Foot position during plantarflexion changes *gastrocnemii* motor unit discharge rate in runners with Achilles tendinopathy, but not in the way you might think.

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Abstract (207 words)

Runners with Achilles tendinopathy (AT) have lower neural drive to *gastrocnemius lateralis (GL)* and it has been shown that modified foot position during plantarflexion activity affects motor unit discharge properties of *GL*. This paper tested the motor unit (MU) responses of GL and *gastrocnemius medialis (GM)* to *feet-neutral* and *feet-in*. We recruited runners with (n=18) and without (n=19) AT for experiment 1(EXP1) and nine healthy individuals for experiment 2(EXP2). High-Density electromyography was used to analyse MU discharge rates (MUDR) for *GL* and *GM*, during an isometric plantarflexion (EXP1) with *feet-neutral* and *feet-in*; and during a 30%-peak torque (EXP2) using a dynamometer. In EXP1 MUDR were lower during *feet-in* in *GL* ($p<0.001$) and in *GM* ($p<0.001$), without group difference ($p=0.84$). Furthermore, cumulative spike train analysis showed no difference in *GL* or *GM* neural drive between group or condition. EXP2 showed no condition differences in *GL* ($p=0.91$)*;* and lower MUDR in *GM* ($p=0.01$). Finally, the AT group have lower *triceps surae* endurance observed during single leg heel raise. Our data indicate that *feet-in* reduces *gastrocnemii* MUDR, compared to *feet-neutral*, irrespective of tendinopathy. Current understanding of modulation strategies to *GL* driven by feet position is conflicting; thus, plantarflexion using *feet in* may not be a viable treatment strategy for AT.

NEW & NOTEWORTHY:

Plantarflexion performed with feet inwards does not increase the neural drive to *gastrocnemius lateralis* as suggested in the literature. In fact, the *feet-in* condition reduced the motor unit discharge rates in both *gastrocnemii* during isometric plantarflexion and isometric plantarflexion using dynamometry. Therefore, this is not a viable treatment strategy for runners with Achilles tendinopathy. Furthermore, prioritising strategies to improve *triceps surae* endurance should be a key component in physiotherapy program.

Keywords

Achilles tendon; running; feet position; heel lifts; neural drive; triceps surae; high density electromyography; motor unit.

2. Introduction

Achilles tendinopathy, is a highly prevalent injury among runners[1,2], and is associated with deficits in *triceps surae* performance[3,4]. Runners with Achilles tendinopathy exhibit lower neural drive to *gastrocnemius lateralis*, resulting in a 28% lower contribution to submaximal triceps surae isometric force in acute presentations[5] (<3 months) and during dynamic tasks such as bilateral and unilateral heel drops[6]. This lower neural drive to *gastrocnemius lateralis* is also present in chronic Achilles tendinopathy[7] (> 3 months) evidenced by lower motor unit discharge rate during submaximal isometric contraction and seems to be specific to *gastrocnemius lateralis*; since there seems to be no differences in neural drive to *gastrocnemius medialis* and *soleus* compared to healthy controls [5–7]. In fact, *soleus* force contribution was greater than controls in some dynamic tasks[6], like walking, toe walking and unilateral heel drop. Individuals with Achilles tendinopathy seem to have an altered *triceps* surae muscle coordination strategy, favouring *soleus* over *gastrocnemius lateralis.* Therefore, these deficits in *gastrocnemius lateralis* neural drive observed in runners with Achilles tendinopathy[5,7] may negatively impact Achilles intratendinous load distribution; increasing tendon strain and potentially contribute to tendinopathy[8–10]. Therefore, developing rehabilitation strategies that aim to increase *gastrocnemius lateralis* activation and contribution to triceps surae force could be a promising approach to improve plantarflexor neuromuscular control and provide better rehabilitation outcomes for this population.

Recent evidence suggests that foot position during plantarflexion can independently influence *gastrocnemius medialis* and *gastrocnemius lateralis* recruitment and activation, and thereby alter the contribution of each muscle during plantarflexion tasks. Although a synergist muscle group during ankle plantarflexion, individual muscles of the *triceps surae* have partially independent neural drive[11] to allow for joint control and stability. Changes in foot position seems to influence not only the neural drive[11] but also resistance training-related hypertrophy

of the different gastrocnemii heads. These have been reported as an increase in the neural drive[11] and greater hypertrophy[12] of *gastrocnemius lateralis* occurring when plantarflexion exercise was performed with the feet pointed inwards. Thus, current evidence suggests that the contribution of *gastrocnemius lateralis* to plantarflexion can be increased by internally rotating the hips and lower leg to orient the feet inwards.

This study aimed to investigate whether performing a bilateral isometric plantarflexion task with feet pointed inwards, would increase the neural drive to *gastrocnemius lateralis* in runners with Achilles tendinopathy. These data would inform the development of novel rehabilitation interventions, using different foot position during ankle plantarflexion. We hypothesised that the feet pointed inwards (*feet in*) condition would increase motor unit mean discharge rate of *gastrocnemius lateralis* in both Achilles tendinopathy and controls, compared to *feet neutral (*condition was considered participant's comfortable stance with feet pointing forward). We also aimed to explore changes in coefficient of variation of motor unit discharge rates, as this could potentially increase for both muscles and groups during the isometric testing position with *feet in* as this creates a more unstable position to hold a steady contraction. A second experiment was conducted to better control variables such as balance during sustained testing position and provide visual feedback to ensure muscle contraction remained constant during the isometric task. The hypothesis was the same as for experiment 1: *feet in* condition would increase motor unit mean discharge rate of *gastrocnemius lateralis* in both Achilles tendinopathy and controls, compared to *feet neutral.*

2. Methods

This study compared the influence of two foot positions on *gastrocnemius lateralis and gastrocnemius medialis* motor unit discharge frequencies during standing isometric contraction of the plantarflexors. In experiment 1 we assessed runners with Achilles tendinopathy and

healthy counterparts during bilateral standing isometric contraction of the plantarflexors. Thirty-seven endurance runners were recruited for this study, 18 runners with Achilles tendinopathy (12 males (66.6%), 43.2 years old ±8.9, 165.5 cm ±38.5, 71.5 kg ±12.8); 13 with mid-portion and 5 with insertional Achilles tendinopathy; and 19 healthy controls (10 males (53%), 35.4 years old ±6.5, 172.1 cm ±11.3, 67.5 kg ±13.8). Volunteers were endurance runners, recruited from local running clubs around Southeast Queensland, Australia, via email and social media. The Achilles tendinopathy group had an average of 18.8 (±13.3) years of running experience and a current running routine of 43.6 (±26.8) km/week; the control group had 12.6 (±8.5) years of running experience and a current running routine of 42.2 (±29.5) km/week. Diagnosis of Achilles tendinopathy was confirmed by an experienced physiotherapist during examination if patients presented with localised Achilles tendon pain for more than three months, pain provoked by physical activities in a dose dependent way and had pain with palpation of the tendon. Average symptom presentation of Achilles tendinopathy was 4.9 years (±6.3). Volunteers were excluded if they had previous rupture of or surgery to the Achilles tendon; clinical findings indicating a differential diagnosis for the Achilles tendon pain (such as tendon sheath inflammation, an acute tendon tear, plantaris or tibialis posterior tendon involvement, neural involvement); 4) VISA-A score > 90 points for Achilles tendinopathy group and < 100 for the control group; any other musculoskeletal injuries of the lower limb of the affected leg; any neurological disorder; or mental health issues affecting consent. All participants were free of cardiac, pulmonary, renal or endocrine[13] comorbidities. Prior to testing, all participants read and signed a detailed informed consent document and completed the VISA-A questionnaire[14]. The average VISA-A score for the Achilles tendinopathy group was 65.5 (± 13.2) and 100 (0) for the control group. The Achilles tendinopathy group also completed the Tampa scale of Kinesiophobia (TSK) to identify if kinesiophobia was a factor influencing muscle performance[15,16].

The outcomes of our main experiment (experiment 1) were conflicting with the existing literature[11]. Understanding the importance of addressing these inconsistencies, we conducted a second experiment (experiment 2) to better understand the contrasting outcomes obtained in experiment 1. Our primary objective of experiment 2 was to explore whether methodological factors influenced our outcomes or if our observations simply deviate from current knowledge. Therefore, we decided to replicate and expand our methods by controlling more variables; thus, we conducted experiment 2 in a group of 9 healthy non-runners (5 males (55.6 %), 37.7 years old ± 12.2, 171 cm ± 8.7**,** 71.1 kg ±11.1) to investigate the motor unit discharge characteristics of *gastrocnemius lateralis and gastrocnemius medialis* in *feet in* and *feet neutral* positions using a dynamometer and controlling better for body position. Volunteers were recruited from around Southeast Queensland, Australia, via email and social media. Exclusion criteria were the same as that of controls from the main experiment.

