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International Biomechanics

ISSN: 2333-5432 (Online) Journal homepage: www.tandfonline.com/journals/tbbe20

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To cite this article: Christopher Payne , Katrina A. Taylor & Samuel A. Smith (2026) Muscular activation during e-scooter riding: a controlled electromyography investigation of riding velocity and stance, International Biomechanics, 13:1, 1-16, DOI: 10.1080/23335432.2026.2761455

To link to this article: https://doi.org/10.1080/23335432.2026.2761455

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INTERNATIONAL BIOMECHANICS
2026, VOL. 13, NO. 1, 2761455
https://doi.org/10.1080/23335432.2026.2761455

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Muscular activation during e-scooter riding: a controlled electromyography investigation of riding velocity and stance

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ABSTRACT

The long-term effects on e-scooter rider health are unclear. Research shows e-scooting requires less energy expenditure than walking, but its neuromuscular impact is less understood. While manufacturers claim e-scooter riding can enhance muscular function, little is known about how stance and speed affect these outcomes. This study compared e-scooter riding to time matched walking in a controlled laboratory environment. Walking was performed at a constant speed and E-scooter riding involved incremental and decremental speed changes. Activation of key muscle groups was measured using sEMG and the root mean square (RMS) values were calculated as an indicator of activation. Across lower limb and trunk muscles, RMS values were significantly lower during e-scooter riding compared to walking ($p < 0.05$). Conversely, activity in the left triceps brachii was significantly higher during e-scooter riding ($p = 0.014$). In the tandem stance, RMS values were greater in the rear leg. Trunk muscle activation was highest at the slowest speeds. E-scooter riding requires less muscular activation in the lower body and trunk compared to walking. E-scooter riding requires muscles to stabilise the riding position, unlike walking, which generates propulsive forces. This suggests that sustained e-scooter riding could reduce opportunities for meaningful physical activity.

ARTICLE HISTORY
Received 7 November 2025
Accepted 21 October 2026

KEYWORDS
E-scooter; electromyography; transport; muscle activation; physical activity

Introduction

Electric scooters (e-scooters) have emerged as a convenient alternative for short-distance travel, complementing active transport such as walking and cycling. While they possess the potential to alleviate some perceived barriers to active travel, including inadequate infrastructure, journey length, physical effort, and discomfort, and can promote more sustainable transport behaviours (Bretones et al. 2023), the long-term health implications of prolonged e-scooter use remain unclear. Given the central role of physical activity (PA) in promoting health and wellbeing, understanding the physiological demands of emerging modes of transport is essential to determine the extent to which they contribute to daily PA guidelines (Kelly et al. 2017; Bull et al. 2020; Milakis et al. 2020; Tittlbach et al. 2024).

Recent studies have examined the energy expenditure associated with e-scooter riding, offering insight into its physical demands and potential health implications. Using indirect calorimetry, research reports that e-scooter riding results in notably lower metabolic equivalent of task (MET) values (1.6–2.14 METs) compared to walking (3.1–3.7 METs, Payne et al. 2025; Wen et al. 2025). This contradicts earlier assumptions (López-Dóriga et al. 2022) that proposed e-scooter riding as a moderate-intensity activity (3.5 METs, Holtermann and Stamatakis 2019) comparable to walking (Herrmann et al. 2024). Both recent studies (Payne et al. 2025; Wen et al. 2025) suggest that substituting walking with e-scooter use could inadvertently reduce daily PA levels. This is an important consideration given the global rise in physical inactivity, which is linked to a range of adverse health outcomes, including diminished cardiorespiratory fitness, reduced muscular function, and a heightened risk of chronic conditions such as cardiovascular disease, obesity, and diabetes (Chakrabarti and Shin 2017; Grindle et al. 2018; Lippi et al. 2020).

Although the metabolic demand of e-scooter riding has been evidenced (Payne et al. 2025; Wen et al. 2025), its neuromuscular impact remains poorly understood. Manufacturers have frequently marketed e-scooters as devices that can enhance core strength and exercise the users leg muscles (as cited in Glenn et al.

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Supplemental data for this article can be accessed online at https://doi.org/10.1080/23335432.2026.2761455.

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2020). This notion is often based on the understanding that e-scooters are non-self-balancing, laterally unstable and can induce whole-body vibrations (Cano-Moreno et al. 2021; Cano-Moreno et al. 2023; Ventura et al. 2023). These characteristics are suggested to require continuous micro-adjustments by the rider, potentially engaging muscles of the lower body, trunk, and upper body to regulate postural sway, maintain balance, and ensure rider comfort (Blackburn et al. 2000; Wang et al. 2016; Boström et al. 2018; Ignaccolo et al. 2022; Cano-Moreno et al. 2023; Vella et al. 2024).

This perspective is supported by recent evidence, where adjustments in riding position during e-scooter use were associated with increased muscle activity when compared with walking (biceps brachii, triceps long head) and driving (trunk and leg) (Wen et al. 2025). However, while these findings demonstrate the total activation of key muscle groups during e-scooter use, the functional role of specific foot positioning within the tandem stance, typically adopted by riders (Shichman et al. 2023), has not been explored. In a tandem stance position, the lead (front) foot is oriented forward, with the rear foot positioned behind and externally rotated, resulting in the trunk adopting a rotated and asymmetrical posture. Given this specific positioning, it is plausible that the front and rear legs may serve distinct stabilising functions during e-scooter riding and, consequently, could exhibit differing muscle activation patterns.

Additionally, as observed in other forms of locomotion, muscular activation has been shown to adapt significantly to changes in velocity (Den Otter et al. 2004; Saunders et al. 2004; Anders et al. 2007; Franz and Kram 2012). Consequently, the requirement to accelerate and decelerate to modify velocity in response to the environment whilst riding an e-scooter could place increased demand on neuromuscular pathways responsible for balance and posture. This would necessitate coordinated muscular recruitment to maintain a stable riding position (Wang et al. 2016). Understanding precisely how muscle activity is distributed during e-scooter use, particularly in the context of riding stance and operating speed, could provide important insight into the neuromuscular demands of this emerging mode of transport and its potential implications for health and physical function.

The aim of this study was to examine how muscular activation during e-scooter riding, performed in a controlled laboratory environment, is influenced by rider position and changes in riding speed. Walking was included as a comparator to provide context for the relative level of muscular activation.

To achieve these aims, the following research questions are addressed:

- During e-scooter riding in a tandem stance, how does muscular activation (quadriceps, erector spinae, trapezius, triceps brachii) differ due to the asymmetrical positioning of the lead and rear legs?
- How does muscular activation during e-scooter riding vary across different velocities?

Materials and methods

Ethical approval

This study was approved by the School of Sport & Exercise Sciences (University of Kent) Research Ethics Advisory Group (Prop 20_05_24) and conducted in conformity with the Declaration of Helsinki. Written informed consent was provided by participants prior to their voluntary participation. The trial was not pre-registered in a trial registry.

