Prevalence and functional implications of Soleus and Tibialis anterior activation strategies during cycling

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ABSTRACT

Key areas of sports science research investigate the functional role of muscle activations within human movement. Even within relatively constrained movements like cycling, significant variability is observed in muscle activation strategies. Particular attention has been given to particular muscles, despite Soleus and Tibialis anterior muscles presenting a potentially functionally relevant split between monomodal and bimodal activation strategies. The current study (N = 54) investigated the prevalence and functional implications of these different strategies and identified, in addition to monomodal [Soleus: N = 24, Tibialis anterior: N = 7] and bimodal [Soleus: N = 12, Tibialis anterior: N = 31] strategies, a third group switching between strategies [Soleus: N = 16, Tibialis anterior: N = 13]. The combined Soleus group showed significantly higher Index of Force Effectiveness, lower negative work and lower radial forces than the bimodal group. Furthermore, bimodal Soleus strategies produced a period of significantly greater plantar flexion during the upstroke. No differences were found between the Tibialis anterior groups. These data show an identifiable group of cyclists utilising a combination of monomodal and bimodal strategies potentially benefiting mechanical effectiveness. Awareness of such functional implications can aid researchers and practitioners when interpreting cycling biomechanics data or intervention responses. Further research should investigate the factors that mediate transitions between activation strategies within the combined groups.

KEYWORDS

Pedalling; ankle; electromyography; joint kinematics; mechanical effectiveness; muscle

Introduction

Understanding the functional role of muscle activations within human movement has received major attention in the fields of biomechanics and motor control for decades (Neptune and Herzog, 2000; Ryan and Gregor, 1992; Van Ingen Schenau et al., 1992). Complicated by an apparent redundancy and degeneracy in the musculoskeletal system, previous research has clearly established how multiple muscle activation strategies can produce a similar end-effector trajectory (Horan et al., 2011; Langdown et al., 2012; Van Bolhuis & Gielen, 1999). Such a redundancy has also been highlighted in cycling movements, suggested to explain how high inter-individual variability in muscle activity data can coexist with limited variability in the corresponding pedal forces (Hug et al., 2008).

The relevance of a search for a stereotypical or "optimal" muscle activation pattern is questionable due to the identified importance of movement variability for performance (Bartlett et al., 2007; Horan et al., 2011; Langdown et al., 2012). However, an understanding of the functional implications of interindividual differences in muscle activation strategies remains important as it can facilitate the interpretation of individual specific responses frequently seen in intervention studies (R. R. Bini et al., 2014; Ferrer-Roca et al., 2014; Peveler & Green, 2011; Sanderson & Black, 2003). Within the cycling movement, studies of muscle activity during cycling have predominantly focused on understanding the role of biarticular muscles as they have shown significant inter-individual variability across experienced cyclists (Dorel et al., 2008; Hug et al., 2008, 2010, 2019; Ryan & Gregor, 1992). These findings align with the key role of biarticular muscles in providing a solution to the conflicting kinematic and kinetic demands at certain points of the pedal cycle (Van Ingen Schenau et al., 1992). Managing these conflicting demands could explain the higher inter-individual variability in the activation patterns of bi-articular muscles as inter-individual differences in anthropometric characteristics or bike geometry could affect the kinematic demands and therefore the required biarticular muscle activity (Van Ingen Schenau et al., 1992).

More consistent findings and lower inter-individual variability are found in the literature for the activity of monoarticular muscles (Dorel et al., 2008; Hug et al., 2008, 2010; Ryan & Gregor, 1992). The primary role of mono-articular muscles during pedalling is generally regarded as the production of joint power (Van Ingen Schenau et al., 1992). Given the constrained and cyclical nature of pedalling, it is reasonable to assume that the requirements to produce propelling forces are relatively consistent across cyclists and therefore monoarticular muscles produce activation strategies with lower inter-individual variability than biarticular muscles. Indeed, lower inter-individual variability has been reported for Gluteus Maximus (GMax), Vastus Lateralis (VL) and Vastus Medialis (Ryan and Gregor (1992), Hug et al. (2008), Hug et al. (2010)), covering key monoarticular hip and knee extensors involved in pedalling. However, in comparison, the Soleus (Sol) and Tibialis anterior (TA) muscles have shown relatively high variability (Hug et al., 2008; Ryan & Gregor, 1992). More specifically, Hug et al. (2008) reported how the Sol shows low variability when comparing the downstroke between cyclists – when its main activity burst occurs – but shows much higher variability during the upstroke. The more distal position of the ankle joint could be influential on this higher variability in comparison to the hip and knee crossing musculature as the more proximal hip and knee joint positions might impact on the activity requirement of these distal joints. The role of controlling the ankle joint for the effective orientation of the pedal forces to the crank could induce higher variability in its activation, and a relationship may exist between their activation and the mechanical effectiveness of the force application.

