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Muscle fatigue resistance in the rat hindlimb in vivo from low dietary intakes of tuna fish oil that selectively increase phospholipid n-3 docosahexaenoic acid according to muscle fibre type

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Abstract

Dietary fish oil (FO) modulates muscle O2 consumption and contractile function, predictive of effects on muscle fatigue. High doses unattainable through human diet and muscle stimulation parameters used engender uncertainty in their physiological relevance. We tested the hypothesis that nutritionally relevant FO doses can modulate membrane fatty acid composition and muscle fatigue. Male Sprague-Dawley rats were randomised to control (10 % olive oil (OO) by weight) or low or moderate FO diet (LowFO and ModFO) (HiDHA tuna fish oil) for 15 weeks (LowFO: 0·3 % FO, 9·7 % OO, 0·25 % energy as EPA + DHA; ModFO: 1·25 % FO, 8·75 % OO, 1·0 % energy as EPA + DHA). Hindlimb muscle function was assessed under anaesthesia in vivo using repetitive 5 s burst sciatic nerve stimulation (0·05 ms, 7-12 V, 5 Hz, 10 s duty cycle, 300 s). There were no dietary differences in maximum developed muscle force. Repetitive peak developed force fell to 50 % within 62 (SEM 10) s in controls and took longer to decline in FO-fed rats (LowFO 110 (SEM 15) s; ModFO 117 (SEM 14) s) ($P<0·05$). Force within bursts was better sustained with FO and maximum rates of force development and relaxation declined more slowly. The FO-fed rats incorporated higher muscle phospholipid DHA-relative percentages than controls ($P<0·001$). Incorporation of DHA was greater in the fast-twitch gastrocnemius (Control 9·3 (SEM 0·8) %, LowFO 19·9 (SEM 0·4), ModFO 24·3 (SEM 1·0)) than in the slow-twitch soleus muscle (Control 5·1 (SEM 0·2), LowFO 14·3 (SEM 0·7), ModFO 18·0 (SEM 1·4)) ($P <0·001$), which was comparable with the myocardium, in line with muscle fibre characteristics. The LowFO and ModFO diets, emulating human dietary and therapeutic supplement intake, respectively, both elicited muscle membrane DHA enrichment and fatigue resistance, providing a foundation for translating these physiological effects to humans.

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Muscle fatigue-resistance in the rat hindlimb *in vivo* from low dietary intakes of tuna fish oil that selectively increase phospholipid omega-3 docosahexaenoic acid according to muscle fibre type.

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Running Title: Diet and membrane DHA affects muscle fatigue

Abstract.

Dietary fish oil (FO) modulates muscle oxygen consumption and contractile function, predictive of effects on muscle fatigue. High doses unattainable through human diet and muscle stimulation parameters used engender uncertainty in their physiological relevance. We tested the hypothesis that nutritionally relevant FO doses can modulate membrane fatty acid composition and muscle fatigue. Male Sprague-Dawley rats were randomised to control (10% olive oil (OO) by weight) or low or moderate FO diet (hiDHA tuna-fish oil) for 15 weeks (LowFO: 0.3% FO, 9.7% OO, 0.25% energy as EPA+DHA; ModFO: 1.25% FO, 8.75% OO, 1.0% energy as EPA+DHA). Hindlimb muscle function was assessed under anaesthetic *in vivo* using repetitive 5s-burst, sciatic nerve stimulation (0.05ms, 7-12V, 5Hz, 10s duty cycle, 300s). There were no dietary differences in maximum developed muscle force. Repetitive peak developed force fell to 50% within 62±10s in control took longer to decline in FO-fed rats (LowFO 110±15s; ModFO 117±14s) ($p<0.05$). Force within bursts was better sustained with FO and maximum rates of force development and relaxation declined more slowly. The FO-fed rats incorporated higher muscle phospholipid DHA relative percentages than control ($p<0.001$). Incorporation of DHA was greater in fast-twitch gastrocnemius (Control 9.3±0.8%, LowFO 19.9±0.4, ModFO 24.3±1.0) than slow-twitch soleus muscle (Control 5.1±0.2, LowFO 14.3±0.7, ModFO 18.0±1.4) ($p<0.001$), which was comparable to myocardium, in line with muscle fibre characteristics. The LowFO and ModFO diets, emulating human dietary and therapeutic supplement intake respectively, both elicited muscle membrane DHA enrichment and fatigue resistance, providing a foundation for translating physiological effects to humans.