Participants

Twenty healthy participants (11 males, 9 females; mean ± SD: age 28 ± 7 years; height 1.73 ± 0.1 m; body mass 72.1 ± 11.5 kg; body mass index 24.1 ± 3.5 kg/m 2) volunteered to participate in the study. Participants with impaired balance, a body weight ≥ 120 kg (maximum rider weight as per e-scooter manufacturer guidelines), a medical condition affecting the ability to be physically active, a musculoskeletal injury, or any other medical condition or current pregnancy were excluded from the study. Before attending the laboratory, participants were instructed to avoid vigorous PA (24 hours prior) and abstain from consuming food (3 hours prior), alcohol (12 hours prior) and caffeine (4 hours prior).

Initial sample size considerations were informed by prior electromyography e-scooter research ($n = 20$; Wen et al. 2025). As no effect size estimates were reported by Wen and colleagues, an a priori power analysis

was conducted using G*Power (version 3.1; Faul et al. 2007) for a paired-samples t-test (two-tailed), with an alpha level of 0.05 and statistical power of 0.80. The expected effect size was derived from comparable locomotor electromyography research (Dewar et al. 2021), which reported a large effect (Cohen's d = 0.97) for differences in vastus lateralis activation between assisted and unassisted walking conditions, yielding a required sample size of 11 participants. To provide a more conservative estimate, an additional analysis using d = 0.80 indicated a required sample of 15 participants. Accordingly, the target sample size for this study was set to meet or exceed these thresholds, ensuring adequate power to detect between-condition differences.

Experimental overview

Participants attended the Physiology Laboratory at the School of Sport and Exercise Sciences (Chipperfield Building) for a single visit. After the recording of anthropometric data (height and weight), they received instructions on mounting, riding, and dismounting the e-scooter (see *'E-scooter'*), as well as guidance on establishing front and rear leg riding positions. Following this, participants were familiarised with e-scooter riding on a calibrated motorised treadmill (H-P Cosmos Pulsar, H-P Cosmos, Nussdorf-Traunstein, Germany). The treadmill is a research-grade ergometer widely used in physiological and biomechanical assessments (Tofari et al. 2015). The familiarisation phase was performed at incremental (8–16 km/h) and decremental (16–8 km/h) speeds. This allowed participants to gradually build competence, confidence, and safety at a range of speeds relevant to the experimental protocol. Afterward, muscle sites were landmarked and prepared for the placement of surface electromyography (sEMG) electrodes (see *'muscle activation and sEMG measurements'*).

Participants completed two trial conditions in a randomized and counterbalanced order on the treadmill. Each trial simulated an average e-scooter rental time of 15 minutes, divided into three 5-minute segments, to allow for (1) the randomization of the order in which muscles were analysed, thereby minimizing any order effect between participants, and (2) to facilitate the transfer of the sEMG transmitter between anatomical regions (lower body, trunk, and upper body; see *'Muscle Activation and sEMG Measurements'*). The three segments were used to record different anatomical regions, with electrode placement repositioned between segments, and each muscle site was therefore recorded once per condition within a session.

The two randomized trial conditions were:

(1) Walking Trial: Consisted of three 5-minute segments of walking at a constant speed of 4.8 km/h.
(2) E-scooter Trial: Consisted of three 5-minute segments of standing on an e-scooter mounted on the treadmill. The treadmill was programmed to operate at 30-second intervals with incremental speeds (8 km/h – 16 km/h) and decremental speeds (16 km/h – 8 km/h, Figure 1). These speeds

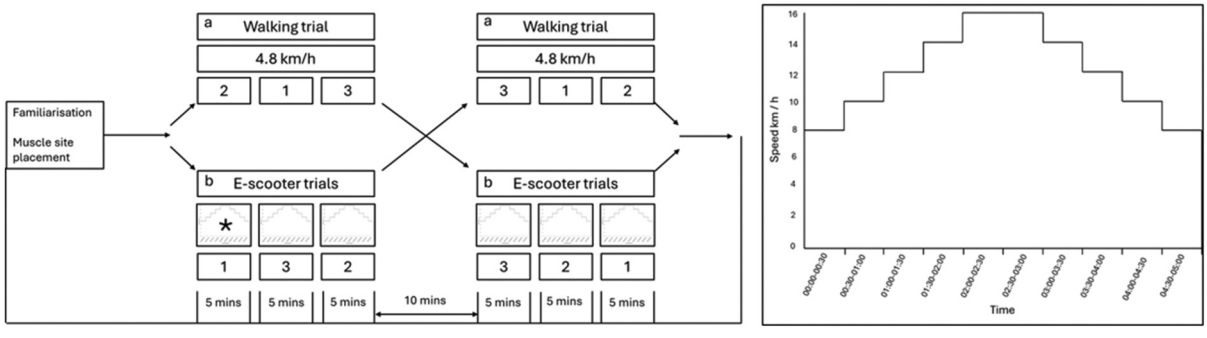


Figure 1. Schematic overview of the experimental design and procedures with an example of randomised order. Each trial segment demonstrates incremental and decremental speed changes for e-scooter riding and muscle regions assigned numbers to allow for randomisation across trial segments: 1 = lower body, 2 = trunk, 3 = upper body. * = enlarged e-scooter trial, 5 mins segment example.

were selected based on reported operating ranges in both European and US cities (Huo et al. 2021; Gioldasis et al. 2024).

A rest period of 10 minutes was provided between the two trial conditions to minimise residual fatigue and allow physiological variables to return towards baseline. A schematic of the overall experimental design and protocol is outlined in Figure 1.

E-scooter

E-scooter trials were conducted using a Pure Air e-scooter (Pure Air Electric Scooter, 2nd Gen, Pure Electric, London, UK; 500 W maximum) motor, 25 km/h maximum speed, battery capacity 7800 mAh, weight 17 kg) consistent with previously reported e-scooter mechanical and performance characteristics (Cano-Moreno et al. 2023). Technical specifications were obtained from manufacturer information. Although the specific e-scooter model has not been formally validated as a research instrument, it was used to provide a standardised riding condition within the controlled laboratory environment.

The e-scooter was mounted on the treadmill and secured to its frame at the base and top of the handlebar stem using a tethered rope (Figure 2a). This safety tether was positioned to ensure that, within the confines of the treadmill belt, natural postural sway movement and riding position were not restricted. Whilst on the e-scooter, participants were required to maintain a set posture for the duration of the trial (Figure 2b).

