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Original article

Muscular activity patterns in 1-legged *vs.* 2-legged pedaling

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Abstract

Background: One-legged pedaling is of interest to elite cyclists and clinicians. However, muscular usage in 1-legged *vs.* 2-legged pedaling is not fully understood. Thus, the study was aimed to examine changes in leg muscle activation patterns between 2-legged and 1-legged pedaling.
Methods: Fifteen healthy young recreational cyclists performed both 1-legged and 2-legged pedaling trials at about 30 Watt per leg. Surface electromyography electrodes were placed on 10 major muscles of the left leg. Linear envelope electromyography data were integrated to quantify muscle activities for each crank cycle quadrant to evaluate muscle activation changes.
Results: Overall, the prescribed constant power requirements led to reduced downstroke crank torque and extension-related muscle activities (vastus lateralis, vastus medialis, and soleus) in 1-legged pedaling. Flexion-related muscle activities (biceps femoris long head, semitendinosus, lateral gastrocnemius, medial gastrocnemius, tensor fasciae latae, and tibialis anterior) in the upstroke phase increased to compensate for the absence of contralateral leg crank torque. During the upstroke, simultaneous increases were seen in the hamstrings and uni-articular knee extensors, and in the ankle plantarflexors and dorsiflexors. At the top of the crank cycle, greater hip flexor activity stabilized the pelvis.
Conclusion: The observed changes in muscle activities are due to a variety of changes in mechanical aspects of the pedaling motion when pedaling with only 1 leg, including altered crank torque patterns without the contralateral leg, reduced pelvis stability, and increased knee and ankle stiffness during the upstroke.

Keywords: Electromyography; Muscle activity; One-leg; Pedaling

1. Introduction

During normal bicycle pedaling with 2 legs, crank torque is generated mainly during the downstroke phase of each leg when the leg extensor muscles are active in the first half of the 360° crank cycle.[1] In the subsequent upstroke phase that completes the crank cycle, the majority of the crank torque is produced by the simultaneous contralateral leg downstroke, with only a small contribution from ipsilateral flexor muscles.[2] For training and rehabilitation purposes, riders sometimes engage in 1-legged pedaling with crank torque generated only by 1 leg, emphasizing the need for ipsilateral upstroke flexor activity to generate crank torque and produce smooth pedaling motion over the entire crank cycle. Therefore, 1-legged pedaling requires cyclists to alter how they control multiple extensor and flexor leg muscles during the crank cycle. As such, 1-legged pedaling has been suggested as a training tool to improve pedaling performance[3] and is used in clinical settings for rehabilitation.[4] It has been suggested that 1-legged pedaling is a good tool for evaluating stroke patients in pedal force production[5] and for evaluating leg strength and endurance.[6]

The few studies that have compared 1-legged and 2-legged pedaling have found differences in both kinetics and kinematics.[7−9] For example, with 1-legged pedaling the proportion of mechanical work is lower in the downstroke and higher in the upstroke compared to 2-legged pedaling.[7] Others report that 1-legged pedaling has smaller peak hip extensor torques but larger peak knee flexor and ankle dorsiflexor torques, which is associated with a larger flexion angle of the knee joint at the bottom of the crank cycle.[10] These kinetic changes are accompanied by greater variation in crank angular velocity throughout the crank cycle in 1-legged pedaling (−30% to 20% of the mean) than in 2-legged pedaling (−10% to 10%),[9] with crank speed ranging from about 35 to 60 revolutions per minute (rpm) at the start and end of leg extension during 1-legged pedaling.

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The modified joint and crank dynamics in 1-legged pedaling are accompanied by alterations in muscular control as measured by electromyography (EMG). One study found increased overall activity in 5 major leg muscles in 1-legged pedaling compared to 2-legged.[8] Changes in activity of specific muscles have been shown after learning to direct pedal forces in a 1-legged pedaling task,[11] but this study did not include a 2-legged condition, with direct comparisons only between 1-legged pedaling before and after practice in their pedal force directing task. Furthermore, these studies[8,11] examined activity from only 6 leg muscles, thus limiting their view of the extent of the adaptation. A related study on single-leg pedaling[12] investigated activity in more leg muscles ($n = 10$), but these participants pedaled with 2 legs using mechanically independent crank arms. In true 1-legged pedaling, the leg motions are distinctly asymmetrical, with the contralateral leg providing little mechanical support for the pelvis while the ipsilateral leg produces crank torque. The protocol with independent crank arms involves less kinematic and kinetic asymmetry between legs and better pelvis support during ipsilateral crank torque production. Furthermore, it has been shown that sensory feedback from the contralateral leg may affect muscle activities of the ipsilateral leg in 1-legged pedaling.[13]

Therefore, the aim of this study was to examine and compare activity in 10 leg muscles while participants performed both 2-legged and 1-legged pedaling. Participants were asked to perform 2-legged pedaling with crank dynamics of 30 rpm and about 60 Watt (W), and equivalent 1-legged pedaling at 30 rpm and about 30 W. Based on previous studies, we hypothesized that 1-legged pedaling would exhibit greater upstroke activity in the hip, knee, and ankle flexor muscles, while downstroke extensor muscle activities would be reduced in magnitude.

