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Influence of lateral pedal translation on muscle recruitment and kinematics in cyclists

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A B S T R A C T

Background/Objective: Current cycling pedals constrain the pedaling motion to the sagittal plane. This study aimed to evaluate novel pedal systems that allow lateral translation through the pedal stroke via frontal plane kinematics and muscle recruitment.
Methods: Sixteen cyclists were recruited to pedal on three pedal systems: standard pedals (STD), free lateral translation (LAT), and a guided lateral translation pedal (VL). Frontal plane kinematics were measured via markers on the hip, knee, and foot. EMG recordings were collected from 8 leg muscles and expressed as a percentage of functional threshold power activation levels.
Results: Knee and ankle range of movement was significantly more highly correlated in the VL pedals compared to STD ($r = .46 \pm .08$, vs. $.23 \pm .05$; $p = .028$). The rectus femoris was recruited significantly less in the VL vs. STD pedals ($23.6 \pm 7.7\%$ lower, $p = .008$). The hip abductors were more highly recruited in VL vs. STD: gluteus medius ($16.9 \pm 7.2\%$ higher, $p = .033$) and the tensor fascia latae ($30.9 \pm 8.5\%$ lower, $p = .003$).
Conclusion: VL pedals may improve knee-to-ankle tracking through the pedal stroke and may allow cyclists to increase power output through the additional recruitment of hip abductors.

Introduction

Cycling is a prevalent form of transportation, with more than 100 million people over the age of 3 having ridden a bike in 2014 in the United States[1] Over 35 million people rode a bike 6 or more times in that same year, and approximately 53% of those individuals rode for fitness.[2] Given the pervasiveness of cycling, there is a need for ongoing research regarding[3] the interface of the cyclist with the bicycle. A cyclist achieves forward motion via the connection between their foot and the pedal platform. Further optimization of this connection between cyclist and bike may offer the possibility of minimizing risk of knee injury, while also improving the performance of the cyclist.

Current cycling pedals allow a rider's foot to be "locked" to the pedal. This type of pedal system (available from a number of manufacturers) consists of a cleat on the bottom of the shoe and a corresponding 'clipless' pedal that engages the cleat. These pedals typically allow a few degrees of both foot abduction and adduction (rotation), referred to as "float". This float is beneficial to the rider as it reduces the applied moment to the foot and likely reduces knee pain.[4] However, these pedals only allow the cyclist to rotate their foot and leg in the sagittal plane motion of the pedal stroke, with no lateral translation.

Because of this repetitive knee and hip flexion and extension in the sagittal plane, professional cyclists commonly have hypertrophied extensor/flexor muscles,[5] with disproportionately weaker stabilizing muscles. As a result, cyclists commonly experience iliotibial band syndrome (ITBS).[6] This occurs as a result of the repetitive movement of the band against the lateral femoral condyle during the cycle stroke[6] and is most often associated with weak hip abductor muscles in both runners and cyclists.[7,8]

Ice skating is similar to cycling in that forward body motion is achieved through repetitive flexion/extension of the knee and hip. However, ice-skating achieves this motion with the addition of significant hip abduction through muscles such as the gluteus medius.[9,10] Cyclists, who commonly have disproportionate development of the extensor/flexor muscles, would likely benefit from abductor muscle strengthening and engagement. Furthermore, 57%

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of time-loss injuries sustained by professional cyclists are knee related,[11] which could possibly be reduced by improved knee kinematics through the pedal stroke.

One avenue for engaging stabilizing muscles that generate abduction is to use a pedal that allows medial-lateral translation during the pedal stroke. A previous investigation evaluated pedals that allowed lateral translation (either 15 mm or 32 mm) and found no changes in cardiovascular or metabolic markers. However, the author suggested that there may be kinematic benefits, though none were evaluated.[12] Another study computed knee loads with medial/lateral translation pedals that allowed $\pm$ 7 mm of translation, and most participants self-selected a position near the lateral stop.[13] Both of these previous studies were laboratory based, and until recently, no commercially available pedals have allowed lateral translation.

