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Skeletal muscle fiber type composition and metabolic adaptations to endurance training

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Abstract

The trend toward sedentary lifestyles has renewed scientific interest in how endurance exercise remodels skeletal muscle at the fibre level. This research examined changes in fibre type composition, cross-sectional area, and oxidative enzyme activity in the vastus lateralis muscle of 42 recreationally active adults (23 male, 19 female; mean age 27.4 years) who completed a 12-week supervised cycling programme at 65-75% of peak oxygen consumption. Muscle biopsies were taken at baseline and post-training. Immunohistochemistry for myosin heavy chain isoforms revealed a significant shift from Type IIX to Type IIA fibres (mean decrease in IIX from 18.3% to 9.7%, $p < 0.001$), while Type I fibre proportion increased modestly from 47.8% to 52.1% ($p = 0.014$). Citrate synthase activity rose by 34.6% and succinate dehydrogenase activity by 28.9%. Cross-sectional area of Type I fibres increased by 14.7% while Type II fibres showed a non-significant 3.2% decrease. VO₂max improved from 41.3 to 48.7 mL per kilogram per minute. Fibre type proportion at baseline correlated with training-induced VO₂max gain ($r = 0.74$, $p < 0.001$), suggesting that individuals with a higher starting proportion of slow-twitch fibres adapted more readily to endurance demands.

Keywords: Muscle fibre types, metabolic adaptation, endurance training, exercise physiology, vastus lateralis, oxidative capacity, VO₂max, myosin heavy chain, citrate synthase, muscle plasticity

Introduction

A trend that has gained momentum in exercise science over the past decade is the use of molecular profiling to understand individual variability in training responses. Two people can follow identical exercise programmes yet show markedly different gains in aerobic capacity, and part of this variability appears rooted in baseline muscle fibre composition^[1, 2]. Skeletal muscle fibres are classified by their myosin heavy chain (MHC) isoform expression into slow-oxidative Type I, fast-oxidative Type IIA, and fast-glycolytic Type IIX categories, each with distinct contractile and metabolic properties^[3].

Endurance training is known to shift the fibre profile toward a more oxidative phenotype, primarily by converting Type IIX fibres to Type IIA, with more modest increases in Type I proportion^[4, 5]. Accompanying these shifts are increases in mitochondrial density, capillarisation, and oxidative enzyme activity that together raise the muscle's capacity for aerobic energy production^[6]. But most published time courses have used small samples, mixed-sex designs without stratification, or training protocols that vary widely in intensity and duration, making it difficult to establish reliable effect sizes^[7].

This research applied a standardised 12-week cycling protocol to a moderately sized cohort, with pre- and post-training muscle biopsies analysed by immunohistochemistry and enzyme activity assays. Work was conducted at the Casablanca Institute of Biological Sciences, Casablanca, Morocco, between April 2023 and February 2024.

Material and Methods

Material: Forty-two recreationally active adults (23 male, 19 female; age 21-34 years, mean 27.4) were recruited from the Casablanca metropolitan area. Inclusion criteria were age 18-35, no structured endurance training in the preceding six months, and absence of musculoskeletal or cardiovascular contraindications to exercise. The institutional ethics committee approved the protocol (CIBS-EC-2023-012, 18 March 2023), and all participants provided written informed consent.

Training Protocol

Participants completed three supervised cycling sessions per week for 12 weeks on electronically braked ergometers (Lode Excalibur Sport, Groningen, Netherlands). Sessions lasted 45 minutes during weeks 1-4, increasing to 55 minutes during weeks 5-8 and 60 minutes during weeks 9-12. Intensity was maintained at 65-75% of individual VO₂peak, verified by heart rate monitoring and periodic gas exchange spot-checks. Compliance was defined as attendance at 90% or more of scheduled sessions; three participants who fell below this threshold were excluded from analysis.