2. Methods

2.1. Participants

Fifteen right-leg dominant healthy adults (11 males, 4 females; age = 25.8 ± 4.5 years; height = 1.72 ± 0.09 m; weight = 67.2 ± 9.8 kg; mean ± SD) with no previous professional or 1-legged pedaling experience participated in this study. They were free of cardiac, orthopedic, or neurologic disorders. Participants signed an informed written consent form approved by the Institutional Review Board at the University of Massachusetts Amherst. The data presented here are part of a larger study on learning to direct pedal forces during 1-legged pedaling.[14]

2.2. Experimental task

Two-legged and 1-legged pedaling trials were performed on a standard road bicycle attached to a computerized ergometer (Velodyne; Schwinn Bicycle, Chicago, IL, USA). The bicycle seat was adjusted to about 95% of hip−pedal distance in the lowest pedal position. Participants wore bicycle shoes with Look Delta cleats to securely connect the feet and pedals, with enough practice at attachment and detachment to become comfortable with their use.

Participants first stretched and completed a 2-min, 2-legged warm-up pedaling session at 60 rpm and about 60 W. After a 1-min break, each participant performed a 2-min, 2-legged pedaling trial (labeled as "Two-L") at 30 rpm and about 60 W. Two-L was followed by four 45-s, 1-legged pedaling trials at 30 rpm and about 30 W separated by 1-min rest intervals, with 30 W chosen to match the single-leg output of the 60 W Two-L condition. Each 1-legged trial was initiated by 2-legged pedaling for about 15 s to achieve the designated pedaling rate, followed by about 30 s of pedaling only with their left leg. At about 13 s, participants detached and placed their right leg on a nearby high-friction nonslip support where it would not interfere with crank rotation or invoke pelvis misalignment. Participants were instructed to maintain a constant crank angular velocity at 30 rpm, which required a mean crank torque of about 9.5 N·m. This resulted in crank power output at about 30 W, a load at which crank "freewheeling" (no rear wheel resistance) and hip flexor muscle fatigue are minimized.[11] In each trial, only the last 25 s of data were analyzed to exclude the 2-legged to 1-legged pedaling transition. The 4th trial was labeled as "One-L" for comparison with Two-L. Real-time visual feedback of crank speed was provided to participants on a computer screen to help them maintain the specified target velocity.

2.3. Data collection and analysis

Applied left pedal forces were measured with Kistler piezoelectric load washers.[15] Digital optical encoders (resolution = 0.35°, LS7184; US Digital, Vancouver, WA, USA) were used to measure left crank arm and pedal angular positions. Surface bipolar EMG electrodes (Delsys Trigno wireless system; DELSYS Inc., Natick, MA, USA) were placed according to the Surface ElectroMyography for the non-invasive Assessment of Muscles guidelines[16] on 10 muscles of the left leg (after proper skin cleaning by shaving and alcohol wipe): tensor fasciae latae (TFL), rectus femoris, biceps femoris long head (BFL), semitendinosus (ST), vastus lateralis (VL), vastus medialis (VM), lateral gastrocnemius (LGA), medial gastrocnemius (MGA), soleus (SOL), and tibialis anterior (TA). All force, angle, and EMG data were collected synchronously at 1000 Hz with an A/D convertor (USB-6259; National Instruments, Austin, TX, USA) connected to a desktop computer running a customized LabVIEW program (LabVIEW 2012; LabVIEW, National Instruments).

Force and angle data were smoothed with a fourth-order, low-pass, zero-lag Butterworth digital filter (MATLAB, MathWorks, Natick, MA, USA), using 1-Hz (crank angle) and 4-Hz (pedal force and angle data) cutoff frequencies.[11] Crank angular velocity was computed from the filtered angle data by the central difference method. Pedal angles were computed relative to horizontal (0°), with positive angles representing toe down pedal positions. The pedal forces were projected from the pedal coordinate system into the global coordinate system, with anterior and vertical downward pedal forces considered positive. EMG data were de-trended, band-pass filtered (20−450 Hz), and rectified before low-pass filtering at 6 Hz[17] with a 4th-order, 0-lag Butterworth digital filter to produce EMG linear envelopes (EMG_LEs). Crank angular velocity, pedal forces, and EMG_LEs were expressed in 1° crank angle intervals (360 points per crank cycle) using cubic spline interpolation. After interpolation, the pedal force vector component perpendicular to the crank arm was calculated and multiplied by the crank arm length (0.17 m) to compute crank torque from the left leg pedal force (single-leg crank torque).

The number of complete crank revolutions varied between trials, with a minimum of 7 across all trials and participants. Therefore, for each trial the last 7 consecutive crank cycles were used to compute mean pedal angle, crank angular velocity, crank torque, and EMG curves. Each muscle EMG_LE was normalized by the mean of the Two-L trial peak amplitudes to facilitate comparisons of muscle activity amplitudes between trials. Crank angular velocity and torque data were integrated over each complete crank cycle and quadrant (Q1: 0°–90°; Q2: 90°–180°; Q3: 180°–270°; Q4: 270°–360°; Fig. 1) to evaluate mechanical demand, while the EMG_LE data were integrated to quantify muscle activity (iEMG). The terms "top-dead-center" (TDC) and "bottom-dead-center" (BDC) refer to the 0° and 180° crank positions, respectively.