Introduction

The gradual decline in repetitive force development that defines muscle fatigue can be attenuated by exercise training or dietary modulation of carbohydrate intake to optimise glycogen storage and availability, but there are no other recognised physiological approaches to fatigue prevention. Increased membrane phospholipid incorporation of long-chain n-3 polyunsaturated fatty acid (LC n-3 PUFA) docosahexaenoic acid (DHA; 22:6n-3), obtained from the diet via fish or fish oil, is associated with increased efficiency of oxygen utilisation in the heart independent of heart rate [1] and improved cardiac work recovery after ischaemic stress [1, 2]. Dietary fish oil is also associated with increased whole human body oxygen efficiency during exercise [3], implicating modified skeletal muscle oxygen consumption. In humans and other vertebrate animals, DHA is the most unsaturated fatty acid present in cell membranes, accounting for up to 5% of all phospholipid fatty acids in most tissues. However, skeletal muscle [4-7] has a predisposition to greater DHA incorporation, well beyond its relative percentage amongst circulating fats [4, 8]. Skeletal muscle shares this propensity for concentrated phospholipid DHA incorporation with other highly excitable tissue (myocardium, brain and retina) [4, 9, 8, 5, 10, 11]. These parallels in membrane fatty acid composition, together with certain shared physiological properties [12], imply an important role for adequate intake of LC n-3 PUFA supporting striated muscle physiology [13].

High dietary intakes of fish oil in the rat are associated with apparent resistance of contracting skeletal muscle to fatigue [14, 15]. Earlier *in vitro* studies suggested a role of essential fatty acids (both n-6 PUFA and n-3 PUFA) in maintaining skeletal muscle function, compared to animals fed an essential fatty acid deficient diet [16]. In these and other animal and human studies, physiological effects of LC n-3 PUFA have largely been investigated in relation to high intakes of fish oil [13, 7], commonly ranging from five to over ten percent of diet by weight in animals or five to eight grams per day in humans. However, dose-response studies show that the rat responds to very small dietary intakes of fish oil with large changes in myocardial membrane DHA incorporation [17]. This suggests that physiological changes may be achieved with lower, nutritionally relevant dietary interventions.

While studies already reveal potential influences of LC n-3 PUFA on skeletal muscle function, the single twitch model of contraction employed in those dietary studies [15, 14] or tetanic stimulation protocols in other fatigue studies may not best represent submaximal and usual muscle activity [18, 19]. Moreover, the translation of results to human nutrition must be made

cautiously, since the high doses of fish oil previously used [15, 14, 3] are well beyond what could be obtained in the human diet.

The present study employed the *in vivo* muscle function model of autologous pump-perfused hindlimb in anaesthetised rats. We developed this model [20] in order that the experiments could be carried out at physiological temperature to avoid the widely accepted influence of temperature on fatigue development and at physiological blood flow and arterial oxygen content so that the muscle could be oxygenated at physiological levels throughout and not randomly subjected to hypoxia or ischaemia [21, 19]. The autologous pump-perfusion also ensured that muscle blood flow was controlled independently of intra-experimental fluctuations or dietary influences on cardiac output or blood pressure [20]. For this study we further incorporated a stimulation protocol for the sciatic nerve: gastrocnemius-soleus-plantaris muscle bundle designed as a more physiological model to mimic functional fatigue. Two fish oil doses, derived from the studies of Slee and co-workers [17], were chosen to best replicate human nutritional and therapeutic supplement equivalents respectively. This study tested the hypothesis that membrane change produced by low intakes of fish oil would be associated with resistance to physiologically relevant muscle fatigue.

Experimental Methods

Animals

Eighteen adult male Sprague-Dawley rats were housed two per cage at 23-25ºC on a 12 hour light-dark cycle in the University of Wollongong's Animal facility. Experiments were approved by the University of Wollongong Animal Care and Ethics committee and were conducted according to the Australian Code of Practice for the Care and Use of Animals for Scientific Purposes (NHMRC, 2004). The research was conducted according to the ARRIVE guidelines for reporting *in vivo* animal experiments[22].

Rats were obtained at 7 weeks of age (Animal Resources Centre, Perth, Australia) and fed on a standard laboratory chow prior to randomly allocating them to be fed one of three prefabricated diets *ad-libitum* for 15 weeks from 8-10 weeks of age. The diets were prepared as previously developed for similar animal feeding studies [15, 17]. Based on the American Institute of Nutrition AIN 93M diet [23], they contained a balanced mix of macro and micronutrients to avoid any nutritional deficiencies. All diets contained 10% fat by weight ($100g.kg^{-1}$). Two sources of fat were used in this study to produce a control diet (10% olive oil (OO)), low fish oil (LowFO) diet (0.31% FO, 9.7% OO) or a moderate fish oil (ModFO) diet (1.25% FO, 8.75% OO). Olive oil