This study was approved by the Queensland University of Technology Human Research and Ethics Committee in line with the Declaration of Helsinki. Data collection was partially conducted during the COVID-19 pandemic and all safety procedures followed local state government policies.

2.1 Data collection and analysis

Experiment 1

Plantarflexor isometric peak torque was measured using an isokinetic dynamometer (Biodex Medical Systems, Shirley, New York). For the bilateral Achilles tendinopathy presentations (n=9), the most symptomatic leg was used and for the control group, the dominant leg was used for testing. Leg dominance was selected by asking the participants which leg they would use to kick a ball. Participants were seated (75 degrees of hip flexion) with their knee straight and with the ankle joint at 10 degrees of plantarflexion. Warm up consisted of 2 × 4 s

isometric contractions of each participant's perceived 30, 50, 70 and 80% maximal voluntary isometric contraction intensity. After warm-up, participants performed at least 3 maximal voluntary isometric contractions, until <5% variation was observed between contractions; the highest value was used. Participants then performed, 8 bilateral standing heel-raise, 4 in each condition, *feet neutral* and *feet in*; in a randomised order. *Feet neutral* condition was considered participant's comfortable stance with feet pointing forward; whereas for *feet in* condition, participants would internally rotate at their hips so that the long axis of their feet were at 90-degrees to each other[11]. All participants were able to achieve and stay comfortably in *feet in* position for testing. Participants were instructed to perform a heel raise to full range followed by a slow drop until their heels lightly touched a 6.5 cm height soft foam (supervised by tester) and to hold when in position. Participants were also instructed to lightly touch a table placed in front of them to reduce oscillation and assist balance. Once in position, a 20 second isometric contraction was recorded. After all contractions were finalised, participants were given ~10 min rest, seated in a chair. Thereafter, a single leg heel raise (SLHR) endurance test was performed, using a metronome set to 60 bpm[17,18] to control tempo. Participants were instructed to go as high as possible and come down to fully touch their heel to the ground before going up again. Test was ceased once performance was no longer correct (reduced plantarflexion range, bending knees, hip hinge or other compensatory strategies or unable to follow pace, for 2 consecutive repetitions).

Experiment 2

The purpose of experiment 2 was to replicate experiment 1 while controlling certain variables, not accounted for in experiment 1, that might have influenced our results. The set up in experiment 2 allowed for control of each participant's relative force in each condition (*feet in* and *feet neutral*) by utilising a percentage of participant's peak isometric plantarflexor torque. This control was facilitated using visual feedback and torque trace. Body position was

also controlled, ensuring that *feet in* condition was based solely on medial hip rotation and therefore, reducing a potential contribution of ankle passive stiffness on eversion torque. Additionally, only healthy participants were recruited for this methodological experiment, irrespective of their level of physical activity, as the primary focus was on methodology rather than group comparisons. Dominant leg plantarflexor isometric peak torque was measured using an isokinetic dynamometer (Biodex Medical Systems, Shirley, New York). Participants were seated (75 degrees of hip flexion) with their knee straight and with the ankle joint at 0 degrees of plantarflexion. Warm up consisted of 2 × 4 s isometric contractions of each participant's perceived 30, 60 and 80% maximal voluntary isometric contraction intensity. After warm-up, participants performed at least 3 maximal voluntary isometric contractions, until <5% variation was observed between contractions; the highest value was considered. Thereafter, 25% of each participant's peak isometric torque was calculated and used for the trapezoidal contractions. Trapezoidal contractions consisted of a 6-second torque rise and decline with a 14-second plateau, followed by 40 seconds rest between contractions. Participants received real-time visual feedback of the trapezoidal pathway via a monitor placed ~1 m away from them and had 3 attempts to become familiar with task. Testing protocol involved 2 contractions for each condition *foot neutral* and *foot in*, and for each muscle (8 contractions in total) in a randomised order. *Foot neutral* consisted of a neutral position of the isokinetic foot plate and *foot in* consisted of the same foot plate tilted, creating an angle of ~30 degrees medial rotation from neutral.

High-density electromyograms recordings and analyses

HD-EMG (Sessantaquattro, OTBioelettronica, Torino, Italy) signals were recorded from *gastrocnemius medialis* and *gastrocnemius lateralis* using OT Biolab+ software (version 1.3.0., OTBioelettronica, Torino, Italy) during isometric plantarflexion and during the

trapezoidal contractions. A b-mode ultrasound (ESAOTE, MyLabSeven. Genova, Italy) was used to identify muscle fibre orientation and muscle boundaries, to guide electrode position. To ensure good skin-electrode contact and conductance, a bi-adhesive layer with a conductive paste was used. One 64-channel electrode grid (GR08MM1305, OTBioelettronica, Torino, Italy) was placed over *gastrocnemius medialis* and one 64-channel electrode grid over *gastrocnemius lateralis*. The ground strap electrode (WS2, OTBioelettronica, Torino, Italy) was dampened and positioned around the ankle joint of the tested leg. EMG signals were recorded in monopolar mode, amplified (256x), band-passed filtered (10-500Hz) and converted to digital signal at 2048Hz by a 16-bit wireless amplifier (Sessantaquattro, OTBioelettronica, Torino, Italy), before being stored for offline analysis. The grid adapter device used (AD1x64SE, OTBioelettronica, Torino, Italy) has only 1 channel for the 64-channel electrode connection, so each condition had to be performed twice, once with electrodes connected to the *gastrocnemius medialis* and once with the electrodes connected to the *gastrocnemius lateralis*, in randomised order. We decided to use a single 64-channel instead of one 32-channel electrode in each muscle, based on observations from pilot testing and a previous study[7]. Although using 2×32 channels (ne electrode for each muscle) would have enabled us to measure both muscles during the same contraction, we chose to use the 64-channel electrode for several reasons. Firstly, we observed that the 32-channel electrode yielded a limited and lower number of motor units, which is particularly important for *gastrocnemius lateralis* that typically yields a low number of motor units. Additionally, the larger 64-channel electrode offered a greater surface area, providing more comprehensive coverage of the muscle's electrical activity. HD-EMG signal was recorded and analysed offline, decomposed into motor unit spike trains, then converted into instantaneous discharge rates with specialised software using blind source separation decomposition technique with DEMUSE tool software (v.4.1; The University of Maribor, Slovenia)[19]. All contractions were analysed, and motor units were

visually inspected (erroneous discharge times were excluded, and missed discharges included). Manual inspection is required to reduce automatic decomposition discharge errors and improve data[19,20]. Only motor units with a pulse-to-noise ratio (PNR) >30dB, sensitivity > 90%, were used for data analysis[19,21]. The best contraction for each muscle, those with the smallest deviations from trapezoidal target torques and highest PNRs, was used for analysis. After identifying the best contraction for each muscle and condition, motor units were tracked between conditions for each muscle for experiment 1. The operator for the motor unit analysis and tracking was blinded by group. Tracking motor units across conditions allows a better understanding of the effect of foot position on the discharge patterns of the same motor unit and therefore, the influence of each condition on the neural drive to each muscle. Motor units that discharged intermittently during the 20 second isometric plateau were excluded from the tracked analysis. Individuals who did not yield motor units after tracking were not included in statistical analysis of said muscle. Individual motor unit mean discharge rates for each muscle are also reported.

Due to the lower number of participants, we decided to only use the analysis of individual motor units in experiment 2 to limit the number of motor unit losses in the tracking analysis. We compared the results from experiment 2 with those from the main experiment.

The sum of individual motor unit discharge times, the cumulative spike train, represents an estimation of the neural drive to a muscle during a contraction[11,22–24]. The cumulative spike train of the individual motor units was compared for each muscle, between conditions (*feet neutral* and *feet in*) and groups. The analysis for the cumulative spike train was calculated using the 20 second isometric plateau, using MATLAB (TheMathWorks, Natick, MA, USA). The binary arrays representing the number of discharge times was summed then smoothed using a Hanning window of 400-ms duration[11,24,25]. The mean cumulative spike train was normalised

by the total number of motor units, representing an index of neural drive[26], this is referred to in the manuscript as normalised neural drive.

