthy trained cyclists (12,27), there are no studies to date investigating temporal differences in quadriceps and hamstring activation patterns in trained cyclists with PFPS. Therefore, the purpose of the present study was to determine whether temporal differences in the muscle activity of the VM, VL, ST, and BF are correlated to patellofemoral pain in cycling. It was hypothesized that cyclists with PFPS would display a greater delay in the VM onset relative to VL than asymptomatic cyclists. Further, it was hypothesized that cyclists with PFPS would display a greater difference in the mean onset and offset times of ST/SM compared with the BF than the asymptomatic control group, with the lateral hamstrings (BF) displaying an earlier activation than the medial hamstrings (ST/SM).

METHODS

Subjects. Seventeen cyclists age 20–57 yr volunteered for the study. Participants were recruited from the university community and surrounding communities through posted flyers, word of mouth, and university newspaper advertisements. Participants were divided into two groups based on whether they self-reported PFPS (n = 7, PFPS group) or not (n = 10, control [CTL] group). Cyclists with a self-reported or clinically diagnosed history of the following musculoskeletal disorders were excluded from the study: intra-articular pathology, peripatellar tendinitis or bursitis, plica syndromes, Sinding-Larsen disease, Osgood–Schlatter disease, and neuromas. The study was approved by the University of Idaho Institutional Review Board, and participants were informed of any possible risk and discomfort associated with the experimental procedure before signing an informed consent form.

Procedure. Each participant reported to the laboratory on one occasion and completed a single 1-h testing session. Demographic and anthropometric data were collected from each participant. These data included height, weight, age, sex, years of cycling experience, and average miles ridden per week.

Height was recorded to the nearest 0.5 cm, and body mass was obtained using a calibrated digital scale to the nearest 0.1 kg. The knee used in the study was also documented for each participant. The knee selected for the CTL group was based on the self-reported dominant leg. For the PFPS participants, the PFPS symptomatic knee was selected.

Kinematic data. Sagittal plane kinematic data of the knee were recorded using a twin axis electronic goniometer (SG150 SG-Series Twin Axis Goniometer; Biometrics Ltd., Newport, UK). The SG150 SG-Series Twin Axis Goniometer has a reported accuracy of ±2° and a repeatability of 1° over a range of 90°. The electrogoniometer was placed with the proximal and distal ends in line with the mechanical axis of the femur and tibia and the center passing through the sagittal plane axis of rotation. A magnetic impulse device was used to indicate each time the pedal passed through one full pedal cycle. The sampling rate of the goniometer was set at 50 Hz in accordance with manufacture recommendations. Goniometer data were interpolated using Biometrics data analysis software (Analysis Software version 8.51; Biometrics Ltd.) to match the sampling rate of the EMG signal.

EMG data. Surface EMG data were collected using bipolar, differential EMG sensors (SX230 EMG sensor; Biometrics Ltd.). The participant's skin was shaved and cleaned with alcohol before placement of the electrodes to minimize impedance. Surface EMG electrodes were placed longitudinally with respect to the underlying muscle fiber arrangement, in accordance with the recommendations of the Surface EMG for Non-Invasive Assessment of Muscles on the VL, VM, ST, and BF muscles. The raw EMG signals were preamplified close to the electrodes and sampled at a rate of 1000 Hz.

Cycling trial. The cycling trials were conducted on the participant's own bicycle on an indoor trainer (Minoura Mag-500 trainer; Minoura, Anpachi, Japan). A bicycle computer was used to monitor cadence (CatEye CC-RD300W; CATEYE, Osaka, Japan). The Borg RPE scale was used to monitor and control relative workload across participants (2). The RPE has been shown to be a valid and practical method in the regulation of exercise intensity in cycling, and an RPE score of 14 has been shown to produce consistent, submaximal workloads across participants in cycling studies (13,32).