was provided as "extra light" olive oil, being largely devoid of the antioxidant polyphenols found in less refined oils. Olive oil consisted principally of oleic acid (18:1, 75%) and provided a minimum concentration of linoleic acid (18:2n-6) to avoid essential fatty acid deficiency [2]. The fish oil was provided as HiDHA tuna fish oil (Nu-Mega Lipids, Altona, Australia), containing 29% DHA and 7% EPA, 20% palmitic acid (16:0) and 14% oleic acid as the major fatty acids. The fatty acid profiles of the control and fish oil diets are provided in Table 1. The energy intake from these diets, based on a 300g rat eating $20g.d^{-1}$ was approximately $325kJ.d^{-1}$. The LowFO diet ($3.1g.kg^{-1}$) was selected to emulate a human dietary EPA+DHA intake of 0.24% energy calculated equivalent to a human intake of $570mg.d^{-1}$ EPA+DHA and is a dose that approximately doubles myocardial DHA relative percentage [17]. The ModFO diet ($12.5g.kg^{-1}$) was selected to emulate a human therapeutic supplement EPA+DHA intake of 1.0% energy equivalent to $2.3g.d^{-1}$ EPA+DHA and is a dose that produces changes in n-3 PUFA relative percentage that approach the asymptote of the dose-response curve for n-3 PUFA incorporation in cardiac [17, 8] and skeletal muscle [5]. This ModFO dose, already shown to be cardioprotective, is the lowest dose that has been tested physiologically to date [24].

Surgical hindlimb preparation

The *in vivo* autologous, pump-perfused rat hindlimb preparation used in the present study has been described in detail and validated physiologically[20, 25]. Briefly, rats were anaesthetised (pentobarbitone sodium, $60mg.kg^{-1}$ i.p.) and maintained throughout the experiment with supplementary injections of $20mg.kg^{-1}$ i.p. pentobarbitone sodium. Rat body temperature was maintained at 37ºC with the aid of a heated perspex chamber maintained at 31±1ºC and ancillary radiant heat lamp. Animals were ventilated at 60 breaths per minute and systemic blood pressure was monitored via the carotid artery. The left sciatic nerve was isolated for electrical stimulation of the hindlimb and the gastrocnemius-soleus-plantaris muscle bundle was attached to a force transducer (FT03C, Grass Technologies, West Warwick, RI) at the Achilles tendon. A pump-perfusion system supplied the hindlimb muscles of the left leg below the knee with oxygenated arterial blood [20]. The femoral vein was cannulated for post-muscle blood sampling with venous blood returned passively to the systemic circulation. The extracorporeal perfusion circuit was primed with 6% dextran (w/v) (dextran 60, Sigma-Aldritch, NSW, Australia) and $5000IU\ heparin.100ml^{-1}$ (Sigma-Aldrich, NSW, Australia) in normal saline. The extracorporeal circuit plus perfused muscle held a total volume of approximately 3mL.

Blood flow and muscle stimulation

Once all cannulations were in place and blood flowed freely throughout the system, the pump was engaged to perfuse the left leg at 1 $mL.min^{-1}$, supporting resting blood flow requirements [20], for 30 min equilibration prior to stimulating muscle contraction. Hindlimb perfusion pressure was monitored via a pressure transducer (Argon CDXIII, Maxim Medical, USA) distal to the pump. Sciatic nerve was stimulated at supramaximal voltage to elicit muscle contraction and the muscle stretched to optimal length for maximal twitch contraction force. Perfusion flow was increased to 1.5 $mL.min^{-1}$ to support the increased oxygen demand [20] for the duration of the muscle contraction protocol. Contractions were evoked using 5s burst trains of pulses (5Hz, 7-12V, 0.05ms) with 10s duty cycle for 5 min (Figure 1).

Muscle samples and fatty acid analysis

Gastrocnemius and soleus muscles were separated from the contralateral, unstimulated hindlimb during surgical preparation of the perfused limb and the left ventricle was collected on completion of the hindlimb stimulation protocol, after euthanasia by rapid exsanguination under anaesthetic. Samples were rapidly taken from three sites: the left ventricle free wall; the entire soleus muscle cleared of connective tissue; and the lateral superficial gastrocnemius muscle belly. All samples were rapidly frozen and stored at -80°C. Skeletal and cardiac muscle samples (100-200mg) underwent total lipid extraction using a modification of the Folch method [26]. Phospholipids were isolated from the total muscle lipid by solid phase extraction using silica Sep-pak™ cartridges (Waters, Australia). Fatty acid methyl esters were prepared by direct transesterification [27] of phospholipids and analysed by gas chromatography [17] using a Shimadzu GC-17A with flame ionisation detection. Individual fatty acid peaks on the chromatogram were identified by comparison to authentic fatty acid methyl ester standards (Sigma-Aldrich Corporation, Castle Hill, NSW) and Nu-Chek-Prep Inc. (Elysian, MN, USA) and expressed as percentage of total fatty acids in the phospholipid fraction. Peroxidisability index was calculated as the sum of bis-allelic hydrogen atoms (located on the methylene carbon atoms between two double bonds) according to the formula: (% dienoic acids × 1) + (% trienoics × 2) + (% tetraenoics × 3) + (% pentaenoics × 4) + (% hexaenoics × 5).[28]