2.2 Statistical analysis

All analyses were performed using R studio (version 1.3.1093). Models were fitted using the *lme4 and lmerTest* [27] and *flexplot* package[28]. Separate linear mixed-effect models were used to compare motor unit discharge rates and coefficients of variation of motor unit discharge rates from tracked motor units from *gastrocnemius medialis* and *gastrocnemius lateralis* between conditions (*feet neutral* and *feet in*) and groups (Achilles tendinopathy and control), and for individual (non-tracked) motor units for each condition and muscle. The models were tested using participant ID as random intercept to account for the correlation between repeated observations for each participant. For the tracked motor unit analysis, motor unit ID was also included in the model as random intercept to estimate individual change in neural drive in the same motor unit, influenced by condition. A linear mixed model was also used to compare the normalised neural drive between conditions and between groups. Analysis of covariance (ANCOVA) was used to compare peak isometric plantarflexor torque between groups, using body mass as covariate and a Welch two sample t-test was use for single leg heel raise (SLHR) analysis. Furthermore, a Pearson's r was used to test a possible correlation between the SLHR values and the kinesiophobia scores of each participant. The estimated marginal mean difference and 95% confidence intervals (CI) for motor unit mean discharge rate between groups, were determined using the *emmeans* package[29]. Normality assumptions were confirmed by analysis of the histogram of residuals (Q-Q Plot). Sensitivity tests were utilised in some cases to assess the influence of outliers identified by the models in the output, and these are reported in the results section. For the t-test and ANCOVA, a Bonferroni correction was used when relevant. Statistical significance was accepted at $P \leq 0.05$ for all

tests. Cohen's d effect size is presented for the t test. Data is presented as mean (± SD) or mean (95% confidence interval lower to upper limits).

3. Results

3.1 Motor unit identification

We found a total of 1944 motor units in Experiment 1, 1082 motor units in the Achilles tendinopathy group (15.0 (± 10.6) per participant) and 862 motor units in the control group, (11.3 (± 11.8) per participant) across the two muscles and conditions. After motor unit tracking across conditions, there were a total of 560 motor units; 305 (8.5 (± 9.1) per participant) in the Achilles tendinopathy group and 255 motor units (6.7 (± 9.3) per participant) in the control group, across the two muscles. In Experiment 2, we found a total of 369 motor units across the two muscles. The total number, mean and standard deviation (± SD) of identified individual and tracked motor units, per muscle, group and condition are reported in Table 1.

Table 1. Total number, mean (± SD) of identified individual and tracked motor units (MU) per group, muscle, and condition

Achilles tendinopathy	**Mean (± SD)**	**n**	**Total number of MU**
Tracked motor units			
Gastrocnemius lateralis	6.2 (5.6)	10	68
Gastrocnemius medialis	14.8 (9.0)	16	237
Individual motor units			
Gastrocnemius lateralis			
Feet neutral	11.7 (7.1)	17	198
Feet in	10.2 (9.0)	17	173
Gastrocnemius medialis			
Feet neutral	20.1 (10.4)	17	342
Feet in	21.6 (9.3)	17	367
Cumulative spike train			
Gastrocnemius lateralis			
Feet neutral	11.8 (6.9)	17	200
Feet in	10.3 (8.7)	17	175
Gastrocnemius medialis			
Feet neutral	20.3 (10.2)	17	345

Feet in	21.7 (9.0)	17	368
Control			
Tracked motor units			
Gastrocnemius lateralis	6.9 (6.5)	11	76
Gastrocnemius medialis	11.9 (11.2)	15	179
Individual motor units			
Gastrocnemius lateralis			
Feet neutral	8.6 (8.6)	15	129
Feet in	8.2 (8.4)	13	123
Gastrocnemius medialis			
Feet neutral	16.6 (12.7)	18	281
Feet in	17.9 (13.6)	19	313
Cumulative spike train			
Gastrocnemius lateralis			
Feet neutral	8.7 (8.3)	15	131
Feet in	9.5 (8.0)	13	123
Gastrocnemius medialis			
Feet neutral	15.1 (12.3)	18	282
Feet in	15.8 (13.7)	19	317
Experiment 2			
Gastrocnemius lateralis			
Feet neutral	4.8 (3.7)	8	38
Feet in	6.5 (4.8)	8	52
Gastrocnemius medialis			
Feet neutral	14.8 (8.5)	9	133
Feet in	16.2 (10.8)	9	146

This table shows mean MU used in each condition for statistical analysis, the number of participants (n) who yield MU and total number of MU found per muscle and condition.

3.2 Motor Unit discharge rate

3.2.1 Tracked motor unit analysis

The analysis of *gastrocnemius lateralis* motor unit mean discharge rate was different between conditions (F=19.73, p<0.001) but not between groups (F=0.04, p=0.84), nor was there a condition × group interaction (F=0.04, p=0.84). Discharge rate was lower during *feet in* with mean difference between conditions of -0.57 (-0.8 to -0.3), with mean discharges rate for *feet in* of 10.3 pps (9.6 to 11.0) and 10.9 pps (10.2 to 11.5) for *feet neutral* (Figure 1). Individual group means for each motor unit analysis are reported in Table 2.

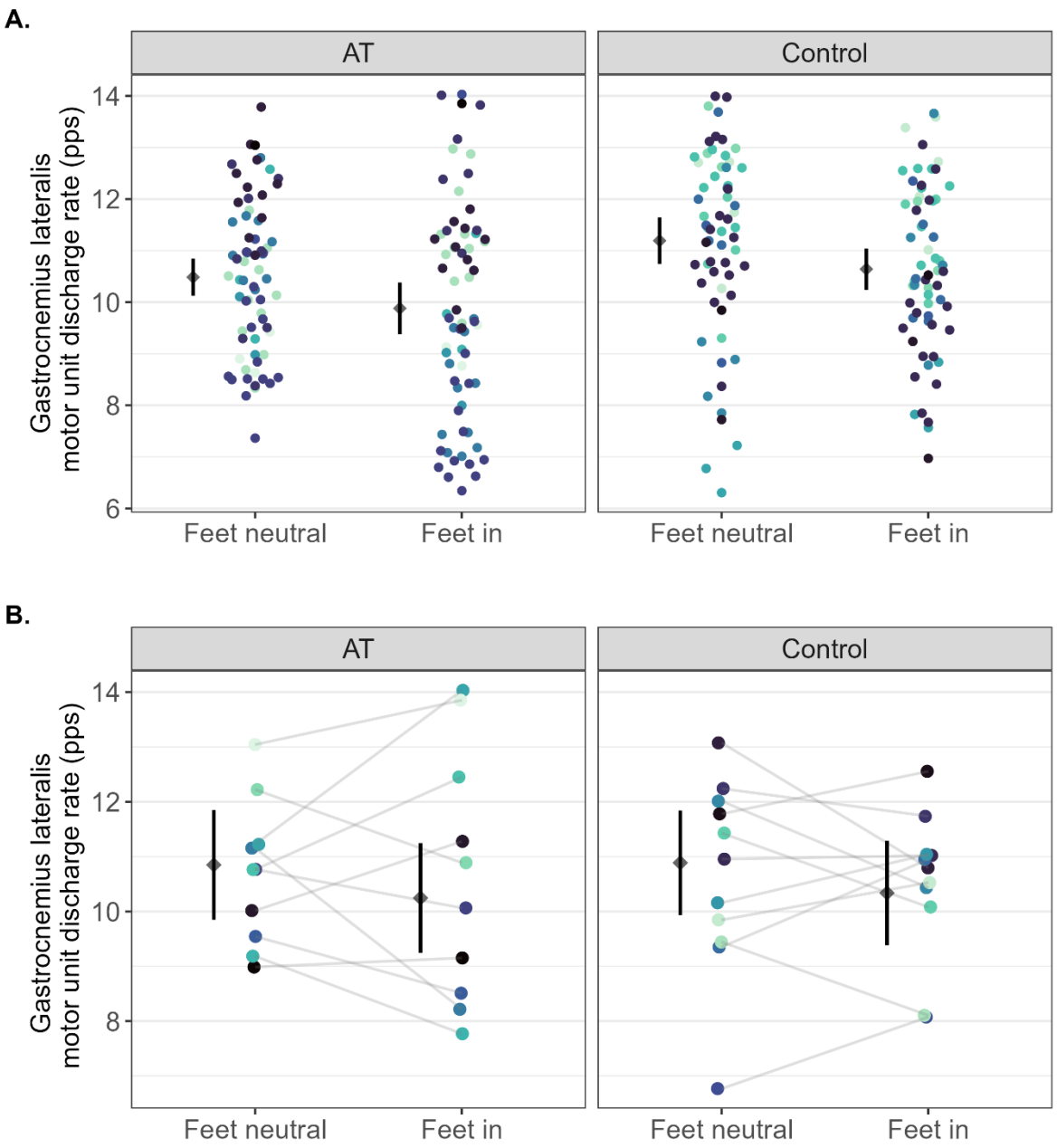

Figure 1
Gastrocnemius lateralis motor unit discharge with *feet neutral* and *feet in* between groups during the tracked motor unit analysis. Figure **A.** Each dot represents a single motor unit data point, coloured by participants. Figure **B**. represents the mean motor unit data for each participant and the light gray line connecting same participant's response across conditions. Mean and 95% confidence interval are offset to the left to facilitate visualisation. pps = pulse per second. AT = Achilles tendinopathy

Table 2. Group mean for motor unit discharge rate in the tracked and individual analysis, Coefficient of variation (Cov) of motor unit discharge rate and normalised neural drive.

