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Effect of Seat Tube Angle and Exercise Intensity on Muscle Activity Patterns in Cyclists

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ABSTRACT

International Journal of Exercise Science 10(8): 1145-1156, 2017. Previous studies have reported improved efficiency at steeper seat tube angle (STA) during ergometer cycling; however, neuromuscular mechanisms have yet to be fully determined. The current study investigated effects of STA on lower limb EMG activity at varying exercise intensities. Cyclists (n=11) were tested at 2 workloads; 160W and an individualised workload (IWL) equivalent to lactate threshold (T_{Lac}) minus 10%δ (derived from maximal incremental data), using 3 STA (70, 75 and 80°). Electromyographic data from *Vastus Medialis* (VM), *Rectus Femoris* (RF), *Vastus Lateralis* (VL) and *Biceps Femoris* (BF) were assessed. The timing and magnitude of activation were quantified and analysed using a two-way ANOVA. STA had significant (P < 0.05) effects on timing of onset and offset of VM, timing of offset of VL, and angle at peak for RF, all occurring later at 80 vs. 70° STA at IWL. In RF, increased activity occurred during the first 108° of the crank cycle at 80 vs. 70° at IWL (P < 0.01). As most of the power in the pedal stroke is generated during the mid-section of the down-stroke, movement of the activation range of knee extensors into the predominantly power phase of the pedal stroke would potentially account for increased efficiency and decreased cardio-respiratory costs. Greater activity of bi-articular RF, in the first 108º of the crank cycle at IWL (80 vs. 70º) may more closely resemble the pelvic stabilising activity of RF in running biomechanics; and potentially explain the more effective transition from cycling to running reported in triathletes using steeper STA.

KEY WORDS: Cycling, electromyography, biomechanics

INTRODUCTION

Over the last 2 decades, cycling has seen significant development in equipment; modern bicycle designs, used both in competitive time-trials and triathlons, are vastly different to their predecessors. One noticeable development has been a shift towards greater seat tube angles. The seat tube angle (STA) is defined as the position of the saddle relative to a horizontal line through the crank axis of the bicycle (Figure 1). Road racing bicycles usually have a STA between 72 and 76º, claimed to be the most mechanically effective for racing (1). However, triathletes commonly use STA in excess of 76º, facilitating bike-to-run transition with greater comfort and efficiency (4). The frame geometry of bicycles used in road-races and other mass start events is governed by International Cycling Union (UCI) who state that the saddle's nose must be a minimum of 5 cm behind a vertical line drawn through the center of the crank axle (5), effectively limiting maximal STA to approximately 76º. However, UCI regulations governing time-trial bicycles allow the saddle's nose to be positioned up to the vertical line from the centre of the crank axle. Similar rules govern the geometry of triathlon bikes, specifically those used for longer distance events such as "Ironman".

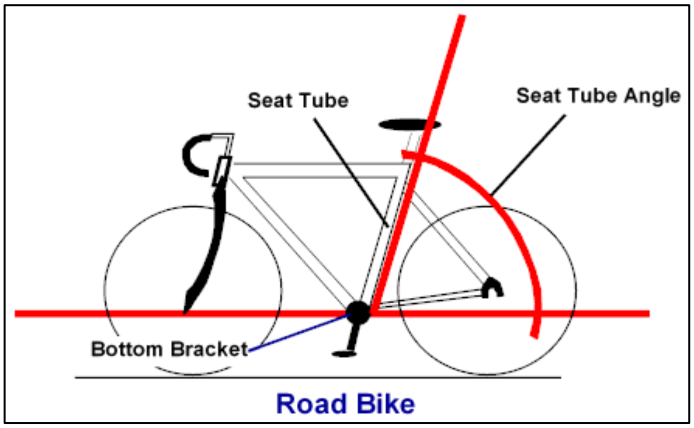

Figure 1. Diagram describing the calculation of seat tube angle (STA).

Increasing STA moves the cyclist to a more forward inclination, reducing drag and improving aerodynamics (6); however, this does not explain improvements in economy reported on stationary cycle ergometers (7,16). Price and Donne (16) investigated variation in STA at different seat heights and reported improved cycling efficiency at steeper STA, attributed, in part, to an altered ankling pattern. This study also documented significantly lower oxygen uptake (VO_2), heart rate (HR), minute ventilation and ratings of perceived exertion at steeper STA. Heil *et al.* (7) also concluded that steeper STA (76, 83 and 90˚) produced lower cardio-respiratory (HR, VO_2) responses when compared to a shallow STA (69˚) during steady-state cycle ergometry. Kinematic analysis in that study identified greater hip extension and ankle plantar flexion at steeper STA. As hip angle increases the length of bi-articulate muscles crossing the hip (*Rectus Femoris*, *Biceps Femoris, Semimembranosus* and *Semitendinosus*) are systematically altered. Researchers have suggested that increasing hip angle enhances power production from these muscles by altering their force-velocity and/or length-tension relationships (19,22). Garside and Doran (4) subsequently demonstrated that steeper STA attenuated fatigue associated with transitioning from cycling to running and improved subsequent 10-km running time.

