

Dynamic muscle quality of the plantarflexors is impaired in claudicants with peripheral arterial disease and associated with poorer walking endurance

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Keywords: Specific tension, gastrocnemius, plantarflexors, strength, exercise

Acknowledgements: We would like to thank Professor Ian Chetter and Dr Risha Lane for patient recruitment and clinical guidance

Abstract

Objectives: Peripheral arterial disease and intermittent claudication (PAD-IC) negatively affects physical activity and function. There is evidence for plantarflexor muscle dysfunction and weakness, however, the extent to which this dysfunction can be attributed to reduced muscle size and/or quality is not yet known. This study investigated whether *in vivo* plantarflexor muscle quality during static and dynamic contractions are altered by PAD-IC and whether such changes are associated with impaired walking endurance (according to initial and absolute claudication distances). **Methods:** A total of 22 participants were recruited, consisting of 10 healthy controls and 12 claudicants with occlusion of the superficial femoral artery (seven unilateral and five bilateral). Muscle quality of the combined gastrocnemius muscles during static contractions was calculated by normalising the estimated maximal potential muscle force to the physiological cross-sectional area of both lateral and medial gastrocnemius. Muscle quality during dynamic contractions of the combined plantarflexor muscles was calculated as the ratio of peak voluntary concentric plantarflexor power and the summed volume of lateral and medial gastrocnemius. **Results:** Dynamic muscle quality was 24% lower in both the claudicating-limb and asymptomatic-limb groups compared to controls ($P=.017$ and $P=.023$). The differences were most apparent at the highest contraction velocity ($180^\circ/\text{s}$). Dynamic muscle quality was associated with reduced walking endurance ($R=.689$, $P=.006$ and $R=.550$, $P=.042$ for initial and absolute claudication distance, respectively). The claudicating-limb group demonstrated a trend towards reduced static muscle quality compared to controls (22%, $P=.084$). The relative contribution of the soleus muscle to plantarflexion maximum voluntary contraction was significantly higher in both claudicating-limb and asymptomatic-limb groups compared to controls ($P=.012$ and $P=.018$). **Conclusions:** The muscle strength of the plantarflexors in those with PAD-IC appears to be impaired at high contraction velocities. This may be

1 explained by some reduction in gastrocnemii muscle quality and a greater reliance on the
2 prominently type I fibred soleus muscle. The reduced dynamic capability of the plantarflexor
3 muscles was associated with disease severity and walking ability, therefore efforts to improve
4 plantarflexor power through dynamic exercise intervention are vital to maintain functional
5 performance.

6

7

1 **Introduction**

2 Peripheral arterial disease and intermittent claudication (PAD-IC) refers to a chronic lower-
 3 limb atherosclerotic disease that primarily affects the older population⁽¹⁾. The disease
 4 negatively impacts on functional ability⁽²⁾, physical activity levels⁽³⁾ and quality of life⁽⁴⁾. The
 5 most frequent site of claudication pain is in the plantarflexor (triceps surae) muscles⁽⁵⁾, where
 6 there are clear signs of dysfunction, such as reduced ankle power generation during gait^(6,7).
 7 However, the few previous studies directly investigating plantarflexor function are
 8 inconsistent about whether strength is diminished in claudicants compared to healthy
 9 controls⁽⁸⁻¹⁰⁾. Plantarflexor strength is a strong predictor of mortality in men with PAD-
 10 IC^(11,12), so it is essential to understand the nature of any strength impairments and the
 11 underlying mechanisms, so that exercise interventions may be designed accordingly.

12

13 The “strength” of a muscle group, as measured externally by hand-held or isokinetic
 14 dynamometer, depends on numerous factors, including: muscle size and quality; voluntary
 15 activation level; any resistance to intended effort from co-activation of the antagonist muscle;
 16 and length of the moment arm about which the muscle is working⁽¹³⁾. Muscle quality during
 17 isometric contractions (often known as specific tension or specific force) is defined as the
 18 maximal potential muscle force (calculated using the above factors) normalised to the
 19 physiological cross-sectional area⁽¹³⁾. In PAD-IC voluntary joint moments have been
 20 measured previously⁽⁸⁻¹⁰⁾ but the factors that determine externally-measured strength have
 21 not. Consequently, the underlying mechanisms explaining any disease-induced strength
 22 losses have not been identified, and muscle quality has not yet been quantified in claudicants.
 23 Thus, it remains unknown if/how any deleterious changes in muscle properties contribute to

1 reduced functional ability. Therefore, it is not apparent exactly how exercise interventions
2 should be optimally designed to improve physical function.