Achilles tendinopathy	Mean (95% CI)	Control	Mean (95% CI)
Tracked motor units		**Tracked motor units**	
Gastrocnemius lateralis		*Gastrocnemius lateralis*	
Feet neutral	10.5 pps (10.1 to 10.9)	Feet neutral	11.2 pps (10.7 to 11.6)
Feet in	9.8 pps (9.3 to 10.3)	Feet in	10.6 pps (10.2 to 11.0)
Gastrocnemius medialis		*Gastrocnemius medialis*	
Feet neutral	10.9 pps (10.2 to 11.6)	Feet neutral	11.3 pps (10.6 to 12.1)
Feet in	10.0 pps (9.3 to 10.7)	Feet in	10.8pps (10.0 to 11.5)
Cov of motor unit discharge rate		**Cov of motor unit discharge rate**	
Gastrocnemius lateralis		*Gastrocnemius lateralis*	
Feet neutral	11.9 (11.0 to 12.8)	Feet neutral	14.2 (13.1 to 15.3)
Feet in	14.8 (13.8 to 15.8)	Feet in	15.5 (14.4 to 16.6)
Gastrocnemius medialis		*Gastrocnemius medialis*	
Feet neutral	11.7 (11.2 to 12.2)	Feet neutral	13.0 (12.1 to 13.9)
Feet in	13.3 (12.7 to 13.8)	Feet in	14.2 (13.4 to 15.0)
Individual motor units		**Individual motor units**	
Gastrocnemius lateralis		*Gastrocnemius lateralis*	
Feet neutral	10.4 pps (10.1 to 10.6)	Feet neutral	10.4 pps (10.0 to 10.7)
Feet in	9.9 pps (9.6 to 10.1)	Feet in	10.6 pps (10.2 to 10.9)
Gastrocnemius medialis		*Gastrocnemius medialis*	
Feet neutral	10.2 pps (9.9 to 10.4)	Feet neutral	10.7 pps (10.4 to 10.9)
Feet in	9.8 pps (9.6 to 9.9)	Feet in	10.4pps (10.1 to 10.6)
Normalised neural drive		**Normalised neural drive**	
Gastrocnemius lateralis		*Gastrocnemius lateralis*	
Feet neutral	0.77 (0.73 to 0.81)	Feet neutral	0.78 (0.70 to 0.86)
Feet in	0.88 (0.78 to 0.98)	Feet in	0.79 (0.74 to 0.84)
Gastrocnemius medialis		*Gastrocnemius medialis*	
Feet neutral	0.74 (0.71 to 0.77)	Feet neutral	0.79 (0.75 to 0.83)
Feet in	0.76 (0.74 to 0.78)	Feet in	0.77 (0.73 to 0.81)

This table shows group mean for motor unit discharge rates for tracked and individual analyses, coefficient of variation of motor unit discharge rate and the normalised neural drive. Data is reported as mean (95% CI lower to upper limits).

The analysis of *gastrocnemius medialis* motor unit mean discharge rate showed a condition × group interaction. However, this interaction was of no relevance to our hypothesis, as post-hoc testing detected a statistically significant difference only between *feet in* values from one group with *feet neutral* values from the other group; *feet in* AT × *feet neutral* Controls, -1.32 pps (-2.3 to -0.34, p=0.05). Motor unit mean discharge rate was different between conditions (F=226.69, p<0.001) but not between groups (F=1.41, p=0.24). Mean discharge rate

was lower for *feet in* with a mean difference of -0.73pps (-0.79 to -0.63); mean discharge rate for *feet in* was 11.1pps (10.6 to 11.6) and 10.4pps (9.88 to 10.9) for *feet neutral* (Figure 2).

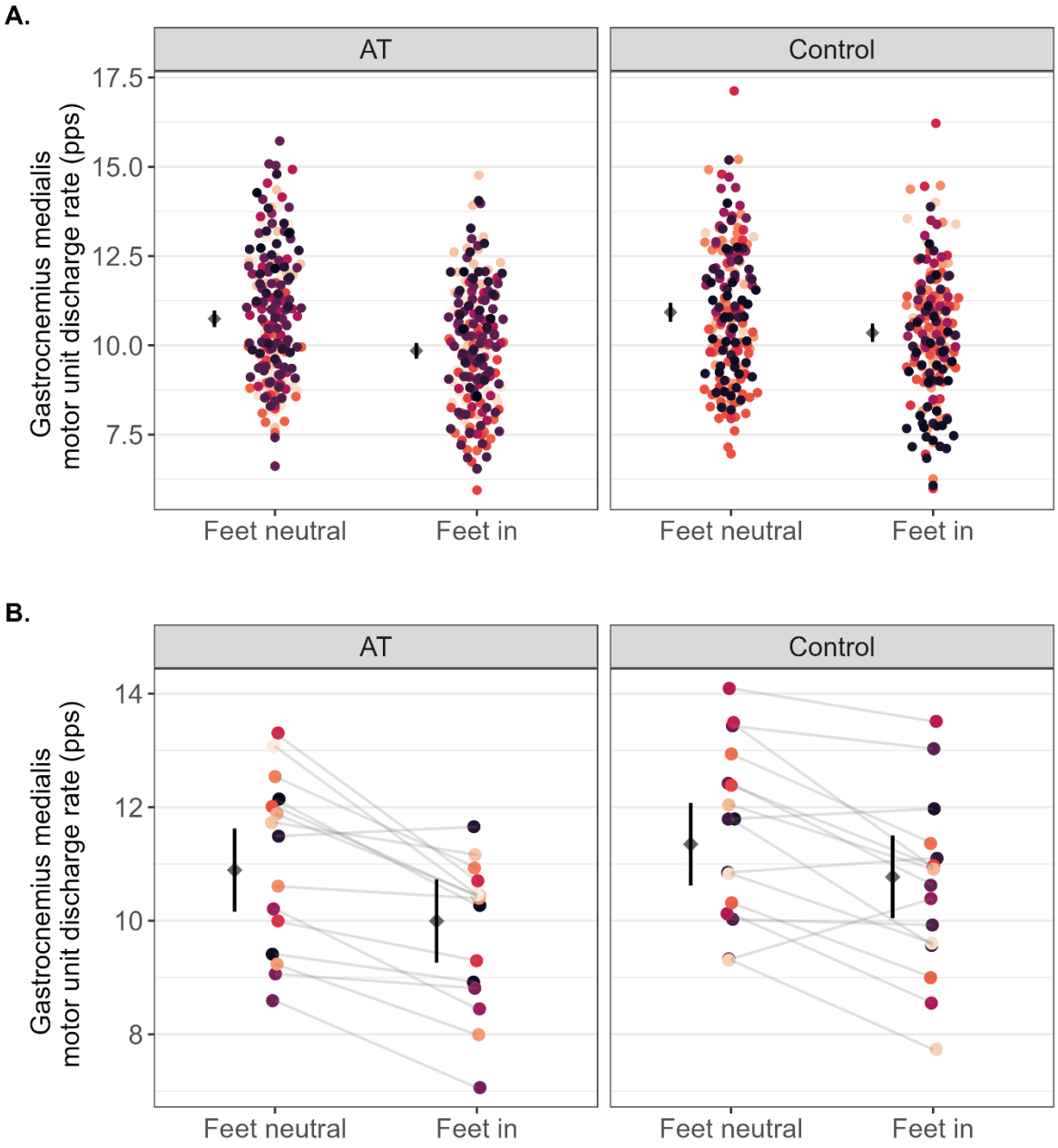

Figure 2
Gastrocnemius medialis motor unit discharge with *feet neutral* and *feet in* between groups during the tracked motor unit analysis. Figure **A.** Each dot represents a single motor unit data point, coloured by participants. Figure **B**. represents the mean motor unit data for each participant and the light gray line connecting same participant's response across conditions. Mean and 95% confidence interval are offset to the left to facilitate visualisation. pps = pulse per second. AT = Achilles tendinopathy

We also analysed the coefficient of variation of motor unit discharge rates for each condition. *Gastrocnemius lateralis* analysis showed a condition difference (F=52.10, p<001), with no differences between groups (F=0.03, p=0.86). Both groups had greater variation of motor unit discharge rate during *feet in* with a mean difference of 2.2 (1.6 to 2.8); mean variation of discharge rate for *feet in* was 15.7 (14.4 to 17.0) and 13.5 (12.2 to 14.8) for *feet neutral*. (Figure 3).