Several studies (1, 20, 23) have assessed effects of altering STA on muscle recruitment patterns; however, study findings are conflicting. Ricard *et al.* (20) reported that increasing STA significantly reduced *biceps femoris* (BF) activity, despite no change in power output during a Wingate test, hypothesizing that this reduction in activity likely explained the improved economy previously reported. However, Silder *et al.* (23) observed no difference in BF activity when increasing STA, instead reporting a significant increase in *rectus femoris* (RF) activity, specifically during the final 90° of the crank cycle. Bisi *et al.* (1) compared STA of 73 and 78° and reported no difference in activity from the seven muscles examined. In addition to conflicting evidence regarding the effect of STA on the magnitude of muscle recruitment, there is also a lack of published data examining the timing of recruitment patterns. Rankin and Neptune (18) performed a forward dynamics simulation to model muscle recruitment patterns at varying STA and saddle height. Their results predicted that increasing STA would result in later activation of knee extensor and flexor musculature during the crank cycle; however, this model has yet to be tested.

The primary study aim was to assess effects of varying STA on timing and magnitude of activity in four lower limb muscles contributing to power production in cycling. A secondary aim was to assess differences, if any, in timing and magnitude of muscle activity as cycling intensity increased.

METHODS

Participants

11 competitive male cyclists (age 31 ± 4 yr, mass 73.8 ± 7.1 kg, height 1.8 ± 0.1 m, trochanteric height 0.9 ± 0.1 m, cycling experience 12 ± 6 yr; mean ± SD) were recruited from local cycling clubs to perform the study. All participants were fully informed of the procedures and risks associated with the study and each provided informed consent prior to enrolment. The study, which conformed to the Declaration of Helsinki, and received approval from the University Health Sciences Ethics Committee, consisted of two visits to the laboratory, 7 to 14 days apart.

Protocol

The effect of STA variation (70, 75 and 80°) on muscle recruitment patterns of selected lower limb muscles was evaluated at 2 exercise intensities (160W and IWL). An electromagnetically loaded cycle ergometer (Excalibur Sport, Lode, Gronigen, The Netherlands) was used for all testing sessions. Saddle height and STA were adjusted to individual anthropometric measurements. Cyclists used their own pedals and cleated cycling shoes, and maintained a cadence between 80 and 85 rev.min^{-1} throughout all visits. Visit 1 involved a medical screening prior to participation and a subsequent graded incremental test to assess maximal oxygen uptake (VO_2peak) and power output (Pmax), and facilitate blood lactate threshold (T_{Lac}) profiling. Gas exchange variables were recorded using a Quark b^2 (Cosmed, Rome, Italy) metabolic analyser. Blood lactate data were assessed using a YSI 1500 lactate analyser (Yellow Springs Instruments, OH, USA) from capillary samples collected in the final 30-s of each increment from the fingertip following sterile lancing. The initial power output for the test was 120W with successive increments increasing by 40W every 3-min in a stepwise fashion to volitional failure. Heart rate and metabolic data were recorded every 15-s and averaged over the final minute of each increment. Maximal VO_2 (mL ·kg^{-1} ·min^{-1}) recorded in any 15-s interval during the incremental test was recorded as VO_2peak. Load at T_{Lac} was calculated using the V-slope method (14). The primary objective of visit 1 was to accurately determine each individual's sub-maximal workload (IWL) for visit 2. In addition, visit 1 allowed participants to familiarise themselves with equipment and protocol, thereby reducing potential "learning effects" during the subsequent STA protocol. A fixed STA of 75 ° was used for all maximal incremental tests.