3
4 Muscle quality is known to reduce with ageing and disuse⁽¹⁴⁾ and increase in response to
5 resistance training⁽¹⁵⁾. It is reasonable to assume muscle quality would be altered in
6 claudicants given that the disease primarily affects the elderly⁽¹⁾ and is associated with
7 reduced physical activity⁽³⁾. Additional factors associated with PAD-IC that may further
8 affect muscle quality include intra-muscular fat infiltration⁽¹⁶⁾, which would reduce the
9 quantity of contractile material within a given muscle, and altered fibre type composition,
10 with contradicting findings of shifts towards more type II (fast-twitch)⁽¹⁷⁻¹⁹⁾ and conversely to
11 more type I fibres (slow-twitch)^(20,21). As specific tension differs between fibre types⁽²²⁾ any
12 changes at the fibre level may affect whole muscle quality, force producing potential and thus
13 functional strength. If isometric muscle quality is altered with PAD-IC then it follows that the
14 ability to utilise this force producing potential during dynamic contraction would also be
15 impaired, especially if the proportion of fast type-II fibres is reduced. Any change in muscle
16 quality might also reduce the responsiveness of muscles to exercise training, a vital
17 component of treatment for PAD-IC⁽⁵⁾. This may contribute to the inconsistent effects
18 reported following progressive resistance training in claudicants⁽²³⁾.

19
20 The purpose of the study was to determine whether PAD-IC causes changes in the strength
21 characteristics of the plantarflexors and quality of the gastrocnemii muscles. This was
22 achieved by exploring relationships between static and dynamic measures of muscle quality
23 and disease severity (as assessed through the ankle brachial pressure index; ABPI), and
24 comparing asymptomatic and symptomatic limbs of claudicants to those of healthy controls.

To explore the effects of muscle quality on function, correlations were performed between the factors affecting muscle strength and walking endurance (quantified through initial and absolute claudication distances). Our first hypothesis was that increased disease severity would be associated with lower voluntary isometric plantarflexion moments and concentric plantarflexion powers, and that this would be explained by smaller muscle size and reduced static and dynamic muscle quality. Our second hypothesis was that walking endurance would be associated with reduced maximum isometric plantarflexion moment, concentric plantarflexion power, and static and dynamic muscle quality.

Methods

Participants

Ethical approval was granted by the National Health Service Research Ethics Committee (REC reference: 11/YH/0335). A total of 22 participants were recruited consisting of 12 claudicants (seven unilateral, five bilateral) and ten healthy controls (Table I). Claudicants were recruited via consultant referral from a local outpatient vascular clinic. Male and female participants aged between 55-80 years who were diagnosed with Rutherford Grade 1 Chronic Limb Ischemia⁽²⁴⁾ with an arterial narrowing of the superficial femoral artery were considered for inclusion. Those with extensive disease were also included, however the primary stenosis identified using vascular imaging was located in the superficial femoral artery for all participants. Healthy controls were recruited from the local community via email and word of mouth. Individuals deemed to have severe or acute cardiovascular, musculoskeletal or pulmonary illness were excluded along with those with a previous lower-limb joint replacement. Any individuals with a history of neurological disorders, stroke, myocardial

infarction or life-limiting diseases, such as cancer, were also excluded. All participants gave written informed consent prior to testing

Disease severity

Disease severity was determined using the ankle brachial pressure index/ratio (ABPI).

Systolic blood pressure was measured in the posterior tibial and dorsalis pedis arteries of each leg and the brachial pressure of both arms, separately, using a sphygmomanometer cuff and a hand held Doppler instrument (Parks Medical Electronics Inc, Oregon, USA). ABPI

measures for both lower limbs were taken pre- and post- a standardised exercise protocol performed on a motorised treadmill (5minutes at 2.5km/h at 10% incline)⁽⁵⁾. Those unable to

complete 5 minutes were able to stop at the point of maximum claudication pain. In

accordance with standard protocol, the ABPI for both legs was then calculated as the higher of the two leg artery pressures normalised to the higher brachial pressure of the two arms⁽⁵⁾.

The post-exercise ABPI was subsequently used to categorise the limbs of the participants as well as classify disease severity. Any limb with an ABPI <0.9 was classified as claudicating and represents the ‘claudicating-limb’ group. The asymptomatic limb of the unilateral claudicants was identified (ABPI \geq 0.9) and represents the ‘asymptomatic-limb’ group.

Control participants also undertook the exercise protocol to determine ABPI values, confirming the absence of PAD-IC.