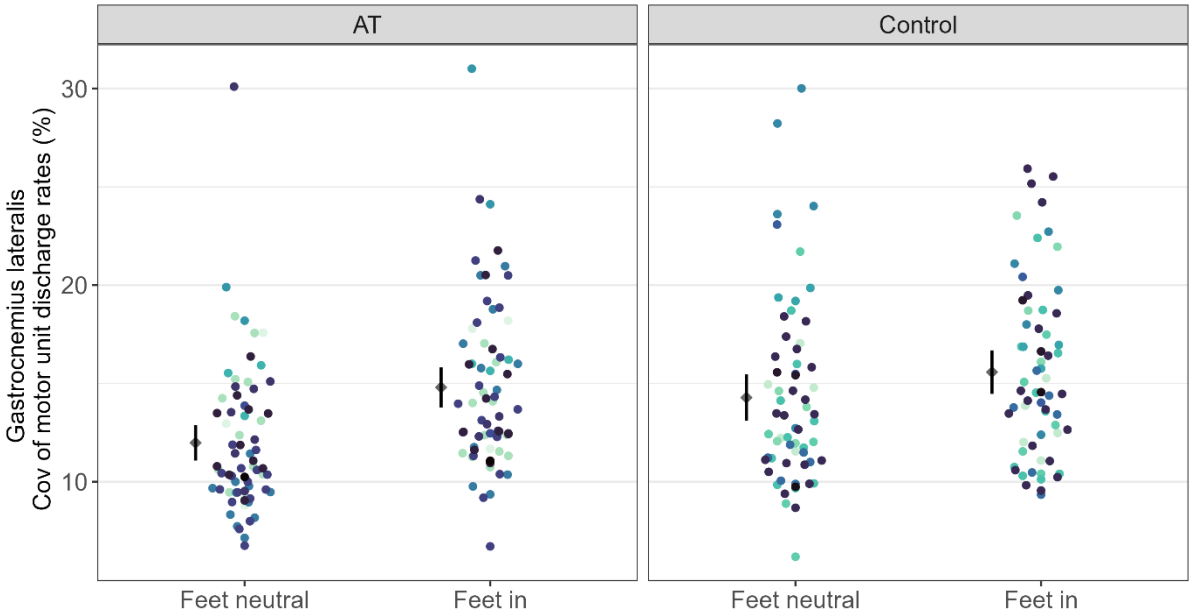

Figure 3
Gastrocnemius lateralis coefficient of variation (Cov) of motor unit discharge rate with *feet neutral* and *feet in* between groups during the tracked motor unit analysis. Each dot represents a single motor unit data point, coloured by participants. Mean and 95% confidence interval are offset to the left to facilitate visualisation. AT = Achilles tendinopathy

In *gastrocnemius medialis* analysis we only found a difference between conditions (F=67.50, p<0.001), with no difference between groups (F=1.90, p=0.18) and no condition × group interaction (F= 1.70, p=0.19). Similarly to what we observed in *gastrocnemius lateralis*, both groups had greater variation of discharge rate during *feet in*, with a mean difference of 1.4 (1.1 to 1.7); mean variation of discharge rate for f*eet in* was 14.2 (13.1 to 15.2) and 12.7 (11.7 to 13.7) for *feet neutral*. (Figure 4).

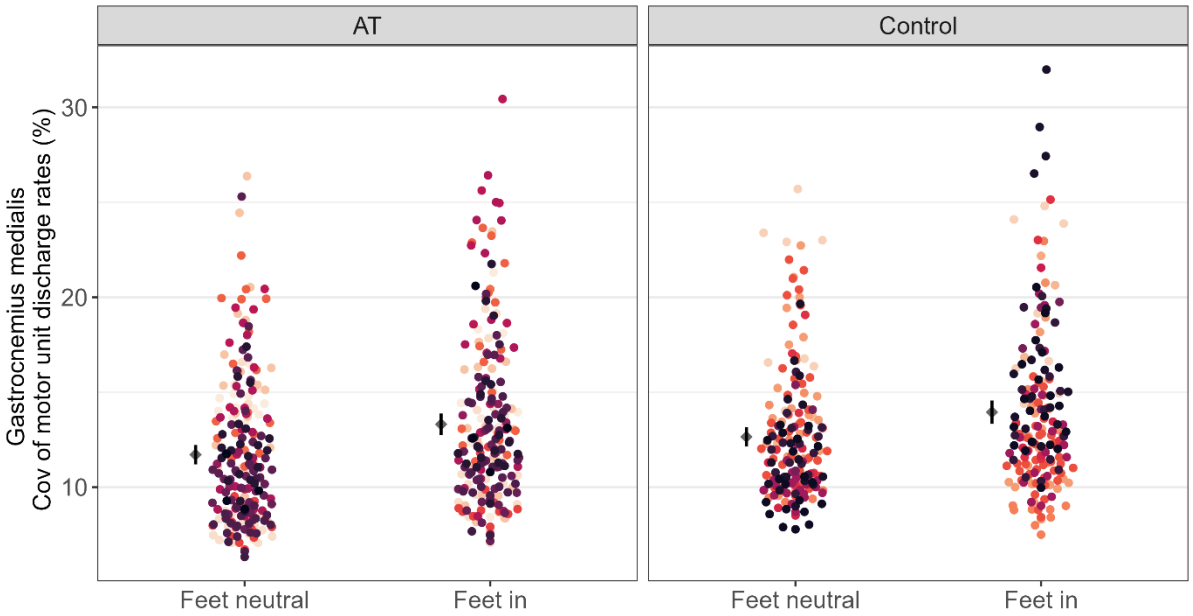

Figure 4
Gastrocnemius medialis coefficient of variation (Cov) of motor unit discharge rate with *feet neutral* and *feet in* between groups during the tracked motor unit analysis. Each dot represents a single motor unit data point, coloured by participants. Mean and 95% confidence interval are offset to the left to facilitate visualisation. AT = Achilles tendinopathy

3.2.1 Non-tracked motor unit analysis

Analysis of *gastrocnemius lateralis* motor unit mean discharge rate showed no difference between conditions (F=1.46, p=0.22), or groups (F=0.08, p=0.77) and no condition × group interaction (F=0.95, p=0.32).

(Figure 5 A).

Gastrocnemius medialis, motor unit analysis on the other hand; showed similar results to the tracked motor unit analysis, demonstrating difference between conditions (F= 18.28, p<001) but no differences between groups (F=2.30, p=0.13) and no condition × group interaction (F= 0.40, p=0.55). Discharge rate was lower during *feet in* with a mean difference between conditions of -0.38 pps (-0.5 to -0.2), mean discharge rate was 10.4 pps (9.9 to 10.9) for *feet in* and 10.8 pps (10.3 to 11.3) for *feet neutral* (Figure 5 B).

3.2.2 Non-tracked motor unit analysis – Experiment 2

Similarly to the results found in experiment 1, *gastrocnemius lateralis* motor unit mean discharge rate showed no difference between condition (F=0.01, p=0.91). Mean difference between conditions was 0.03 pps (-0.51 to 0.57), with mean discharge rate of 8.37 pps (7.49 to 9.24) for *feet in* and 8.34 pps (7.49 to 9.2) for *feet neutral.*

Also in agreement with the results obtained from experiment 1, *gastrocnemius medialis* motor unit analysis showed a difference between conditions (F= 6.30, p=0.01). Mean discharge rate for *feet in* was 9.21 pps (8.37 to 10.0) and 9.65 pps (8.81 to 10.5) with *feet neutral (m*ean difference between conditions; -0.44 (-0.78 to -0.09)).