Visit 2 involved an 8-min warm-up (120 to 160W) and stretching, followed by two discontinuous sub-maximal protocols: firstly, at 160W, and, secondly, at an individualised workload (IWL) similiar to race pace, slightly below each individual's lactate threshold (T_{Lac} minus 10%δ, where δ equals Pmax minus load at T_{Lac}). Ten sub-maximal exercise elements were assessed: Five at 160W and five at IWL. Each participant cycled at five STA for each workload which progressed through in the order 75→70→75→80→75^o (n=6), or 75→80→75→70→75^o (n=5), initially at 160W and then at IWL. The order of randomization was performed to provide a washout interval between the highest (80 ^{o}) and lowest (70 ^{o}) STA, as previously described (16). Elements lasted 5-min and were immediately followed by 2-min rest and stretching while STA and saddle height were adjusted for the next element.

EMG data were recorded on the right side of the body from four lower limb muscles involved in the pedaling action: *Rectus Femoris* (RF), *Vastus Medialis* (VM), *Vastus Lateralis* (VL) and *Biceps Femoris* (BF). Prior to electrode application designated recording sites were shaved, abraded and cleaned with alcohol. Pairs of Ag/AgCl circular bipolar, pre-gelled surface electrodes (Red Dot, 3M, MN, USA) were applied in accordance with SENIAM recommendations (8). Electrodes were placed four-fifths of the distance between the anterior superior iliac spine and the joint space in front of the anterior border of the medial collateral ligament for VM; half-way between the anterior superior iliac spine and the superior part of the patella for RF; two-thirds of the way between the anterior superior iliac spine and the lateral part of the patella for VL; and half-way between the ischial tuberosity and the lateral epicondyle of the tibia for BF. Electrodes were oriented longitudinally to the muscle fibres with a fixed inter-electrode distance of 20mm. Reference electrodes were applied over electrically neutral sites (skin overlying bone or tendon) and all recording electrodes and leads were fixed to the skin using strapping (Prowrap, Meuller Sports Medicine, WI, USA), thereby minimizing potential movement artifacts. Signal to noise ratio was evaluated *post-hoc* via visual inspection, with abnormal data sets being eliminated when two independent assessors identified the same signal artifact.

Raw EMG data were recorded via a 14 bit AD converter (ME6000, Mega Electronics, Kuopio, Finland) at a sampling rate of 2 kHz, band-pass filtered between 8 to 500 Hz, pre-amplified and transmitted to a standalone computer via wireless telemetry. Synchronisation of EMG activity to crank angle was facilitated via a magnetic sensor attached to the end of the crank, which transmitted a 5V pulse whenever the crank passed top dead centre (TDC) of the pedal cycle. EMG data and TDC trigger pulses were synchronously transmitted in real time to Megawin software (Mega Electronics, Kuopio, Finland) for 30-s during the final minute of each exercise element. Raw EMG data were exported to Matlab (Mathworks, MA, USA) for subsequent processing via customised programmes. Data were root-mean-squared (20ms window, 0% overlap) and amplitude normalised to peak amplitude recorded in any single condition (24), temporally normalised via cubic spline fitting and averaged over the first 10 consecutive cycles within the final 30-s of each stage to produce ensemble averages for each muscle during each condition. From the processed data four temporal variables were used as indicators of timing of muscle recruitment patterns (10):

1. Onset: Crank angle at which muscle activity rose above 10% of normalised amplitude (measured in ° from TDC).
2. Offset: Crank angle at which muscle activity fell below 10% of normalised amplitude (measured in ° from TDC).
3. Duration: Crank angle from onset to offset of muscle activity (measured in °).
4. Angle at peak activity: Crank angle at which maximal muscle activity was recorded (measured in ° from TDC).

Statistical Analysis

An *a priori* power analysis was conducted for expected outcomes with a type 1 error probability of 0.05 and a power of 0.8, this analysis indicated that a sample of eight (n=8) would provide a statistical power of 82% (G*power v3.0.10) accordingly a larger group of participants (n=11) were enlisted to accommodate, which resulted in a calculated statistical power of 92%. Recorded data were averaged within each 10% interval (decile) of the crank cycle to assess the magnitude of muscle activation at discrete time points. Statistical analyses were performed on temporal and magnitude data using a 2 factor (STA by intensity) repeated measures ANOVA (SigmaStat V3.5, Systat Software, CA, USA). Detected differences were quantified using *post-hoc* Tukey tests ($P < 0.05$ inferring significance).