Walking endurance

The 6-minute walk test was modified to be performed on level ground and combined with a pain rating based on the ACSM claudication pain scale⁽²⁵⁾. This method is a reliable

alternative to treadmill walk tests⁽²⁶⁾ and allows participants to walk for longer than 6-minutes if they are able. Patients walked continuously along a 10m walkway at a self-selected pace and informed the investigator of the level of pain and position on the pain scale every 20m. Initial claudication distance was classed as level 1 on the pain scale and signified the onset of pain. Absolute claudication distance was classed as level 4 on the pain scale, represented maximal pain and signified the end of the test.

Experimental protocol

The static muscle quality (specific tension) of the combined gastrocnemii muscles was defined as maximal potential Achilles tendon force (equation 1) normalised to the reduced gastrocnemii physiological cross-sectional area (equation 2)⁽²⁾;

$$1) \text{ Maximal Achilles tendon force} = \frac{(\text{Joint MVC} + \text{Antagonist moment} - \text{Soleus moment}) * 100}{(\text{Moment arm} * \text{Voluntary activation})}$$

$$2) \text{ Reduced gastrocnemii PCSA} = \left(\frac{GL V}{GL FL_{MVC}} \right) * \cos \cdot GL \theta_{MVC} + \left(\frac{GM V}{GM FL_{MVC}} \right) * \cos \cdot GM \theta_{MVC}$$

where *PCSA* is physiological cross-sectional area, *GL* is lateral gastrocnemius, *GM* is medial gastrocnemius, *V* is muscle volume, *FL* is fascicle length and θ is pennation, both quantified during maximum voluntary contraction (MVC).

The methods used to determine each component of these equations are detailed below.

Measurements and calculations for maximal Achilles tendon force

Joint moment

Participants were secured into the chair of an isokinetic dynamometer (Biodex System 3, Biodex Medical Systems Inc, New York, USA), sat in an upright position with their hip flexed (85°), knee extended (0°) and the lateral malleolus aligned with the centre of rotation of the dynamometer arm during muscle contraction. To ensure isometric muscle strength of the gastrocnemii muscles was measured at the optimum joint angle, MVCs were elicited at 10° intervals from maximum plantarflexion to maximum dorsiflexion. Verbal encouragement was given throughout all trials. Three maximal isometric plantarflexion contractions were performed at each joint angle and the peak gravity corrected joint moment was taken forward for further analysis. For all participants, peak joint moment was achieved at maximum dorsiflexion, which was consistent with healthy populations⁽²⁸⁾. All further trials to establish voluntary and antagonist activation, soleus contribution, fascicle length and pennation were performed in this joint position.

Antagonist co-activation

The contribution of antagonist muscle activity to the measured joint moment was estimated from the surface electromyography (EMG) (Telemetry 2400T, Noraxon, Arizona, USA) of the tibialis anterior, to represent the ankle dorsiflexors. Electrode placement and skin preparation were according to standardised guidelines⁽²⁹⁾. The EMG of the tibialis anterior was recorded at 2000Hz synchronously with joint moments during the isometric plantarflexion contractions (working as an antagonist) and then combined with the EMG-moment relationship during dorsiflexion contractions (working as an agonist) to estimate the antagonist co-activation moment⁽²⁷⁾.

1 *Soleus contribution*

2 The contribution of soleus to plantarflexion moment was quantified with additional
 3 plantarflexion contractions with the knee flexed where gastrocnemii muscle does not
 4 contribute to the measured joint moment⁽²⁸⁾. Activation changes between the two positions
 5 were corrected using the EMG-moment relationship in two joint configurations using
 6 equation 3;

$$7 \quad 3) \text{ Soleus moment Knee } 0^\circ = \frac{\text{Soleus moment Knee } 90^\circ * \text{Soleus EMG Knee } 0^\circ}{\text{Soleus EMG Knee } 90^\circ}$$

8

9 *Activation capacity*

10 The level of muscle activation achieved during voluntary contraction was calculated using the
 11 interpolated twitch technique⁽³⁰⁾. Percutaneous neuromuscular electrical stimulation (200 μ s
 12 pulse duration, 400 V; Digitimer model DS7AH, Welwyn Garden City, UK) was used to
 13 evoke involuntary twitches of the plantarflexor muscles. Maximal current intensity was
 14 determined by progressively stimulating the calf with electrical twitches of increasing current
 15 steps of 50 mA until further increments in current did not increase joint torque. Once this
 16 level was established, a superimposed twitch was evoked at the point of isometric MVC and a
 17 resting twitch was applied approximately 3 s afterwards. This was repeated during three trials
 18 at peak joint angle. The percentage of voluntary activation was calculated using equation
 19 4⁽³¹⁾:

$$20 \quad 4) \text{ Voluntary activation} = \left(1 - \frac{\text{Superimposed twitch}}{\text{Resting twitch}} \right) \times 100$$

21

1 *Measurement of moment arm length*

2 Achilles tendon moment arm length was calculated using the tendon travel method⁽³²⁾ and
 3 using ultrasound imaging (50-mm probe length, MyLab50 x-vision, Esaote Biomedica,
 4 Genoa, Italy) to quantify linear myotendinous junction displacement.