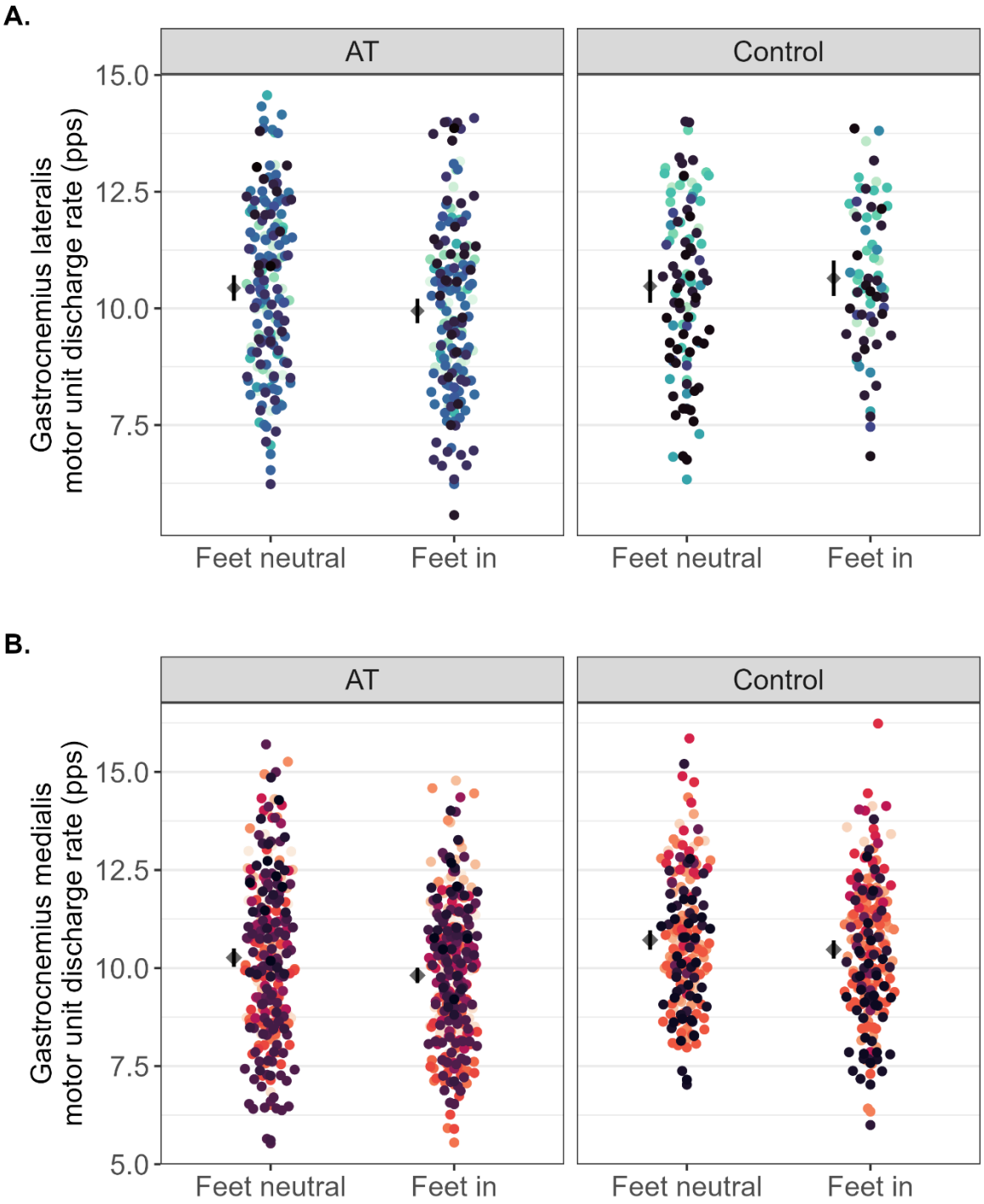

Figure 5
Motor unit discharge with *feet neutral* and *feet in* between groups during the individual motor unit analysis. Each dot represents a single motor unit data point, coloured by participants. Figure **A.** represents data from *gastrocnemius lateralis*; figure **B.** displays data from *gastrocnemius medialis*. Mean and 95% confidence interval are offset to the left to facilitate visualisation. pps = pulse per second. AT = Achilles tendinopathy

3.3 Cumulative Spike Train analysis (normalised neural drive)

Cumulative Spike Train analysis for *gastrocnemius lateralis* showed no differences between conditions (F=3.30, p=0.07), or groups (F=0.28, p=0.59) and no condition × group interaction (F= 1.48, p=0.23), (Figure 6 A).

Cumulative Spike Train analysis for the *gastrocnemius medialis* also showed no differences between conditions (F=0.03, p=0.85), or groups (F=2.35, p=0.13) and no condition × group interaction (F= 1.95, p=0.17), (Figure 6 B).

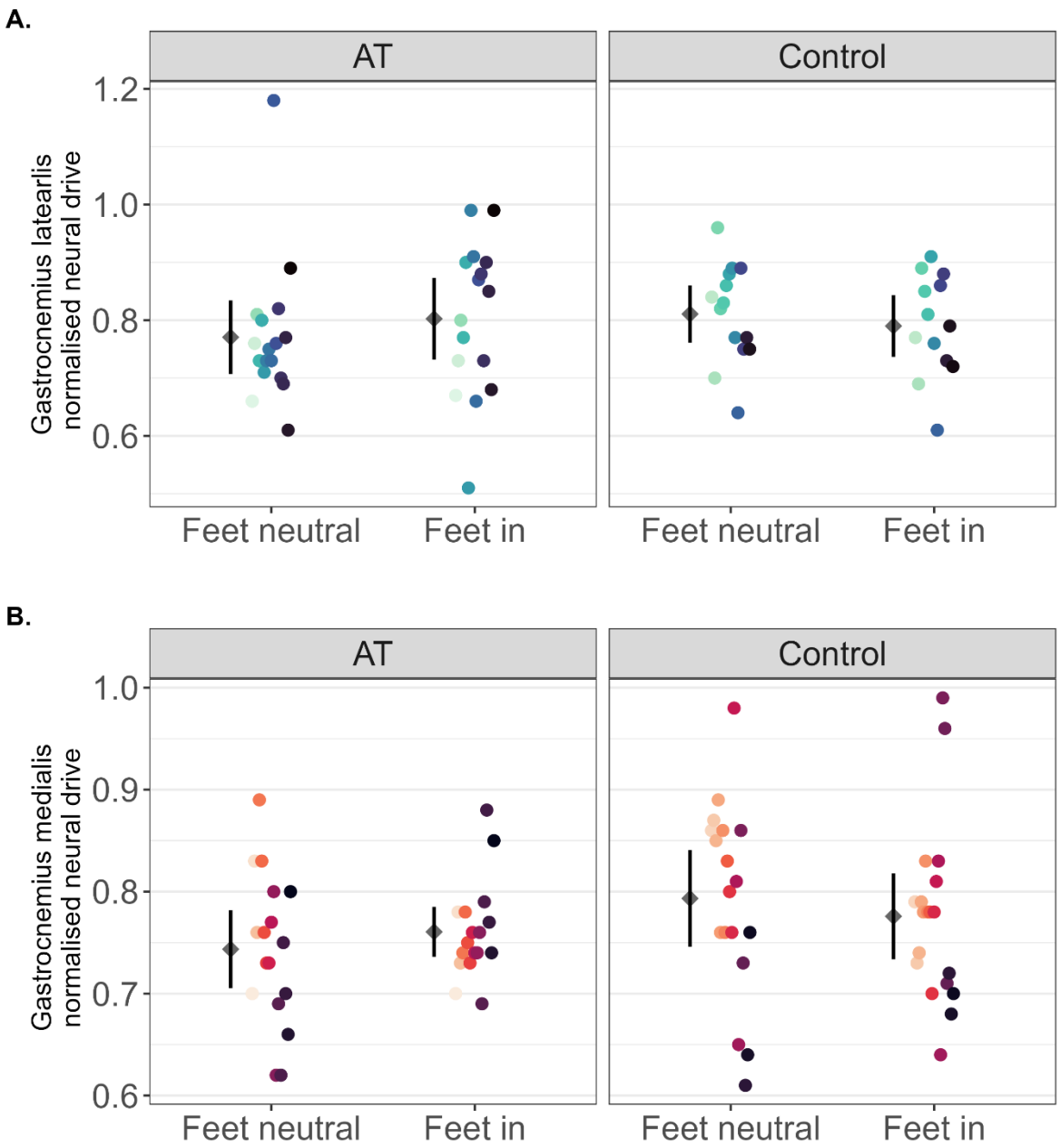

Figure 6
Cumulative spike train analysis during feet positioned inwards and feet neutral between groups during the individual motor unit analysis. Cumulative sum was normalised by the number of motor units used in each participant's analysis (normalised neural drive). Each dot represents data point by participants. Figure **A**. represents data from *gastrocnemius lateralis*; figure **B.** displays data from *gastrocnemius medialis*. Mean and 95% confidence interval are offset to the left to facilitate visualisation. pps = pulse per second. AT = Achilles tendinopathy

3.4 Peak torque and SLHR

We found no differences between groups for peak isometric torque (F=2.77, p=0.10). Peak plantar flexor isometric torque in the Achilles tendinopathy group was 137 N·m (126 to 148) and 131 N·m (120 to 141) in the control group. Data for the SLHR was not normally distributed in the control group due to the presence of outliers. However, after running a sensitivity test, we still found similar statistical results and effect size on both analyses. The Achilles tendinopathy group performed on average -13.2 (24.5 to 1.82) SLHR (p=0.024, d=-0.77, large effect size[30]) than controls when tested with outliers. When outliers were removed, the Achilles tendinopathy group performed about 34 (29 to 39) repetitions, 7.3 (-13.9 to -0.75) fewer SLHR (p=0.03, d=-0.78) than controls 41 (36 to 45) (Figure 7).

Kinesiophobia values for the Achilles tendinopathy group was 32.1 (±6.5) and there was no correlation between levels of kinesiophobia and SLHR values, r = 0.1, p=0.69.