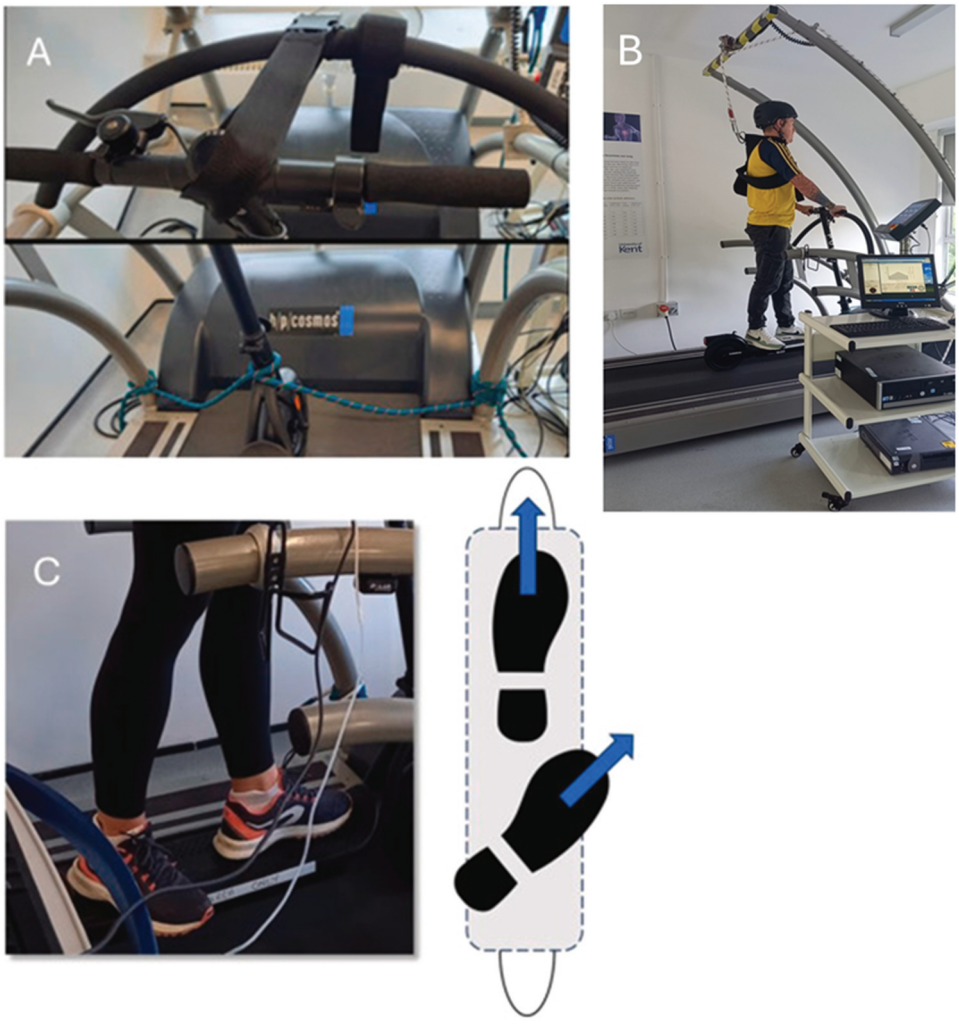


Figure 2. (a) E-scooter tethered to treadmill frame; (b) posture and body positioning; (c) front and rear foot positioning, as chosen by the participant during familiarisation.

Participants were instructed to stand upright and facing forward, always keep their hands on the handlebar grips, and place one foot facing forward in a straight line, the other foot positioned behind with slight external rotation in a tandem style stance (Figure 2c). Participants were able to determine which foot assumed the leading and rear positions, which was recorded during familiarisation and maintained for experimental trials.

Muscle activation and surface electromyography (sEMG) measurements

sEMG signals were collected using a BIOPAC MP150 wireless EMG system, and BIONOMADIX EMG transmitter (BN-EMG2-T, BIOPAC Systems, Inc., Goleta, CA, USA) with a sampling rate of 1000 Hz. Disposable Ag/AgCl surface electrodes (Ambu White Sensor, Ambu A/S, Denmark) with a sensor area of 77 mm^2 and overall electrode dimensions of 37.5 × 37.5 mm were used in a bipolar configuration with an inter-electrode distance of 20 mm. In accordance with SENIAM guidelines (Hermens et al. 1999) electrodes were positioned on the muscle belly of the vastus lateralis and vastus medialis on both legs, the erector spinae muscles (bilaterally), the trapezius (upper) muscles (bilaterally), and the triceps brachii (long head) on both arms in a bipolar configuration (Figure 3). All electrode placement sites were clean-shaven (where necessary), lightly abraded, and sanitised with alcohol wipes to remove surface debris, reduce skin–electrode impedance, and improve signal quality. Prior to data collection, EMG signal quality was visually assessed using BIOPAC AcqKnowledge software to identify excessive noise or signal artefacts.

To ensure acceptable signal quality and to minimise movement artefact, electrode leads were secured to the skin using adhesive tape, ensuring cable stability during trials. Raw sEMG signals were recorded using Acqknowledge software (BIOPAC Systems, Inc.) and subsequently exported for offline processing and analysis in MATLAB (version r2023b, The MathWorks Inc 2023).

The raw sEMG data were processed using a band-pass filter (10–400 Hz) to remove movement artefacts and high-frequency noise (Mello et al. 2007). The filtered signals were then full-wave rectified, and root mean square (RMS) values were calculated for both the e-scooter and walking tasks. RMS values, expressed in millivolts (mV), provide a time-averaged measure of muscle electrical activity and are commonly used as an indicator of muscle activation. Under conditions where no changes are made to the electromyography setup (e.g. electrode placement, amplification, and

Electrode placement	
1	Left side trapezius upper
2	Right side trapezius upper
3	Left arm triceps brachii long head
4	Right arm triceps brachii long head
5	Left side erector spinae
6	Right side erector spinae
7	Right leg vastus lateralis
8	Left leg vastus lateralis
9	Right leg vastus medialis
10	Left leg vastus medialis

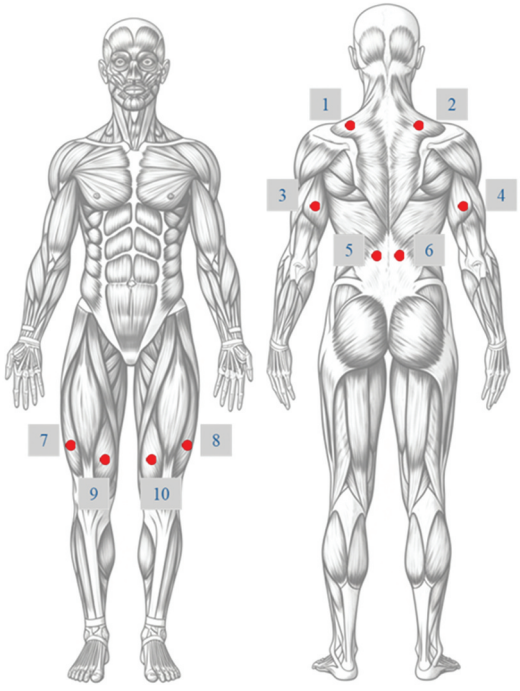


Figure 3. Muscle sites by anatomical position. Adapted from Nugent et al. (2020).

filtering), and trials are performed under controlled conditions within a short period of time, non-normalised EMG amplitude can be used to compare relative differences in muscle activation between tasks within individuals (Halaki and Ginn 2012). In the present study, all trials were conducted under controlled laboratory conditions with consistent electrode placement and acquisition settings, allowing for within-subject comparison of muscle activation between e-scooter riding and walking.

Walking was used as a task-specific reference condition, with EMG amplitude during e-scooter riding expressed relative to walking (% of walking). This approach is consistent with previous studies that have employed task-specific reference conditions to facilitate within-subject comparisons during low-intensity activities (Gao et al. 2017). It therefore represents task-based (dynamic) normalisation relative to a standardised functional activity, rather than physiological normalisation to maximal muscle capacity (Ball and Scurr 2010; Sousa and Tavares 2012).