In an earlier qualitative observation, Ryan and Gregor (1992) reported a clear distinction between some cyclists producing a single Sol activity burst (monomodal) compared to other cyclists presenting with two activity bursts per pedal revolution (bimodal) – providing further evidence for relatively high interindividual variability in Sol activity. Individuals producing a bimodal Sol strategy showed a similar activation burst as seen in the monomodal strategy, but with an additional burst just after bottom dead centre (BDC). A similar distinct difference was observed within the TA data; all cyclists presented a major activity burst during the second half of the upstroke, but an additional activation was seen just before BDC in only some individuals. Ryan and Gregor (1992) were unable to expand on the functional implications of these differences in activation strategies of Sol and TA muscles as they did not have access to corresponding kinetic and kinematic data. Despite later studies showing similar inter-individual variability in these muscles' activity patterns, and Hug et al. (2019) identifying the Soleus as a key muscle differentiating activation pattern between cyclists, none has presented the kinematic or kinetic output parameters associated with different activation strategies (Hug et al., 2008, 2010, 2019). In addition, more data on the prevalence of these activation strategies in a relatively large cycling cohort are needed to better evaluate the potential of any functional implications for the pedalling movement during cycling.

Previous research has shown that different Sol and TA activation strategies can be used by cyclists to execute the required movement. Data on the prevalence of these strategies remain limited and to the authors' knowledge no research so far has explored the functional implications of adopting a monomodal or bimodal activation strategy for the Sol and TA muscles. Better understanding the prevalence of different activation strategies and their association with different kinematic and kinetic patterns could provide unique information on the role of these muscles in a cycling movement. By identifying which muscle activation strategy is adopted by cyclists and expressing these relative to their corresponding kinematic and kinetic output parameters, this study aims to identify the prevalence and functional implications of different activation strategies for the Sol and TA muscles in cycling.

Materials and methods

Experimental design

Data from 54 cyclists (age: 37.3 ± 10.9 years, stature: 1.80 ± 0.06 m, mass: 77.4 ± 8.5 kg) were recruited from local cycling clubs and included in this study after providing written informed consent. This study was approved by the Research Ethics committee at Leeds Beckett University. Saddle and handlebar position of the participant's bike were recorded in a 2D coordinate system with the bottom bracket as the origin. A customised Wattbike ergometer (Wattbike Ltd, Nottingham, UK) was adjusted to reflect these coordinates. The saddle and pedals were transferred from the personal bike to the ergometer, crank length and saddle angle were also copied to mirror the participants' training position as closely as possible. The resulting testing positions reflected a range of bike setups typically seen in competitive cycling. Following a standardised 13-min warm-up (100–

125 W at a self-selected cadence with 3 × 30 s bouts at 80–90% of perceived maximal effort), participants underwent a self-paced 20-min maximal effort. The power output and cadence achieved during this 20-min test were used as the target power and cadence for later measurements to ensure biomechanical data were captured at a similar relative intensity across the tested cohort.

On a second testing day, separated by at least 48 hours from the maximal test, participants were positioned on the ergometer in their trained position and a comprehensive dataset on their cycling biomechanics was collected. Following the same 13-min warm-up, participants cycled for 3 min while receiving live feedback on cadence and power on a visual display. In the first minute intensity increased gradually towards the target power and cadence determined during their maximal effort, which was then maintained (mean ± SD: 95 ± 7 rpm and 276 ± 35 W) for the remainder of the trial. The second minute allowed for stabilising of pace and movement pattern, followed by a 60-s data capture in the final minute of cycling. The data collection consisted of the synchronised capture of muscle activation, kinematics and pedal force data.

Data capture

Pedal reaction forces were recorded in two-dimensions (tangential [F_t] and radial [F_r] to the crank, combined to produce total force [F_{tot}]) at 500 Hz using a Powerforce system (Radlabor, Freiburg, Germany) as described by Stapelfeldt et al. (2007). Pedal force data were filtered using a zero-lag fourth order low-pass Butterworth filter at a 20 Hz cut-off frequency in agreement with the manufacturer's recommendations.