Before the cycling trial, the participant was instructed to lie down, remain completely still, and relax their leg musculature. An EMG recording was taken for 10 s to establish a baseline EMG signal from each muscle for later analysis. To replicate the normal cycling strategy for each participant, vertical and horizontal positions of the saddle, handlebar height, and stem length were set to match the usual riding position of the participant (21). Knee angles were measured

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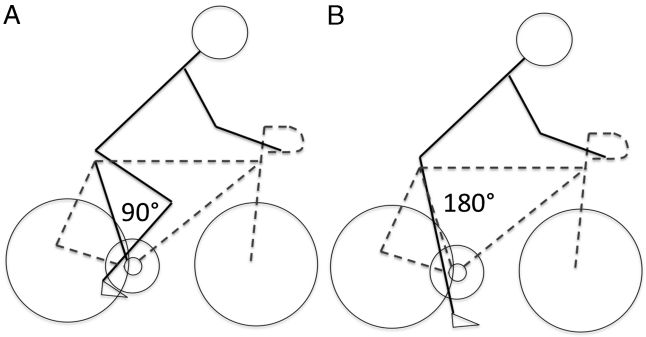

FIGURE 1—Measurement conventions for knee angles. A, Depiction of knee angle measured at 90°. B, Depiction of knee angle measured at 180°.

both electronically and using a handheld goniometer at top dead center (TDC) and bottom dead center (BDC). TDC and BDC are cycling positions when the pedal is at the top and the crank is oriented vertically upward and when the pedal is at the bottom and the crank is oriented vertically downward, respectively. Each participant was then familiarized with the Borg RPE scale and instructed to cycle at a workload equivalent to 14, between a moderate and heavy workload, on the RPE scale. The cyclists were instructed to maintain a standardized cadence of 90 RPM during the cycling trials (5,26). Visual feedback for the cadence was provided through a cycling computer (CatEye CC-RD300W; CATEYE) mounted on the handlebars.

The participant then performed a 10-min cycling warm-up. Immediately after the warm-up, the participant performed a 10-min cycling trial, during which EMG and kinematic data were collected during the first 30 s of each minute, beginning at the second minute and concluding at beginning of the eighth minute. The first 2 min of the trial allowed the rider to find his or her cadence and appropriate workload. The last 2 min was excluded to minimize any fatigue effects and voluntary change in workload. RPE ratings were recorded every 30 s using verbal communication.

Data processing and analysis. The EMG data were band-pass filtered between 10 and 450 Hz and then processed in Matlab (version 7.12.0, R2011a; Mathworks, Natick, MA) using custom-written scripts. EMG data for each muscle were separated into individual pedal cycles, and RPM was calculated for each cycle using angular velocity. A moving average was used to find the 10 consecutive cycles whose mean was closest to 90 RPM and displayed the lowest variance. Each cycle was time normalized to an angular velocity of 90 RPM.

The signals were demeaned and rectified. Linear envelopes for each muscle were developed using a low-pass, zero-lag, fourth-order Butterworth filter at a cutoff frequency of 10 Hz and averaged to establish a muscle activation profile for each participant. Ten hertz was selected as the cutoff frequency based on frequency analysis conducted during the pilot study, and as recommended by cycling specific surface EMG studies (5,21,22). Onset and offset times were determined using the double threshold method (24). The first threshold occurred when the value of the signal exceeded 3 SD above the baseline signal, and the second threshold required the signal to remain above this value for 30 ms as recommended by Kamen and Gabriel (23) and as established in EMG literature (21,22,24). The specific value used for the first threshold, an amplitude of 3 SD above the baseline signal, was calculated for each participant using the baseline EMG data. The associated knee angles for each onset and offset event were calculated with 180° representing full extension (for knee angle conventions, see Fig. 1). Absolute onset and offset times were calculated for the VM, VL, BF, and ST during the pedal cycle. A value of 0 ms indicates BDC (180°) of the cycle, and 333 ms