Data analysis and calculations

Contractile force was recorded and contraction characteristics analysed using LabView for Windows with custom programming. Force and contraction characteristics were analysed for the first and 25^{th} (last) contraction in each 5s contraction burst (Figure 1). Fatigue was recorded: a) as the decline in developed force from 1^{st} to 25^{th} contraction within each burst; and b) as the decline in force between contraction bursts over time. The rate of fatigue between bursts was

determined, from both 1st and 25th contractions in each burst, as the time taken for the individual contraction developed force to decline to 50% of the maximum peak contraction force.

Statistics

Researchers were blinded to the allocation of animals to dietary groups until data collection and analysis was completed. Sample size calculation for membrane fatty acids estimated n=4 to detect 25% relative change in DHA (80% power for dose, α=0.05, $\bar{x}$ = 7.69%, SD = 1.35%[17]); and for contractile function, based on a 2Hz continuous stimulation protocol n=5 required to detect 35% increase in time to fatigue (80% power, α=0.05, $\bar{x}$ = 522s, SD = 142s). Results are expressed as mean±SEM. Two-way repeated measures ANOVA was used to analyse between muscle-type differences and effects of diet on fatty acid incorporation into muscle tissues, with tissue and diet main effects and (diet × tissue) interaction, followed by Tukey's *post-hoc* comparison of means (Statistix for Windows, Analytical Software, Tallahassee, USA). Statistical significance was accepted at $p<0.05$.

Results

Effects of diet on body weight and muscle weight

One rat was lost to the experiment due to excessive blood loss during preparative surgery, with no experimental data obtained, leaving final numbers of: Control n = 6; LowFO n=4; ModFO n = 7 for all measures. After 15 weeks of dietary intervention there were no significant dietary differences in body mass (Control: 463±30g, LowFO: 457±44g, ModFO: 464±12g) ($p>0.05$); gastrocnemius-soleus-plantaris mass (Control: 3.02±0.12g, LowFO: 3.15±0.15g, ModFO: 3.03±0.09g) ($p>0.05$) or ratio of gastrocnemius-soleus-plantaris mass / tibia-length (GSP/TL; Control: 6.91±0.24, LowFO: 7.30±0.24, ModFO: 6.89±0.15) ($p>0.05$).

Effect of muscle type on membrane phospholipid fatty acid composition

Statistically significant, between-tissues differences were observed in most fatty acids. In control animals, the few exceptions were: no between-tissues differences in the minor LCn-3 PUFA, DPA (<1%) or EPA (not detected); or in linoleic acid (18:2 n-6), which was the most abundant individual fatty acid at about 20% of total. There were no differences in membrane peroxidisability index between tissues in control animals (Table 2).

In control animals, the gastrocnemius muscle had significantly lower percentages of the saturated fatty acid (SFA) stearic acid 18:0 and monounsaturated fatty acid (MUFA) oleic acid 18:1 than either soleus or myocardium, which were not significantly different to each other. In

contrast, gastrocnemius had significantly higher percentages of: the SFA palmitic acid 16:0; and LC n-3 PUFA DHA; and lower ratio of n-6/n-3 PUFA, than either the soleus or myocardium, which were not significantly different to each other (Table 2). In soleus and myocardium, the principal SFA 18:0 was found at twice the percentage of 16:0, whereas in gastrocnemius the two were approximately equal. There were significant variations with tissue type in total relative percentages of SFA (gastrocnemius > soleus, myocardium), MUFA (soleus > myocardium, gastrocnemius) and PUFA (myocardium > gastrocnemius, soleus).

With respect to long-chain PUFA (Table 2), gastrocnemius muscle exhibited greater: 22:6n-3 DHA; total n-3 PUFA; and lower: 20:4n-6 arachidonic acid; 18:2n-6 linoleic acid; total n-6 PUFA percentages; and n-6/n-3 PUFA ratio, compared to either soleus or left ventricle (all $p<0.001$). The soleus further differed from the left ventricle having lower percentages of: 20:4n-6 arachidonic acid; and total n-6 PUFA (all $p<0.001$). The LC n-3 PUFA 20:5n-3 EPA was not detectable in any of the muscle tissues from control animals.