Following this, muscular activation was then compared between muscles sites during e-scooter riding and analysed based on the stance leg positioning (front or rear), relative to the tandem-style stance adopted during e-scooter riding. The leg muscles were labelled as front and rear vastus lateralis and vastus medialis rear according to their alignment with the front or rear leg. The erector spinae muscles categorised as front-side or rear-side based on their alignment with the corresponding leg, reflecting the asymmetric posture characteristics of riding. In contrast, the trapezius and triceps brachii maintained their anatomical left and right side, relative to their respective positions on the handlebars. This classification approach ensured that muscle activation patterns were interpreted in relation to their functional roles in stance support (lower limbs), trunk stability (erector spinae), and handlebar control (upper limbs).

To compare muscular activation during e-scooter riding across different speeds, mean RMS values for each incremental and decremental speed section were combined, and direct comparisons made between speeds. The full 30-second interval was analysed for each speed condition, including the transition between speeds (see 'statistical analysis').

Statistical analysis

Data are presented as mean ± standard deviation (SD) or as median (Mdn) and interquartile range (IQR) when not normally distributed. Prior to statistical analysis, all data were checked for the assumptions associated with a paired samples t-test and repeated measures ANOVA as appropriate. Any data with missing values (vastus lateralis and vastus medialis) were excluded ($n = 1$). An alpha level of $p < 0.05$ was used to determine statistical significance. Where multiple comparisons were conducted, appropriate corrections were applied to control for Type I error. All statistical analyses were performed using IBM SPSS Statistics (Version 29.0; IBM Corp., Armonk, NY, USA).

E-scooter muscle activation compared to walking

A paired samples t-test was used to directly compare muscle activation of e-scooter riding compared to walking based on the anatomical left and right sides of each muscle site. Prior to statistical analysis, data were inspected for outliers using the standard criterion of ±1.5 box lengths from the edge of the box. Outliers removed for these comparisons included: vastus lateralis (left $n = 1$, right $n = 4$), vastus medialis (left $n = 2$, right $n = 4$), erector spinae (left $n = 4$, right $n = 3$), trapezius (right $n = 1$), and triceps (left and right $n = 1$). Sensitivity analyses were conducted by repeating all paired comparisons with outliers retained to examine the influence of outlier exclusion on the results (Supplementary Table S1). To account for multiple comparisons across the 10 paired tests, p-values were adjusted using the Benjamini–Hochberg false discovery rate (FDR) procedure (Benjamini and Hochberg 1995). Adjusted p-values are reported alongside unadjusted values, with statistical significance determined at $p < 0.05$ following correction.

Muscular activation between sites relative to e-scooter riding position

A paired samples t-test was used to compare muscular activation between muscle sites relative to their functional role during e-scooter riding (e.g. front leg compared to rear leg, front side compared to rear side trunk and left compared to right-side upper body muscles) a paired samples t-test or exact sign test were employed, as appropriate for data distribution.

Effect of e-scooter riding speed on muscular activation

To assess the effect of riding speed on muscle activation during e-scooter usage, either a one-way repeated measures ANOVA or a Friedmans ANOVA was conducted on the mean RMS values, depending on data normality. For analysis revealing a significant effect, pairwise comparisons were performed. For parametric ANOVAs, a Bonferroni correction was applied for post-hoc tests. For Friedman's ANOVA, a post-hoc Wilcoxon signed-rank tests with Bonferroni correction were used.

Results

Muscular activation compared to walking

Table 1 presents mean RMS values during e-scooter riding and walking, for muscles on the left and right side of the body. Across all lower limb and trunk muscles, RMS values were significantly lower during e-scooter riding compared to walking ($p < 0.05$), with the largest mean difference (MD), 0.097 millivolts (mV) (95% CI: 0.057–0.136) observed in the left vastus lateralis. In the upper body, the trapezius muscles exhibited significantly reduced RMS values during e-scooter riding, with mean differences of 0.020 mV (95% CI: 0.007–0.034) on the left and 0.012 mV (95% CI: 0.002–0.021) on the right, although the differences were relatively small compared to lower limb and trunk muscles. Triceps brachii activity on the left side was significantly higher during e-scooter riding compared to

Table 1. Muscle activation during e-scooter riding compared to walking: absolute and relative sEMG measures.

Muscle	Side	n	E-scooter RMS (mV) mean (± SD)	Walking RMS (mV) mean (± SD)	Mean difference (Mv)	E-scooter (% walking)	95% CI	t (df)	*p* – value	*p* – value (FDR adjusted)	*d*
Vastus lateralis	Left	18	0.023 (0.017)	0.120 (0.091)	0.097	19	0.057–0.136	5.166 (17)	<.001	0.002**	1.218
	Right	15	0.034 (0.024)	0.092 (0.081)	0.058	37	0.014–0.102	2.836 (14)	0.013	0.014*	0.731
Vastus Medialis	Left	17	0.016 (0.009)	0.101 (0.070)	0.084	16	0.047–0.121	4.867 (16)	<.001	0.002**	1.180
	Right	15	0.025 (0.012)	0.090 (0.071)	0.064	28	0.026–0.103	3.603 (14)	0.003	0.005**	0.930
Erector Spinae	Left	16	0.018 (0.010)	0.043 (0.014)	0.025	42	0.016–0.033	6.025 (15)	<.001	0.002**	1.506
	Right	17	0.022 (0.009)	0.047 (0.017)	0.025	47	0.016–0.035	5.953 (16)	<.001	0.002**	1.444
Trapezius	Left	20	0.029 (0.015)	0.050 (0.035)	0.020	58	0.007–0.034	3.221 (19)	0.004	0.006**	0.720
	Right	19	0.033 (0.021)	0.046 (0.026)	0.012	72	0.002–0.021	2.769 (18)	0.013	0.014*	0.635
Triceps brachii	Left	19	0.042 (0.030)	0.018 (0.016)	0.024	229	0.006–0.040	2.889 (18)	0.010	0.014*	0.663
	Right	19	0.038 (0.026)	0.030 (0.031)	0.007	127	0.008–0.023	0.968 (18)	0.346	0.346	0.222

Note: Values are presented as mean ± standard deviation (SD) of root mean square (RMS) sEMG amplitudes (mV) during e-scooter riding and walking. MD denotes the mean difference in RMS amplitude (e-scooter – walking), with percentage (%) representing relative activation during e-scooter riding compared to walking. E-scooter muscle activation (% walking) was calculated by dividing the unrounded mean RMS value during e-scooter riding by the corresponding unrounded mean RMS value during walking and multiplying by 100. Minor differences may arise when recalculating percentages from the rounded mean RMS values presented in the table. Ninety-five percent confidence intervals (CI) are reported for the mean difference. Statistical comparisons were performed using paired-samples t-tests. To account for multiple comparisons, *p*-values were adjusted using the Benjamini–Hochberg false discovery rate (FDR) procedure. Effect sizes are reported as Cohen's *d*. Statistical significance was set at $p < 0.05$ following FDR adjustment. $p < 0.05$, $p < 0.01$, $p < 0.001$ (FDR-adjusted).