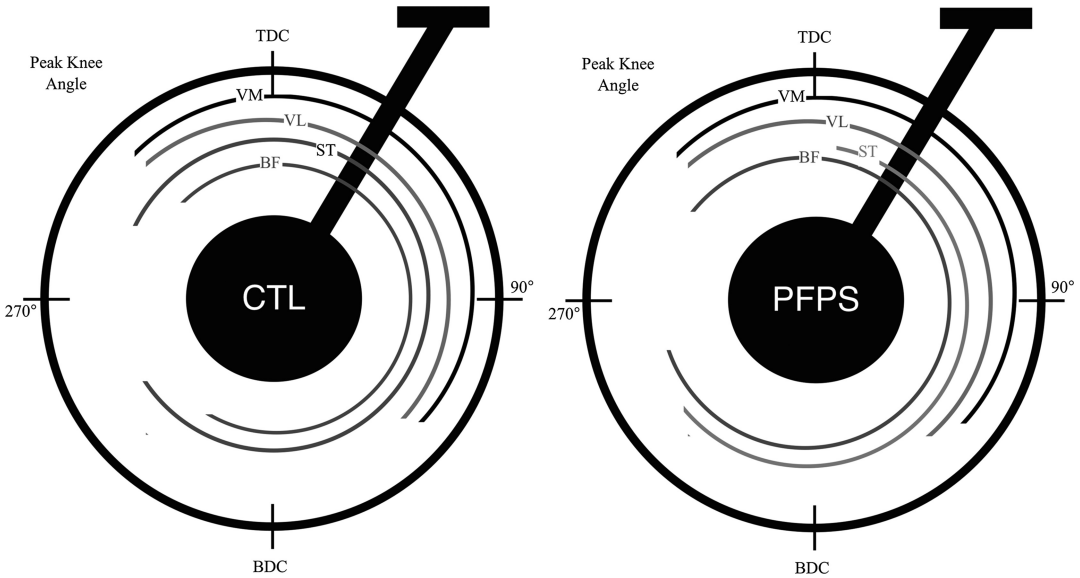

FIGURE 2—Muscle activation patterns of the VM, VL, ST, and BF for the CTL group and the PFPS group as a function of the pedal cycle. TDC, top dead center; BDC, bottom dead center; VM, vastus medialis; VL, vastus lateralis; ST, semitendinosus; BF, biceps femoris.

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TABLE 1. Descriptive characteristics of participants.

	CTL (n = 10; 6 F, 4 M)	PFPS (n = 7; 6 M, 1 F)
Variable		
Age (yr)	40 ± 12	46 ± 114
Mass (kg)	71.9 ± 16.5	89.8 ± 9.4
Height (m)	1.74 ± 0.10	1.84 ± 0.08
Cycling experience (yr)	12 ± 10	16 ± 12
Cycling volume (km·wk^{-1})	199.5 ± 82	228 ± 51

Data are presented as mean ± SD. $P > 0.05$ for all comparisons.
CTL, control group; PFPS, patellofemoral pain syndrome group.

indicates TDC (0°) (for pedal cycle conventions, see Fig. 2). The pedal cycle was divided into 11 periods, and muscle activity relative to peak amplitude was calculated using root mean square (RMS) values as established in literature (12). Absolute times are reported to draw conclusions about patellofemoral joint (PFJ) kinematics and kinetics occurring at onset and offset of the muscles.

Sagittal plane knee kinematic data from the electronic goniometer were recorded in synchronization with the EMG data and were used to establish knee angles at onset and offset times for each of the muscles.

For descriptive purposes, mean and SD values were calculated for the onset and offset times of each muscle, along with corresponding knee angles. Differences in onset and offset times for the quadriceps (VM/VL_{ON}, VM/VL_{OFF}) for each participant were calculated by subtracting VL onset and offset times from the VM onset and offset times, respectively. Differences in onset and offset times for the hamstrings (ST/BF_{ON}, ST/BF_{OFF}) for each participant were calculated by subtracting ST onset and offset times from the BF onset and offset times, respectively.

Two CTL subjects displayed no distinct onset or offset of the ST but rather had continuous low levels of activity throughout the cycle. The activation patterns of the VM, VL, and BF from these two subjects were similar to the rest of the CTL subjects. Together, these data suggest that the patterning observed in these participants is similar to the other CTL participants. However, as no distinct ST onset and offset were detected, the ST and BF data from these subjects were removed from statistical analysis.

An ANOVA was conducted to determine whether differences existed between the groups for descriptive characteristics and VM/VL_{ON}, VM/VL_{OFF}, ST/BF_{ON}, and ST/BF_{OFF}. An ANOVA was also conducted to determine whether differences existed in absolute onset times and corresponding knee angle. All statistical analyses were performed using the Statistical Package for the Social Sciences (version 17.0; SPSS Inc., Chicago, IL) statistical software. The level of significance for this study was set at $\alpha = 0.05$.