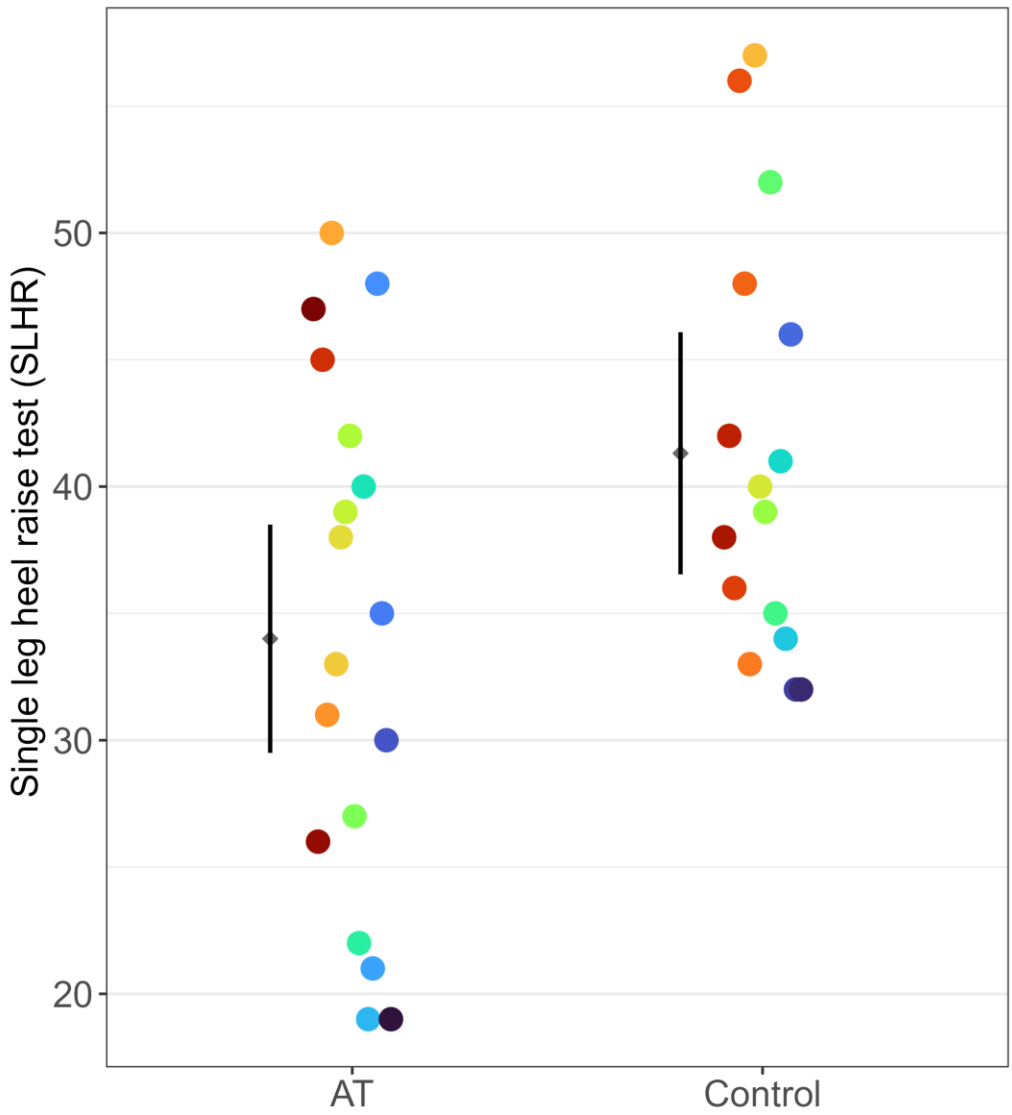

Figure 7
Single leg heel raise (SLHR) data is coloured by participant. Mean and 95% confidence interval are offset to the left to facilitate visualisation. AT = Achilles tendinopathy

4. Discussion

4.1. Main findings

We investigated the effect of different foot position during bilateral isometric plantarflexion in *gastrocnemius lateralis and medialis* neural drive, in runners with and without chronic Achilles tendinopathy. We analysed motor unit discharge rates of *gastrocnemius lateralis* and *gastrocnemius medialis* individual responses and tracked across conditions and

compared them between groups and conditions (*feet neutral*, *feet in*). We also looked at the coefficient of variation of motor unit discharge rate of *gastrocnemius lateralis* and *gastrocnemius medialis* as well as the normalised neural drive to each muscle during the two conditions and between groups.

Contrary to what is described in the literature, we found that bilateral plantarflexion with feet pointed inwards reduced both *gastrocnemii* motor unit discharge rate, instead of increasing it. These inconsistencies between the outcomes from our main experiment and the available evidence motivated us to conduct a second experiment. In experiment 2, we expanded our testing protocol to control more variables, as explained in detail in the methods section. This time, we recruited a different subgroup of healthy individuals and utilised a dynamometer for the plantar flexor isometric tasks using the same two conditions (*feet in* and *feet neutral)*. Despite these modifications in set up, our results remained consistent with those of experiment 1, and their implications are discussed in the subsequent paragraphs.

We found no effect of Achilles tendinopathy in *gastrocnemii* motor unit discharge rates during isometric plantarflexion. In our main experiment in the tracked analysis, plantarflexion with *feet in* reduced the motor units discharge rates of both *gastrocnemius lateralis* and *gastrocnemius medialis* compared to *feet neutral*, but in the non-tracked analysis, *feet in* reduced motor unit discharge rate only in *gastrocnemius medialis* discharge rate. These changes in discharge rate derived from the different foot position occurred without any changes in neural drive.

Through the tracked analysis we can observe the discharge responses of motor units and gain valuable insight into how each condition affected their discharge frequencies. Contrary to our initial hypothesis, the tracked motor unit analysis revealed that, rather than increasing motor unit discharge rate, turning the *feet in* reduced motor unit firing for both *gastrocnemius lateralis* and *gastrocnemius medialis* compared to *feet neutral.* This effect was observed in participants with and without Achilles tendinopathy. Alongside that, the coefficient

of variation of motor unit discharge rate in both *gastrocnemius lateralis* and *medialis* increased with *feet in* compared to *feet neutral*, suggesting a higher degree of variability in motor unit discharge frequency in this position. Coefficient of variation of motor unit discharge rate is related to force output during submaximal isometric contractions and this increase in the discharge variability can partially explain the reduction in muscle performance[31]. It is possible that the sustained plantarflexion position with *feet in* creates a more unstable position, leading to greater variability in motor unit discharge frequency during the 20-second contraction. Greater instability can stimulate inhibitory proprioceptive feedback from muscle spindles and Golgi tendon organs, which may impact motor unit behaviour in various ways[32,33], including reducing motor unit discharge rate. In addition, it is possible that this increased joint stretch created by the testing position *feet in*, may increase the contribution of passive joint structures (stretch-sensitive afferent receptors in ligaments) in conjunction with the ankle muscles to increase joint stiffness and provide better support and joint stability[33–35]. These afferent receptors from the ankle ligaments may assist with the adjustment of the activity of other ankle stabilizers during plantarflexion such as the *soleus* and the *fibularis longus*[36,37]. S*oleus* and *fibularis longus* can work as ankle stabilisers and are highly responsive to sudden change in body position[36,37]; however, this is only speculation as these muscles were not monitored during testing.

In experiment 2 we implemented measures to address all the factors we thought could have influenced our results. We controlled participant's stability during testing position to minimise the influence of motor unit discharge variability which could have been influenced by a more unstable base of support in the *feet in* position. By using a seated and stable position, we could better control and test the hypothesis of inhibitory proprioceptive stimuli influencing our experiment 1 results. To account for the possible increased contribution of passive joint structures and reduced plantarflexor demand to maintain isometric testing position, we used

visual trace feedback to ensure participants maintained isometric torque throughout the contraction. Despite implementing these controls in experiment 2, our results yielded similar findings as in experiment 1.

