

Research article

Relationships between muscle fatigue characteristics and markers of endurance performance

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Abstract

The aim of this study was to examine the relationship of a range of in-vivo whole muscle characteristics to determinants of endurance performance. Eleven healthy males completed a cycle ergometer step test to exhaustion for the determination of the lactate threshold, gross mechanical efficiency, peak power and VO_2 max. On two separate occasions, contractile and fatigue characteristics of the quadriceps femoris were collected using a specially designed isometric strength-testing chair. Muscle fatigue was then assessed by stimulating the muscle for 3 minutes. Force, rate of force development and rates of relaxation were calculated at the beginning and end of the 3 minute protocol and examined for reliability and in relation to lactate threshold, VO_2 max, gross mechanical efficiency and peak power. Muscle characteristics, rate of force development and relaxation rate were demonstrated to be reliable measures. Force drop off over the 3 minutes (fatigue index) was related to lactate threshold ($r = -0.72$ $p < 0.01$) but not to VO_2 max. The rate of force development related to the peak power at the end of the cycle ergometer test ($r = -0.75$ $p < 0.01$). Rates of relaxation did not relate to any of the performance markers. We found in-vivo whole muscle characteristics, such as the fatigue index and rate of force development, relate to specific markers of peripheral, but not to central, fitness components. Our investigation suggests that muscle characteristics assessed in this way is reliable and could be feasibly utilised to further our understanding of the peripheral factors underpinning performance.

Key words: Muscle contractile characteristics; lactate threshold; electrical stimulation; VO_2 max.

Introduction

Muscle contractile characteristics are a key component of exercise performance that can be directly measured utilising electrical stimulation techniques. In animals a direct relationship between muscle fibre type and electrically stimulated muscle characteristics has been established (Gordon et al. 1990). In humans, muscle contractile properties have been described in a range of clinical populations (Harridge et al. 1996; Scott et al. 1990; Scott et al. 1985) and their relationship with muscle fibre type confirmed in human cadavers (Dahmane et al. 2005) and a small number of subjects (Harridge et al. 2002). The non invasive nature of obtaining muscle characteristics allows its repeated use thus opening up opportunities for monitoring muscle response to acute and prolonged training. Initial studies suggest that changes in muscle characteris-

tics following exercise are dependent on the exercise intensity (Skof et al. 2006a; 2006b; Theurel et al. 2008) and that muscle characteristics are an indicator of aerobic performance during controlled leg extension exercise (Garland et al. 2004). However to our knowledge the relationship of muscle characteristics to other determinants of exercise performance have not been fully explored. This information may expand our understanding of muscle in relation to exercise performance and the utility of muscle contractile characteristics as a tool to understand muscle response to individual exercise sessions and training regimes.

In this investigation we have examined the reliability of contractile and fatigue characteristics of the quadriceps femoris muscle and their relationship to established physiological markers of cycling endurance. Maximal oxygen uptake (VO_2 max), gross mechanical efficiency and the lactate threshold, defined as the percentage of VO_2 max that an increase in blood lactate concentrations above baseline levels occurs, are determinants often used to assess endurance ability. Further to the direct findings in animal studies (Gordon et al. 1990) and the work done in humans (Garland et al. 2004) we hypothesise that 1) a greater fatigue resistance would correlate with a higher VO_2 max, greater gross mechanical efficiency and a higher lactate threshold and 2) a smaller reduction in rate of force development (RFD) and relaxation rate (RR) would correlate with a higher VO_2 max, greater gross mechanical efficiency and a higher lactate threshold.

Methods

Eleven healthy recreationally active males, mean age 26.1 ± 4 yrs, weight 78.1 ± 10 kg and height 1.79 ± 0.05 m participated in the study. After being fully informed of the risks associated with their participation, each subject gave written informed consent. The study was approved by the local University Ethics Committee and carried out according to the Declaration of Helsinki (2000).

All subjects were fully habituated to the testing procedures before participating in the study. The habituation session allowed the subjects to experience the sensation of electrical stimulation. If subjects were unfamiliar with the methods for collecting expired air this was also practised during this session. Following habituation, subjects attended assessments on three occasions, each separated by one week. In assessments 1 and 2, muscle per-

formance data was collected. Assessment 3 consisted of the collection of VO_2max , lactate threshold and gross mechanical efficiency data. To minimise any diurnal effects all sessions were conducted at the same time of day (\pm 2hrs). Prior to testing, subjects were asked to refrain from exhaustive exercise 48hrs prior to the session, and to maintain their normal dietary habits and come to the laboratory in a euhydrated state.