Effect of FO diets on membrane fatty acid composition

There were significant effects of FO diets on both types of skeletal muscle and cardiac membrane composition (Table 2). The major effects of dietary FO were: increased percentages of DHA (22:6n-3, $p<0.001$) and reduced AA (20:4n-6, $p<0.001$). Smaller changes were observed in other fatty acids, including reduced percentages of LA (18:2n-6, $p<0.001$) and a small but statistically significant incorporation of EPA (20:5n-3, $p<0.001$). These changes resulted in increased relative percentage of total n-3 PUFA ($p<0.001$) and peroxidisability index ($p<0.001$) and decreased relative percentage of total n-6 PUFA ($p<0.001$) and n-6/n-3 PUFA ratio ($p<0.001$). The incorporation of n-3 PUFA in exchange for n-6 PUFA was greater in the gastrocnemius muscle (all $p<0.05$, diet*tissue interaction).

In gastrocnemius muscle the higher dose ModFO diet was associated with significant further decrease in relative percentage of AA and increased DHA compared to the LowFO diet, with further reduced total n-6 PUFA and increased total n-3 PUFA ($p<0.05$) (Table 2). In soleus muscle and myocardium, the ModFO diet was associated with a small but significant further lowering in relative percentage of total n-6 PUFA ($p<0.05$) compared to the LowFO diet but no significant differences in DHA, LA, AA or any other major individual fatty acid, or total n-3 PUFA (Table 2).

Force characteristics

Maximum peak contractile force was reached within the first few 5s bouts of 5Hz stimulation. The first contraction in each repeated 5s bout was characterised by a rapid decline from bout to bout over 2-2.5 min to a plateau level which was maintained over the final minutes of the protocol (Figure 1a). The developed tension of the 25th (last) contraction in repeated bouts also declined rapidly from bout to bout over 1-1.5 min, to a plateau level maintained over the final minutes of the protocol (Figure 1b). Peak developed force declined from contraction to contraction (1 to 25) within the 5s bouts (Figure 2).

There were no dietary differences in the maximum peak force (Control: 222±14; LowFO: 212±4; ModFO: 218±9 N.100g^{-1} muscle mass) ($p>0.05$). Peak developed force declined over time and significant diet*time interactions were evident (contraction 1 $p=0.020$, contraction 25 $p<0.001$). A significantly longer time was taken for 1st contraction force to decline by 50% in the FO groups compared to control (Table 3) ($p<0.02$) (Figure 1a) and developed force was better sustained in the FO groups throughout and at the end of the five minutes of contractions (Figure 1) (contraction 1, contraction 25 $p<0.001$). There were no significant differences between LowFO and ModFO groups (contraction 1 $p=1.000$, contraction 25 $p=0.993$).

Peak developed force declined within each 5s burst (contraction 1-25), and over the first 60s there was significantly less within-burst decline in the FO groups compared to control (Figure 2). The FO groups took significantly longer for the 25th contraction peak developed force to decline by 50% (Table 3) ($p<0.05$). Maximum rates of force development and relaxation (Figure 3) slowed markedly over the first 60 to 100s and the decline in contraction and relaxation velocity was significantly greater in the control muscle than in FO muscles over the duration of the stimulation protocol. There were no significant differences between the LowFO and ModFO diets.

Hindlimb perfusion pressure and resistance

There were no significant differences in resting hindlimb perfusion pressures across dietary groups (at 1 mL.min^{-1}: Control 73±11 mmHg; LowFO 77±2; ModFO 76±4), (at 1.5mL.min^{-1}: Control 106±13 mmHg; LowFO 109±6; ModFO 104±5). Mean hindlimb perfusion pressure (at 1.5mL.min^{-1}) decreased during muscle contractions in FO dietary groups ($p<0.05$) with a non-significant trend in the control group ($p=0.08$) (Control 92±13 mmHg; LowFO 85±3; ModFO 88±4). There were no significant differences in perfusion pressure between dietary groups at rest or during muscle activity ($p>0.05$). A significantly greater percentage fall in mean hindlimb

vascular resistance occurred during muscle contraction in the FO dietary groups compared to control ($p=0.010$).