2.4. Statistical analysis

Multiple paired *t* tests were performed on overall (complete crank cycle) and quadrant-specific crank torque, crank angular velocity, and pedal angle values to ascertain changes in pedaling kinematics and kinetics between the Two-L and One-L conditions. Paired *t* tests were performed with overall and quadrant-specific integrated EMG (iEMG) values for each muscle to help understand the related muscle activity changes between the Two-L and One-L. TA EMG from 1 participant was corrupt due to an electrode malfunction, so TA $n = 14$.

Cohen's effect size (*d*) was computed for each paired *t* test [18–20] to gauge the strength of differences (low: <0.2, medium: 0.2–<0.5, and strong: 0.5–<0.8). Differences in iEMG (ΔiEMG; Eq. 1) and effect size values were represented relative to the Two-L, with positive values representing increases in the One-L (Eq. 1).

$$\Delta\text{iEMG} = \left(\left(\text{iEMG}_{(\text{quadrant, One–L})} - \text{iEMG}_{(\text{quadrant, Two–L})}\right)/\text{iEMG}_{(\text{quadrant, Two–L})}\right) \times 100\% \qquad (\text{Eq.}1)$$

All statistical analyses were performed in R software (Version 3.5.0; R Core Team, Vienna, Austria) with a critical alpha level of $p < 0.05$, using Bonferroni adjustments as appropriate.[21]

3. Results

3.1. Pedal and crank dynamics

The patterns of pedal and crank dynamics were altered significantly when pedaling with 1 leg compared to 2 legs (Fig. 1 and Table 1). Over the entire crank cycle, there was a small

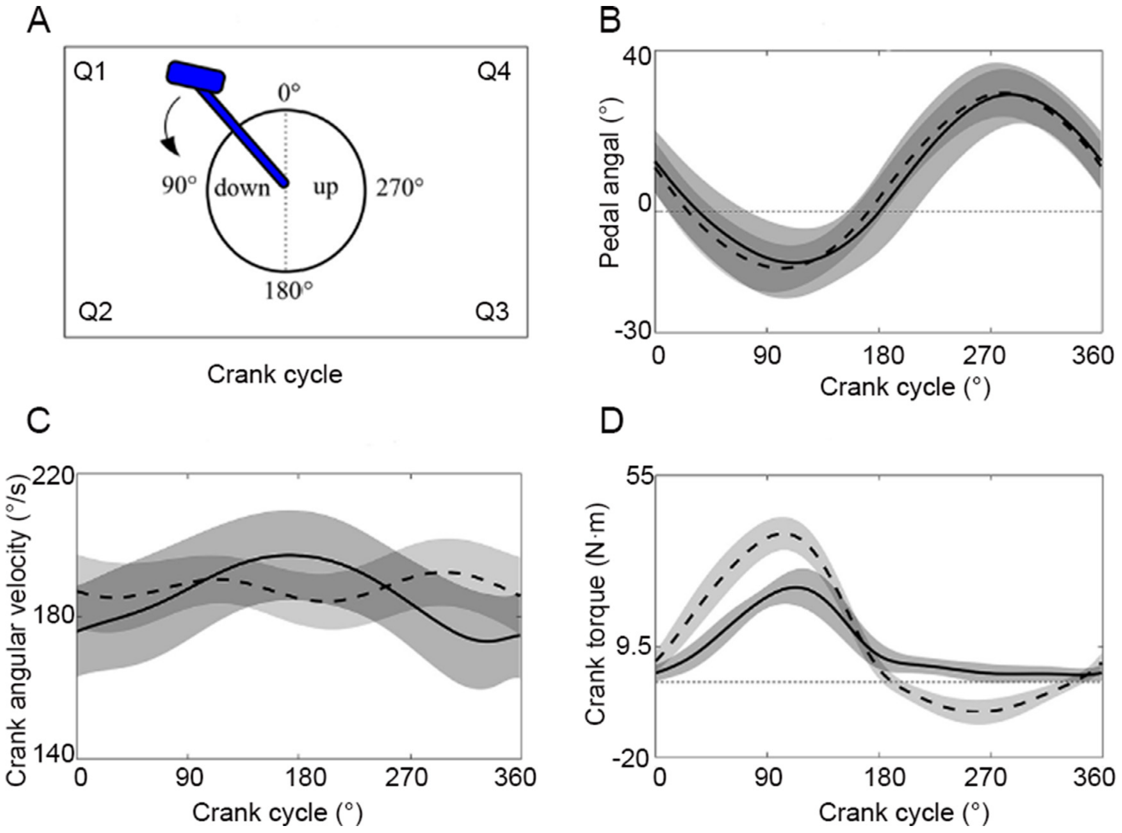

Fig. 1. (A) Crank cycle; (B) Comparison of mean ± SD pedal angle; (C) Crank angular velocity; (D) Crank torque between 2-legged pedaling (Two-L; dashed line, light gray ± 1 SD) and 1-legged pedaling (One-L; solid line, dark gray ± 1 SD) trials. For pedal angle, positive angles indicate the toe pointed downward, with 0° indicating a horizontal pedal.