Measurement of muscle performance

Quadriceps muscle function was collected using a specially designed isometric strength-testing chair and a four strain-gauge bridge torque transducer (Figure 1). Electrical signals from the torque transducer were amplified (Digitimer Neurolog NL107 Recorder Amplifier) and digitised (Cambridge Electronic Design, micro1401). Torque from maximal voluntary isometric contractions (MVIC) and electrically elicited contractions of the quadriceps femoris muscle were recorded on a PC for subsequent analysis using Spike data analysis software (Spike 2 Version 5.0 for Windows).

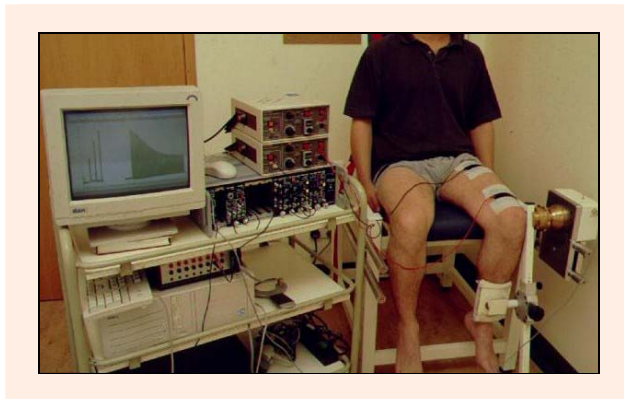


Figure 1. Subject set up on the strength-testing chair.

Subjects sat in an upright position with the knee and hip held at 90° . Shoulder and lap straps restricted upper body movement in order to isolate the muscle action. The axis of the lever arm attached to the torque transducer was aligned with the knee flexion-extension axis whilst the subject's tibia was placed behind a plate, connected to the lever arm, 3cm above the lateral malleolus. The chair was fully adjustable and the subjects' position on the chair was recorded for subsequent testing. Subjects were instructed to push against the plate as maximally as possible. Three 5s MVICs were carried out on each visit. Each effort was separated by 1-minute. If the final MVIC torque was the highest, further contractions were made until there was no further improvement. MVIC was measured as the peak value obtained from the recorded contractions and was required to set the appropriate electrical stimuli amplitude.

Electrical stimuli were delivered to the muscle with a Digitimer DS7 constant current stimulator via two carbon rubber electrodes (EMS), one placed proximally over the muscle belly of the rectus femoris and the second placed distally over the vastus medialis. Electrical stimuli was set at an appropriate intensity to elicit force outputs of approximately 20% of the subjects' MVIC at 40Hz. Muscle fatigue was then assessed using a modified Burke

protocol (Burke et al. 1973). This entailed stimulating the muscle at 40Hz for 250ms every second for 180 seconds. Pulse width was set at $300\mu\text{s}$ with stimulation intensity ranging from 60-100mA.

The amount of fatigue was calculated as a percentage of the initial torque lost over the 180s period using the following equation: Fatigue Index (FI) = (Initial Force – Final Force/Initial Force) \times 100

A low fatigue index was thus indicative of greater fatigue resistance and a high fatigue index indicative of lower fatigue resistance.

Changes in the rate of force development and relaxation were also calculated on force outputs at the beginning and end of the fatigue test. The initial contraction at the onset of the protocol was always ignored. Calculations were made on the second and final contractions. Rate of force development and relaxation rate were calculated from dF/dt (Gordon et al. 1990). RFD was calculated from the slope of the force trace from baseline to peak force following the electrical stimulus. RR was calculated from the slope of the force trace from peak force back to baseline and also from peak force to half peak force ($\text{RR}_{1/2}$) (Figure 2).

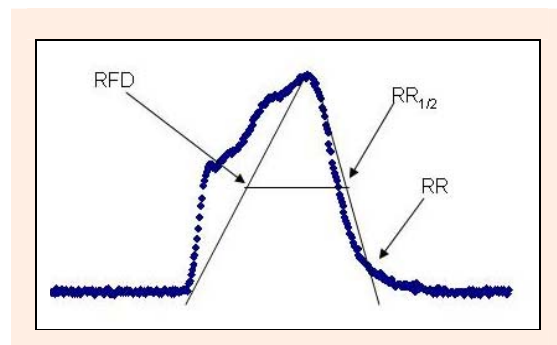


Figure 2. Calculation of RFD, $\text{RR}_{1/2}$ and RR on individual torque outputs. RFD = rate of force development, RR = rate of relaxation.