RESULTS

Participant characteristics are presented in Table 1. Overall, the PFPS group was older ($P = 0.356$) and had more cycling experience ($P = 0.445$) and weekly mileage compared ($P = 0.426$) with the CTL group; however, these differences were not significant. Absolute onset and offset times and associated knee angles for VM, VL, ST, and BF are presented in Table 2 and Figure 2. There were significant differences in absolute onset times for VL_{OFF} ($P = 0.007$), ST_{ON} ($P = 0.007$), BF_{ON} ($P = 0.013$), and BF_{OFF} ($P = 0.017$) and in knee angle for BF_{OFF} ($P = 0.015$). Briefly, VL_{OFF}, ST_{ON}, and BF_{OFF} occurred later in PFPS group, whereas BF_{ON} occurred earlier in PFPS group. These data were recorded for descriptive purposes to highlight PFJ joint configuration in regard to the pedal cycle and muscle activation patterns.

Quadriceps activation. No significant difference ($P = 0.805$) was found in VM/VL_{ON} between CTL and PFPS. A significant difference ($P = 0.032$) was found in the VM/VL_{OFF} between groups. These results are reported in Table 3. Average VL offset occurred 22 ± 23 ms after the VM in PFPS, whereas VL and VM offset occurred simultaneously in CTL. No significant differences ($P > 0.05$) between groups were found for knee angle at onset or offset of VM or VL. These results are reported in Table 2 and Figure 2.

Hamstring activation. A significant difference ($P < 0.001$) was found in the ST/BF_{ON} between CTL and PFPS. The average BF onset occurred 39 ± 44 ms after ST onset in CTL, whereas the BF onset occurred 111 ± 78 ms before ST onset in the PFPS group. These results are reported in Tables 2 and 3. Onset of the ST and BF occurred at different points in the pedal cycle for both groups. Absolute onset

TABLE 2. Absolute onset and offset times and associated knee angles for VM, VL, ST, and BF.

	CTL (n = 10)		PFPS (n = 7)	
Variable	Time (ms)	Knee angle (°)	Time (ms)	Knee angle (°)
VM_{ON}	245.5 ± 13.3	93.78 ± 10.1	253.0 ± 9.1	90.7 ± 14.3
VM_{OFF}	563.5 ± 16.5	144.9 ± 11.9	575.3 ± 22.0	142.0 ± 5.9
VL_{ON}	249.6 ± 13.2	92.7 ± 10.1	256.0 ± 12.1	88.7 ± 11.1
VL_{OFF}	563.2 ± 12.4	146.2 ± 8.4	597.1 ± 31*	146.8 ± 6.78
ST_{ON}[a]	232.5 ± 39.1	99.8 ± 12.3	346.57 ± 91.3*	94.5 ± 20.2
ST_{OFF}[a]	795.0 ± 55.0	129.1 ± 18.1	794.6 ± 60.6	127.4 ± 20.3
BF_{ON}	271.5 ± 22.3	91.2 ± 8.0	235.7 ± 30.1*	96.7 ± 9.4
BF_{OFF}	767.8 ± 89.6	135.2 ± 25.1	869.6 ± 51.0*	105.5 ± 15.9*

Data are presented as mean ± SD. Quadriceps muscles are in the gray section (VM, vastus medialis; VL, vastus lateralis), hamstring muscles are in white section (ST, semitendinosus; BF, biceps femoris).
*$P < 0.05$.
[a]Two participants in the CTL displayed continual ST activity; therefore, two onset and offset measures are not included in calculations.
CTL, control group; PFPS, patellofemoral pain group.

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TABLE 3. Difference in onset and offset times between VM–VL and ST–BF

Variable	CTL (n = 10)	PFPS (n = 7)	Interpretation
VM–VL onset difference (VM/VL_{ON}) (ms)	−4.1 ± 6.9	−3.0 ± 11.2	No difference
VM–VL offset difference (ms) (VM/VL_{OFF})	0.3 ± 14.4	−21.9 ± 23.3*	VM deactivates first in PFPS
ST–BF onset difference (ST/BF_{ON}) (ms)[a]	38.9 ± 44.2	−110.9 ± 77.8*	BF activates first in PFPS
ST–BF offset difference (ST/BF_{OFF}) (ms)[a]	−23.8 ± 50.2	75.0 ± 95.4*	ST deactivates first in PFPS

Data are presented as mean ± SD. Quadricep muscles are in the gray section, and hamstring muscles are in the white section.
*Significant difference between groups at $P \leq 0.05$.
[a]Two participants in the CTL group displayed continual ST activity; therefore, two onset and offset measures are not included in calculations.
CTL, control group; PFPS, patellofemoral pain syndrome group.

times and knee angles are presented in Table 2 and Figure 2. No significant differences ($P > 0.05$) were found between groups for knee angle at onset of ST or BF; however, because of the timing of ST onset in regard to the pedal cycle, ST onset occurred during flexion in the CTL group whereas no ST contraction was observed during flexion in PFPS.