Full body kinematic data were captured at 250 Hz using a 12-camera optoelectronic setup (Oqus 7+, Qualisys, Gothenburg, Sweden), of which the lower body data will be evaluated here. Twenty-three markers were placed to capture 3D kinematics of the leg of interest, of which 15 were used for dynamic tracking, including two clusters of four markers for thigh and shank. These data were first filtered using a zero-lag fourth order low-pass Butterworth filter, with the cut-off frequency determined independently for each marker coordinate trajectory using residual analysis (Winter, 2009). Filtered marker data was imported into Visual 3D V6.0 (C-Motion, Germantown, USA) for further kinematic analysis. Joint angles were described as a relative angle with all angles set to 0° at the anatomical reference position and positive angles representing the level of (dorsal) flexion. Each revolution was resampled to 360 data points, to allow for an average revolution to be calculated that reflected the 60-s cycling effort. In addition to time-series data showing the progression of ankle joint angle and velocity throughout the crank revolution, discrete parameters of mean angle and range of motion (RoM) were extracted for hip and knee joints.

Bipolar surface EMG electrodes with an inter-electrode distance of 10 mm (Trigno wireless sensors, Delsys, Natick, USA) were used to capture the muscle activity of the right leg's GMax, Rectus Femoris (RF), VL, Semitendinosus (ST), Gastrocnemius Lateralis (GL), Sol and TA at 2000 Hz with a bandpass filter of 20–450 Hz. To check the quality of the output EMG signal, samples of raw data and corresponding frequency spectra from participants of all groups were inspected to confirm that dominant frequencies were within the expected ranges. Electrode placement to optimise signal quality was based on expert judgement and guidelines by De Luca (1997). The portion of the muscle belly palpable at the skin surface was identified and then prepared through dry shaving and cleaning with alcohol before attachment to reduce electrical impedance.

Raw EMG data were corrected to ensure that its average was set to zero, rectified and processed with a moving average (25 ms window with 12.5 ms overlap as recommended by Hug and Dorel (2009). Finally, the data were normalised to their maximal activation. A custom written MATLAB R2017b (The Mathworks Inc., Natick, USA) script indicated when normalised activity levels exceeded 20% of their maximum, previously recommended as an appropriate threshold for determining activation onset (Hug & Dorel 2009). Using this threshold as a guide, graphical inspection determined when a second activation could be identified and to confirm that exceeding of the threshold value was not merely due to noise in the data.

Using pedal force data, negative crank work was calculated to describe the amount of energy per crank revolution that resists propulsive motion. For the evaluation of radial forces, the quantity of the mean absolute F_r was calculated by taking the average of the rectified signal. This was used for quantification of the absolute magnitude of the radial forces during the revolution. To allow comparisons of the data across tests at different power outputs and cadences, pedal force data were normalised. The negative work was expressed as a ratio to the net work done and pedal force profiles were normalised to their mean F_t value. The Index of Force Effectiveness (IFE) was calculated from the force data and crank angle (CA) displacement as the ratio between the area under the F_t-CA curve and the area under the F_{tot}-CA curve (Coyle et al., 1991).

Definition of groups

All participants were divided into groups twice: once using Sol activity and once using TA activity as a grouping variable. This resulted in two independent variables which were used for further analysis. Identifying the activation strategy used by the Sol and TA muscles required graphical inspection of the data for each participant individually. These graphical inspections revealed monomodal and bimodal strategies, but also showed some cyclists who switched between a monomodal and bimodal strategy during the 60 seconds of data capture (Figure 1). As a result, a third group was identified (the "combined" group) and could be characterised as having >15% of their revolutions presenting a different activation strategy than their predominant one. This distinction was made for both Sol and TA and resulted in the groups as seen in Table 1. For two participants' Sol and three participants' TA, the EMG electrode became detached from the skin during data collection. Their data were eliminated from group comparisons. When grouped by Sol strategy, the monomodal group was significantly younger than the Sol bimodal group (Table 1). Other descriptive characteristics were comparable across all Sol and TA groups.