Baseline was established at the beginning of the testing session and was defined as a stable force trace at rest for a 2-minute period before commencement of the electrical stimulation. Baseline remained stable throughout the testing session. The change in rate of force development and relaxation was also assessed. The change in rate of force development (% RFD) was calculated as the % change in rate of force development from the beginning to the end of the fatigue test. Calculation of the % change in rate of relaxation (% RR) and the % change in $\text{RR}_{1/2}$ (% $\text{RR}_{1/2}$) was the same as that used for % RFD.

Measurement of Peak Oxygen Consumption (VO_2max) and Lactate Threshold (LT)

Tests were conducted on an electromagnetically braked cycle ergometer (Lode, Gronigen, The Netherlands). Each subject was allowed to warm up for 5 minutes prior to following an incremental protocol similar to that utilised by Burnley et al. (2000). Subjects were instructed to maintain a cadence of 80 RPM throughout the test. Cycling commenced at a work rate of 70-100W, and was increased by 20W every 4 minutes. At the end of each 4-minute stage, a finger-prick blood sample was taken for

lactate analysis (Analox PGM-7, Hammersmith, London, UK). Once the blood lactate concentration had increased by 1-mmol^{-1} above the baseline level achieved during earlier work rates, the work rate was increased by 20W every minute until volitional exhaustion. Pulmonary gas exchange was measured breath-by-breath using an automated metabolic analysis system (Oxycon Gamma, Jaeger, Hoechberg, Germany). Prior to each test, the gas analysers were calibrated with gases of known concentrations and flow volume was calibrated with a 3-L syringe (Hans Rudolph) according to manufacturer's specifications. Subjects wore a nose clip and breathed through a mouthpiece connected to a low-resistance volume transducer (Jaeger Triple V, Hoechberg, Germany). Heart rate was recorded continuously throughout the testing protocol using short-range telemetry (Polar S810, Finland). Steady state VO_2max was calculated as the average VO_2max in the last 60s of each 4-minute stage, whilst VO_2max was recorded as the highest 60s average before the termination of the test. Peak power output (PPO) was calculated as the sum of the final completed workload, plus the fraction of the partly completed workload performed before exhaustion (Moseley et al. 2001). The lactate threshold was identified as the point at which in blood lactate concentrations increased 1-mmol^{-1} above baseline measures, as evident on plots of blood lactate versus work rate. This threshold was expressed as a percentage of VO_2max .

Gross mechanical efficiency (GME)

For all work rates below the lactate threshold and below a respiratory exchange ratio (RER) of 1.00, GME was calculated as the ratio of actual work rate ($\text{kcal}\cdot\text{min}^{-1}$) to the rate of caloric expenditure ($\text{kcal}\cdot\text{min}^{-1}$) (Sidossis et al. 1992). Energy expenditure ($\text{kcal}\cdot\text{min}^{-1}$) was calculated from VO_2 and RER data (Lusk 1924).

Statistical analysis

Descriptive statistics include mean \pm SD for all measured variables. Test-retest reliability was assessed on the muscle contractile measures using student t-tests, intraclass correlation coefficient [3,1] and bias and random error analysis.

All data was examined for normality. The relationship between variables was examined using a Pearson's correlation coefficient (one-tailed) to assess whether there was any relationship between measured muscle characteristics and VO_2max , peak power, LT and GME. Linear regression was found to best describe relationships for all measures using both visual inspection and examination of R and R^2 values. Due to multiple tests statistical significance was accepted at $p < 0.01$ following a Bonferroni adjustment to help avoid a Type I error.

Results

Mean and standard deviation data for VO_2max , LT gross mechanical efficiency (GME), fatigue index and % drop in force development (RFD) and relaxation rate (RR) are displayed in Table 1.

Reliability of muscle performance test (MPT)

Reliability of the fatigue index, change in RFD and RR, and $\text{RR}_{1/2}$ measured in the electrical stimulation protocol was assessed. Test-retest data indicated high reliability for the fatigue index and also the change in RFD (Table 2). The % change in RR displayed low test-retest reliability as evidenced with a poor ICC. However, % change in $\text{RR}_{1/2}$ demonstrated high reliability. $\text{RR}_{1/2}$ was utilised for further correlation analysis.