A significant difference ($P = 0.024$) was found in the ST/BF_{OFF} between CTL and PFPS. Average BF offset occurred 24 ± 50 ms before ST offset in CTL, whereas the BF offset occurred 75 ± 95 ms after ST offset in the PFPS. These results are reported in Tables 2 and 3. Significant differences were found between groups for knee angle ($P = 0.0164$) and absolute times ($P = 0.022$) at BF offset, indicating BF offset occurred at different knee angles and at different points in the pedal cycle between the groups. Absolute onset times and knee angles for ST_{OFF} and BF_{OFF} are presented in Table 2 and Figure 2.

Muscle activity level. RMS values for muscle activity were significantly lower for ST in PFPS compared with CTL from 132° to 297° of the pedal cycle ($P < 0.01$). RMS values for BF activity were significantly higher in PFPS compared with CTL from 198° to 231° and from 297° to 360° ($P < 0.01$). RMS values for BF were significantly greater than ST activity from 99° to 264° in the PFPS group ($P < 0.01$). No

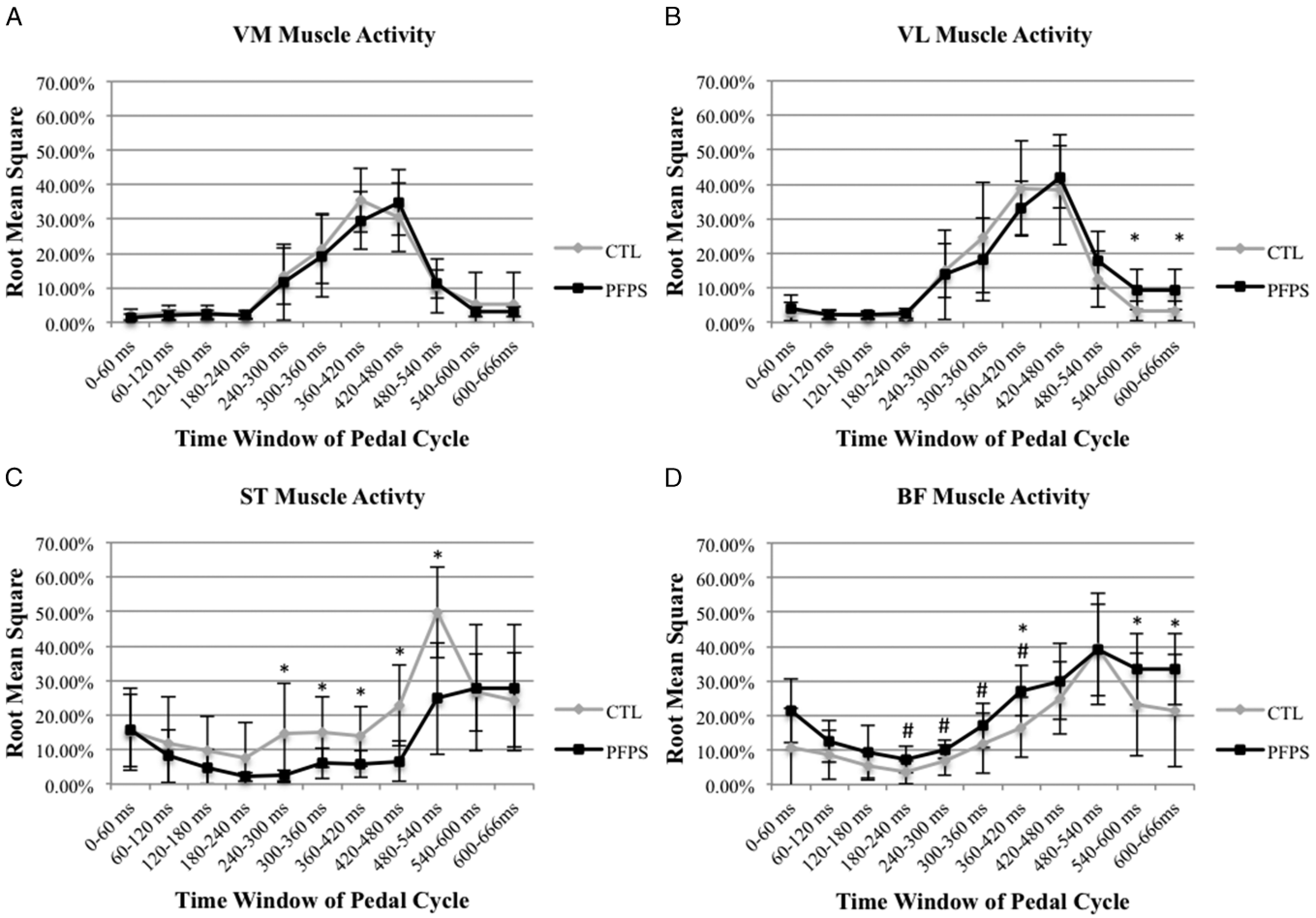

FIGURE 3—RMS values of EMG amplitude for (A) vastus medialis (VM), (B) vastus lateralis (VL), (C) semitendinosus (ST), and (D) biceps femoris (BF). All values presented relative to peak muscle activity. Error bars represent SD. *Significant differences between groups ($P < 0.05$). #Significant differences within group between ST and BF ($P < 0.01$).

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significant differences between ST and BF activity were detected in the CTL group ($P > 0.05$). RMS data are presented in Figure 3.

DISCUSSION

The primary purpose of the study was to determine whether temporal components in the muscle activity between VM and VL as well as between ST/SM and BF were different between cyclists with and without PFPS. These results demonstrate that muscle activity patterns in trained cyclists with PFPS differ from cyclists without PFPS, suggesting temporal muscle activity as a possible mechanism contributing to PFPS in cyclists. This is the first study to demonstrate these temporal differences in trained cyclists.

Quadriceps activation patterns. These results indicate there was no difference in VM/VL_{ON} between CTL and PFPS. VM and VL were activated at similar times in the pedal cycle and at similar knee joint angles for both groups. VM/VL_{OFF} was significantly different between groups, with the VL staying activated 22 ± 23 ms longer than the VM in the PFPS group.