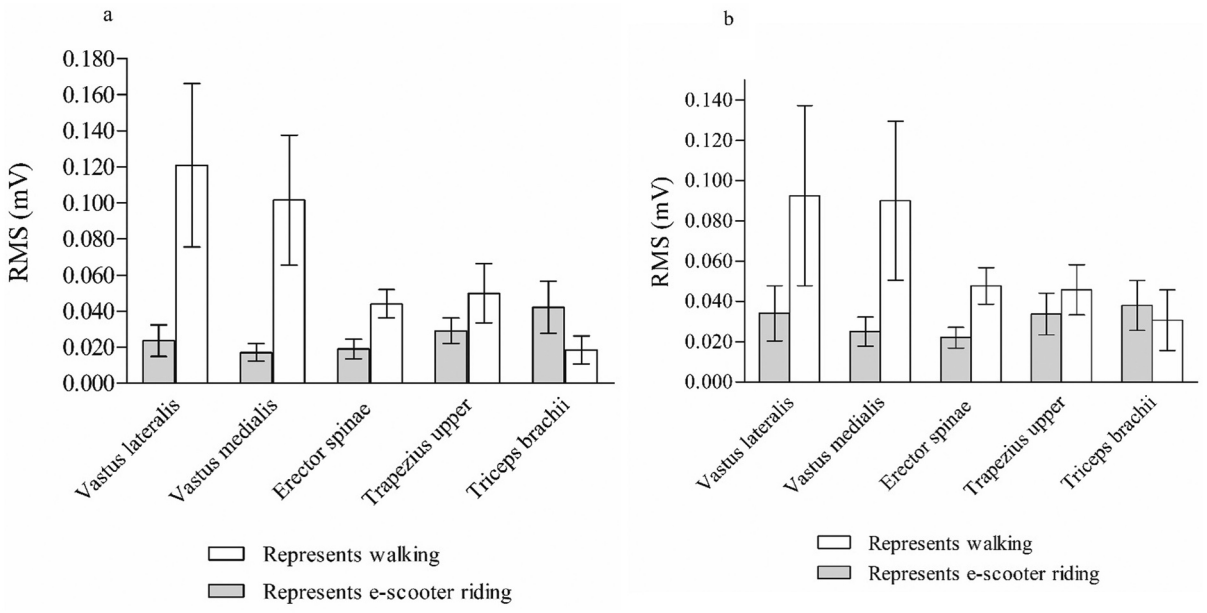


Figure 4. Muscle activity during walking and e-scooter riding. (a) Left-side muscles; (b) right-side muscles. Muscles assessed were vastus lateralis, vastus medialis, erector spinae, upper trapezius, and triceps brachii. Bars represent root mean square (RMS) amplitude (mV), and error bars indicate 95% confidence intervals.

walking (MD = 0.024 mV, 95% CI: 0.006–0.040, $p = 0.014$). Figures 4a and 4b illustrate RMS values for the left and right sides, respectively.

Sensitivity analysis including outliers showed that the overall pattern of results was unchanged, with lower limb and trunk muscles remaining significantly different following FDR correction. The triceps brachii (left) comparison was no longer significant. Full results are presented in Supplementary Table S1.

Muscular activation between sites relative to e-scooter riding position

Front and rear leg vastus lateralis

A paired samples t-test revealed a significant difference in RMS values of the vastus lateralis between the front and rear leg during tandem e-scooter stance ($t_{18} = 3.17$, $p = .005$, CI_{95} 0.005 to 0.025, $d = 0.73$). RMS values were significantly greater in the rear leg (0.0371 ± 0.023 mV) compared front leg (0.022 ± 0.017 mV).

Front and rear leg vastus medialis

An exact sign test indicated no statistically significant difference in RMS values of the vastus medialis between the front and rear leg ($p = 0.77$).

Front and rear side erector spinae

A paired samples t-test revealed no significant difference in RMS values of the erector spinae muscles relative to front and rear leg position ($t_{18} = 0.51$, $p = 0.620$, CI_{95} −0.004 – 0.007, $d = 0.12$).

Left and right trapezius

A paired sample t-test showed no significant difference between left and right-side trapezius ($t_{19} = 0.947$, $p = 0.355$, CI_{95} −0.006 – 0.017, $d = 0.21$).

Left and right triceps brachii

An exact sign test showed no statistically significant difference in RMS values between left and right-side triceps brachii ($p = 0.648$).

Effect of speed on muscle activation

The effect of e-scooter speed on muscle activation varied across muscle groups. Rear leg vastus lateralis activation was unaffected by speed ($p = .159$, Figure 5a), while front leg vastus lateralis, rear leg vastus medialis, and front leg vastus medialis all showed a significant effect ($p < .05$, Figure 5b–d). Activation was highest at 8 km/h, compared to faster speeds, with no significant differences observed among 10–16 km/h. A similar pattern was observed in both the front and rear side erector spinae where a greater activation was observed at 8 km/h ($p = .001 - <.001$, Figure 6a–b), compared to higher speeds. An effect of e-scooter speed was found for the left and right trapezius ($p = .018 - .049$, Figure 7a–b), but post-hoc tests revealed no significant pairwise differences. No significant speed effects were observed for the triceps ($p = .124 - .326$, Figure 7c–d). All statistical results, including both significant and non-significant findings, are presented in Table 2. Descriptive statistics are provided in Supplementary material Table S2.

Discussion

This study is the first to use sEMG in a controlled laboratory environment to examine muscular activation during e-scooter riding across varying speeds whilst adopting a tandem stance. Overall, muscle activity in the lower limbs and trunk was significantly lower during e-scooter riding compared to walking, except for the upper arms. Within the tandem e-scooter riding stance, the rear leg demonstrated greater activation of the vastus lateralis and vastus medialis than the front leg. Additionally, muscle activity in both the legs and trunk was also the greatest at the lowest riding speed (8 km/h) compared to all faster speeds, with no further differences observed at the higher speeds. These findings suggest that e-scooter riding imposes distinct neuromuscular demands that are partly determined by both the foot position and the riding speed employed.