Table 1. Data for endurance performance determinants and muscle characteristic measures (mean \pm standard deviation).

	Mean	SD
VO_2max ($\text{ml}\cdot\text{kg}\cdot\text{min}^{-1}$)	55.3	8.8
Peak Power (W)	336.4	42.9
LT (% VO_2)	61.3	6.8
GME (%)	18.4	1.0
Fatigue Index (%)	39.6	8.9
% Change in RFD	44.2	15.9
% Change in RR	48.8	26.9
% Change in $\text{RR}_{1/2}$	36.3	17.1

VO_2max = maximum oxygen consumption, LT = lactate threshold, GME = gross mechanical efficiency, RFD = rate of force development, RR = rate of relaxation.

Relationship of the measured muscle characteristics with measures of endurance performance

The FI related significantly with lactate threshold with subjects that displayed low fatigue resistance having a low lactate threshold and vice versa (Figure 3). In contrast there was no significant relationship between FI and VO_2max , GME and peak power. Table 3 displays the relationships of FI to endurance performance measures. There was also a significant relationship between FI and %RFD ($r = 0.79$, $p < 0.01$). There was a significant relationship between % change in RFD and peak power with subjects displaying the greatest reduction in RFD having a higher PPO (Figure 4). There were no significant relationships between % change in $\text{RR}_{1/2}$ and any of the endurance measures.

Discussion

In agreement with previous observations that individuals who were endurance trained had less fatigable muscles (Garland et al. 2004) we observed that muscle contractile

Table 2. Test-retest reliability of rate of force development, rate of relaxation, % change in RFD, % change in RR and % change in $\text{RR}_{1/2}$.

	t test	95% CI	95% CI	Bias	Random Error	ICC [3,1]	ICC CI Lower	ICC CI Upper
Fatigue Index	-.26	-10.27	8.37	-.95	17.4	.87	.34	.98
% Change in RFD	-.56	-14.30	8.95	11.60	62.2	.72	.02	.95
% Change in RR	.30	-23.00	29.5	3.26	55.7	.14	-.63	.77
% Change in $\text{RR}_{1/2}$	-1.06	-2.58	1.01	-.37	1.00	.92	.60	.99

ICC = intraclass correlation coefficient, RFD = rate of force development, RR = rate of relaxation.

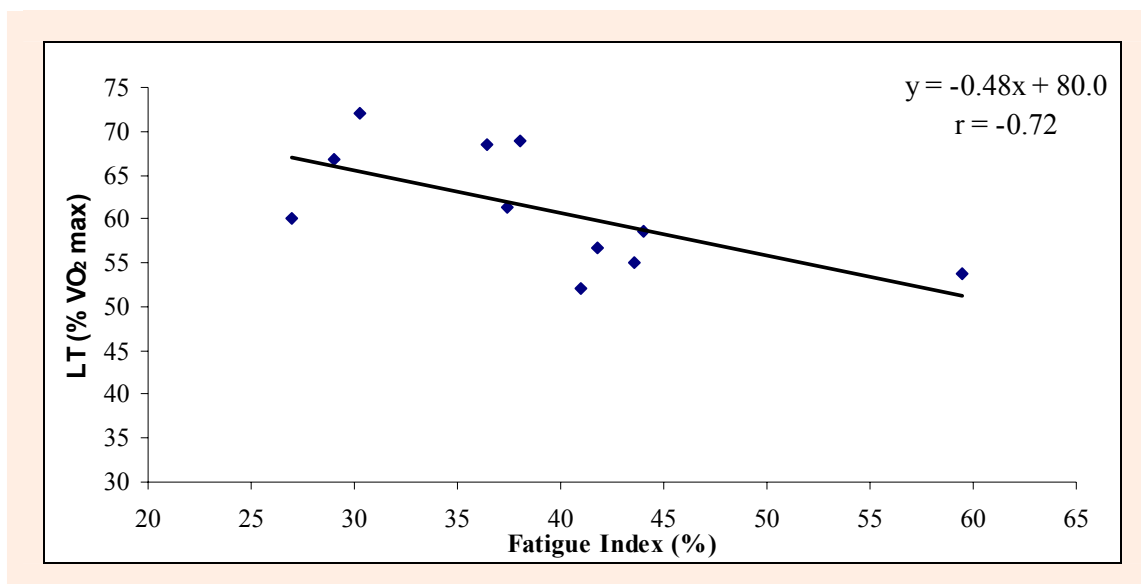


Figure 3. Relationship between lactate threshold (LT) and the fatigue index.