5

6 *Measures of muscle size at rest and architecture during MVC*

7 Participants were asked to lie prone on a plinth with their ankle plantarflexed and supported
 8 on the bed with the musculature relaxed. To quantify lateral and medial gastrocnemius
 9 muscle volume, serial transverse ultrasound images of each muscle were overlaid to
 10 reconstruct a full anatomical cross-sectional area at 25, 50 and 75 % of muscle length.
 11 Muscle volume was then calculated using the anatomical cross-sectional area's and muscle
 12 length by considering each muscle as two cones at either end of two truncated cones which is
 13 a reliable and valid alternative to MRI imaging⁽¹⁵⁾. Lateral and medial gastrocnemius volume
 14 were combined for total gastrocnemii muscle volume.

15

16 Optimum fascicle length and pennation angle during MVC were measured from synchronised
 17 sagittal-plane ultrasound video-recordings of the muscle belly of lateral and medial
 18 gastrocnemius , captured at 25Hz. The frame corresponding to peak tendon force was
 19 extracted for each muscle during three separate MVC trials and analysed in ImageJ (version
 20 1.44, NIH, USA)⁽²⁷⁾.

21

22 *Measures of dynamic muscle quality*

Isokinetic plantarflexion joint power was measured across the participants' full range of motion at angular velocities of 60, 90, 120 and 180 °/s in the same dynamometer set up described above. These velocities were selected to represent the range of joint speeds experienced during gait⁽³³⁾. Five concentric contractions were performed at each velocity. Peak power from each trial was recorded and the power-velocity profile constructed. The volume-normalised power-velocity relationship was established by normalising power at each velocity to gastrocnemii muscle volume, since the relative size of the gastrocnemii muscles and the soleus remain constant with ageing⁽³⁴⁾. Dynamic muscle quality was defined as peak power normalised to gastrocnemii muscle volume. Adequate rest (>1 min) was provided between trials.

Statistical analysis

A linear relationship exists between advancing age and dynamic muscle quality⁽³⁵⁾ therefore a Pearson's partial product-moment correlation was performed to control for the influence of age and assess relationships between disease severity (as assessed by ABPI), walking endurance (as assessed by initial and absolute claudication distance) and gastrocnemii physiological cross-sectional area, volume and measures pertaining to static and dynamic muscle quality.

A one-way ANOVA was conducted to determine if significant between differences existed between the claudicating-limb and asymptomatic-limb groups and healthy controls. Data were assessed for normality, using Shapiro-Wilk's test for normality, and for outliers through

box plot analysis. Sidak post-hoc was applied when appropriate. Mann-Whitney *U* tests were performed for non-parametric measures.

For all statistical tests, significance was accepted at $P \leq .05$ and trends were accepted at $P < .10$. For correlation and regression analyses, a moderate relationship was accepted as $R = .40-.59$, a strong relationship was accepted as $R = .60-.79$ and a very strong relationship was accepted as $R = .80-1^{(36)}$. Since low ABPI values indicate high disease severity a positive relationship indicates a decrease in the respective parameter with worsening disease.

Results

No significant differences were found between groups in height ($P = .230$) or mass ($P = .167$) (Table I). Whilst age and gender were not exactly matched between groups, the between group age-difference (~ 5 years) was not statistically significant and likely too small to have influenced our results⁽³⁵⁾ and there is no reason to believe gender differences influenced our measures of muscle quality⁽²⁷⁾. Between-group differences in ABPI were consistent with disease presentation. One participant (unilateral claudicant) had type II diabetes that was being managed by diet intervention only. Inspection of this data, in comparison to the full claudicant cohort, revealed adaptations that were in keeping with those with similar ABPI values and of similar ages. We do not believe that, for this individual participant, diabetes was a confounding factor.

- 1 **Table I.** Participant characteristics. Data are presented as group mean (SD) unless otherwise
 2 stated. BMI – Body mass index, ABPI – Ankle brachial pressure index.