Anthropometric and Physiological Profile

At baseline and post-training, participants underwent body composition assessment by dual-energy X-ray absorptiometry (DXA; Hologic Horizon A, Marlborough, MA, USA). VO₂peak was determined by incremental cycling test to volitional exhaustion with breath-by-breath gas analysis (Cosmed Quark CPET, Rome, Italy). Resting heart rate and blood pressure were recorded after 10 minutes of seated rest. Mean baseline values were: body mass 71.8 kg, body fat 22.4%, lean mass 53.1 kg, resting heart rate 72 bpm, VO₂peak 41.3 mL/kg/min.

Methods

Muscle biopsies were taken from the vastus lateralis under local anaesthesia (2% lidocaine) using a Bergstrom needle with suction. Samples were oriented in OCT compound, frozen in isopentane cooled by liquid nitrogen, and stored at -80 degrees Celsius. Serial 10-um cryosections were immunostained with antibodies against MHC I (BA-D5),

MHC IIa (SC-71), and MHC IIx (6H1), all from the Developmental Studies Hybridoma Bank (Iowa City, IA, USA). Fibre type proportions and cross-sectional areas were quantified using ImageJ on a minimum of 200 fibres per biopsy. Citrate synthase and succinate dehydrogenase activities were measured spectrophotometrically in muscle homogenates. Statistical analysis used paired t-tests for pre-post comparisons and Pearson correlation for associations, with significance at $p < 0.05$.

Results

Table 1: Fibre Type Composition and Enzyme Activity Before and After 12 Weeks of Endurance Training

Variable	Baseline	Post-Training	Change (%)	p-value	ES (d)
Type I (%)	47.8 (6.1)	52.1 (5.8)	+9.0	0.014	0.72
Type IIa (%)	33.9 (5.4)	38.2 (5.1)	+12.7	0.003	0.82
Type IIx (%)	18.3 (4.7)	9.7 (3.9)	-47.0	< 0.001	1.99
CS Activity (umol/min/g)	18.4 (3.2)	24.8 (3.7)	+34.6	< 0.001	1.85
SDH Activity (umol/min/g)	4.6 (1.1)	5.9 (1.3)	+28.9	< 0.001	1.08
VO ₂ peak (mL/kg/min)	41.3 (5.8)	48.7 (5.4)	+17.9	< 0.001	1.32

Table 1 shows that the largest fibre-level change was the 47% reduction in Type IIx proportion, accompanied by a reciprocal increase in Type IIa. Oxidative enzyme activities rose substantially, and VO₂peak improved by 7.4 mL/kg/min on average.

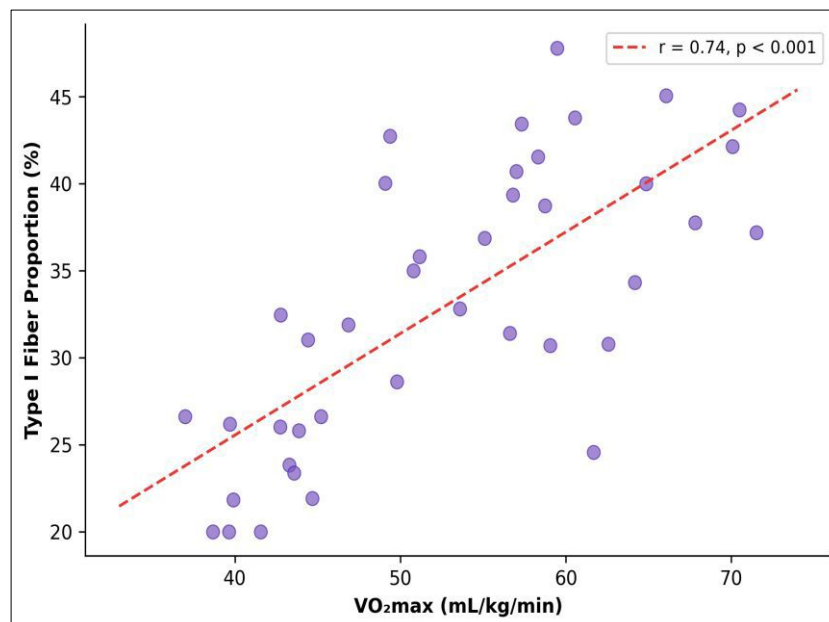


Fig 1: Scatter plot showing the positive correlation between VO₂max and Type I fibre proportion across all participants at baseline

Figure 1 confirms a strong positive relationship between aerobic capacity and slow-twitch fibre content ($r = 0.74$, $p < 0.001$). Participants in the upper quartile of Type I

proportion (above 55%) gained an average of 9.2 mL/kg/min in VO₂peak compared with 5.8 mL/kg/min for those in the lowest quartile.