Discussion

Membrane phospholipid fatty acid composition of rat skeletal muscle was highly responsive to dietary fish oil, and elevated incorporation of DHA was associated with resistance to muscle fatigue. This was achieved with a low-dose human nutritional equivalent of 1-2 fish meals per week with little further dose-related changes, in either the membrane composition or contraction parameters, obtained from the higher dose human therapeutic equivalent of 6-7 g of fish oil per day [17]. The tuna fish oil supplement used in this study, with its high proportion of DHA, is consistent with the predominance of DHA in the human diet when obtained through common food fish [29] and in contrast to most dietary fish oil supplements that commonly provide EPA:DHA in the ratio 180:120 $mg.g^{-1}$. The *in vivo* hindlimb perfusion model permitted examination of dietary effects on muscle function and fatigue under well-oxygenated, well-perfused, appropriate physiological conditions [20]. Effects on fatigue could be directly attributable to change in muscle function without the potential confounding effects of dietary fish oil on cardiovascular function or behaviour. The membrane changes and fatigue resistance were achieved using much lower dietary LC n-3 PUFA concentrations than previously reported in the literature. From these intakes, both of which were within a range that could reasonably be modulated nutritionally in man, skeletal muscle and myocardium incorporated high relative percentages of LC n-3 PUFA DHA into membrane phospholipid. Muscle types exhibited differences in fatty acid composition in accord with their contrasting physiological functions and fibre type characteristics. Soleus muscle and myocardium had comparable patterns of fatty acid incorporation including high DHA incorporation, in contrast to the fast twitch, fatigable gastrocnemius muscle, which incorporated even higher relative percentages of DHA.

The lower of the two fish oil doses increased gastrocnemius and soleus muscle membrane DHA incorporation by 10% of the total fatty acids despite providing less than 1% of all the fatty acids in the diet. In contrast, linoleic acid diminished slightly in the membranes, despite being present as 8% of dietary fat and in an n-6/n-3 PUFA ratio of 5:1 in the lowFO diet, with the LA concentration almost 10 times that of DHA. Concomitant reductions occurred in membrane arachidonic acid of less than 4% in skeletal muscle or 6% in the heart. Thus, skeletal muscle of the rat incorporated DHA into membrane phospholipid well above its relative percentage in the diet, as seen with high dietary fish oil doses [5] and against an unfavourable ratio of n-6/n-3 PUFA. This finding confirms studies of skeletal muscle from developing rats and studies of rat

329 myocardium that show the absolute delivery of DHA is more important than its ratio to n-6
330 PUFA [17, 6], even at these low intakes of LC n-3 PUFA. Although there can be no doubt that
331 dietary n-6/n-3 PUFA ratio powerfully influences n-3 PUFA membrane incorporation when it is
332 dependent upon the shorter chain precursor alpha-linolenic acid (18:3n-3) [30], this is due to
333 competition for enzyme sites for desaturation or elongation limiting metabolic conversion to
334 EPA and DHA. The current study demonstrated that the incorporation into membrane
335 phospholipids is not subject to the same competition and confirms the previously reported lack
336 of influence of dietary n-6 PUFA on LC n-3 PUFA incorporation into rat myocardium [17] or for
337 clinical effect [31]. Striated muscle membranes preferentially incorporate DHA and this is further
338 illustrated by the very low incorporation of EPA into skeletal muscle or myocardium despite
339 significant dietary presentation in this study or when it is provided in purified form in the diet [32]
340 or as high EPA fish oil that delivers plasma fatty acid EPA well in excess of DHA [8]. Some
341 tissues e.g. platelets, preferentially incorporate EPA and the underlying physiological basis for
342 differential incorporation is not known.
343
344 The slow contracting, oxidative and fatigue resistant soleus muscle, which provides slow-to-
345 fatigue ankle stability and balance is in many ways similar to ventricular myocardium. Soleus
346 muscle and myocardium share a common isoform of myosin heavy chain that exhibit low basal
347 rates of ATP consumption (termed MHC_{slow} in type I muscle fibres and MHC_{β} in ventricular
348 myocardium) [33]. The ATP reserve capacity associated with MHC_{slow} and the lower ATP cost
349 for any developed tension in type I fibres [34] confers ATP conservation and fatigue resistance on
350 soleus muscle [35]. In contrast, in terms of fibre type, the portion of gastrocnemius muscle
351 sampled for fatty acid analysis in this study typically comprises mainly fast glycolytic / type IIb
352 fibres with few of the slow twitch, oxidative and fatigue resistant type I fibres that almost
353 exclusively make up the soleus muscle [36, 37]. Type II fibres are characteristically glycolytic, fast
354 twitch and provide short-term power generation. They are rich in MHC_2 isoforms [33], which
355 exhibit high rates of ATP consumption and low ATP reserve [34], making them rapidly subject to
356 fatigue with extended use. Preferential incorporation of DHA into fast contracting, powerful
357 gastrocnemius muscle compared to the slower contracting soleus has previously been reported in
358 developing rats [6]. A similar very high incorporation of DHA into faster compared to slow
359 muscle types is emphasised in species such as the rattlesnake and the hummingbird, which
360 possess muscle groups of even more extreme contrast in contraction speed within the one animal
361 [38]. The higher retention of DHA in gastrocnemius of non-supplemented rats may reflect an
362 adaptive response to the higher maximum rates of ATP turnover of the largely fast-twitch
363 gastrocnemius muscle fibres compared to soleus and heart.