RESULTS

Group mean ± SEM VO_2 peak and maximal workload data during incremental testing were 64.5 ± 2.0 $mL.kg^{-1}.min^{-1}$ and 345 ± 8 W, respectively. Mean load at T_{Lac} was 266 ± 9 W, BLa at T_{Lac} was 3.4 ± 0.6 $mmol.L^{-1}$ and HR at T_{Lac} was 161 ± 4 $beats.min^{-1}$. Based on maximal and T_{Lac} data the group mean load at IWL was 256 ± 9 W. Visual inspections of recorded raw EMG signals resulted in several data sets being eliminated due to unacceptable signal to noise ratio. In total, RF and VL data from 11 participants, VM data from 10 participants and BF data from 7 participants were statistically analysed.

Group mean ± SEM data for temporal EMG variables are presented in Table 1. An overall STA effect was observed for onset ($P < 0.05$) and offset ($P < 0.01$) in VM. *Post-hoc* analysis identified that onset outcomes were significant comparing 80 vs. 70° ($P < 0.01$) and 75 vs.70° ($P < 0.05$) at IWL only, while offset outcomes were significant for 80 and 75 vs. 70° ($P < 0.05$) at 160W; and for 80 vs. 70° ($P < 0.05$) at IWL. Mean angle at peak in VM also exhibited an overall STA effect ($P < 0.05$); however, *post-hoc* analysis identified that this was only significant comparing 80 vs. 70° ($P < 0.05$) at 160W. An overall STA effect was observed for angle at peak activity in RF ($P < 0.05$); however, the effect was significant for 80 vs. 70° ($P < 0.05$) at IWL only. No other STA effects were observed in RF. For VL, a significant overall STA effect was observed for offset comparing 80 vs. 70° ($P < 0.05$). An overall intensity effect was also observed in VL for offset; however, this was only significant at 75° ($P < 0.05$). Assessing BF onset data, *post-hoc* analysis identified a significant STA effect for 75 vs. 70° ($P < 0.05$) at 160W. Significant intensity effects for onset and duration were identified at a STA of 75° ($P < 0.01$) comparing IWL and 160W. No interactions were observed for any of the temporal EMG variables assessed.

Table 1. Group mean (± SEM) temporal EMG data for 160W and IWL across assessed STA for onset, offset, duration and angle at peak. Onset, offset and peak are measured in º from TDC, while duration is measured in º. Asterisk symbol (*) infers significant difference to STA of 70º (* P < 0.05; ** P < 0.01). Dollar symbol ($) infers significant difference to STA of 80º ($ P < 0.05).

	160W			IWL		
	70°	**75°**	**80°**	**70°**	**75°**	**80°**
RF						
Onset	282 ± 17	270 ± 27	262 ± 16	255 ± 17	275 ± 8	279 ± 8
Offset	96 ± 11	101 ± 10	87 ± 11	85 ± 6	93 ± 5	102 ± 4
Duration	174 ±22	191 ± 12	185 ± 23	127 ± 14	113 ± 6	126 ± 7
Peak	7 ± 16	12 ± 16	18 ± 11	29 ± 8	30 ± 6	36 ± 8*
VM						
Onset	339 ± 5	343 ± 5	345 ± 5	336 ± 4	343 ±4*	344 ± 5**
Offset	95 ± 2	107 ± 7	108 ± 3	96 ± 4	100 ± 3	106 ± 3
Duration	115 ± 6	123 ± 12	122 ± 7	120 ± 5	117 ± 5	122 ± 5
Peak	27 ± 7	40 ± 7	42 ± 8*	28 ± 8	36 ± 8	38 ± 9
VL						
Onset	327 ± 12	344 ± 3	338 ± 6	334 ± 3	339 ± 3	333 ± 12
Offset	94 ± 3	96 ± 3	105 ± 2*	103 ± 7	109 ± 5$	114 ± 6*
Duration	127 ± 14	113 ± 6	126 ± 7	129 ± 8	130 ± 6	141 ± 18
Peak	29 ± 8	30 ± 6	36 ± 8	16 ± 9	27 ± 11	32 ± 9
BF						
Onset	26 ± 11	63 ± 9*	39 ± 11	13 ± 8	9 ± 9$	33 ± 8
Offset	163 ± 14	169 ± 12	193 ± 16	172 ± 13	189 ± 14	188 ± 18
Duration	137 ± 19	106 ± 14	154 ± 16	159 ± 19	180 ± 18$	155 ± 22
Peak	109 ± 13	110 ± 17	154 ± 15	104 ± 13	108 ± 13	110 ± 7