The VM and the VL have synergistic actions for mediolateral control of the patella; thus, the recruitment of the VM and VL must be suitably timed for efficient and proper biomechanical function of the PFJ (17). Currently, no literature has investigated the differences in onset times of the VM and VL in PFPS during cycling. However, this relationship has been studied in PFPS during functional tasks including stair stepping (11,37) and musculoskeletal modeling (31).

Van Tiggelen et al. (37) and Cowan et al. (11) used EMG to examine the relative timing of these muscles during knee flexion and extension in healthy individuals to identify appropriate patterning. These studies reported that VM activation precedes VL activation between 0.5 and 4.86 ms to properly control patella tracking. In the present study, the CTL group exhibited a relative onset of −4 ± 7 ms, in which the VM was activated before the VL. Both Cowan et al. (11) and Van Tiggelen et al. (37) found significant differences in relative VM and VL onset between a healthy and PFPS population with the VM onset occurring before VL onset. The results of the current study are in contrast to the findings of Van Tiggelen et al. (37) and Cowan et al. (11). We found that there was no difference in the onset of VM activity compared with VL activity between the PFPS and the CTL group. The highly dynamic nature of the movement examined in the current study and the difference in the potential underlying cause of PFPS in cycling may explain the disparity in the results between the current study and those found by Van Tiggelen et al. (37) and Cowan et al. (11).

In the current study, VM/VL_{OFF} was significantly different between groups (CTL: 0.30 ± 14.40; PFPS: −21.86 ± 23.33 ms). In the PFPS group, the VL remained activated longer than the VM. Currently, no research has been conducted in cycling that investigates relative offset times of the quadriceps muscles and PFPS; however, this variable has been associated with osteoarthritis of the knee (7,19). In gait analysis studies, Hubley-Kozey et al. (19) and Childs et al. (7) found prolonged VL quadriceps activation in knees with osteoarthritis (KOA) when compared with asymptomatic control knees. The delayed offset found in KOA patients in Childs et al. (7) and the prolonged activity found in Hubley-Kozey et al. (19) suggest that altered temporal characteristics in the VL has implications for the kinematics of the PFJ during functional activities.