Table 1
Crank torque, crank angular velocity, and pedal angle over the entire crank cycle ("Overall") and during each crank quadrant in Two-L and One-L (mean ± SD).

Trial	Overall	Crank quadrants			
		Q1	Q2	Q3	Q4
Crank torque (N·m)					
Two-L	10.79 ± 1.09	23.45 ± 4.62	27.03 ± 3.41	−4.71 ± 2.33	−2.59 ± 1.83
One-L	9.21 ± 1.38*	11.47 ± 2.83*	19.20 ± 4.23*	4.08 ± 1.98*	2.12 ± 1.94*
Crank velocity (°/s)					
Two-L	188.05 ± 8.33	186.65 ± 9.02	188.70 ± 6.88	186.34 ± 8.21	190.49 ± 9.71
One-L	185.83 ± 12.33	181.17 ± 14.03	194.06 ± 13.05	192.10 ± 11.79	176.11 ± 12.50*
Pedal angle (°)					
Two-L	7.30 ± 5.12	−4.11 ± 6.66	−8.83 ± 4.88	18.49 ± 5.25	23.63 ± 5.74
One-L	7.35 ± 7.53	−1.57 ± 8.73	−9.36 ± 7.98	16.07 ± 10.16	24.19 ± 6.63

* $p < 0.05$, compared with Two-L.
Abbreviations: One-L = 1-legged pedaling trial; Two-L = 2-legged pedaling trial.

but significant decrease in the average single-leg crank torque production in One-L compared to Two-L ($\Delta = -1.58$ N·m, $p = 0.003$, $d = -0.92$). One-L crank torque was smaller in Q1 ($\Delta = -11.98$ N·m, $p < 0.001$, $d = -2.22$) and Q2 ($\Delta = -7.83$ N·m, $p < 0.001$, $d = -1.76$), but larger in Q3 ($\Delta = 8.79$ N·m, $p < 0.001$, $d = 4.26$) and Q4 ($\Delta = 4.71$ N·m, $p < 0.001$, $d = 2.71$). Overall mean crank angular velocity and pedal angle were not significantly different between the 2 conditions. However, in Q4, crank velocity was lower in One-L ($\Delta = -14.38$ °/s, $p = 0.003$, $d = -1.13$) without the contralateral support, but there was a tendency for increased velocity in Q3 ($\Delta = 5.76$ °/s, $p = 0.066$, $d = 0.7$). Together, these findings suggest that participants altered their normal 2-legged crank mechanics when pedaling with 1 leg only.

3.2. Muscle activities

The Two-L muscle activity patterns (Fig. 2) were similar to those described in other cycling studies.[17,22,23] In Two-L, the uni-articular knee extensors VM and VL were active from about 330° to 135° synergistically with the ankle plantarflexor SOL (about 0°–180°) to produce crank torque during the downstroke. The hip flexor/knee extensor rectus femoris was active during Q4 and Q1 (about 270° to 90°), to help with a smooth transition through TDC. The biarticular plantarflexor/knee flexor muscles (LGA, MGA) and hip extensor/knee flexor hamstrings (BFL, ST) were mainly active in Q2 and Q3, helping to produce a similar smooth transition at BDC. Finally, the hip abductor/pelvis stabilizer TFL and ankle dorsiflexor TA were synergistically active during the late upstroke into early downstroke across TDC.

In 1-legged pedaling, the modified crank torque profiles were accompanied by widespread changes in EMG_LE patterns and statistically significant changes in muscle activity magnitudes (Fig. 2 and Table 2). Over the entire crank cycle, One-L muscle iEMG values were greater for TFL (313.3%, $p < 0.001$, $d = 1.26$), BFL (131%, $p < 0.001$, $d = 1.28$), ST (115%, $p < 0.001$, $d = 1.05$), MGA (57%, $p = 0.007$, $d = 0.82$), and TA (152%, $p = 0.002$, $d = 1.07$) but lower for VL (−47%, $p < 0.001$, $d = -2.5$), VM (−48%, $p < 0.001$, $d = -2.43$), and SOL (−25%, $p < 0.001$, $d = -1.15$). The only muscles that did not show iEMG changes between conditions were rectus femoris (9%, $p = 0.08$, $d = 0.67$) and LGA (10%, $p = 0.557$, $d = 0.16$), although the LGA pattern exhibited a phase shift in its peak value to later in the crank cycle in One-L (Fig. 2).

Consistent with the alterations in EMG_LE profiles, many muscle iEMG changes in One-L were focused on specific quadrants of the crank cycle (Fig. 3). Compared to Two-L, the 1-legged downstroke demonstrated decreased activity in some muscles (VL, VM, LGA, and SOL) and increased activity in others (BFL, ST, and TA). For example, in One-L the Q1 amplitudes were reduced for VL (58%, $p < 0.001$, $d = -3.38$), VM (63%, $p < 0.001$, $d = -4.53$), and SOL (36%, $p < 0.001$, $d = -1.75$), but increased for TA (157%, $p = 0.034$, $d = 0.83$). One-L activity amplitudes were also reduced in Q2 for SOL (37%, $p < 0.001$, $d = -1.47$) and LGA (29%, $p = 0.017$, $d = -0.88$). BFL and ST amplitudes increased in Q2 by 71% ($p < 0.001$, $d = 1.27$) and 66% ($p = 0.006$, $d = 1.01$), respectively.