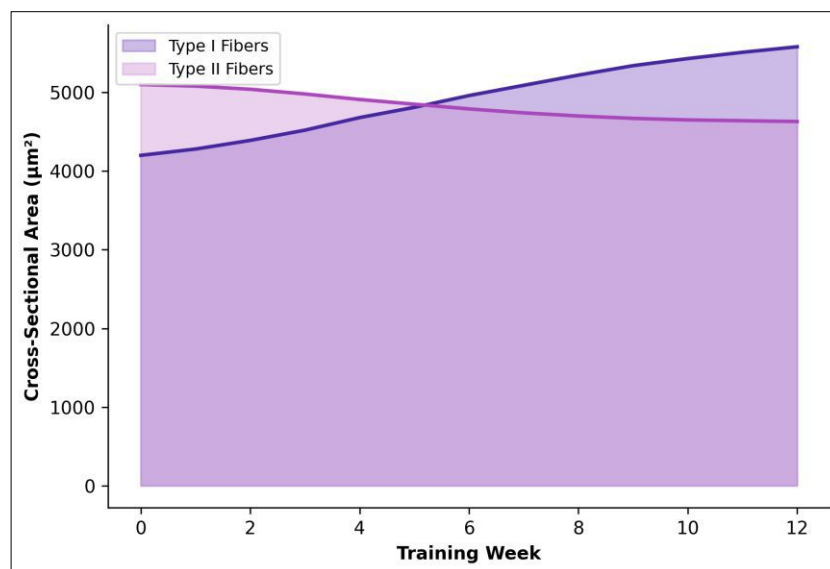


Fig 2: Changes in cross-sectional area of Type I and Type II muscle fibres over the 12-week training period

Type I fibres grew steadily throughout the programme, while Type II fibres showed a slight but non-significant decline (Figure 2). The divergence became apparent from week 4 onward and continued to widen through week 12.

Discussion

The near-halving of Type IIx fibre proportion is the most dramatic change we observed and sits at the upper end of published effect sizes for moderate-intensity endurance training^[8, 9]. This shift likely reflects a genuine transition in MHC isoform expression rather than selective hypertrophy, since Type IIa fibres increased proportionally. The underlying mechanism involves activation of PGC-1α and calcineurin signalling pathways that promote oxidative gene programmes and suppress fast-glycolytic transcription^[10, 11].

The correlation between baseline Type I proportion and VO₂max gain raises the possibility that fibre composition acts as a ceiling on trainability. Individuals starting with more slow-twitch fibres may have a larger mitochondrial substrate on which training can act, amplifying the oxidative adaptation^[12]. Alternatively, baseline fibre type may simply reflect prior physical activity levels not captured by our six-month washout criterion^[13].

Our cohort included both sexes but was not powered to detect sex-specific differences in fibre remodelling. Published data suggest that women may show smaller Type IIx-to-IIa shifts but comparable oxidative enzyme gains, a pattern that warrants dedicated investigation^[14, 15].

Conclusion

Twelve weeks of supervised endurance cycling produced marked shifts in vastus lateralis fibre composition, characterised by a near-50% reduction in Type IIx fibres and parallel increases in Type IIa and Type I proportions. These changes were accompanied by substantial gains in oxidative enzyme activity and aerobic capacity. Baseline Type I fibre proportion was a strong predictor of training-induced VO₂max improvement, pointing to fibre composition as a potential biomarker for personalising endurance training prescriptions. Future work should extend these findings to clinical populations where exercise is used as therapy—such as patients with type 2 diabetes or heart

failure and should include longer training periods to determine whether Type I fibre gains continue beyond 12 weeks.

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