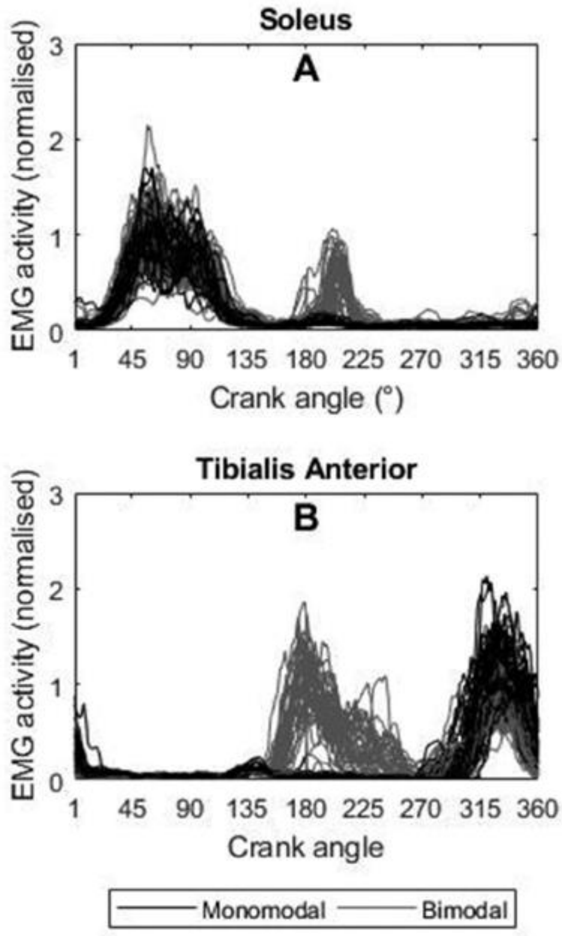

Figure 1 Revolution based Soleus (a) and Tibialis anterior (b) data for typical participants from the combined groups. Black and grey lines representing monomodal and bimodal traces, respectively.

Statistical analysis

Differences between groups were tested for statistical significance (α = 0.05) using one-way analysis of variance (ANOVA). When appropriate, post-hoc testing with a Bonferroni correction was used to identify the pairs that differed significantly. Statistical tests for discrete parameters were performed using SPSS 25 (IBM, Armonk, USA). To compare time series of ankle joint angle and velocity, statistical parametric mapping (SPM) was used with ANOVA tests as described by Pataky (2010) using spm1d version M.0.4.5. in MATLAB R2017b (The Mathworks Inc., Natick, USA). When SPM curves were created, no post-hoc testing was performed and only the main effect reported as the

Table 1 Soleus and Tibialis anterior groups by activation strategy. Descriptive data reported as mean ± SD.

Muscle	Soleus				Tibialis Anterior			
Activation strategy	Mono-modal	Bi-modal	Combined	Main effects	Mono-modal	Bi-modal	Combined	Main effects
N	24	12	16	7	31	13		
Age (years)	33.9 ± 10.9	43.2 ± 9.6[a]	38.8 ± 10.4	$F_{2,49} = 3.30$ $p = 0.045$ $n_p^2 = 0.12$	33.6 ± 11.5	38.1 ± 10.8	37.7 ± 9.7	$F_{2,49} = 0.52$ $p = 0.600$ $n_p^2 = 0.02$
Stature (m)	1.80 ± 5.6	1.78 ± 6.5	1.79 ± 6.9	$F_{2,49} = 0.60$ $p = 0.552$ $n_p^2 = 0.02$	1.80 ± 0.05	1.80 ± 0.05	1.80 ± 0.07	$F_{2,49} = 0.02$ $p = 0.984$ $n_p^2 = 0.01$
Mass (kg)	77.9 ± 6.8	78.6 ± 10.0	76.1 ± 10.3	$F_{2,49} = 0.32$ $p = 0.730$ $n_p^2 = 0.01$	77.2 ± 6.4	78.0 ± 8.9	76.7 ± 9.5	$F_{2,49} = 0.12$ $p = 0.886$ $n_p^2 = 0.01$
Cadence (RPM)	94.4 ± 7.3	98.2 ± 6.4	92.6 ± 6.8	$F_{2,49} = 2.20$ $p = 0.122$ $n_p^2 = 0.08$	89.1 ± 9.8	95.9 ± 6.8	95.1 ± 5.1	$F_{2,49} = 2.78$ $p = 0.072$ $n_p^2 = 0.10$
Power (Watts)	281 ± 38	270 ± 22	277 ± 45	$F_{2,49} = 0.33$ $p = 0.719$ $n_p^2 = 0.01$	285 ± 53	274 ± 34	282 ± 34	$F_{2,49} = 0.36$ $p = 0.701$ $n_p^2 = 0.01$

a= significant different from monomodal group ($T_{34} = 2.50$, $p = 0.047$, $d_s = 0.88$).

software developers have commented on the risk for invalid results when performing post-hoc calculations in SPM (Pataky 2019).

Results

Qualitative observation of the mean EMG revolution data for monomodal, bimodal and combined Sol groups confirmed the differences in muscle activation (Figure 2(a)). GMax, RF, VL, ST and GL presented with similar activation parameters across the three groups and all TA strategies were represented in each of the Sol groups (Table 2). SPM analysis revealed significant ankle angle differences across the Sol activation strategy groups in the range of 266–334° of crank angle ($p = 0.023$; Figure 2(b)). The ankle appeared more plantar flexed during the upstroke for those cyclists who exhibited a secondary Sol activity burst (bimodal and combined groups). The ankle angular velocity data also showed significant differences between the different Sol activation groups between 222° and 279° of crank angle ($p < 0.001$; Figure 2(c)). Knee or hip joints showed no significant kinematic differences when tested for mean angle ($F_{2,49} = 0.16$ and 0.55, $p = 0.853$ and

0.518 and η_p^2 = 0.06 and 0.02, respectively) or range of movement ($F_{2,49}$ = 0.31 and 0.44, p = 0.738 and 0.646 and η_p^2 = 0.01 and 0.02, respectively) across the different Sol groups.