The findings of the current study for differences in VM–VL timing in PFPS were similar to those reported previously for noncycling activities in patients with KOA; there was a delay in VL offset relative to VM offset in KOA patients. However, in the current study, the knee angle at which this asynchrony occurs was approximately 147°. At this angle of flexion, the articular surfaces are highly congruent and the PFJ is stable, suggesting that imbalance in the offset of the VM and VL may not be the main contributor to altering joint kinematics in this population. However, it may contribute to the increased loading of the lateral tissue and development of pain.

Hamstring activation patterns. ST/BF_{ON} was significantly different between groups. The BF onset occurred 111 ± 78 ms before ST activation in the PFPS group, compared with the CTL group where ST activation occurred 39 ± 44 ms before BF activation. ST/BFOFF was significantly different between groups. Offset of the BF occurred 75 ± 95 ms later than the ST in the PFPS group, where BF offset occurred 24 ± 50 ms before ST offset in the CTL group. Muscle activation profiles for the CTL and the PFPS groups and the associated knee angles are presented in Figure 2 and Table 2, respectively.

Differences between medial (ST) and lateral (BF) hamstring activation patterns have not been previously examined as a cause of PFPS in cycling. However, in 2011, Patil et al. (19) found that participants with PFPS displayed a mean onset difference of 53.8 ± 51.8 ms, with the lateral hamstrings onset occurring before the medial hamstrings during maximal isometric contractions. A similar patterning was observed in the current study, although the mean onset difference (111 ± 78 ms) was larger in the present study, indicating a greater difference in medial and lateral hamstring activation.

In gait analysis studies, Rutherford et al. (35), Hubley-Kozey et al. (19), and Hubley-Kozey et al. (20) found that lateral hamstring activity occurred before medial hamstring activity in participants with osteoarthritis, whereas medial and lateral hamstring activity was tightly coupled in healthy participants. The authors of these studies concluded that the asymmetric loading seen in their respective studies might produce a harmful loading environment in the knee joint. In the current study, BF activation occurred without ST activation during flexion in the PFPS group. This asymmetry during flexion in the PFPS may provide an explanation for

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the correlation altered hamstring activation patterns and PFPS found in the present study.

Activation patterns and PFPS. Differences present in EMG patterns have been argued to be a factor leading to a change in the tracking of the patella (29–31). In the current study, BF activation occurred at high levels of flexion (approximately 97°) in both groups, and BF activation occurred earlier than the ST in the PFPS group, along with prolonged VL activity as compared with the CTL group. The differences in the onset and offset of the BF and ST in the PFPS group resulted in the absence of ST activation in the presence of BF activation for roughly the first 60° of muscle activity during the pedal cycle. Most importantly, BF activation occurred without ST activation during high degrees of knee flexion in the PFPS group. Rotation of the tibia about the transverse plane is less constrained at higher degrees of flexion and more constrained in extension (24). Because of this characteristic, external tibial rotation occurring at higher levels of knee flexion are most likely to be problematic (9,24,36). Thus, the early BF onset coupled with delayed ST onset may result in an abnormally externally rotated tibia at the beginning of knee extension during the pedal cycle. External rotation lateralizes the tibial tubercle, increasing the Q-angle and the lateral component of the quadriceps force vector; thus, an externally rotated tibia at the beginning of knee extension may result in a lateralized patella. It has been found that fixing the tibia in 15° of external rotation resulted in significant increases in average and peak PFJ contact pressures on the lateral patellar articular facets at all angles of knee flexion (25). Other literature has supported the findings of Lee et al. (24) and has linked increased external tibial rotation to patellofemoral pain (9,24,36).