Group mean data for EMG amplitude across crank cycle deciles are presented in Figure 2 (160W) and Figure 3 (IWL). For VM, overall STA effects were observed in 3rd and 10th deciles, activity significantly increased in the 3rd (P < 0.05) and decreased in the 10th decile (P < 0.01), as STA increased. Subsequent *post-hoc* analyses identified that significant effects were observed comparing 80 vs. 70º at both intensities in the 3rd decile (P < 0.05) and at IWL only in the 10th decile (P < 0.01). An intensity effect was identified in the 10th decile for VM; however, this effect was only significant at a STA of 70º (P < 0.01). For RF, significant overall STA effects were observed in the 1st, 2nd and 3rd deciles with greater activity as STA increased; however, these effects were only significant comparing 80 and 70º at IWL (Figure 3). Overall intensity effects for RF were observed in the 1st (P < 0.001), 2nd and 3rd (P < 0.05) and 10th deciles (P < 0.01). For VL, overall STA effects were identified in the 1st, 2nd, 3rd and 10th deciles. However, these effects were only significant at IWL (Figure 3). Overall intensity effects were identified in the 3rd and 10th deciles, where activity in IWL was significantly greater than at 160W (P < 0.05). No significant STA effects were identified at any decile for BF. However, intensity had a significant effect on BF activity in the 2nd, 3rd and 5th deciles. No interactions were observed for any of the magnitude EMG variables investigated.