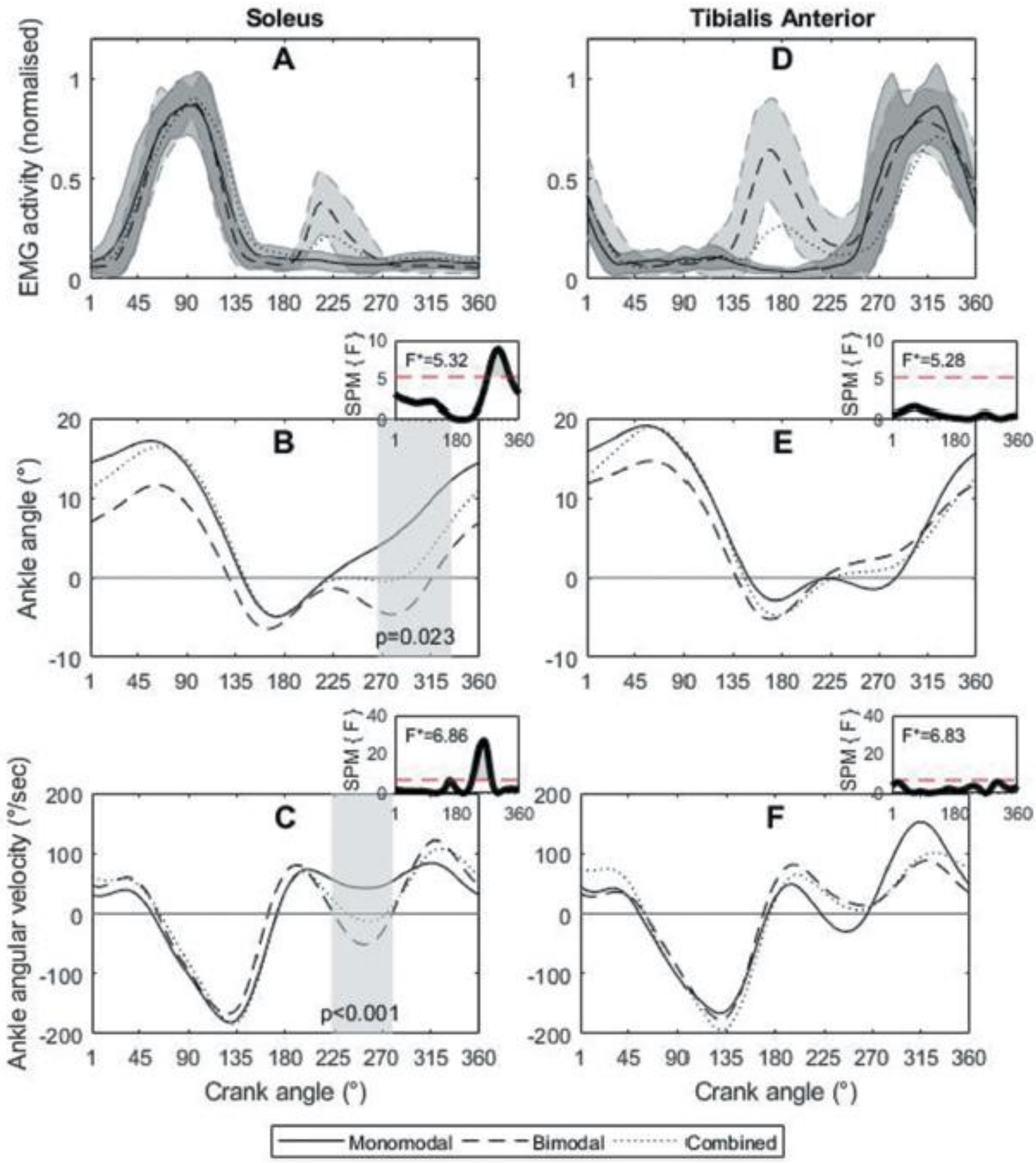

Figure 2 EMG and ankle kinematic when grouped by Soleus (left) or Tibialis anterior (right) activation strategy. Shaded band curves show SD values for the muscle activity plots, those for the combined groups are omitted for better clarity. Kinematic curves show SPM results with shaded areas presenting areas where curves were significantly different. Insets with SPM{F} curves show corresponding statistical results with df = 2,49 for Soleus and df = 2,48 for Tibialis anterior comparisons. SD bars are omitted for kinematic data for better clarity of the SPM results.

Table 2 Subdivision of participants in the Soleus and Tibialis anterior groups by antagonist strategy.