Although the concurrent onset times of the VM and the VL and the delayed offset of the VL seen in the PFPS group may not be the main contributor to altered PFJ kinematics, the role they play as antagonists and coactivators to the hamstrings during knee flexion indicates there may be implications for the kinematics and kinetics of patellar tracking. The coactivation of the quadriceps occurred 17 ms after onset of the BF and coincided with maximum knee flexion where the PFJ displays its lowest congruency and smallest contact areas. Because of the low levels of PFJ congruency, the small contact areas, the forces present during coactivation, and the angle of knee flexion, the resultant excess lateral muscle torque can compress the lateral joint space, increase lateral peak forces acting on the patella, and increase stress (14,17,18). The subsequent forces placed on the lateral soft tissue may surpass its physiological limit, inducing the activation of nociceptive fibers in the bone, synovium, or retinaculum, resulting in patellofemoral pain (15,16). It has been suggested that increased lateral loading is the leading cause of overuse injuries during repetitive movement tasks (37).

In the PFJ, the lateral femoral condyle sits higher and extends more anteriorly than the medial femoral condyle. A lateralized patella at the beginning of knee extension may lead to an anterior shift, increasing the lever arm of the VL muscles (29,39). The increased lever arm for the more lateral muscle (VL) increases its ability to create torque relative to the medial muscle (VM), furthering the ability of the VL to produce a laterally tracking patella. If the force production of the VM and VL muscles remains consistent throughout knee extension during the pedal cycle, an increased moment arm for the VL, along with the greater force-producing capabilities of the VL relative to the VM, the medially directed force of the VM may be unable to correct an initially lateralized patella (17).

Muscle activity level. Although EMG is capable of accurately identifying temporal imbalances in muscle activation patterns, these observed imbalances are an indirect indicator of the mechanical outcome. Muscles must produce substantial amounts of force to alter the mechanics of the PFJ. The temporal imbalances observed in this study do not necessarily indicate that the muscles are creating enough force to alter patellofemoral mechanics. It is possible the temporal imbalances observed in the PFPS group have no mechanical effect on tibial rotation and PFJ mechanics. However, data presented in Figure 3 suggest there is greater BF activity relative to ST activity in the PFPS group than the CTL group. The translation of the recorded activity to force cannot be determined at this time. Further study is required to confirm the link between timing imbalances, amplitude, muscle force production, and alterations to patellar mechanics. However, the presence of a change in motor control seen in this study may result in the changes in PFJ mechanics discussed.

Strengths and limitations. This study was the first to examine the correlation between muscle activation patterns and PFPS in trained cyclists. These findings provide an argument for future research focused on determining the mechanical effects of different activation patterns and whether the altered patterns are indeed an etiological factor of PFPS in cycling.

The limitations of this study were the small sample size, the restrictions on the muscles studied, and the nonuniversal bicycle configuration. It is possible that cyclists in this study adopted altered activation patterns in those muscles not recorded. In regard to the quadriceps, surface EMG of rectus femoris and the vastus intermedius were not recorded; thus, their potential effect on patellar tracking cannot be determined. However, the line of action of the rectus femoris and vastus intermedius is oriented laterally, indicating they are unable to aid in medializing a laterally tracking patella. Also, because of their line of action and smaller physical cross-sectional areas relative to the VM and VL, it is unlikely that they have large impact on patellar kinematics in the frontal plane (1,39). In regard to other muscles capable of producing medial tibial rotation, surface EMG of the gracilis, sartorius, and the popliteus muscles were not collected. The physical cross-sectional area and the peak force production capabilites of these muscles suggest it is unlikely they are able to counter an imbalance created by the BF seen

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in PFPS cyclists in this study (1,38,39). To maintain the integrity of the participants' normal recruitment patterns, seat height, saddle position, and pedal orientation were not standardized to allow the cyclists to display their normal activation patterns, thus limiting control over those variables; a limitation the researchers felt was unavoidable.

CONCLUSIONS

The findings from the current study suggest that a difference in onset of the quadriceps activity is not correlated to PFPS in this population of cyclists and that differences in offset of the quadriceps activity are not likely to be a main contributor to altering joint mechanics but may still be a contributory to factor to pain. Furthermore, the difference in the temporal activation patterns of the BF and ST between the CTL group and the PFPS group suggest that these altered activation patterns, coupled with the present coactivation of the quadriceps, may result in changes to PFJ kinematics and kinetics. Currently, it is not known whether the different muscle activation patterns seen in the two groups are causal or compensatory to PFPS in these participants, and further research is warranted.

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