	Claudicating- limb	Asymptomatic- limb	Healthy control
#	12	7	10
% Males	75	57	40
Age (years)	65.0 (6.7)	66.1 (7.5)	61.6 (3.6)
Height (m)	1.71 (0.08)	1.69 (0.10)	1.66 (0.09)
Mass (Kg)	81.5 (18.2)	82.3 (21.1)	72.3 (10.9)
BMI (Kg/m²)	27.7 (5.1)	28.5 (4.8)	26.1 (3.7)
ABPI pre-exercise	0.81 (0.23)	1.01 (0.16)	0.99 (0.10)
ABPI post-exercise	0.55 (0.21)	0.90 (0.06)	1.00 (0.13)
Initial claudication distance (m)	105 (45)	N/A	N/A
Absolute claudication distance (m)	265 (136)	N/A	N/A
% Hypertension	50	43	10
% Hypercholesterolemia	58	71	20
% past smokers	58	57	30
% present smokers	42	43	0

3

4

1 *Correlations*

2 Increased disease severity was not associated with any change in isometric MVC joint
3 moment or static muscle quality, but was significantly correlated with reduced power at
4 120°/s and reduced power/volume at 120°/s and 180°/s, the latter being defined as
5 significantly reduced dynamic muscle quality (all R and p values are presented in Tables II,
6 and III). A trend was observed for smaller gastrocnemii physiological cross-sectional area
7 with higher disease severity ($P=.073$) (Table II).

8

9 Shorter initial and absolute claudication distance were associated with larger gastrocnemii
10 muscle volume, lower activation capacity and reduced dynamic muscle quality. Shorter
11 absolute claudication distance was also correlated with reduced static muscle quality and
12 shorter moment arm lengths (all R and p values are presented in Tables II and III). Trends
13 towards an association existed between shorter absolute claudication distance and reduced
14 tendon force ($P=.053$) (Table II).

15

16

Table II. Pearson correlations (controlled for the influence of age) between disease severity (ABPI), walking endurance (ICD and ACD) and gastrocnemii size and measures of static muscle quality. PCSA – physiological cross-sectional area. Dark shaded values represent those reaching significance ($P \leq .05$) and light shaded values represent those demonstrating trends towards significance ($P < .10$).

		MVC	Soleus contribution	Activation capacity	Moment arm	Tendon force
ABPI	Correlation	.055	-.048	-.312	-.377	.198
	Significance	.847	.865	.258	.165	.480
ICD	Correlation	-.161	-.419	.589	-.424	.091
	Significance	.566	.120	.021	.116	.747
ACD	Correlation	.188	-.277	.514	-.668	.508
	Significance	.502	.318	.050	.007	.053
		Gastrocnemii volume	Gastrocnemii reduced PCSA	Static muscle quality		
ABPI	Correlation	-.368	.475	-.009		
	Significance	.117	.073	.976		
ICD	Correlation	-.858	-.386	.353		
	Significance	.000	.156	.257		
ACD	Correlation	-.851	-.079	.632		
	Significance	.029	.779	.011		

- 1 **Table III.** Pearson correlations (controlled for the influence of age) between disease severity (ABPI), walking endurance (ICD and ACD) and
 2 measures of dynamic muscle quality. Dark shaded values represent those reaching significance ($P \leq .05$).

Power		60°/s	90°/s	120°/s	180°/s
ABPI	Correlation	.071	.375	.674	.375
	Significance	.803	.398	.012	.168
ICD	Correlation	-.256	-.277	-.123	-.368
	Significance	.357	.318	.688	.177
ACD	Correlation	-.007	-.148	.064	-.262
	Significance	.981	.598	.836	.346
Power/Volume		60°/s	90°/s	120°/s	180°/s
ABPI	Correlation	.174	.323	.716	.541
	Significance	.600	.240	.006	.037
ICD	Correlation	.418	.364	.408	.689
	Significance	.121	.182	.166	.006
ACD	Correlation	.421	.263	.372	.550
	Significance	.118	.344	.211	.042

1 *Between group comparisons*

2 There were no differences between groups in isometric joint MVC, however the soleus
3 contribution to this joint moment was significantly greater in both the claudicating-limb and
4 asymptomatic-limb groups than in healthy controls ($P=.008$ and $P=.012$, respectively). The
5 claudicating-limb group demonstrated trends towards reduced static muscle quality compared
6 to healthy controls ($P=.084$) (Table IV).

7

8 At $120^\circ/\text{s}$ the asymptomatic-limb group demonstrated trends towards reduced power ($P=.071$)
9 with similar trends observed at $180^\circ/\text{s}$ in the claudicating-limb group compared to healthy
10 controls ($P=.100$). When normalised to gastrocnemii muscle volume, the asymptomatic-limb
11 group had significantly reduced power/volume at $120^\circ/\text{s}$ ($P=.036$) compared to healthy
12 controls and both the asymptomatic-limb ($P=.023$) and claudicating-limb ($P=.017$) groups
13 had significantly reduced power/volume at $180^\circ/\text{s}$ (dynamic muscle quality) (Figure 1).