During the One-L upstroke, many muscles displayed greater activity, consistent with the increased crank torque. TFL iEMG amplitudes increased by 515% in Q3 ($p < 0.001$, $d = 2.05$) and 390% in Q4 ($p = 0.002$, $d = 1.18$), with similar increases for the hamstrings BFL (305%, $p = 0.001$, $d = 1.24$ in Q3; 165%, $p = 0.034$, $d = 0.79$ in Q4) and ST (324%, $p < 0.001$, $d = 1.42$ in Q3; 198%, $p = 0.005$, $d = 1.05$ in Q4). The uni-articular knee extensors VL and VM showed increased One-L activities in Q3 (VL: 26%, $p = 0.006$, $d = 1.01$; VM: 70%, $p = 0.005$, $d = 1.04$), but reduced activity in Q4 (VL: 45%, $p < 0.001$, $d = -1.27$; VM: 40%, $p = 0.01$, $d = -0.94$). Below the knee, MGA (160%, $p = 0.018$, $d = 0.87$) and TA (556%, $p = 0.005$, $d = 1.08$) activities increased in Q3, while all 4 muscles showed increased One-L activities in Q4 (LGA: 132%, $p = 0.03$, $d = 0.8$; MGA: 100%, $p = 0.007$, $d = 1.00$; SOL: 40%, $p = 0.038$, $d = 0.78$; TA: 103%, $p = 0.008$, $d = 1.04$) (Fig. 3).

4. Discussion

All participants were able to produce smooth 1-legged and 2-legged pedaling at the designated crank mechanical demands. In One-L the absence of the contralateral leg altered the profiles of crank torque and angular velocity, accompanied by widespread changes in muscle activity patterns and