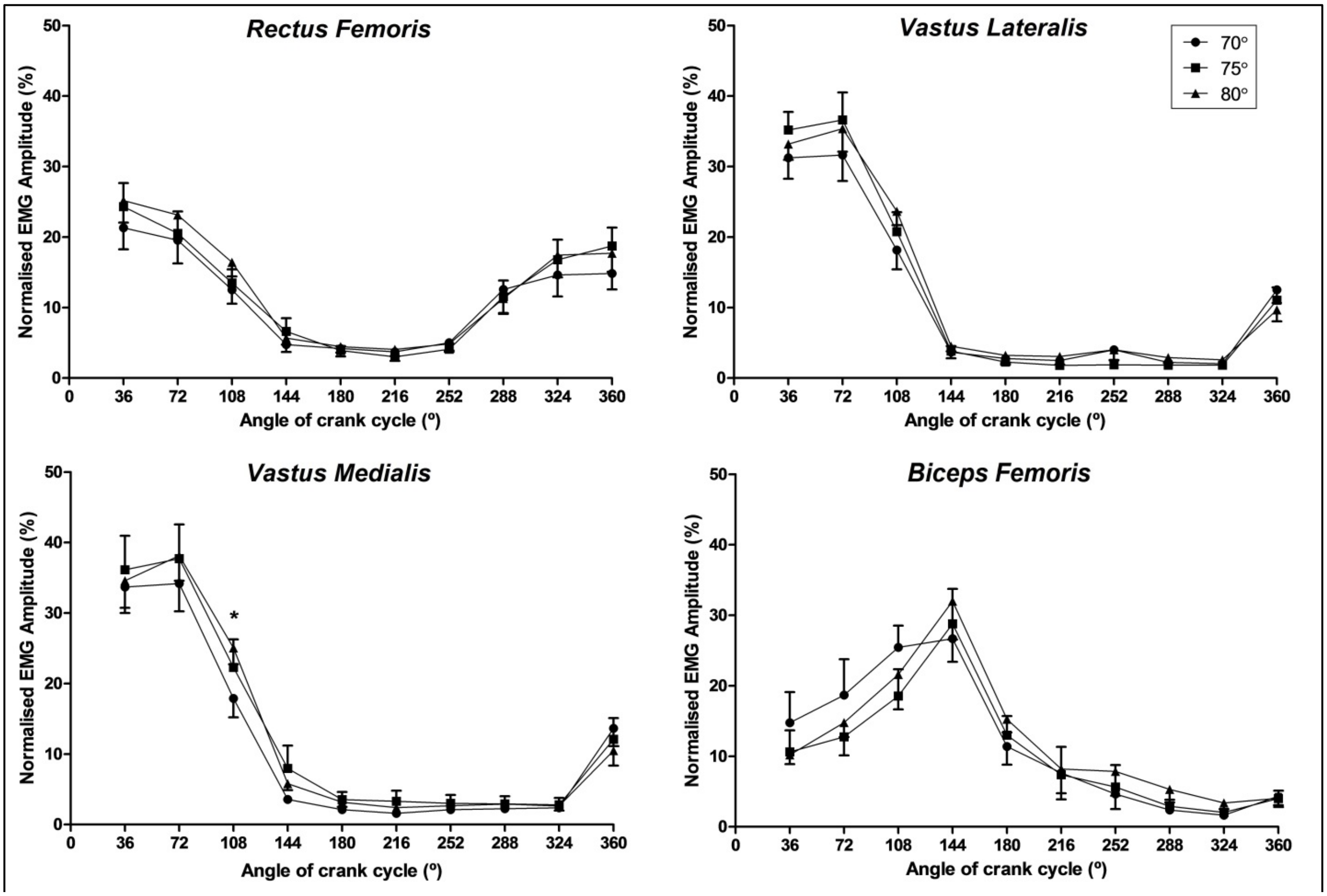

Figure 2. Group mean (SEM) normalised EMG data at each 10% interval of the crank cycle for 160W. Asterisk symbol (*) infers significant difference between STA of 80 and 70 º (* $P < 0.05$).

DISCUSSION

The primary aim of the current study was to assess the effect of increasing STA on timing and magnitude of EMG activity from four lower limb muscles during sub-maximal cycling. The results highlight two important changes in recruitment patterns, which may, in part, explain the improvements in metabolic efficiency (16) and attenuated fatigue response (4) previously reported. Firstly, RF activity significantly increased at steeper STA, specifically during the first 108° (30%) of the pedal stroke; a phase of critical importance for power production (13). Secondly, the results suggest that STA significantly affects timing of activation of the primary power producing muscles in cycling, namely VM and VL. Both knee extensors were active for the same duration but later in the pedal stroke, thereby, increasing the time spent active in the critical force generation phase.