		Tibialis anterior			
		Monomodal	Bimodal	Combined	Missing
Soleus	Monomodal	3	15	5	1
	Bimodal	2	8	1	1
	Combined	2	7	6	1
	Missing	0	1	1	

Likewise, the TA presented with monomodal, bimodal and combined activation strategies across the tested cohort (Figure 2(d)). In line with the Sol groups, similar activation characteristics were observed for the other leg muscles recorded and all Sol activation strategies were represented in each of the TA groups (Table 2). However, in contrast to the Sol activation strategies, no differences exceeding statistical thresholds were observed in the SPM analyses comparing activation strategies for ankle angle and ankle angular velocity (Figure 2(e ,f). No significant differences were found for knee and hip mean angle ($F_{2,48}$ = 0.44 and 1.40, p = 0.650 and 0.257 and η_p^2 = 0.02 and 0.06, respectively) or range of movement ($F_{2,48}$ = 0.97 and 0.94, p = 0.388 and 0.398 and η_p^2 = 0.04 & 0.04, respectively) between the TA groups.

The pedal force data corresponding to the cyclists grouped by Sol activation strategy showed differences in the tangential and radial force profiles (Figure 3). Across parameters of IFE, net negative work and absolute radial forces, the combined Sol group showed significantly different values than the bimodal group but not significantly different compared to the monomodal group (Table 3). When grouped by TA strategy, IFE scores, normalised negative work and mean absolute radial forces did not differ significantly between the monomodal, bimodal and combined groups, indicating similar pedal force profiles across the groups (Table 3).

Discussion

The data of 54 cyclists collected in this study revealed that for both the Sol and TA muscle, the activation strategies adopted by cyclists cannot be fully described by a single and discrete activation

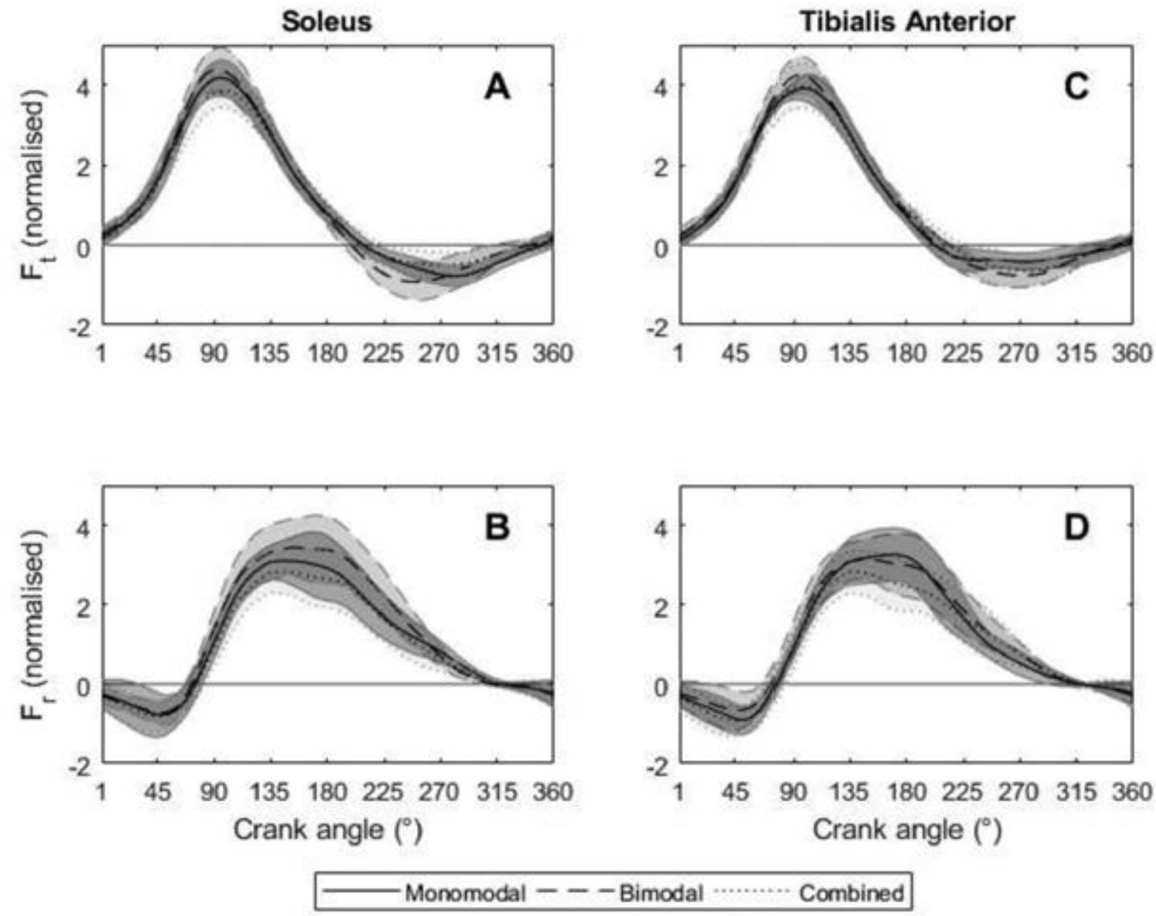

Figure 3 Normalised tangential (Ft) and radial (Fr) pedal force data grouped by Soleus (left) and by Tibialis anterior activation strategy (right). Shaded bars presenting group SD values.