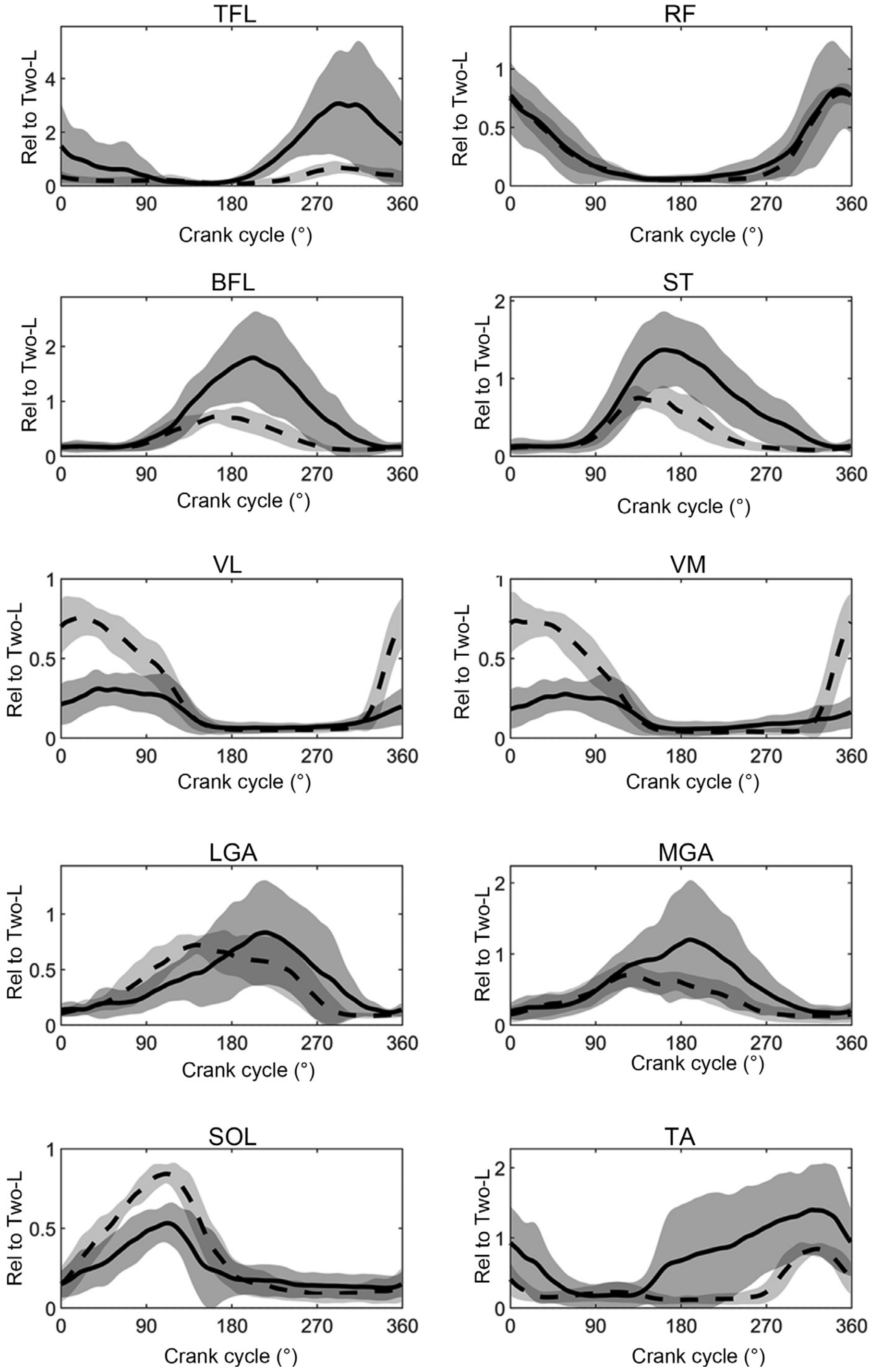

Fig. 2. Comparison of mean activity electromyography linear envelope profiles for the 2-legged pedaling condition (Two-L; dotted line, light gray ± SD) and the 1-legged pedaling condition (One-L; solid line, dark gray ± SD). BFL = biceps femoris long head; LGA = lateral gastrocnemius; MGA = medial gastrocnemius; RF = rectus femoris; SOL = soleus; ST = semitendinosus; TA = tibialis anterior; TFL = tensor fasciae latae; VL = vastus lateralis; VM = vastus medialis.

magnitudes. As hypothesized, activity levels of extension-related muscles were decreased during the downstroke, while flexion-related muscles increased activity during the upstroke. Unexpected findings included greater activity in TA during Q1, in the uni-articular knee extensors during Q3, and SOL during Q4. Furthermore, the 2 heads of gastrocnemius (MGA, LGA) demonstrated differing adaptations to the use of only 1 leg in pedaling.

4.1. Altered crank mechanics in One-L

In One-L without the use of the contralateral leg, crank torque was reduced in the downstroke and switched from negative to positive in the upstroke. The use of only 1 leg resulted in greater fluctuation of the crank angular velocity from the designated pedaling rate, consistent with a previous report,[9] with a tendency for increased velocity near BDC and a significant decrease in Q4

Table 2
Integrated muscle activities (integrated electromyography, arbitrary units) of the entire crank cycle (Overall) and each quadrant in Two-L and One-L (mean ± SD).

Muscle	Trial	Overall	Crank quadrants			
			Q1	Q2	Q3	Q4
TFL	Two-L	102.62 ± 18.95	19.48 ± 11.93	13.74 ± 11.72	20.36 ± 10.57	49.04 ± 11.05
	One-L	415.56 ± 248.66*	68.51 ± 89.16	14.16 ± 11.09	99.70 ± 37.82*	233.18 ± 157.17*
RF	Two-L	95.02 ± 13.49	38.39 ± 8.41	7.80 ± 4.00	5.53 ± 2.63	43.30 ± 8.64
	One-L	102.99 ± 37.50	39.11 ± 21.07	7.49 ± 3.70	8.93 ± 5.80	47.46 ± 26.15
BFL	Two-L	118.61 ± 18.69	15.86 ± 7.90	48.47 ± 10.01	41.87 ± 13.63	12.41 ± 4.30
	One-L	263.92 ± 108.23*	16.77 ± 8.65	82.49 ± 30.60*	132.35 ± 65.79*	32.30 ± 26.27*
ST	Two-L	103.32 ± 17.30	12.57 ± 4.42	55.28 ± 7.67	27.07 ± 11.64	8.39 ± 3.59
	One-L	210.34 ± 71.30*	13.99 ± 9.45	90.72 ± 35.33*	82.31 ± 34.68*	23.31 ± 14.67*
VL	Two-L	104.75 ± 11.55	60.32 ± 6.26	19.67 ± 6.46	4.71 ± 1.96	20.05 ± 6.35
	One-L	55.78 ± 18.64*	25.14 ± 8.34*	14.41 ± 7.81	5.95 ± 2.83*	10.28 ± 4.57*
VM	Two-L	98.38 ± 13.92	59.33 ± 5.79	16.33 ± 5.57	3.61 ± 1.98	19.12 ± 7.28
	One-L	51.17 ± 19.41*	21.90 ± 7.55*	13.05 ± 8.71	6.06 ± 3.67*	10.17 ± 5.87*
LGA	Two-L	133.92 ± 22.45	21.00 ± 8.14	57.58 ± 6.71	45.46 ± 18.76	9.88 ± 4.13
	One-L	144.01 ± 61.47	16.63 ± 8.33	40.45 ± 19.00*	65.05 ± 36.96	21.89 ± 16.18*
MGA	Two-L	132.17 ± 28.82	27.30 ± 13.29	56.38 ± 9.55	36.00 ± 12.85	12.48 ± 9.09
	One-L	205.30 ± 99.33*	25.91 ± 14.40	76.17 ± 33.14	81.04 ± 51.85*	22.20 ± 12.54*
SOL	Two-L	119.32 ± 14.07	42.62 ± 6.89	55.43 ± 6.66	12.18 ± 6.04	9.09 ± 5.69
	One-L	88.42 ± 25.19*	27.21 ± 10.36*	34.28 ± 11.98*	14.81 ± 7.87	12.12 ± 6.85*
TA	Two-L	103.92 ± 20.68	18.42 ± 8.23	16.05 ± 9.51	12.48 ± 6.88	56.96 ± 8.55
	One-L	264.48 ± 156.50*	40.52 ± 27.54*	29.59 ± 23.26	79.97 ± 66.81*	114.39 ± 55.79*