and fatigue characteristics were related to specific endurance performance determinants. We found that subjects displaying greater fatigue resistance during the muscle fatigue protocol demonstrated a higher lactate threshold in the cycle ergometer test. Interestingly the fatigue index did not relate to the general marker of cardiovascular performance as measured by VO_2max . Our observations support the evidence that the lactate threshold specifically reflects muscle performance and not cardiovascular performance (Farina et al. 2007; Gladdon 2000). In contrast, other contractile characteristics measured by the change in the rate of force development during the muscle fatigue protocol related to the individuals' ability to attain a greater peak power, but not to any metabolic exercise testing measures. Individuals with less change in the rate of force development could keep going for longer during exercise testing. Rate of force development characteristics have been shown to reflect underlying muscle fibre composition in animal studies (Gordon et al. 1990) and thus may reflect individuals' muscle myosin isoform profile. Muscle contractile characteristics can thus give an indication of different areas of performance. Importantly, analysis of the reliability of muscle contractile characteristics measurements suggests good repeatability for day to day assessment of muscle function. The % change in $\text{RR}_{1/2}$ demonstrated good reliability compared to that of %change in the rate of relaxation (%change in RR) and we would recommend using the former measure for measurements of muscle relaxation.

The lactate threshold, a measure of metabolic control during exercise and strongly related to endurance performance, had an inverse linear relationship to the fatigue index. Research has shown that individuals with less fatigable muscles produce less lactate during exer-

cise, have a higher lactate threshold and are able to perform at higher relative exercise intensities for prolonged periods (Coyle 2005). The % change in RFD related significantly to PPO, with subjects displaying a higher PPO in the maximal cycle ergometer test demonstrating a greater alteration in the rate of force development. A possible factor influencing this finding is muscle fibre composition. The rate of force development increases from type I<IIa<IIx muscle fibres (Burke et al. 1973). In this current study individuals that were unable to produce high peak powers on the cycle ergometer had muscle characteristics whereby the rate of force development was maintained throughout the fatigue protocol. In cats, the maintenance of RFD has been shown to be characteristic of slow, highly fatigue resistant muscle fibres (Gordon et al. 1990) and it may be a useful indicator of muscle fibre composition in humans. The weak relationship of VO_2max to the muscle variables agrees with the findings of Sinacore et al (1994) in that VO_2max is a global marker of endurance capacity, affected by both central and peripheral factors.

Although there was a significant relationship between the FI and lactate threshold, this may have been stronger had we employed a more controlled movement such as the knee extension protocol utilised by Garland et al (2004). However, the aim of this current investigation was to utilise a more dynamic exercise modality.

During voluntary progressive exercise such as that utilised in the maximal cycle ergometer test, it has been suggested that muscle fibres are recruited according to the Henneman size principle (Henneman et al. 1965). However, it has recently been reported that motor unit recruitment strategy is more multi-factorial and is dependent on the task requirements (Hodson-Tole et al. 2008). A

Table 3. Relationships between the fatigue index and measures of endurance performance.

	Regression	R ²	r	p Value
LT	$-0.48x + 80.0$	.40	-.72	<0.01
Peak Power	$-1.17x + 384.2$	.14	-.52	NS
GME	$-0.07x + 21.0$	.33	-.60	NS
VO_2max	$-0.02x + 5.0$	.06	-.29	NS

LT = lactate threshold. GME = gross mechanical efficiency. VO_2max = maximum oxygen consumption.