This new pedal system (Zivo® Pedals; Nikola Innovation, Rocky River, OH) was developed to allow lateral pedal translation. It also provides a lateral stop that changes throughout the pedal cycle to allow application of hip abduction force via a stop to bear against. The position of the lateral stop moves as the pedal is rotated, with the pedal moving outward on the downstroke (inward on upstroke), with its furthest lateral position occurring at the lowest point of the pedal stroke (6 o'clock or "bottom dead center").

This study aimed to investigate the kinematic and electromyographic differences during pedal motion between a standard clipless pedal system (STD), a pedal that allows for unrestricted lateral pedal motion (LAT), and a pedal that offers a variable lateral pedal motion (abbreviated as VL; Zivo® pedals). It was hypothesized that cyclists would self-select lateral translation in a pedal that incorporated lateral translation, and that this motion would result in more highly correlated medial-lateral movement between ankle and knee in the frontal plane. It was also hypothesized that pedals with lateral motion would encourage the recruitment of hip abductor muscles, and that the VL pedal would result in the highest abductor recruitment.

Methods

Participants

Road cycling enthusiasts were recruited from the local area for study participation. The 16 participants had mean anthropometric values of (mean $\pm$ SE): height of 178.5 $\pm$ 1.6 cm, body mass of 78.7 $\pm$ 2.5 kg, and age of 42.3 $\pm$ 2.3 yr. To qualify for the study, participants must have completed a cycling event of 32 km (20 mi) during the previous year and engage in a minimum of 2 cycling sessions a week. The participants had been actively involved in cycling for 8.9 $\pm$ 5.9 years. The study received Institutional Review Board (IRB) approval, and all participants provided written informed consent prior to participating.

Procedures

Participants were asked to bring their own bike to the lab to ride throughout the experimental procedure. Allowing participants to ride a bike they were familiar with minimized variability that could result from positional changes related to the handlebar, saddle, or other components. Each participant's bike was set-up on a smart trainer (Kickr Snap, Wahoo Fitness, Atlanta, GA) for the duration of the testing, allowing them to ride in stationary position in the lab. The trainer was controlled with cycling specific software (TrainerRoad version 2.7.7, Reno, Nevada). This software was used to sequence the riders through the testing protocol and allowed remote operation of the trainer, with precise control over power output.

Participants were first asked to complete a test of their functional threshold power.[14] Functional threshold power (FTP) is the maximum cycling output power that a cyclist can maintain for an hour period. The test consisted of a warmup period, an 8 min period of maximum effort, and a cooldown.[15] Furthermore, rather than determining a precise FTP for a subject, the intent of the FTP test was to establish an effort level for their pedal testing. Following the cooldown period, participants were allowed to rest for 20 min or more off the bike and rehydrate as necessary.

The established FTP was used to determine the power level of the smart trainer, and thus the power output of the subject, for the pedal trials. It has been proposed that for optimal performance in an endurance event, cyclists should ride at 65–85% of their FTP.[14] For the pedal trials, the power of the trainer was set at 70% of each rider's established FTP, ensuring that participants were riding at a resistance proportionate to their own capabilities.

Participants completed three subsequent trials in a randomized order. Each trial involved riding on a different pedal style on their bike for 5 min (Fig. 1). (Note: all trials used the same cleat on the shoe.) The first style was a standard (STD) pedal, the commonly available Look Keo® compatible pedal offering 9° of float (Alpe D'Huez pedals, Nashbar.com, USA) and no lateral motion. The second pedal system (LAT), designed for laboratory use, utilized a custom manufactured spindle that allowed for both 9° of float and up to 20 cm of lateral plane motion. The final pedal allowed 9° of float and had guided variable lateral motion (VL) via a helix machined into the spindle shaft, with a following pin in the pedal body allowing 2.5 cm of lateral motion (Zivo Pedals; Nikola Innovation, Rocky River, OH). For the VL pedal, the maximum lateral displacement occurred at the bottom of the pedal stroke, with the minimum lateral position occurring at the top of the stroke.