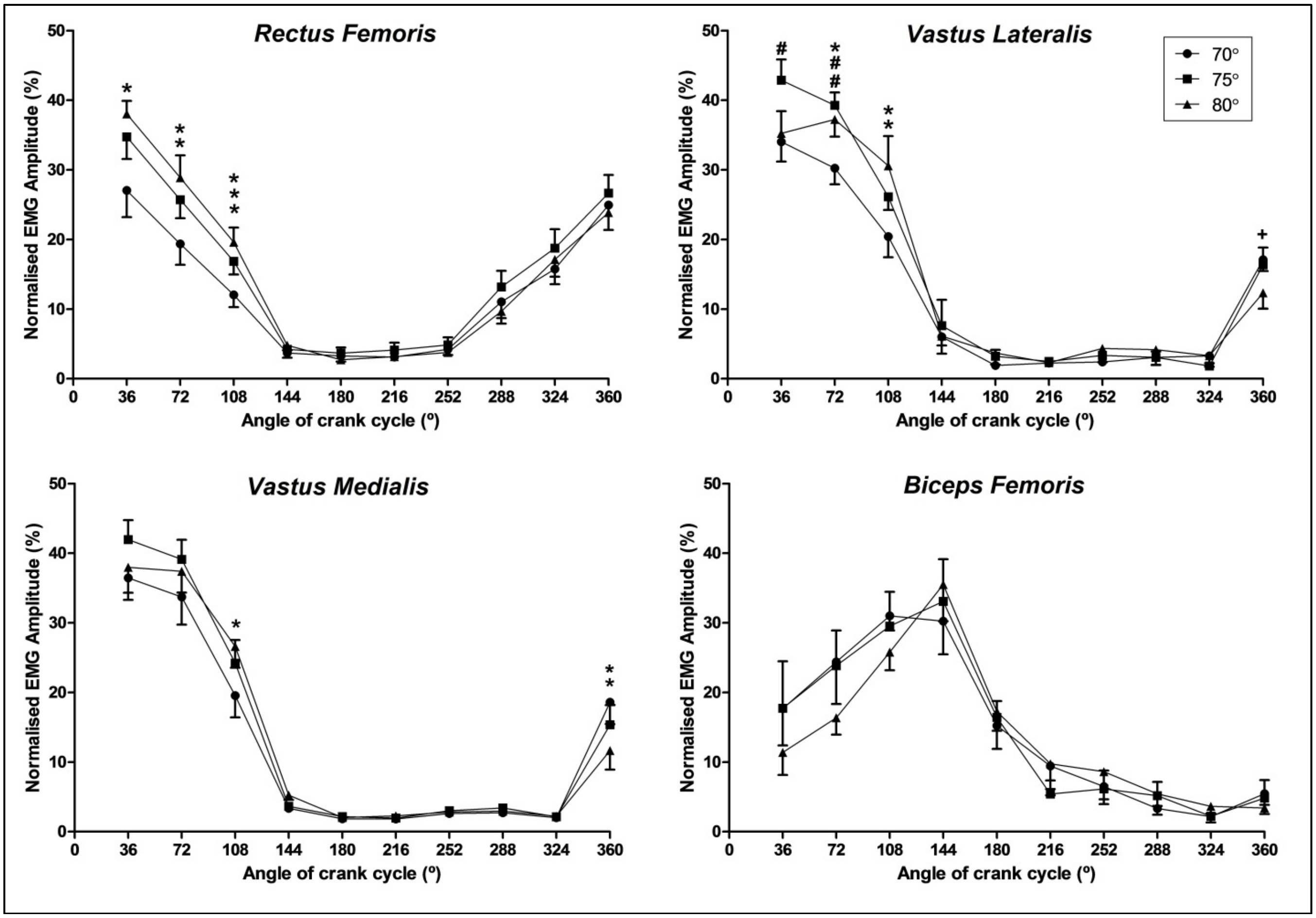

Figure 3. Group mean (SEM) normalised EMG data at each 10% interval of the crank cycle for IWL. Asterisk symbol (*) infers significant difference between STA of 80 and 70º (* $P < 0.05$; ** $P < 0.01$). Hash symbol (#) infers a significant difference between STA of 75 and 70º (## $P < 0.01$). Plus symbol (+) infers a significant difference between STA of 80 and 75º (+ $P < 0.05$).

LaFortune *et al.* (13) reported that the majority of power in cycling was generated during the mid-section of the down-stroke (60 to 120° past TDC), and EMG studies have reported that the knee extensors are important power generators during this phase of the crank cycle (17, 21). Results of the current study suggest that STA significantly affects timing of activation in mono-articulate knee extensors, extending their activation range into this predominantly power generating phase. This finding may account for the increased efficiency and decreased cardio-respiratory costs previously observed at steeper STA (7,16). Steeper STA was associated with a later onset and offset of activity for VM, particularly comparing 80 and 75 to 70º at IWL, see Table 1. VL also became active significantly later comparing STA of 80 vs. 75º at IWL. However, the duration of activity for both VM and VL did not change with STA. Rankin and Neptune (18) simulated the effect of altered STA during high-intensity cycling and their model predicted activity phases occurring later in the pedal stroke for knee extensors and flexors, as STA increased. The current study supports this model for mono-articulate knee extensors, however, no such trend towards later activity was observed for the bi-articulate knee extensor (RF) or for the knee flexor (BF). Previous kinematic analysis identified greater hip extension, ankle plantar flexion and lower-limb orientation more directly over the crank axis when STA was increased (7,16). It is interesting to note that increasing STA was associated with later activation of mono-articulate knee extensors in the current study, despite these muscles not being functionally linked to the hip joint. However, preferential recruitment of the bi-articulate RF during the initial phase of the down-stroke may have facilitated a change in timing of VM and VL activity, such that they were more effectively utilised during the down-stroke. Thus, the recruitment pattern of mono-articulate knee extensors may be indirectly linked to hip joint kinematics via their agonist, RF.

While there is a general consensus on timing of activation for knee extensor (10), results concerning knee flexors are more controversial. Some authors have documented an activation region from just after TDC to BDC (3), while others have documented a longer activation region from around TDC to about 270º (12). Ryan and Gregor (21) reported two different patterns for BF activation during pedaling. In a study involving 18 cyclists, they reported high variability both within and between cyclists in respect of EMG patterns, with 2 patterns emerging for BF, despite relatively similar experimental conditions. The high intra- and inter-subject variability regarding BF activity may in part explain discrepancies in the literature regarding STA variation on timing and magnitude of activity in BF.

In the current study, RF was significantly more active in the first 30% of the crank cycle when comparing 80 vs. 70º STA at IWL (Figure 3). Garside and Doran (4) previously suggested that steeper STA facilitated a more efficient and comfortable bike-run transition in triathletes. Herzog *et al.* (9) reported that cyclists tended to be stronger at short compared with long RF lengths, whereas the opposite was true for runners, and speculated that this may be associated with an adaptation of the RF muscle to the requirements of cycling and running. Triathletes spend a significant amount of their training time running, which may in part explain their preference for steeper STA which allow for larger hip angles and a longer RF length while cycling. It could be speculated that at steeper STA, a longer RF length and higher activity in the first 30%, more closely resembles the biomechanics of running, therefore facilitating an easier and more effective bike-run transition. The greater activity of the bi-articular RF in the first 108º of the pedal cycle at IWL (80 vs. 70º) in the current study may therefore explain the more effective transition from cycling to running in triathletes using steeper STA.