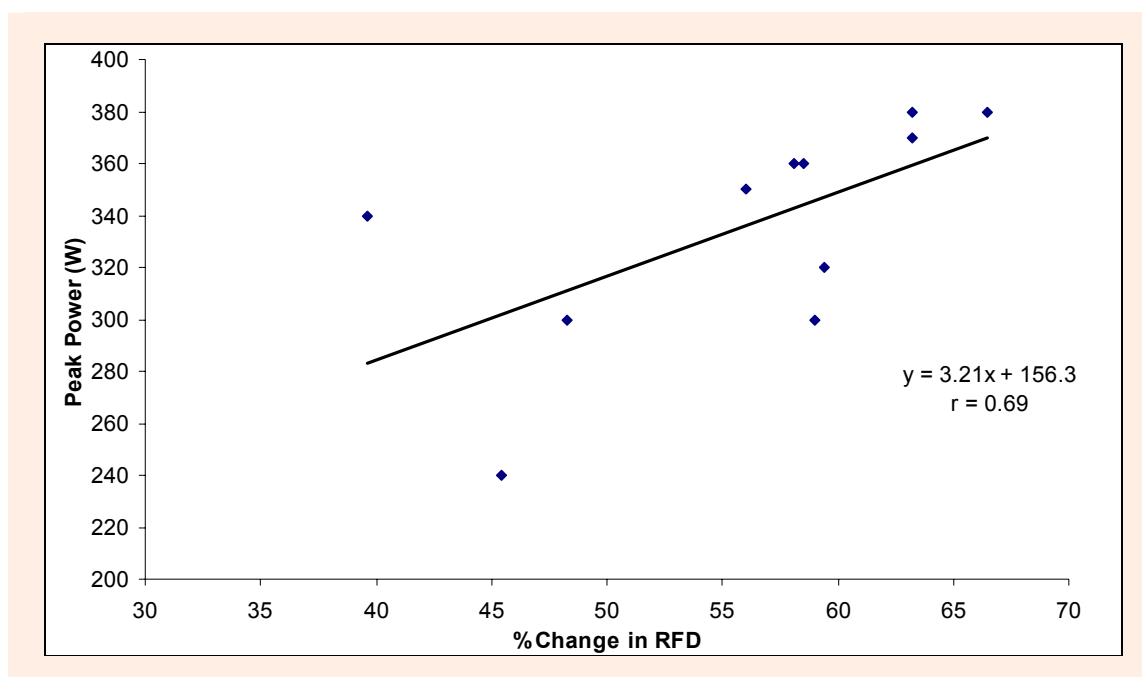


Figure 4. Relationship between peak power and the % change in rate of force development (RFD).

possible limitation to the electrical stimulation technique utilised in the current study is the sequence of muscle fibre recruitment. It has been reported that direct electrical stimulation of the muscle recruits muscle fibres in a reverse order (fast to slow) (Trimble et al. 1991) or perhaps in a less organised manner (Binder-Macleod et al. 1995; Hodson-Tole et al. 2008). Many factors can influence the recruitment order during electrical stimulation such as axonal branch size and arrangement within the stimulated area (Knaflitz et al. 1990). In light of the findings from Hodson-Tole et al. (2008), the recruitment pattern during electrical stimulation could be more closely related to voluntary recruitment order than first thought. Studies of voluntary fatigue have demonstrated a similar profile of force output decreases to that reported in electrical stimulation studies (Marsden et al. 1983). An advantage of the electrical stimulation technique is the ability to not only assesses the amount of force drop off but also the alteration in RFD as demonstrated in this current study. Although the sample size was small in the current study, it was conducted on a heterogeneous group of healthy male subjects ranging from sedentary to trained cyclists. This is reflected in the range in VO_2max ($38.6\text{-}65.5\text{ml}\cdot\text{kg}\cdot\text{min}^{-1}$), lactate threshold (40-72%), peak power (240-400W) and GME (17.2-20.2%) measured in the maximal cycle ergometer test.

Conclusion

In this investigation we observed that muscle contractile characteristics related to muscle performance markers but not to central performance markers. Specifically from the muscle testing protocol, a smaller drop in force during the fatigue protocol was related to an ability to exercise at higher percentages of VO_2max before the increased appearance of lactate in the blood. A greater drop in rate of force development was related to achieving a higher peak power at exercise test termination. The observation of the

fatigue index relating to aerobic metabolism markers, and the rate of force development changes relating to endurance performance markers, suggests that the electrical stimulation protocol utilised in this study could be profitably used to investigate muscle responses to exercise and their contribution to overall performance. The observed test-retest stability of muscle contractile characteristics further supports the utilisation of this measure within longitudinal studies and as a useful technique alongside established measures when constructing a physiological profile of a subject.

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Key points

- Participants with a high lactate threshold displayed greater fatigue resistance in the electrical stimulation test.
- Muscle performance characteristics relate to specific components of endurance performance.
- The electrical stimulation protocol could be a useful technique, alongside other established measures, when constructing a physiological profile of a participant.