14

15

Table IV. Group mean (SD) measures of static muscle quality. Dark shaded values represent those reaching significance ($P \leq .05$) and light shaded values represent those demonstrating trends towards significance ($P < .10$). PCSA – physiological cross-sectional area.

	Claudicating-limb	Asymptomatic-limb	Healthy control
MVC (Nm)	120.6 (32.5)	121.7 (36.1)	127.5 (34.3)
Antagonist co-activation (%)	2.74 (2.2)	2.35 (2.5)	2.01 (1.85)
Plantarflexor moment (Nm)	123.4 (31.8)	124.0 (35.4)	130.0 (36.9)
Soleus contribution (%)	62.7 (6.3) ^{Co}	62.1 (1.4) ^{Co}	55.6 (7.9)
Gastronemii moment (Nm)	45.1 (10.3)	46.9 (13.3)	58.1 (20.2)
Activation capacity (%)	90.7 (6.5)	87.9 (7.8)	90.4 (4.6)
Gastrocnemii moment at 100% (Nm)	49.6 (10.7)	53.5 (15.5)	64.7 (24.4)
Moment arm (cm)	3.44 (0.58)	3.71 (0.76)	3.24 (0.58)
Tendon force (N)	1500.2 (471.8)	1506.9 (431.2)	2001.7 (722.7)
<i>Muscle size and static quality</i>			
Gastrocnemii volume (cm ³)	267.4 (71.5)	249.8 (51.1)	243.1 (71.3)
Gastrocnemii reduced PCSA (cm ²)	55.4 (9.8)	54.0 (14.1)	58.1 (12.0)
Static muscle quality (N/cm ²)	27.1 (6.6) ^{Co}	28.8 (8.3)	34.5 (10.4)

CI = vs Claudicating-limb group, A = vs Asymptomatic-limb group Co = vs Healthy control group