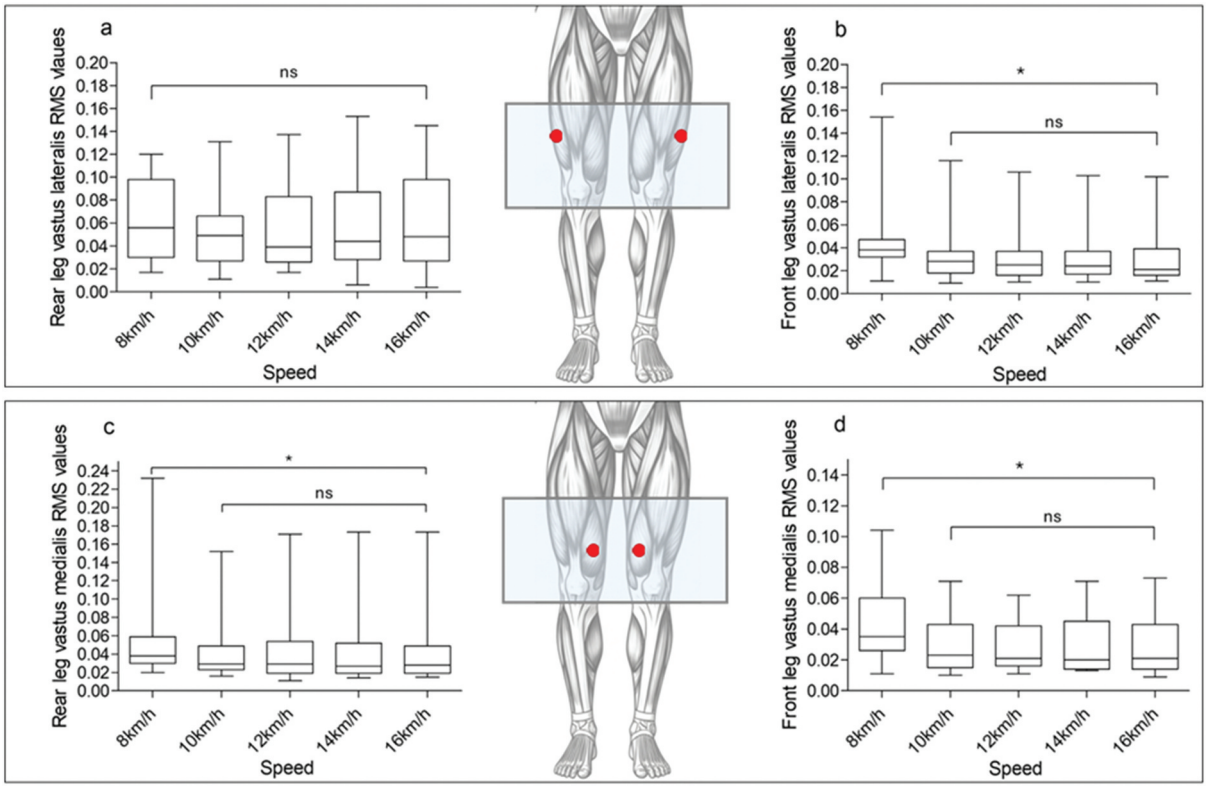


Figure 5. Box plots representing the RMS values of muscle activation for the vastus lateralis and vastus medialis at different e-scooter speeds (8 km/h, 10 km/h, 12 km/h, 14 km/h, and 16 km/h). The central line within each box represents the median, the box represents the interquartile range (IQR), and the whiskers indicate the minimum and maximum values. (a) RMS values for rear leg vastus lateralis. (b) RMS values for front leg vastus lateralis. (c) RMS values for rear leg vastus medialis. (d) RMS values for the front leg vastus medialis. *Denotes significance greater to other speeds. ns = no significance. Anatomical images depict the anterior view of lower body muscle sites under observation.

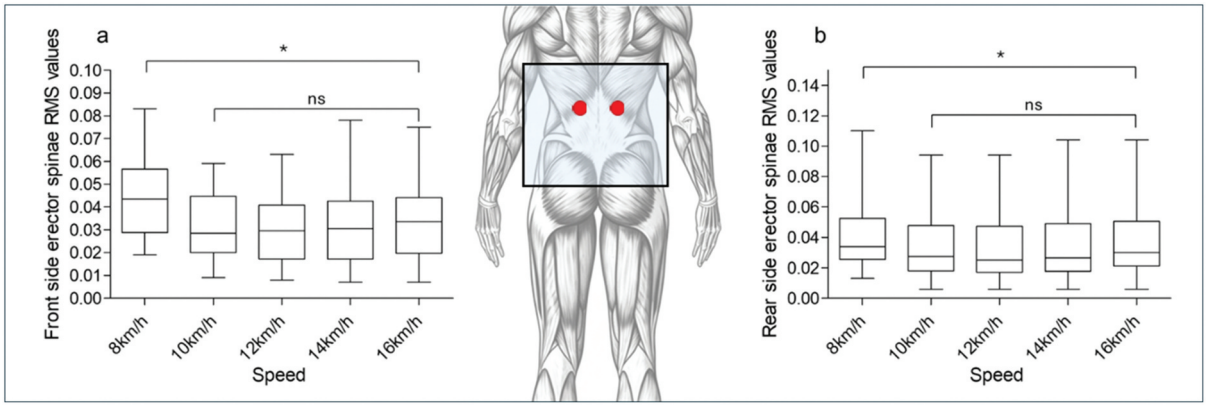


Figure 6. Box plots representing the root mean square (RMS) values of muscle activation for the front side (a) and rear side (b) Erector spinae muscles at different e-scooter speeds (8 km/h, 10 km/h, 12 km/h, 14 km/h, and 16 km/h). The central line within each box represents the median, the box represents the interquartile range (IQR), and the whiskers indicate the minimum and maximum values. *Denotes significance greater to other speeds. ns = no significance. Anatomical images depict posterior view of trunk muscle sites under observation.