Table 3 Mechanical effectiveness parameters specified when grouped by Soleus and when grouped by Tibialis anterior activation strategy. Descriptive data reported as mean ± SD.

Muscle	Strategy	IFE (%)	Negative work (normalised)	Mean absolute radial forces (normalised)
Soleus	Monomodal	47.4 ± 6.2	0.19 ± 0.08	1.35 ± 0.21
	Bimodal	44.6 ± 8.2	0.22 ± 0.14	1.49 ± 0.29
	Combined	52.2 ± 7.4[a]	0.13 ± 0.08[b]	1.23 ± 0.28[c]
	Main effect	$F_{2,49} = 4.47$, $p = 0.016$, $n_p^2 = 0.15$	$F_{2,49} = 3.57$, $p = 0.036$, $n_p^2 = 0.13$	$F_{2,49} = 3.49$, $p = 0.038$, $n_p^2 = 0.13$
Tibialis anterior	Monomodal	49.8 ± 7.4	0.13 ± 0.06	1.32 ± 0.23
	Bimodal	47.2 ± 7.1	0.19 ± 0.10	1.37 ± 0.26
	Combined	51.2 ± 8.0	0.16 ± 0.11	1.25 ± 0.28
	Main effect	$F_{2,48} = 1.48$, $p = 0.239$, $n_p^2 = 0.06$	$F_{2,48} = 1.42$, $p = 0.253$, $n_p^2 = 0.06$	$F_{2,48} = 0.91$, $p = 0.411$, $n_p^2 = 0.04$

a= signficant different from bimodal group ($T_{26} = 2.56$, $p = 0.019$, $d_s = 0.98$).
b= signficant different from bimodal group ($T_{26} = 2.25$, $p = 0.042$, $d_s = 0.86$).
c= significant different from bimodal group ($T_{26} = 2.33$, $p = 0.033$, $d_s = 0.89$).

strategy. Whilst the majority of the cyclists presented a clear and consistent strategy throughout the 60 s of data capture (either monomodal or bimodal), an ability to switch between these two strategies was observed in 16 and 13 of the cyclists for Sol and TA, respectively. The current study was the first to reveal such a switch between activation strategies within a single cycling effort. It shows that despite the monomodal and bimodal strategies presenting a distinct activation pattern, the categorisation of cyclists requires data on individual revolutions as cyclists can be, but are not necessarily, fixed within a single activation strategy.

Functional implications

An evaluation of the functional implications of monomodal, bimodal and combined strategies for Sol and TA muscles showed that no kinematic and kinetic output parameters were affected when cyclists were grouped based on TA activation. In contrast, grouping based on Sol activation strategy showed an association with significantly different ankle kinematics and suggested that those cyclists capable of combining a bimodal with a monomodal strategy were also capable of producing, on average, a more mechanically effective pedal cycle than those adopting only a bimodal strategy. These data clearly show that multiple strategies have the capability to successfully complete a cycling movement. As such, they support existing literature (Hug et al. 2008, Hug et al. 2010, Hug et al. 2019) to call into question the approach of searching for optimal, stereotypical muscle activation patterns during human

The current research was the first to highlight a different neural strategy by identifying a group of cyclists capable of adopting both the monomodal and bimodal Soleus activation strategies and actively switching between these strategies within the same cycling exercise. Interestingly, this combined group was associated with higher IFE scores, lower normalised negative work and lower normalised mean absolute radial force readings, all significantly different to those produced by the bimodal group. Based on the wider research in the field of movement variability (Bartlett et al., 2007; Horan et al., 2011; Langdown et al., 2012), it could be speculated that the combined group's flexibility in selecting different movement solutions to the task demands meant they could easily move from one strategy to another to maintain mechanical effectiveness. This would mean they were able to adjust the muscular coordination strategy according to the demands of the individual pedal revolution, adopting a secondary Sol burst when necessary to maintain high mechanical effectiveness. It is not possible to confirm this hypothesis though, as determining a causal relationship between muscle activity and kinetic and kinematic parameters for individual pedal revolutions was beyond the scope of this study. However, further research is suggested to investigate intra-individual difference in, and factors that affect the transition between, muscle activation strategies during pedalling.