Kinematic analysis

Participants were fitted with reflective markers to measure movement in the frontal plane. Markers were placed on the hip (anterior superior iliac spine – for viewing in the frontal plane), knee (apex of patella), and foot (top of foot, centered medial/lateral, superior to pedal spindle shaft). Two high intensity lights were used to illuminate the markers during the trials. To capture motion in the frontal plane, a digital camera was positioned in front of the cyclist, in line with the bike frame at the height of the knee at full extension. High speed video was collected at 300 fps (GC PX100, JVC, Japan). An in-frame object was aligned with the center of pedal rotation and used to calibrate the motion capture measurements. The markers were digitized using software auto-trackers (Kinovea® version 8.15, Kinovea.org). The software was used to export x,y coordinates in the frontal plane for computation of kinematic variables. Intra-class correlation coefficients (ICC) were evaluated for Kinovea, to check for reproducibility of the analysis. Three videos were evaluated 3 times each, and the ICCs ranged from .945 to .996. This work validated the use of Kinovea for this analysis. Further, the usage of Kinovea has been established for accurate analysis of motion in work involving: gait,[16] drop jumps,[17] cervical movement,[18] soccer kicking,[19] and vertical jumping.[20]

To evaluate the frontal plane movement of the hip, knee, and ankle, the medial-lateral direction of the markers in the side-to-side motion (medial-lateral) was computed. Because the vertical movement of the knee and ankle in the frontal plane is dictated by the attachment of the shoe to the pedal, the uncontrolled movement of the knee and the variable lateral float of the ankle were also assessed. Additionally, the correlation between knee and ankle movement through the pedaling motion was evaluated (discussed in detail in Analysis section).

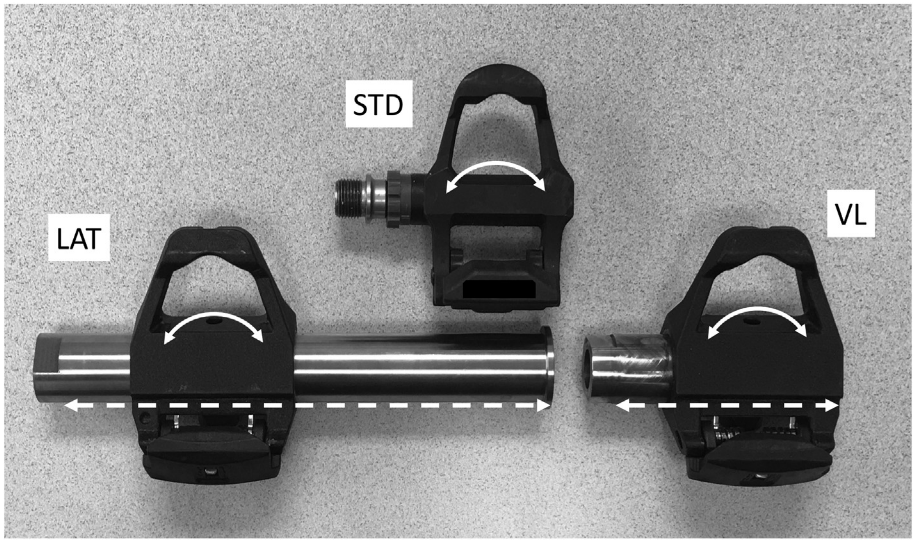

Fig. 1. Three pedal systems used during testing. Left, lateral float pedal (LAT) with 20 cm of lateral motion. Solid arrows indicated the common 9° rotational float on each system, and dashed arrows indicate the lateral float (translation) allowed. Center, standard pedal system (STD) with no lateral float. Right, variable lateral motion pedal (VL) with 2.5 cm guided lateral float.

EMG analysis

Muscle recruitment was measured during the trials using surface electromyography (EMG) equipment (Telemyo 2400T G2; Noraxon, Scottsdale, AZ). The participants skin was shaved with disposable razors and cleaned with alcohol swabs. Bi-polar electrodes (Ag/AgCL electrodes with 2.0 cm spacing) were placed over the muscle belly on the dominant leg in line with the predominant muscle fiber direction[25] for the following muscles: the lateral gastrocnemius (LG – distal to knee, 2 cm lateral from midline), the vastus lateralis (VLO – 3–5 cm above patella, angled lateral to midline), rectus femoris (RF – on midline of thigh, halfway from knee to iliac spine), vastus medialis (VMO – at angle, 2 cm medial to base of patella), the biceps femoris (BF – 2/3 of distance from trochanter to back of knee, on lateral side), the gluteus medius (GM – proximal third of distance between iliac crest and greater trochanter), the tensor fascia latae (TFL – 2 cm below ASIS), and the gracilis/adductor magnus (GR – medial aspect of thigh, oblique angle 4 cm from pubis).