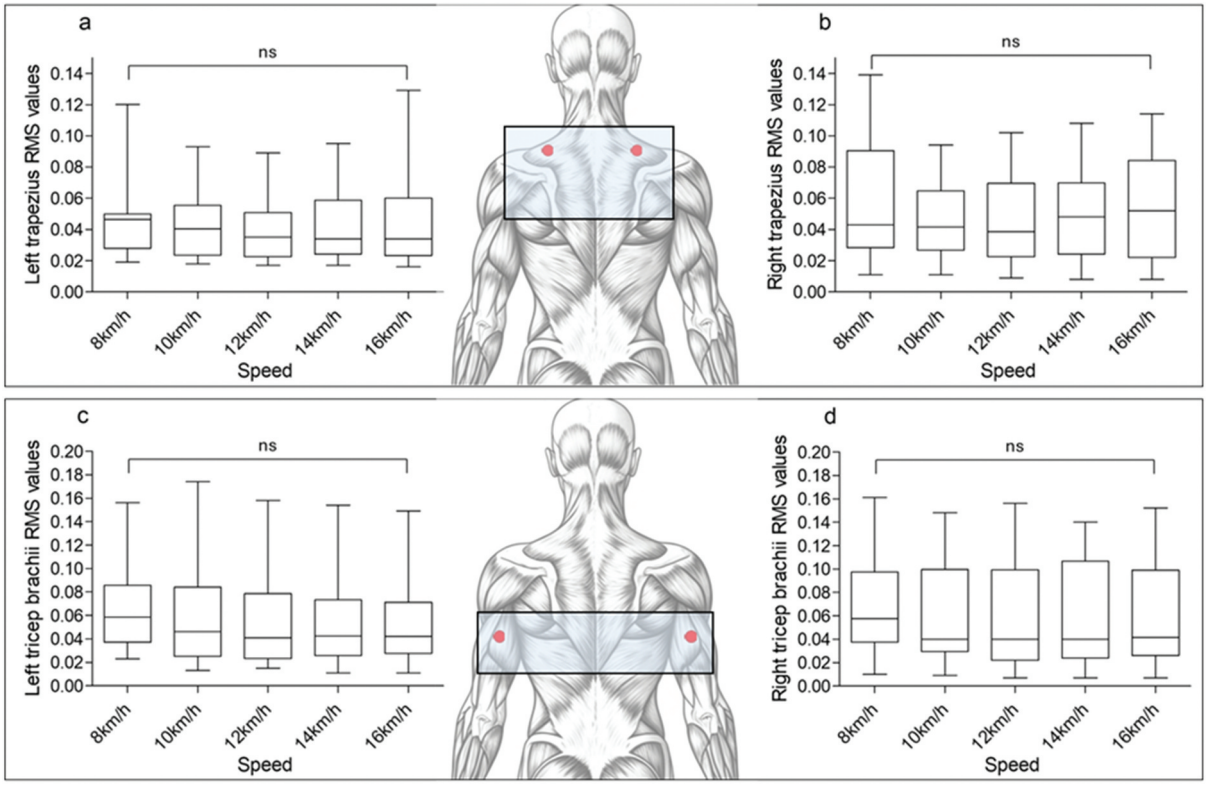


Figure 7. Box plots representing the root mean square (RMS) values of muscle activation across different speeds (8 km/h, 10 km/h, 12 km/h, 14 km/h, and 16 km/h). (a) Left trapezius, (b) right trapezius, (c) right triceps brachii, and (d) left triceps brachii. No significant differences in RMS values were observed across speeds for any of the muscles. *Denotes significance greater to other speeds. ns = no significance. Anatomical images depict the posterior view of upper body muscle sites under observation.

Table 2. Effect of speed on muscular activation during e-scooter riding.

Muscle group	ANOVA Test	*p*-value	Significant Pairwise Comparisons (*p*-values)
Rear leg vastus lateralis	Friedman's ANOVA	0.159	–
Front leg vastus lateralis	Friedman's ANOVA	<.001***	8 km/h vs. 10 km/h ($p = .001$), 12 km/h ($p = .001$), 14 km/h ($p = .001$), 16 km/h ($p = .021$)
Rear leg vastus medialis	Friedman's ANOVA	0.015*	8 km/h vs. 10 km/h ($p = .041$), 12 km/h ($p = .041$), 14 km/h ($p = .041$)
Front leg vastus medialis	Friedman's ANOVA	<.001***	8 km/h vs. 12 km/h ($p < .001$), 14 km/h ($p = .007$), 16 km/h ($p = .005$)
Rear side erector spinae	Friedman's ANOVA	.001**	8 km/h vs. 10 km/h ($p = .014$), 12 km/h ($p = .001$), 14 km/h ($p = .001$)
Front side erector spinae	Repeated-Measures ANOVA	<.001***	8 km/h vs. 10 km/h ($p < .001$), 12 km/h ($p < .001$), 14 km/h ($p < .001$)
Right trapezius	Repeated-Measures ANOVA	0.018*	–
Left trapezius	Friedman's ANOVA	0.049*	–
Right triceps brachii	Friedman's ANOVA	0.326	–
Left triceps brachii	Friedman's ANOVA	0.124	None

Note: *p*-values indicate overall significance for each muscle group, determined using either a Friedman's ANOVA (non-parametric) or repeated-measures ANOVA (parametric). Significant post-hoc pairwise comparisons (Bonferroni-corrected) are shown, comparing 8 km/h to other speeds (10, 12, 14, and 16 km/h). Statistical significance is denoted as: *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$. All other pairwise comparisons were non-significant ($p \geq 0.05$) and are not reported in the table.

E-scooter muscular activation compared to walking

A comparison of muscle activation between walking and e-scooter riding revealed that, walking generally elicited higher levels of muscular activity. This was particularly notable in the muscles of the lower limb and trunk, with the left and right vastus lateralis, vastus medialis, erector spinae and trapezius all exhibiting significantly lower activation during e-scooter riding compared to walking. These differences are likely resultant from the biomechanical differences between the two different modes. For example, in walking, the greater activation can be explained by the need for continued propulsion (activating the vastus lateralis and vastus medialis), postural control and absorption of ground reaction forces (engaging the erector spinae), and co-ordinated arm-swing (trapezius) (Griffin et al. 2003; Grabowski et al. 2005; Anders et al. 2007; Kuhtz-Buschbeck and Jing 2012). In contrast, during e-scooter riding in controlled conditions, these muscles appear to primarily act passively as stabilizers, regulating posture and body sway without contributing to propulsion (Murillo et al. 2012; López-Dóriga et al. 2022).

This stabilising role is consistent with EMG patterns observed during standing. Gao et al. (2017) reported that back muscle activity during standing is 43% of walking activity, while lower limb muscle activity during standing was 17% of walking. In the present study, erector spinae activation during e-scooter riding (~42–47% of walking) closely aligns with these standing values, and the minimum lower limb activation for vastus lateralis and medialis (16–19% of walking) is comparable to standing only activity. These findings suggest that e-scooter riding elicits muscle activation patterns in the trunk and lower limbs broadly equivalent to standing only tasks.

Standing has been associated with modest increases in energy expenditure, reflecting greater muscular metabolic demand compared to sitting, and is characterised by muscle activation levels that are higher than sitting when expressed as a percentage of walking (Gao et al. 2017). This suggests that postural stabilising activities such as e-scooter riding, given the similar muscle activation profile as standing, may confer greater physiological benefit than sedentary modes such as sitting and driving (Wen et al. 2025).

Conversely, e-scooter riding required greater activation in the upper arms (triceps brachii) compared to walking, likely due to the need to continually stabilise and control the position of the handlebars (Wen et al. 2025). The triceps assist in maintaining linear riding position through micro-adjustments relative to shoulder and elbow movements (Brand et al. 2020), and any increases in elbow extension and flexion to counteract handlebar torque places a demand on the triceps (Paudel et al. 2021). Taken together, these findings indicate that e-scooter riding does not elicit the same extent of muscular engagement as walking and should therefore not be considered as a substitute for this moderate form of physical activity.

Muscular activation between sites relative to e-scooter riding position

A key aim of the present study was to evaluate muscle activation during e-scooter riding in the context of riding stance, specifically the tandem stance commonly adopted during e-scooter use. When analysed between muscles for e-scooter riding, the results demonstrated significantly greater activation in the vastus lateralis and vastus medialis of the rear leg compared to the front leg. This supports previous findings that identified individuals typically load more on the rear foot in a tandem-style stance (Jonsson et al. 2005). Combined with the externally rotated position of the rear foot, which is likely to provide a more stable base of support, these findings suggest that the rear leg acts as a postural anchor during e-scooter riding (Jonsson et al. 2005; Wang and Newell 2012).

The tandem stance during e-scooter riding also places the trunk in an asymmetrical anatomical position due to the front and rear foot placement. Unlike the quadriceps, that demonstrate a functional difference relative to foot position, the front and rear side erector spinae muscles displayed almost equal levels of activation with no statistically significant difference between them. In addition, neither the trapezius nor the triceps brachii showed a significant difference in muscle activation between left and right sides during e-scooter riding. For the triceps brachii specifically, this lack of side-to-side difference occurred despite the left side demonstrating a greater activation relative to walking. These upper-body muscles were analysed by left and right sides as, unlike the lower body, the upper body maintains a symmetrical position during e-scooter riding and therefore these muscles are likely to have similar functional roles on both sides of the body.