The dietary fish oil-induced proportional increases in membrane DHA increased the unsaturation and peroxidisability index of the muscle membranes, forecasting increased risk of oxidative damage[28] and fatigability[39], however this is contrary to what was borne out in the physiological measures of fatigue. Similarly, in myocardium the increase in peroxidisability induced by increased membrane DHA is paradoxically associated with reduced ischaemia-reperfusion fatty acid peroxidation and oxidative damage [28, 40]. This has been attributed to an adaptive increase in activity of superoxide dismutase (SOD) and other endogenous antioxidant enzymes[40-42]. It suggests that chronically increased membrane peroxidisability induces chronic but non-damaging oxidative stress and adaptation in the same way that acute exercise induces oxidative stress, yet chronic exercise upregulates antioxidant mechanisms and promotes fatigue resistance[43]. Alternatively, it was recently reported that antiarrhythmic actions of DHA are enhanced by concomitant promotion of oxidation by H_2O_2 and inhibited by antioxidants, effects attributed to the specific non-enzymic oxidative production of DHA-derived neuroprotectins [44]. Irrespective of the mechanism, increased peroxidisability of the membranes by enhanced DHA content is associated with protective rather than damaging effects under oxidative stress.

Non-dietary, adaptive increases in DHA incorporation and lower tissue n-6/n-3 PUFA ratio [45] occur commonly in response to stresses in a variety of tissues including: human exercising skeletal muscle [46]; aging human heart [47]; human placenta at altitude [48]; chronic hypoxic rat heart [49]; and chronic catecholamine stress in rat heart [47]. An adaptive increase can be seen across mammalian species (including man) in relation to high basal metabolic rate or resting heart rate, where the whale with its very low heart rate and high LC n-3 PUFA intake has very low myocardial DHA, in contrast to the mouse that has a very high heart rate, yet very high cardiac DHA relative percentage despite low LC n-3 PUFA intake [47, 45]. In direct contrast, dietary intervention to raise cardiac DHA is associated with slower heart rates and preconditioning protection against these stresses [2, 45, 13]. A similar observation applies to the restriction of acute muscle fatigue with dietary n-3 PUFA [15, 14] in contrast to the preferential incorporation of DHA and lower n-6/n-3 PUFA ratio in the more rapidly fatiguing gastrocnemius [6] and this may be related to the greater metabolic stress prevalent in type II fibres.

The upper dose ModFO (1.25% FO) diet induced DHA incorporation in gastrocnemius to the same extent as reported previously with high dose 7% FO supplementation in the similar, mixed fibre type vastus lateralis muscle [14]. In the current study there was little displacement of tissue

linoleic acid compared to earlier studies that used high fish oil doses. With diets in those studies delivering six times the DHA dose and a n-6/n-3 PUFA ratio of <0.2, it is evident that previous research has used fish oil doses far in excess of requirements for maximal effect.

The modulation of rat muscle phospholipid fatty acid composition, as a result of these small fish oil intakes, induced marked resistance to muscle fatigue *in vivo* without influencing the initial peak force of contraction of the hindlimb. Fatigue in the contracting hindlimb could be characterised in terms of: extent of decline in twitch force within the 25 contractions of any 5s burst; extent of decline in twitch force from burst to burst (which has a recovery component); the time course of the decline in twitch force; the decline in maximum rate of force production and relaxation; and the time course of those changes. The dietary fish oil markedly attenuated the decrease in muscle force production and extended the time course of well sustained isometric force production. In other words, the hindlimb muscles of animals fed fish oil were able to complete more contractions at a force closer to their peak isometric tension. In skeletal muscle, when force is sustained at a higher relative tension over time, it is explained by the optimal coupling relationship between cellular ATP demand, inherently the efficiency of ATP use by the contracting cell, and the metabolic supply [50, 51]. Furthermore, while muscles sustained higher peak contractile force for longer after fish oil feeding, the attenuation in decline in rates of force production and relaxation also implies an optimal coupling of net Ca^{2+} turnover and cellular ATP maintenance, most importantly associated with the powerful but fatigable, fast twitch fibres [52].

Notably, the greatest effect of dietary fish oil, retarding fatigue, occurred in the earliest phase of contraction, which corresponds to the highest rate of tension decline from peak force. With single pulse or tetanic burst contractions, fatigue occurs much more rapidly in fast, type II muscle fibres than in slow, type I fibres in shortening or isometric contractions [21, 19]. This response is likely due to the greater part of the hindlimb muscle bundle representing fast, type II fibres, densely packed with sarcoplasmic reticulum and expressing high sarcoplasmic reticulum Ca^{2+}ATPase (SERCA) concentration, a requirement to sustain rapid force production and relaxation. Highly effective SERCA, like those in the powerful muscle fibres, rely on the phospholipid environment to carry out rapid removal of calcium against its concentration gradient [53]. There is strong evidence that when DHA makes up a high proportion of the membrane fatty acids, this process of Ca^{2+} pumping is optimised [38], thus sustaining force production in the periods of rapid fatigue.