The control of muscle force occurs as a modulation of the rate of active motor unit discharge and the recruitment of new motor units[38]. The tracked motor unit analysis excludes motor units identified in only one condition. Conversely, the analysis of non-tracked motor units, considers all identified motor units in both conditions, and thus includes a different sample of motor units, making it also a relevant analysis. When considering all identified motor units our results for *gastrocnemius lateralis* were different, showing no difference in motor unit discharge rates between conditions. On the other hand, g*astrocnemius medialis* had lower motor unit firing rate during *feet in*, which was a similar response to that observed in the tracked motor unit analysis. The analysis using all identified motor units, is similar to that by Hug and colleagues[11] in non-runners; however, their results differ from ours. Specifically, Hug et al. (2020), found higher motor unit discharge rate in *gastrocnemius lateralis* during *feet in* but no difference in *gastrocnemius medialis*. It is important to note that our study had more than double the number of participants and a larger overall sample of motor units for analysis. In fact, we had twice the amount of motor units for *gastrocnemius lateralis*. Additionally, in our study, both groups showed similar responses for between condition and muscle analysis. It is also important to acknowledge that Hug et al. (2020) had the advantage to monitor both muscles in the same contractions, which is a strength of their study in comparison to ours. However, our study highlights a significant finding, indicating that *gastrocnemius lateralis* motor unit discharge rate during isometric standing plantarflexion with different foot positions displays a high variability amongst individuals, irrespective of the presence of tendinopathy. This can be observed in Figure 1B where mean motor unit discharge rate by participant is showed across conditions. In both AT and control groups there were varied responses in motor

unit mean discharge rates between conditions in *gastrocnemius lateralis*, with some individuals displaying higher and others lower discharge rates when their feet were internally rotated. Perhaps, the sample assessed in Hug's study[11] had a preferential response to increase motor unit discharge rates in *gastrocnemius lateralis. Gastrocnemius medialis* mean individual responses to change in feet position, Figure 1B, had lower discharge rate with *feet in* across the board in both groups. It is worth noting that testing position for *feet in* and *feet neutral* conditions in our experiment 1 was the same as described in Hug et al. A previous study[7] from our group observed different responses in motor unit discharge rates in *gastrocnemius lateralis* in runners with Achilles tendinopathy during the increase in torque intensity, suggesting a lower neural drive to *gastrocnemius lateralis*, and this was not observed in the present study. However, in this previous study[7] we measured motor unit characteristics of the triceps surae during seated unilateral isometric plantar flexion contraction using a dynamometer and a torque isometric plantarflexion. This time we were unable to measure torque during the isometric task. Consequently, we cannot make comparisons between these results and those from the other study that used a different set up.

The Achilles tendon is composed of the *soleus*, *gastrocnemius medialis* and *gastrocnemius lateralis* sub-tendons intertwined together[5,39,40]. These sub-tendons are partially independent and experience heterogeneous strains during movement[5,41,42] A study[39] compared the effect of feet position in *gastrocnemius medialis* and *gastrocnemius lateralis* sub-tendon`s distal movement and elongation during ankle plantar flexion in prone position. The authors observed that a horizontal change in feet position (feet in and feet out) affects the Achilles tendon motion, and that different foot positions affect individual sub-tendons of the *triceps surae* differently. During submaximal isometric actions with *feet in*, the *gastrocnemius lateralis* sub-tendon lengthened more than that of the *gastrocnemius medialis* in the same position and vice-versa. However, the authors found that during a 20 and 40% maximal

voluntary contraction with *feet in*, there was no difference between *gastrocnemius medialis* and *gastrocnemius lateralis* muscle electrical activity (measured using root mean square electromyography- RMS EMG)[39]. This aligns with the results of our experiment 2 for *gastrocnemius lateralis;* where we used a similar submaximal isometric value of 25%. Furthermore, Nunes et al[12] found greater hypertrophy in *gastrocnemius lateralis* after a period of resistance training using a leg-press machine using feet positioned inwards. The seated set up in the leg-press, the added resistance and the dynamic contraction of the plantar flexors may have induced a different response from the *triceps surae* to what we found in our study. This could be attributed to the higher strain created in the individual subtendons and muscle fibres during plantarflexion in the leg-press machine. Perhaps the lower demand on the plantar flexors from our body weight isometric plantar flexion, or 25% isometrics was not enough to change the discharge behaviour of the *gastrocnemii* motor units.

Additionally, to better understand the effect different feet positions have on the neural drive to these muscles, we tested motor units discharge characteristics of the *gastrocnemius lateralis* and *gastrocnemius medialis* using another analysis, the cumulative spike train analysis (normalised neural drive)[23,26]. Cumulative spike train analysis gives a reliable and strong indication of the neural drive to a muscle[11,22–24] as it represents a sum of all identified motor unit discharges during the contractions. For the cumulative spike train analysis we included all identified motor units, including ones that discharged intermittently during the 20 second isometric plateau (these motor unit were excluded from the tracked analysis). This phenomenon of intermittent discharges, is referred to as motor unit rotation[43], and it is believed to represent a normal modulation strategy used by the central nervous system. The central nervous system uses different strategies to adjust for force requirements such as modifying the discharge rates or the recruitment of motor units. Such changes may occur within the same level of neural drive[43]. The normalised neural drive represents the summation of all motor unit discharges

during the contraction, reflecting the level of neural drive. The absence of change we observed in the normalised neural drive between the two conditions demonstrates that the change in feet position during standing plantarflexion from *feet neutral* vs *feet in* had no effect in the neural drive to the *gastrocnemii*.

Emerging evidence from studies of both the triceps surae and the quadriceps suggests that individuals exhibit a highly variable and unique muscle activation patterns[44] during activities such as cycling and walking, and during isometric contractions in the triceps surae[45] and the quadriceps[46]. We also observed high inter-individual variability in participant responses, in particular for *gastrocnemius lateralis* motor unit discharge rates when comparing internally rotated and neutrally orientated foot positions.

Isometric peak torque was not different between groups, which aligns with other studies[7,47]. It becomes clear that plantar flexor isometric peak torque is not lower in runners with chronic Achilles tendinopathy. Conversely, an important muscle deficit observed in this group, which also seems consistent across studies, is plantar flexor endurance[48–51]. We measured plantar flexor endurance using a single leg heel raise to failure (SLHR) test, paced with a metronome[52]. The Achilles tendinopathy group performed 18% fewer repetitions to failure than controls. This finding is similar to an earlier study[50] from our group where we found 28% less repetitions during SLHR in the Achilles tendinopathy.

The kinesiophobia scores for the Achilles tendinopathy group represents moderate kinesiophobia[16]; however our participants still performed a substantial number of SLHRs, without any Achilles tendon pain during testing. These results are similar to values reported in a subgroup of active individuals with Achilles tendinopathy[53]. Furthermore, there was no correlation between kinesiophobia values and SLHR performance Therefore, it is unlikely that kinesiophobia is a feature influencing muscle endurance in our sample of runners.

4.2 Strengths and Limitations

We tested the two *gastrocnemii* muscles in one of the most used exercises for treatment of Achilles tendinopathy, the standing heel raise, and tested a position variation suggested in the literature to increase the neural drive to *gastrocnemius lateralis*. However, we found that such change is highly variable between individuals regardless of whether they have Achilles tendinopathy. In some instances, turning the feet inward markedly reduced mean motor unit discharge rate to both muscles. This modification should not be used as rehabilitation strategy aiming to improve activation to *gastrocnemius lateralis* as the *feet in* position may have more variable effects than previous findings have suggested. In fact, when considering the objective of adopting *feet in,* which was to increase the discharge rate of *gastrocnemius lateralis*, it had the opposite effect in some participants.

We were unable to test both muscles during the same contractions, as the EMG device used was limited to up to 1 × 64-channel adaptor. During pilot testing using one 32-channel electrode in each muscle to record both muscles together did not yield sufficient motor units for analysis and several participants had no detectable motor unit firings in *gastrocnemius lateralis*. Another limitation was not testing the *soleus*. Future studies might consider using devices that allow recording of all three muscles of the triceps surae during the same contractions. A between muscle coherence analysis would be another valuable method when estimating the magnitude of neural drive and the contribution of individual muscles of the triceps surae to force production in runners with Achilles tendinopathy.

Our study helps to reinforce findings from the literature, showing that deficits in triceps surae endurance are an issue in runners with Achilles tendinopathy. Such deficits can be identified with a simple SLHR test that can be easily performed in a clinical setting. Furthermore, normative data for SLHR should be developed for both recreational and

competitive runners as this would serve as benchmarks to assess runners with Achilles tendinopathy.

5. Conclusion

Our paper was the first to investigate the effect different feet position has on motor unit discharge characteristics of *gastrocnemius lateralis* and *medialis* in runners with and without Achilles tendinopathy. Inward rotation of the feet reduced the neural drive to both muscles, which is the opposite of what was previously published in the literature using the same protocol. Therefore, it remains uncertain if performing plantarflexion exercise with feet pointed in would provide any additional benefits to the treatment of runners with Achilles tendinopathy. Further understanding of the mechanisms behind neuromodulation strategies to the triceps surae during plantar flexion driven by modified feet position needs to be investigated further. It is worth noting that runners with Achilles tendinopathy have low triceps surae endurance without deficits in peak isometric torque. Thus, muscle endurance deficits should be addressed during rehabilitation for this group.

Conflict of interests

The authors declare no conflict of interest with the present research.

Data availability

Data and R code are available at https://github.com/GabeFernandess/feet_AT

Acknowledgments

The authors declare not having received funding for this study.

The authors thank all the volunteers who participated in this study for their contribution to the development and achievement of this research.

Author contributions

GLF and GST designed the study. GLF conducted the experiments. GLF analysed the data, conducted the statistical analysis in R and drafted the first version of the manuscript. GLF and LBRO developed a MATLAB script for motor unit discharge rate, coefficient of variation of motor unit discharge rate and cumulative spike train analysis. All authors critically revised the manuscript and provided valuable feedback. All the authors read and approved this final version of the manuscript.

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