Effect of e-scooter riding speed on muscular activation

Speed-related changes in muscular activation were most apparent in the lower limbs and trunk. Despite reduced muscular activation compared to the rear leg, the quadriceps of the front leg (vastus lateralis, vastus medialis) displayed a greater response to changes in speed. This may reflect the front leg's role in managing postural adjustments, potentially compensating for any lateral movement of the e-scooter, particularly at slower speeds. In contrast, the rear leg, acting as the stable base of support, appeared less susceptible to changes in speed than the front leg, suggesting an interdependent relationship in maintaining the asymmetrical foot position (Wang and Newell 2012).

Muscular activation in both the front (vastus lateralis, vastus medialis) and rear (vastus medialis) legs was significantly greater at the slowest riding speed (8 km/h), with comparably lower activation at the higher speeds. This finding is likely due to the greater need for balance adjustments at slower speeds, where the gyroscopic stabilizing effect of the wheels is perhaps less pronounced (Zhang et al. 2011). A similar finding was observed in the erector spinae muscles, where peak activation occurred during slowest riding speed, reinforcing the notion for an increased need to maintain balance and resist lateral instability at slower speeds (Murillo et al. 2012; López-Dóriga et al. 2022). Conversely, muscle activity in the upper body did not change in responses to changes in speed, with no significant difference in the activation of the trapezius or the triceps brachii between e-scooter riding speeds. These findings suggest that, when riding in a straight line, upper body muscle activation remains consistent and are unaffected by the speed at which the e-scooter is operated.

Whilst testing was conducted in a controlled lab environment, analysis in the present study was designed to reflect real-world riding conditions, within which changes in speed form an integral part of e-scooter riding. As such measurements reported reflect the full 30-second interval at each speed, without excluding transition or stabilisation time. It should be noted that this approach does not account for transient responses during acceleration and deceleration which may also have influenced the overall muscle activation results.

Limitations and future direction

The absence of EMG normalisation to a reference such as maximal voluntary isometric contraction (MVIC) represents a limitation of the present study. Although a task-specific reference condition (walking) was used to facilitate within-subject comparisons, this represents task-based scaling rather than physiological

normalisation. Consequently, the absolute RMS values cannot be interpreted relative to maximal muscle capacity, limiting the functional interpretation of muscle activation levels. In addition, the use of non-normalised EMG restricts direct comparison with other studies that report normalised EMG amplitudes (e.g. %MVIC), as recommended for between-study comparability (Burden 2010). While the standardised experimental conditions support valid within-subject comparisons between e-scooter riding and walking, caution is required when interpreting the magnitude of activation and when comparing these findings with existing literature. Sensitivity analyses indicated that the majority of findings were robust to outlier inclusion (Supplementary Table S1), although the triceps brachii (left) comparison was sensitive to the removal of extreme values.

In addition, the a priori power analysis was based on the primary comparison of walking versus e-scooter riding. It was not designed to assess the effect of differences in e-scooter riding speed; this should be considered a limitation when interpreting the speed-related findings.

A further limitation is that within-session test–retest reliability could not be assessed. The three 5-minute segments were used to record different anatomical regions, with electrode repositioning between segments, and therefore did not provide repeated measurements of the same muscle under identical conditions. As reliability metrics such as intraclass correlation coefficients require repeated observations (Weir 2005), these analyses were not feasible within the present design, limiting the ability to quantify measurement consistency across repeated trials. Future studies should assess test–retest reliability in a separate session or, where feasible, use a multi-channel system to record all 10 anatomical sites simultaneously to allow formal intraclass correlation coefficients computation.

Unique to this study was the ability to standardise ground surface allowing for the investigation of muscular activation in maintaining a tandem stance e-scooter riding position and comparing the muscular responses to changes in speed without the influence of terrain. However, the authors acknowledge that while the treadmill-based e-scooter protocol effectively simulated straight-line riding and controlled changes in speed, it did not replicate braking, cornering, or re-acceleration, all of which may form part of outdoor e-scooter riding and may elicit greater muscular engagement. For example, handlebar control during braking and turning has been associated with increased spinal control and upper body loading (Brand et al. 2020).

Additionally, the study focused on the riding position and did not include an assessment of a manual kick or leg push required to initiate motion in the field that may elicit further muscular activation (Wen et al. 2025). However, a manual kick is necessary only for initial propulsion and subsequent movement relies on motorized assistance and thereby requiring minimal additional muscular activation. Engineering research continues to focus on refining e-scooter design and control mechanisms aimed at reducing lateral instability during the riding experience and align their performance with the stability benchmarks of larger-wheeled seated vehicles including eliminating the need for a manual start (Paudel and Fah Yap 2021; Horvath and Takacs 2024; Wen et al. 2025). Although developments to e-scooter design and functionality may enhance user safety and accessibility, it could reduce the physiological demands required to maintain postural stability across varied conditions (Paine 2001; Moore et al. 2009) thus contributing to reduced muscular engagement during habitual use.

While the omission of a manual start in the present study may limit ecological validity, incidental movements are becoming less representative of contemporary e-scooter use (Wen et al. 2025). Furthermore, incidental muscular activity during real-world riding remains highly variable and dependent on the route, terrain, and individual riding behaviour, complicating the establishment of standardised baseline measures of muscular activation. As such, future research should assess muscular activation and related physiological demands during a wider range of real-world e-scooter manoeuvres and across varied outdoor terrains, also considering the influence of evolving e-scooter designs.

Conclusion

The asymmetrical riding position places an emphasis on the rear leg to provide a base of support during e-scooter riding. However, as speeds increase, the demand for this postural anchor decreases. Based on the findings, e-scooter riding requires significantly less muscular activation in the lower body and trunk compared to walking. While the upper body muscles, particularly the arms, play a key role in controlling

the handlebars and maintaining an upright posture, their muscle activation is not affected by speed and does not promote the same level of physical exertion or total muscular metabolic demand as walking.

The relatively static standing posture adopted during e-scooter riding is consistent with predominantly isometric stabilisation, supporting regulation of posture and body sway rather than active propulsion. As velocity increased the stabilising effect was shown to reduce. In contrast, during walking, trunk muscles maintain postural stability and absorb ground forces (Anders et al. 2007), while the quadriceps work mechanically to generate propulsive forces through concentric muscle actions (Griffin et al. 2003) and contributing to metabolic activity (Grabowski et al. 2005). Stabilising isometric contractions do not produce the same metabolic effect as mechanical forces and are therefore associated with a lower energy cost (Elder et al. 2006). Therefore, repeated mechanical workload over time, such as that induced by regular walking can promote musculoskeletal strength, cardiovascular health, and sustained energy expenditure, supporting long-term benefits to metabolic health and physical function. Conversely, this suggests that e-scooter riding may not offer adequate stimulus to actively contribute to positive health outcomes.

Although energy cost was not directly measured, the reduced muscular activation observed here may help explain why previous research reports lower metabolic demand (1.7 METs, Payne et al. 2025; 2.14 METs; Wen et al. 2025) for e-scooter use compared with walking. From a public health perspective, this suggests that e-scooter travel may align more closely as a light-intensity activity than active transport within future physical activity and transport policy frameworks.

Acknowledgments

The authors would like to thank Dr Jake Bowd and Dr Chris Fennell for support with electromyography procedures.

Author contributions

CRediT: **Christopher Payne:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review & editing; **Katrina A. Taylor:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing; **Samuel A. Smith:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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