* $p < 0.05$, compared with Two-L.
Abbreviations: BFL= biceps femoris long head; LGA = lateral gastrocnemius; MGA = medial gastrocnemius; One-L = 1-legged pedaling trial; RF = rectus femoris; SOL = soleus; ST = semitendinosus; TA = tibialis anterior; TFL = tensor fasciae latae; Two-L = 2-legged pedaling trial; VL = vastus lateralis; VM = vastus medialis.

before TDC. In contrast, pedal angle profiles were very similar in One-L and Two-L. Because there is minimal pelvis movement in seated 1-legged pedaling,[24] leg joint kinematics were similar in the 1-legged and 2-legged pedaling conditions. Therefore, the altered crank dynamics originated mainly from changes in muscle activities and forces rather than postural adaptations.

4.2. Changes in muscle activity in One-L

The redistribution of crank torque production and angular velocity changes over the crank cycle are associated with distinct muscle activity changes during One-L. Lower crank torque and acceleration in the downstroke phase was followed by increased

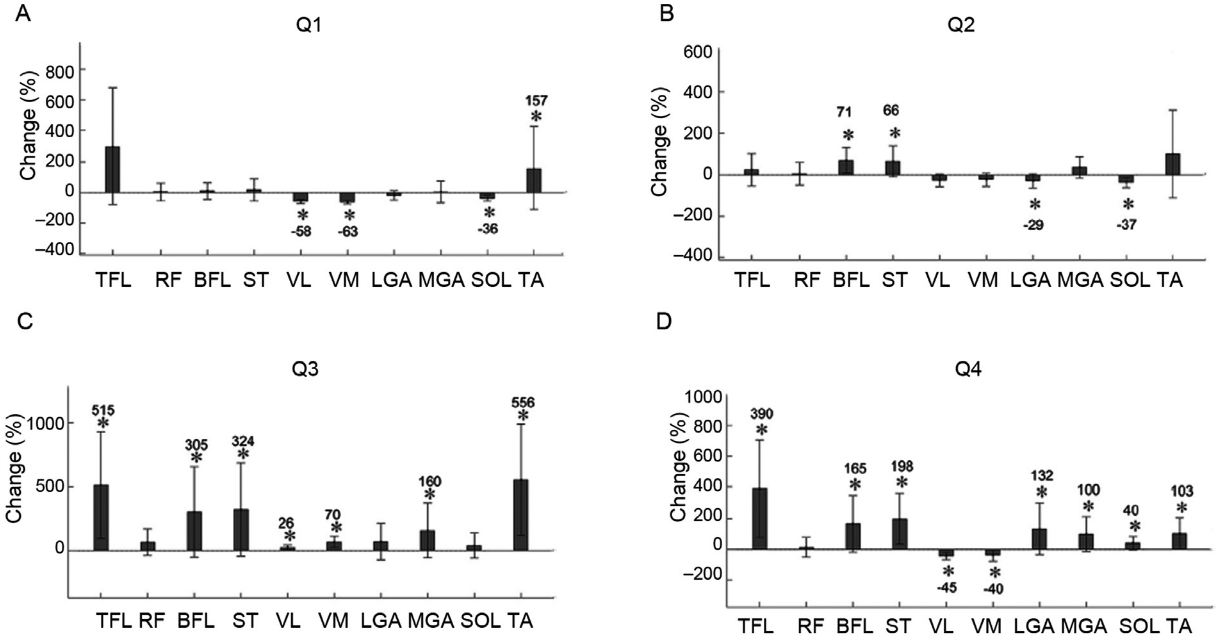

Fig. 3. Changes in integrated electromyography (iEMG) values (mean ± SD) from 2-legged pedaling (Two-L) to 1-legged pedaling (One-L) in (A) Q1; (B) Q2; (C) Q3; (D) Q4. Positive percent values indicate increased iEMG values for that quadrant in One-L, whereas negative values indicate reductions in One-L. *$p < 0.05$ between Two-L and One-L; numerals indicate mean change from Two-L to One-L. BFL= biceps femoris long head; LGA = lateral gastrocnemius; MGA = medial gastrocnemius; RF = rectus femoris; SOL = soleus; ST = semitendinosus; TA = tibialis anterior; TFL = tensor fasciae latae; VL = vastus lateralis; VM = vastus medialis.

torque and acceleration in the upstroke phase. Starting before BDC and continuing through the upstroke, flexion-related muscles TFL, hamstrings, TA, and MGA significantly increased their activity to actively pull the leg to accelerate the crank arm. After TDC, the downstroke crank torque was reduced to prevent freewheeling under the designated power output constraints, consistent with the reduced activities of the extension-related muscles VL, VM, SOL, and LGA, all of which play a major role in producing the downstroke crank torque in 2-legged pedaling.[2,25]

One-legged pedaling also elicited several muscle use adaptations that were not tied directly to the changes in crank torque patterns, such as increased coactivation of agonist and antagonist muscles at the ankle and knee joints during the upstroke phase. In Q3, the uni-articular knee extensors and hamstrings simultaneously increased their activity levels, while in Q4 triceps surae muscles SOL, MGA, and LGA increased their activities together with the dorsiflexor TA. While the reason for this increased antagonism in unclear, in the early stages of walking it has been suggested that such antagonism increases stability at the knee joint and lower leg.[26] In One-L, the muscular coactivation could stiffen and stabilize the knee and ankle to assist the active pull-up. With more practice, the antagonist coactivation could possibly decrease,[27] so future studies should address whether this coactivation originates from an acute adaptation to the relatively novel task or whether it is a feature of 1-legged pedaling itself.