1

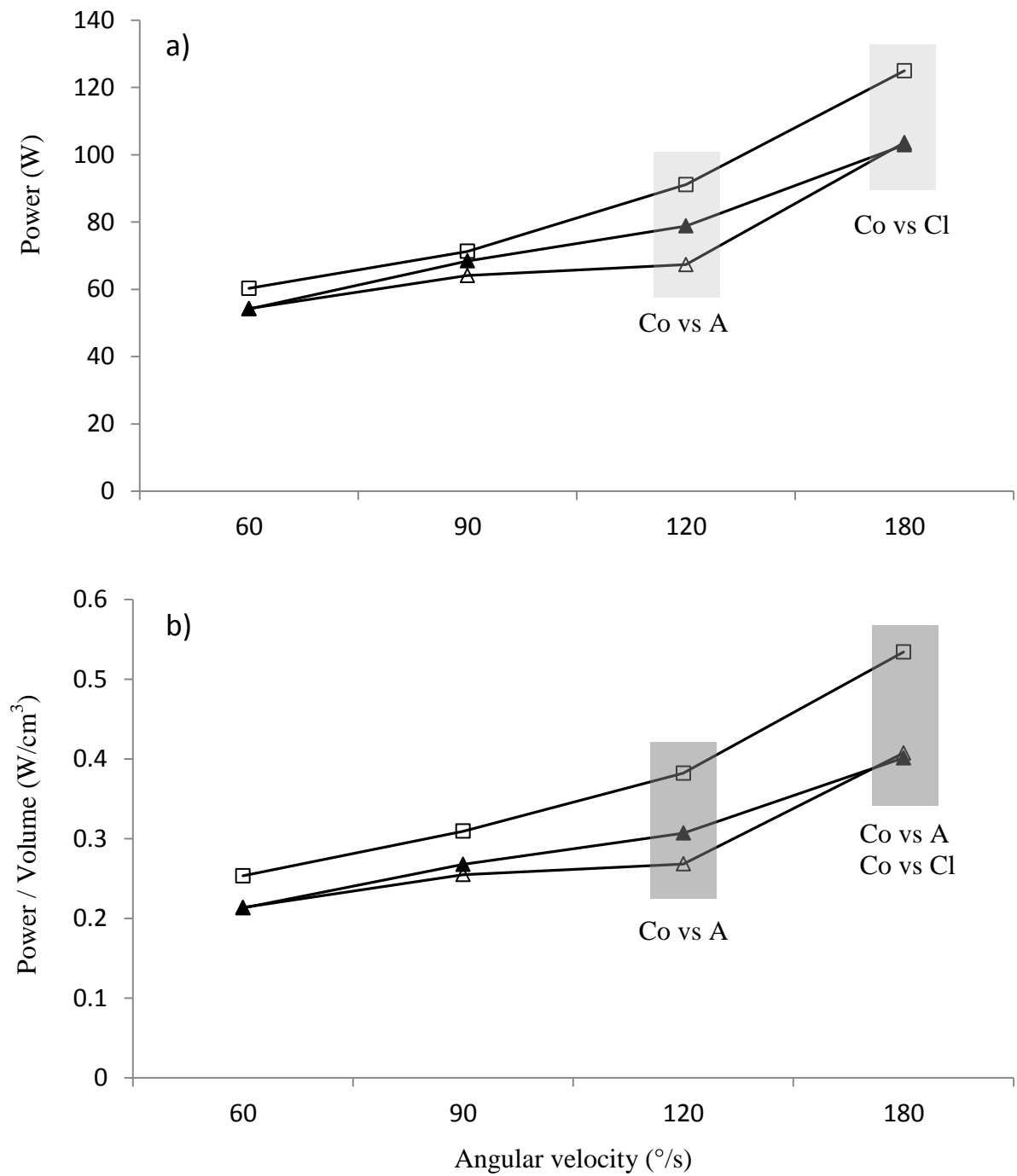


Figure 1. Group mean power-velocity (a) and normalised power-velocity (b) profiles for claudicating-limb (▲), asymptomatic-limb (△) and healthy controls (□). Dark shaded values represent those reaching significance ($P \leq 0.05$) and light shaded values represent those demonstrating trends towards significance ($P < 0.10$). Cl = vs Claudicating-limb group, A = vs Asymptomatic-limb group Co = vs Healthy control group.

Discussion

The aim of the study was to investigate the effects of peripheral arterial disease and intermittent claudication (PAD-IC) on the strength, power, size and *in vivo* whole muscle quality of the plantarflexors. We found no effects of disease on external measures of “strength” during static or low speed contractions, but the claudicants relied on the predominantly type I-fibred soleus to develop overall strength more than healthy controls. Significant strength differences between claudicants and controls were apparent during higher speed ($\geq 120^\circ/\text{s}$) contractions. These data support our hypotheses that the dynamic muscle quality of claudicants was reduced compared to healthy controls, and this was associated with poorer walking endurance. These novel findings suggest that impaired muscle quality and a greater reliance on the soleus muscle contribute to reduced dynamic strength of claudicants at high speeds, which in turn contributes to the impaired functional ability seen in this population.

Previous studies investigating plantarflexor strength in individuals with PAD-IC are inconsistent⁽⁸⁻¹⁰⁾ and comparisons between studies are confounded by differing methods of strength assessment. This study quantified plantarflexor strength across a range of contraction speeds, and observed no between-group differences at low velocities. However, the power generating capacity of the claudicants was 13-26% lower than controls at speeds of 120-180°/s. Interestingly, this was the case for both claudicating-limb and asymptomatic-limb groups. This indicates either the presence of systemic effects of ischemia in the ‘asymptomatic’-limb or that deleterious adaptations were driven by the relative inactivity caused by the symptomatic limb. Isometric plantarflexor strength has previously been reported as a strong predictor of mortality in men with PAD-IC^(11,12); however the current

data suggest that dynamic contractions at higher velocities may be more sensitive to functional deteriorations, which was not apparent in previous sub-group analyses⁽³⁷⁾. Future functional assessments and measures of plantarflexor strength should consider the use of dynamic, concentric tests in order to detect strength losses early in diagnosis and to identify those with greater strength impairments.

Whilst voluntary joint moments and powers are simple and time-efficient measures, they do not provide information regarding the underlying mechanisms contributing to the externally measured strength. Despite minimal between-group differences in isometric MVC, a substantially lower (25%, but non-significant) tendon force was found in both claudicating-limb and asymptomatic-limb groups compared to controls. Combined with similar physiological cross-sectional areas, this led to a trend towards reduced static muscle quality (21%) in the claudicating-limb group, and a non-significant reduction of 16% in the asymptomatic-limb group, compared to controls. These effects were not mirrored in the correlations with ABPI, suggesting other stimuli must exist, such as physical activity levels, to drive these reductions in static gastrocnemii muscle quality of claudicants.