Previous research examining EMG activity when cycling with altered STA has reported contradictory findings. Ricard *et al.* (20) reported that increasing STA significantly reduced BF activity. In the current study, no significant differences in the BF activity were observed. There was a trend towards lower BF activity during the first 108° of the crank cycle at 80º STA, see Figures 2 and 3, however, differences were not statistically significant. Silder *et al.* (23) also observed no difference in BF activity, instead reporting a significant increase in RF activity. However, Silder *et al.* (23) reported that RF activity increased during the final 90° of the crank cycle. In contrast, the current study identified significant increases in RF activity during the first 108° of the crank cycle. It is not immediately clear why the reported increases in RF activity occurred at different phases of the crank cycle. The current study identifying changes during the down-stroke suggests RF being preferentially recruited as a knee extensor at steeper STA. Conversely, the findings of Silder *et al.* (23) would suggest RF is preferentially recruited as a hip flexor at steeper STA. Further examination of the role RF plays in both hip flexion and knee extension is necessary to clarify this discrepancy.

The current study used two sub-maximal workloads; 160W and a load equivalent to 10%δ below T_{Lac} (IWL). Group mean power output at IWL (256W) was comparable with the mean power output of 240W (11) for a six hour stage of the Tour de France. Based on competition heart rate data, time-trials are raced under steady-state conditions, with shorter time-trials being raced at intensities close to onset of blood lactate accumulation (~400 to 420W), and longer time-trials close to individual lactate threshold (~370 to 390W). Mass-start races, on the other hand, are raced at lower mean intensities (~210 W for the flat stages, ~270W for the high mountain stages), but are characterised by their intermittent nature, with cyclists spending on average 5 to 20 min at or above onset of blood lactate accumulation (15). The effect of increasing power output on muscle recruitment patterns was inconsistent across investigated muscles in the current study. The bi-articulate RF and BF appear more responsive to increased power output, with increased activity observed in the first 108° of the pedal stroke in both muscles. In contrast, mono-articulate VM and VL exhibited increases in the final 36° of the pedal cycle, but little or no effect was observed in the primary power generating phase of the down-stroke.

Several methodological limitations should be considered before drawing definitive conclusions. Firstly, a small number of EMG data sets were eliminated due to excessive "noise" during recording. A total of 5 out of 44 (11%) data sets were eliminated due to the appearance of non-physiological signals, with most being confined to BF recordings. Excessive motion artifact associated with electrodes and leads attached to the posterior portion of the leg during the pedal cycle most likely caused this. It may also explain the higher variance in BF activity patterns reported in previous studies (1,20,23). Secondly, joint kinematic data was not collected during this study. Previous studies assessing STA variations on lower limb kinematics have consistently reported that hip extension and plantar flexion are increased (1,7,16); therefore, it is reasonable to assume similar kinematics in the current study. Nonetheless, joint kinematic data would have been a useful addition to the current methodology. Thirdly, only four muscles were investigated; whereas, cycling involves contribution from many other lower-limb muscles. It is recommended that future studies include other lower-limb muscles such as *Gluteus Maximus, Semimembranosus, Semitendinosus, Tibialis Anterior* and the *Triceps Surae* complex. It is likely that *Iliopsoas* activity at varying STA also plays a significant role regarding hip movement and stabilisation but unfortunately it is difficult to measure given its depth and position. Fourthly, the study examined EMG activity at two sub-maximal exercise intensities, both of which were below the aerobic threshold. It is possible that these results are not reflective of the EMG patterns which occur during higher intensity anaerobic cycling. Finally, the current study recruited only male competitive cyclists. Future studies examining potential gender differences in timing and magnitude of EMG activity are warranted.

In conclusion, the study hypothesis that muscle activity patterns would be significantly altered by varying STA cannot be rejected. VM and VL were active for the same duration but timed at a more optimal phase of the crank cycle at steeper STA. This may in part explain previously reported improvements in metabolic efficiency associated with a steeper STA. RF was more active at STA of 80º which may be due to more effective contractile lengths at that hip angle, and may also explain a more efficient bike-run transition in triathlon. Increased activity in RF does not directly explain the lower energy expenditure associated with steeper STA. However, more effective timing and utilisation of power producing muscles likely reduces demand from ancillary muscles, improving overall economy. Reduced activity in BF was observed in the current study. While this was not a significant effect, it serves to highlight how increased recruitment from one muscle can be linked with a simultaneous reduction elsewhere. Further analysis of other lower limb muscles is therefore warranted to fully explain neuromuscular mechanisms underlying improved metabolic efficiency when cycling at steeper STA.

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