TA muscle activity was greater in early downstroke (Q1) in One-L, perhaps because of its synergistic activation with TFL that would help to stabilize the pelvis; such an increase was not shown in pedaling with independent crank arms.[12] In our data, the 1-legged TFL activity was not significantly greater in Q1 due to subject variability, although the mean iEMG value was more than 3 times larger than in Two-L. The change in Q1 TFL activity pattern from Two-L to One-L was similar to that of the TA (Fig. 2). Those 2 muscles have been described as synergists that are co-activated from mid-upstroke to early downstroke in 2-legged pedaling.[25,28] The lack of contralateral leg motion in One-L emphasizes the need for stabilizing the pelvis during the transition from leg flexion to extension around TDC. One possible strategy is to activate the TFL/TA synergists at greater amplitudes to keep the pelvis steady from Q4 into Q1.

The lateral and medial heads of the gastrocnemius showed slightly different adaptations to the 1-legged pedaling condition, possibly due to lower leg positioning. A previous study reported greater relative MGA activity compared to LGA in a unilateral submaximal plantarflexion task with fully extended knee.[29] In pedaling, the knee is in an extended position around BDC,[11,30] and the bicycle cleat places the foot in slight external rotation, suggesting that the MGA may be preferentially activated around the BDC to produce the required ankle and knee torques. In One-L, LGA activity is reduced in Q2, consistent with the reduced Q2 crank torque. In contrast, Q2 MGA activity was the same in One-L as Two-L, continuing to generate knee flexion torque with synergistic hamstring activity to produce the smooth transition into upstroke at BDC.[31] MGA activity increased in Q3 to assist the active upstroke pulling, while LGA activity increased but not significantly compared to Two-L.

4.3. Limitations

One limitation of this study was the reduction in overall crank torque and power output (about 15%) in One-L, despite relatively good participant adherence to the target 180°/s average crank velocity. The 1-legged torque and power deficit is consistent with findings in a previous 1-legged pedaling study.[7] However, qualitative examination of individual participant data demonstrates that muscle activity changes between Two-L and One-L were more distinctly related to crank torque and velocity profiles and quadrant-specific changes than to differences in average crank mechanics. This finding suggests that differences within specific portions of the crank cycle were driving muscular responses to a greater extent than the average crank demands and are mainly responsible for the muscle activity differences between Two-L and One-L.

The results of this study do not necessarily extend to muscular control in 1-legged pedaling tasks with different mechanical demands; our participants were asked to perform pedaling tasks with relatively low crank torque and velocity. These low mechanical demands were based on our previous work in which participants were able to perform repeated 1-legged pedaling trials without significant muscle fatigue.[11] At faster pedaling rates, participants were unable to pedal smoothly with 1 leg due to freewheeling, consistent with a previous study in which some participants found it difficult to produce smooth 1-legged pedaling motion at higher crank demands (80 rpm and 120 W).[7] Based on these observations, the relatively low mechanical demands of 30 rpm and 30 W were chosen for One-L. For the 2-legged pedaling trial, we doubled power output to about 60 W, but kept the pedaling rate at 30 rpm, thereby imposing similar mechanical demand on the left leg in both Two-L and One-L. Therefore, muscle activities from the left leg are comparable between the Two-L and One-L conditions, with similar muscle fatigue and mechanical demand. Although not commonly seen in competitive cycling, slow pedaling rates (20−50 rpm) have been used to examine impaired control and coordination in stroke survivors.[32] Control of foot force in stroke survivors has been examined while the crank arms are moving at 40 rpm.[5] The relatively low mechanical demands we used allowed us to focus on changes in muscle control related mainly to the absence of contralateral leg involvement. Because of these low demands, our results may be informative to clinicians.

5. Conclusion

In this study, we investigated differences in the activity of 10 leg muscles between 2-legged and 1-legged pedaling. As hypothesized, with only 1 leg, the flexion-related muscle activities in the upstroke phase increased to produce crank torque to compensate for the absence of the contralateral leg. In contrast, downstroke crank torque and extension-related muscle activities were reduced to satisfy the constant power task constraint and to maintain smooth crank motion. The observed changes in muscle activities with 1-legged pedaling are due to a variety of changes in mechanical aspects of the pedaling motion, including altered crank torque patterns within the crank cycle, reduced pelvis stability, and the need for increased knee and ankle stiffness during the upstroke.

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Authors' contributions

SP contributed to the study conception and design, data collection and analysis, and wrote the first draft of the manuscript; GEC contributed to the study conception and design, and revised the manuscript critically. Both authors have read and approved the final version of the manuscript, and agree with the order of the presentation of the authors.

Competing interest

Both authors declare that they have no competing interests.

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