EMG data for each of the 8 muscles was collected during the FTP trial and for the 3 different pedal trials, with data sampled at 1500 Hz. The signal was rectified and filtered with a fourth order Butterworth Filter to remove low frequency signals below 20 Hz and high frequency noise above 500 Hz.[21,22,23] The signal was further processed using a root mean square (RMS) algorithm with a 100 ms window. EMG processing and analysis was conducted with myoMUSCLE software (Noraxon U.S.A., INC; Scottsdale, AZ). Mean values over the trial period were computed, and EMG data from each pedal trial was normalized as a percentage of mean activation during the FTP trial. This cycling specific dynamic normalization method[22,24] allowed for a relative comparison of muscle recruitment based on the participant's own endurance cycling threshold effort (FTP).

Analysis

From the kinematic data, the medial-lateral motion of the hip, knee, and ankle were compared within subject, between the three pedal trials. A repeated measures ANOVA with post hoc analysis was conducted using a least significant differences correction for multiple comparisons. Additionally, a Pearson's correlation analysis was used to evaluate for relationship between medial-lateral correlation in knee movement and ankle movement for each pedal style. Pearson r values were calculated for each trial for each subject, and mean r values across participants were used for comparisons between pedal types.

Mean muscle activation levels for each muscle, for each pedal style, were expressed as a percentage of the participant's mean activation levels during the FTP trial. Again, a repeated measures ANOVA with post hoc analysis was conducted using a least significant differences correction for multiple comparisons. All statistical analysis was conducted with SPSS software (ver. 22 for Windows; IBM, Amonk NY). The alpha-level level was set at .05 for all analyses.

Results

All participants ($n = 16$) first completed the FTP protocol, with a mean power of 205.1 ± 11.3 W (mean ± SE), and then completed the three pedal trials in a randomly assigned order.

Kinematics

There was no significant difference in either hip (RM-ANOVA $p = .343$) or knee movement (RM-ANOVA $p = .372$) between pedal types (Fig. 1). However, the ankle movement was significantly different between pedal types (RM-ANOVA $p < .001$). The medial-lateral movement on the LAT pedal was $1.94 \pm .44$ cm higher than control ($p = .001$). The ankle had medial lateral movement $1.99 \pm .21$ cm higher than control ($p < .001$) (Fig. 2).

To evaluate the relationship between knee movement and ankle movement in the frontal plane, a correlation analysis was completed to compute Pearson's r values (correlation coefficients) for each subject within each pedal type. The r values were averaged across pedal types and compared (Table 1).

EMG

To evaluate muscle activation, the muscles were considered in two groups: (1) primary movers for cycling – lateral gastrocnemius