In contrast to the significantly different kinematic and kinetic parameters between Sol strategy groups, no such associations were found when participants were grouped by TA strategy. Previous research has suggested that the TA works in co-activation with the Sol to stabilise the ankle joint, (Ryan & Gregor, 1992) which could explain the lack of impact of variations in TA activation on ankle kinematics. However, data from the current study show, at least at a group level, that overlaying activation timings of bimodal Sol and TA strategies suggest that they are better described as alternating rather than coactivating (Figure 2(a,d). The functional role of this muscle should be explored further, either using experimental data from the combined group or through computer modelling studies, by investigating acute intra-individual kinetic and kinematic responses when cyclists switch their TA activation strategy during a cycling exercise.

The determinants of a monomodal or bimodal activation strategy for mono-articular ankle muscles remain unknown. Previous research exploring the association between muscle activation and kinematic or kinetic output parameters investigated neuromuscular responses to mechanical demands at an inter-individual level (Hug et al. 2008; Raasch and Zajac 1999; Ryan and Gregor 1992;

Van Ingen Schenau et al. 1992). The current dataset has revealed an intra-individual variability in activation strategy. This suggests that even when factors like inertial characteristics and body geometry are constant, some but not all cyclists switch between activation strategies within a cycling effort. While groups presented no significant differences in the cadence and power maintained during the cycling effort, the inter-individual variability seen in these parameters – especially cadence – needs to be acknowledged and considered as a potential influencing factor. Previous research has shown clear effects of cadence and power output on muscle activation (Dorel et al., 2012; Holliday et al., 2019; Hug & Dorel, 2009) and pedal force parameters (Bini et al., 2013; Rossato et al., 2008; Sanderson, 1991). Further work investigating the intra-individual variability in muscle activation strategy and corresponding kinematic and kinetic outputs could provide more insight into the factors influencing the emergence of, and transition between, muscle activation strategies.

Methodological considerations

Any EMG measurement has its inherent issues of signal fidelity and processing. As with all EMG experiments the key extrinsic factors, once a modern high-quality acquisition system incorporating pre-amplifiers, differential amplifier and optimal bandwidths has been employed for the recordings, still affecting the signals are electrochemical noise, electrode placement (including cross-talk) and motion artefacts. As due diligence was performed in the current study to control/diminish the above factors, the authors are confident about the physiological origin of the EMG signals.

A limitation of the current research that must be considered when discussing the outcomes relates to the participant recruitment. The classification of Sol and TA activation strategies was applied retrospectively as their prevalence was not previously known. Therefore, groups could not be matched for cycling performance, bike setup, participant demographics and other potentially confounding variables, resulting in unequal group sizes. In particular, for TA strategy comparisons, the limited group size adopting a combined strategy (N = 7) could have had insufficient statistical power to identify group differences. However, it is this retrospective classification that resulted in the novel finding that a number of cyclists can utilise both monomodal and bimodal activation strategies within a single cycling exercise, creating combined Sol and TA groups in this study. Inherently linked to the novelty of this finding is that there is currently a lack of precedent on an appropriate ratio of strategies used to classify a cyclist as combined.

The current study creates a starting point for discussion on when the combined use of muscle activation strategies becomes functionally relevant and important for cycling performance. Cyclists presenting a single activation strategy (either purely monomodal or purely bimodal) might be capable of transitioning between strategies but did not experience suitable conditions that would trigger a transition, given the task constraints of the current experiment. Therefore, the actual functional implications of intra-individual variability are potentially greater than shown here. These methodological considerations clearly show a need and opportunity for future research to identify any factors that underpin the selection of a specific activation strategy.

Conclusion

This research has discovered that some cyclists can switch between formerly considered “fixed” Sol activation patterns. In those participants, there seems to be a higher level of mechanical effectiveness. Greater plantar flexion was observed in the upstroke of cyclists presenting a bimodal Sol strategy. These findings have implications for understanding the important components of effective pedalling and performance. At present, the robustness of the combined activation patterns across intensities or with fatigue is unknown and the parameters that determine strategy selection also warrant further investigation. In this respect, the current study offers a starting point by identifying a subgroup that switches between muscle activation strategies. Further research is needed to better understand interactions between strategies used across muscles, their impact on metabolic parameters and to identify factors associated with the strategy transitions. Where this study revealed functional implications of different activation strategies at a group level, research evaluating different activation strategies using intra-individual comparisons can continue this investigation into the dynamics of the neuromuscular system and further the practical application of this knowledge. Such studies can provide guidance on the performance impact of activation strategies and report on potential opportunities to train cyclists in transitioning between activation strategies.

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