The reduced tendon force in the claudicating-limb group, despite similar joint moments between groups, can be attributed to a greater (12%) contribution of the soleus to the overall joint moment, compared to healthy controls. This increased reliance on the soleus during plantarflexion contractions may be linked to the proposed shift in fibre type in claudicants⁽¹⁷⁻²¹⁾. Therefore, the increased contribution from the slower, type I-dominant soleus muscle⁽³⁸⁾ may act as a means to reduce the metabolic cost of the task. However, during dynamic

contractions, a greater contribution from soleus would have a detrimental effect on the ability to generate power, particularly at high speeds, which is consistent with the present data.

When muscle power was normalised to volume (dynamic muscle quality) between-group differences became larger and significant associations with walking endurance and disease severity were apparent. This corroborates previous reports of reduced ankle plantarflexor power per kg body mass in gait^(6,7) and demonstrates the importance of plantarflexor power for functional performance. The reductions in dynamic muscle quality were associated with changes in walking performance that have previously been reported as clinically meaningful (>50m)⁽³⁹⁾. Long-term efforts to monitor the implications of this appear warranted, and quantification of dynamic muscle quality may provide a useful outcome measure in these efforts. Exercise prescription is a primary treatment option in PAD-IC to improve mobility and to combat muscle weakness⁽⁵⁾. It appears that such training interventions should target improvements in plantarflexor power by redressing the relative contribution from the soleus and gastrocnemii muscles through dynamic exercise programmes (high-velocity resistance training). Future work should endeavour to assess how these important musculoskeletal parameters respond to (exercise-based) interventions and whether they lead to the predicted improvements in walking capacity.

Correlation analysis revealed that variations in activation capacity amongst the claudicating-limb group significantly affected walking endurance. This would increase the perceived effort of walking, possibly leading to altered gait mechanics to redistribute joint kinetics, and consequently alter movement efficiency and endurance. Activation level was not quantified during the isokinetic trials because muscle stimulation during dynamic contractions is

1 technically very challenging, particularly for the plantarflexors where the muscle group
 2 works almost exclusively on the ascending limb of the force-length relationship, so
 3 stimulation at optimal muscle length is not possible. Future work should endeavour to
 4 investigate the activation capacity of the plantarflexor muscles during dynamic contractions,
 5 since it may be different to that in isometric conditions and could contribute to the specific
 6 power deficits at high velocities. This would provide greater understanding of the
 7 neuromuscular adaptations caused by PAD-IC and their influence on functional performance.

8
 9 Some limitations to the present study must be acknowledged. It is recognised that the present
 10 sample is small with a wide range of disease severity. Nonetheless we were able to detect
 11 between-group differences and meaningful associations with walking endurance, as such we
 12 consider this sample adequate to confirm the hypotheses. Static muscle quality should be
 13 calculated with measures of truly optimal muscle force and length, i.e., plateau of the force-
 14 length relationship. As is typical for the plantarflexors, this plateau was not observed⁽²⁸⁾ and
 15 we do not know whether participants reached optimal fascicle length. However, previous
 16 work has shown that small changes in joint position do not significantly affect estimates of
 17 muscle quality⁽²⁷⁾. By calculating the quality of the entire gastrocnemii muscle group, errors
 18 associated with distributing tendon force between the lateral and medial gastrocnemii
 19 muscles were avoided. However, it was necessary to assume that once soleus contribution
 20 was removed, the Achilles' tendon force reflected only that produced by the gastrocnemii
 21 muscle. Dynamic muscle quality was calculated as plantarflexor joint power normalised to
 22 gastrocnemii muscle volume only, assuming the relative size of these muscles remains
 23 constant, as is the case in ageing⁽³⁴⁾. Claudicants relied on the soleus more than healthy
 24 controls did, meaning any error associated with this assumption will most likely
 25 underestimate the true between-group difference in dynamic muscle quality. Additionally,

moment arm length was determined during passive joint rotations at rest⁽³²⁾ and it is known to change during contraction⁽⁴⁰⁾. However, there is no reason to assume the change from rest to contraction would be different between controls and claudicants; consequently, we consider the comparisons presented in this study to remain valid.

Conclusions

The present study quantified the intrinsic quality of *in vivo* claudicant muscle for the first time. Dynamic plantarflexion strength, particularly at the highest velocity, was lower in claudicants compared to healthy controls and was significantly associated with disease severity and impaired walking endurance. When dynamic strength was normalised to muscle size (to calculate muscle quality) between group differences were larger and relationships with walking endurance were stronger. The impaired function at high velocities may be related to a reduction in maximal (static) muscle quality and an increased reliance on the predominantly type-I fibred soleus muscle. Efforts to monitor strength at high velocities appear the most appropriate way to detect functional losses early, and improving the dynamic capabilities of the plantarflexors is likely to help maintain walking endurance in claudicants.

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