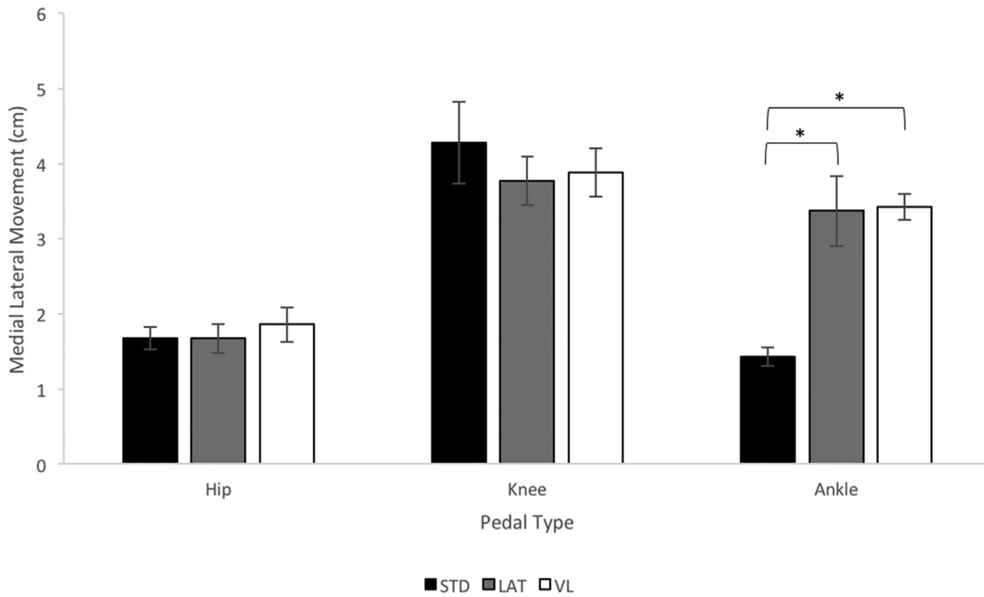

Fig. 2. Frontal plane movement in the medial-lateral direction. Values computed as mean of horizontal range for each subject. STD = standard pedals, LAT = lateral movement pedals, VL = variable lateral pedal motion pedals. * indicates a significant difference (p < .05).

Table 1
Comparison of knee and ankle movement in the frontal plane. The first row presents the knee range divided by the ankle range as a ratio. The second row compares the correlation between knee and ankle movement averaged across each subject. RM-ANOVA was used to evaluate for differences, and post hoc p values were used for comparison to the STD pedals.

	STD	LAT	VL
Knee to Ankle range ratio (K/A)	3.3 ± .43	1.4 ± .19	1.18 ± .12
p value vs STD		*<.001*	*<.001*
Knee to Ankle correlation (r)	.23 ± .05	.49 ± .06	.46 ± .08
p value vs STD		*.007*	*.028*

(LG), rectus femoris (RF), and biceps femoris (BF) (Fig. 3) – and (2) muscles that serve a more stabilizing role – vastus lateralis (VLO), vastus medialis (VMO), gracillis (GR), gluteus medius (GM), and tensor fascia latae (TFL) (Fig. 3). EMG data was expressed as a percentage of FTP for each muscle.

For the prime movers, the lateral gastrocnemius (LG) showed a trend toward less activity in the VL pedals than the LAT pedals, with an 8.4 ± 4.5% lower activation (mean ± SE; p = .080). The activity of the rectus femoris (RF) for the VL pedals was significantly less than that for the STD pedals, 23.6 ± 7.7% lower (p = .008); and the activation was also lower for the VL pedals than the LAT pedals, 15.1 ± 6.5% lower (p = .033).

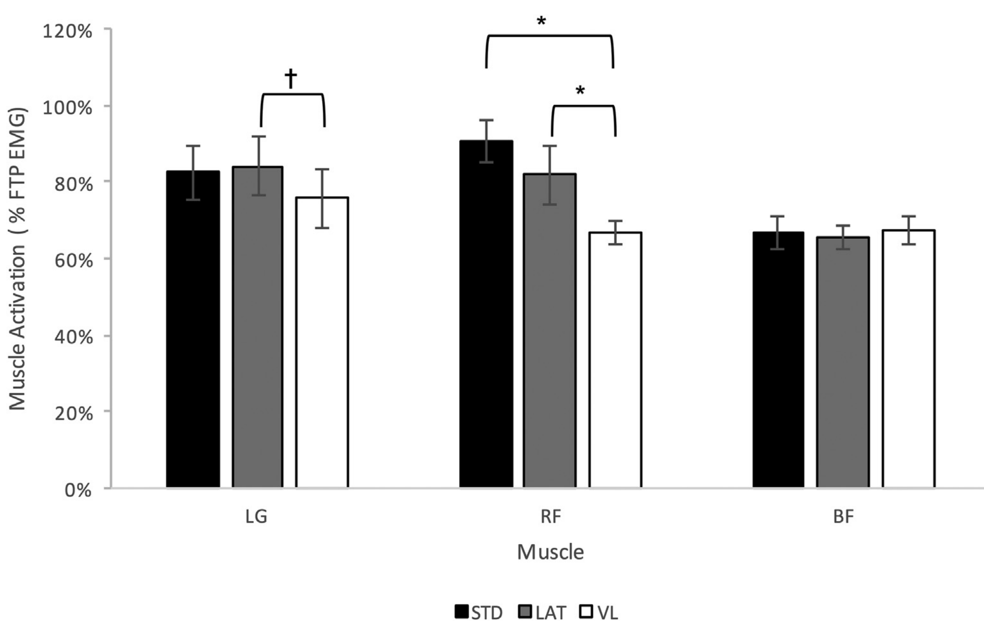

Fig. 3. Muscle activation for prime mover muscles. STD = standard pedals, LAT = lateral movement pedals, VL = variable lateral pedal motion pedals. LG = lateral gastrocnemius, RF = rectus femoris, BF = biceps femoris. * indicates a significant difference (p < .05). †indicates a trend towards significance (p < .1).

For the stabilizing muscles, the vastus lateralis oblique (VLO) showed a trend towards a difference in activation with higher activation for the VL pedals than the STD pedals, 5.8 ± 3.1% higher ($p = .082$). For the gluteus medius (GM), activation as higher with the VL pedals than with the LAT pedals: 16.9 ± 7.2% higher ($p = .033$); and activation was higher for the VL pedals than the STD pedals: 18.8 ± 4.7% higher ($p = .001$). Activation of the tensor fasciae latae (TFL), showed a trend toward being lower with the STD pedals than the LAT pedals: 31.1 ± 16.6% lower ($p = .081$); and activation with the STD pedals was significantly lower than for the VL pedals: 30.9 ± 8.5% lower ($p = .003$) (Fig. 4).

Discussion

The aim of this study was to evaluate the differences in kinematics and muscle activation patterns between pedals that allow no lateral translation, un-restrained lateral translation, and guided lateral translation. The results demonstrate that cyclists naturally incorporate lateral motion into their pedal stroke when permitted, and this lateral motion results in increased hip abductor recruitment, with an associated decrease in rectus femoris (RF) recruitment. Further, pedals that allow lateral translation resulted in improved correlation between knee and ankle movement in the frontal plane, which may hold the potential for decreasing injury risk.

Kinematics

For both the VL and LAT pedals, significantly more lateral ankle movement occurred throughout the pedal stroke as compared to the STD pedals. For the LAT pedals, this result was expected, and for the VL pedals, the lateral motion was driven by the pedal itself. However, the lateral knee motion did not significantly increase with the increased ankle translation, and the knee motion was much more highly correlated with the ankle motion for both of the lateral translation pedal platforms. This reduced disparity in alignment of the knee and ankle in the frontal plane for the VL and LAT pedals could reduce knee varus and valgus moments, which are believed to contribute to pain and injury[24–27] for athletes in a variety of sports, including cycling.[26,28] These findings correspond with those of Ruby et al. who studied a pedal that allowed a small amount of lateral translation (±7 mm) and the results suggested a lowering of varus/valgus moments.[13] Anecdotally, many subjects expressed improved knee comfort while riding the VL pedals.

Electromyography

While riding the VL pedals, the cyclists experienced a significant increase in the recruitment of their hip abductors (gluteus medius [GM] and tensor fasciae latae [TFL]). Correspondingly, the rectus femoris (RF) was activated significantly less with the VL pedals than when using either the LAT or STD platforms. Because power output was kept constant across the pedal platform trials via a power-controlled trainer, the findings indicate that some pedaling effort was transferred from the RF to the abductors. Extrapolating these findings suggests that riders may be able to generate more overall power output without increasing RF activation via the recruitment of hip abductor muscles during the pedal stroke. Little previous work has been done to assess the recruitment of hip abductors in cycling, as they typically play a small role when STD pedal platforms are used.[29–33] In addition to elevated power output, increased recruitment of hip abductors will likely lead to strengthening of the associated muscles as well as a corresponding reduction in the potential for iliotibial band friction syndrome (ITBFS). ITBFS is a common issue for cyclists[34] who have been shown to benefit from a strengthening protocol focused on the hip abductors.[35]

Methodological

Participants in this study were avid non-professional cyclists with a mean age of 42 yr. Most cycling specific studies focus on a population younger than this, and there is a need for more analysis of an age range that accurately reflects cycling demographics.[36] Additionally, this study included only male subjects to minimize variability of the findings. However, there is a need for greater study of female cyclists, as little research exists for this demographic.[36] Females also demonstrate different cycling mechanics,[37] with greater likelihood of patellar-femoral pain syndrome[37] and weaker hip abductors.[39] Therefore, females may

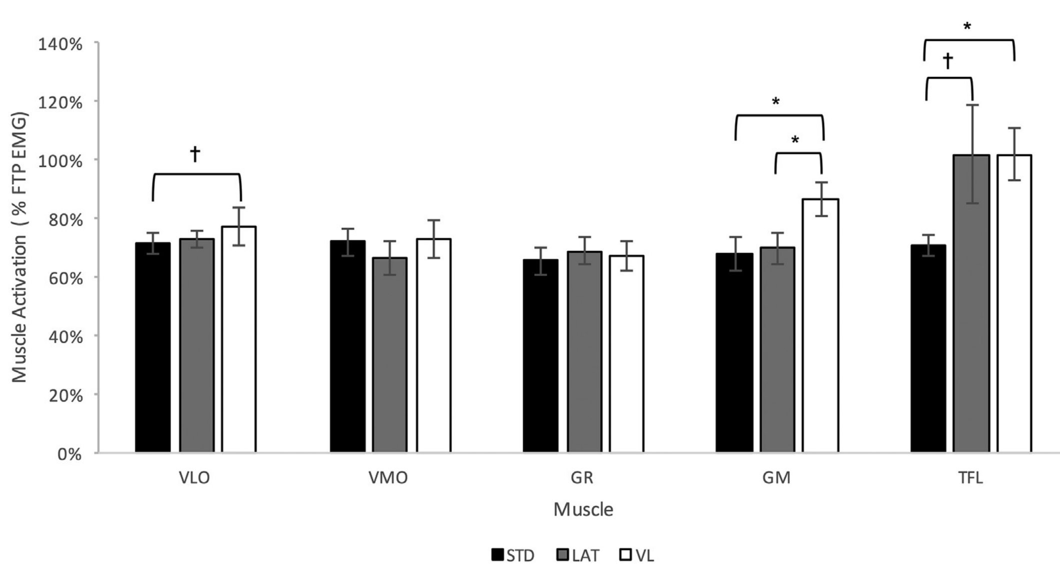

Fig. 4. Muscle activation for stabilizing muscles. STD = standard pedals, LAT = lateral movement pedals, VL = variable lateral pedal motion pedals. VLO = vastus lateralis oblique, VMO = vastus medius oblique, GR = gracillis, GM = gluteus medius, TFL = tensor fasciae latae. * indicates a significant difference ($p < .05$). †indicates a trend towards significance ($p < .1$).

experience greater benefit from the VL pedals than males. Further studies of pedals with lateral translation with women cyclists would be informative.

In this study, the participants used their own existing bike set-up and the bike settings were not standardized. However, the intent was to have riders in their normal riding position where the only thing that was altered was the pedal platform. This was achieved by keeping riders on their own bikes. As each rider was compared to themselves with only the pedal changing between trials, the comparison minimizes the effect of the different positions between riders. Additionally, these pedals were new to all cyclists in the study, and therefore some effects observed may have been due to their initial exposure to the pedals. The intent was to measure immediate changes induced by the switch from STD to VL or LAT. However, further work is warranted to evaluate longer term effects of this switch in pedal platform.

Conclusion

In summary, it was observed that for a pedal that provided guided lateral translation (VL pedals), the hip abductor muscles were more highly recruited than the rectus femoris for the same power output. Additionally, the knee and ankle motion were more highly correlated in the frontal plane while using the VL pedals. These results suggest that guided lateral translation may offer a higher power output through the recruitment of additional musculature, while also reducing varus/valgus loading on the knee.

Conflicts of interest

The author has no conflicts of interest to declare.

Acknowledgments

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jesf.2018.06.002.

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