While this study demonstrates a clear association between dietary fatty acids, muscle incorporation of DHA and fatigue resistance, it does not identify the mechanisms of fatigue that are affected. Since fish oil feeding does not modify glycogen storage or attenuate metabolic acidosis during fatiguing muscle stimulation [15], we can exclude the two most common interventional approaches used ahead of exercise to improve muscle function: promotion of glycogen storage; and metabolic alkalosis inducable by sodium bicarbonate ingestion [54]. We must therefore consider one or more of the many other cellular mechanisms potentially underlying fatigue-resistance [21, 19]. Whilst they are not readily directly examinable *in vivo* [19], some insight into potential mechanisms of action of LCn-3 PUFA fatigue resistance may be gained from comparison to interventions that, in contrast to fish oil, enhance muscle fatigue.

The pattern of improved muscle function by fish oil relative to control contrasts with the effects that the β_2 adrenoceptor agonist clenbuterol has on muscle function. Chronic clenbuterol treatment has found some popularity in body building for its promotion of muscle hypertrophy, but it significantly slows relaxation and decreases resistance to fatigue in fast twitch muscle fibres [55]. Clenbuterol's functional effects appear linked to intracellular Ca^{2+} homeostasis, especially the leakage of SR Ca^{2+} [55]. The decline in SR Ca^{2+} and slow SR Ca^{2+} reuptake, with the latter contributing to slowed isometric relaxation, are believed to underpin fatigue in both fast and slow twitch muscles under tetanic [56] or non-tetanic stimulation [57, 58]. If Fish oil were to prevent SR Ca^{2+} leakage and promote SR Ca^{2+} reuptake, this could explain the fatigue resistance. Indeed, such effect has been observed in myocardium in which altered Ca^{2+} handling is recognised to play a part in DHA action in myocardial intracellular signalling, with modulated SR Ca^{2+} leakage implicated in cardiac pacemaker slowing and arrhythmia prevention in cardiac muscle [13]. Both direct and indirect evidence shows increased efficiency of SR Ca^{2+} handling as a basis for prevention of arrhythmia [44, 1] and reduced mitochondrial Ca^{2+} uptake as a basis for increased oxygen efficiency [1] or as the basis for reduced mitochondrial pyruvate dehydrogenase activity [59] in rat myocardium after fish oil feeding. However the evidence is equivocal with another study finding that dietary fish oil has little influence on cardiac SERCA activity and may even increase cardiac mitochondrial Ca^{2+}-ATPase activity [60]. Moreover, an *in vitro* study of SR function of skeletal muscle from rats fed DHA also revealed reduced SERCA activity and increased Ca^{2+} leakage[61], which would predict slower relaxation and increased energy requirements and fatigability, the opposite to what is actually observed *in vivo* during muscle contraction in the present study. Further studies are needed to investigate the role of altered Ca^{2+} homeostasis in the effects that membrane incorporation of DHA has on muscle fatigue.

Further studies are also required to identify effects more specifically in fast and slow twitch fibre types in accordance with differences in DHA incorporation. The improved muscle function during the early fast-fatiguing component of the non-tetanic repetitive burst stimulation protocol implicates fast, type II fibres in a primary role in this study, in line with the predominance of gastrocnemius muscle in the contracting bundle. However, slow type I fibres and involvement of soleus muscle are also implicated in DHA effects by the sustained greater force and better sustained rates of force development observed after the early fatigue phase, plus the continued greater recovery between contraction bouts after fish oil feeding. While myocardium typically does not fatigue acutely, contractile function and relaxation do decline significantly in heart failure and this can be counteracted by feeding with fish oil [62, 63]. The patterns of enhanced skeletal muscle fatigue in rats with heart failure [21] suggest a benefit could be gained by increasing membrane DHA.

This study demonstrated that marked changes in muscle membrane fatty acid composition together with resistance to muscle fatigue are achievable in rat skeletal muscle with only small dietary supplements of LC n-3 PUFA, in a range readily compatible with human nutrition [13]. The low effective dose and the DHA rich tuna fish oil supplement replicate human dietary patterns achievable from eating a low-moderate intake of fish, and provide a basis for translating to humans, the physiological observations herein and those previously made using high doses of fish oil in animals. Furthermore, tissue differences in membrane fatty acid composition suggest specific incorporation of fatty acids reflective of physiological function, with the fatigue-resistant slower-contracting soleus muscle and myocardium exhibiting many compositional similarities contrasting to the highly-fatigable fast-contracting gastrocnemius muscle. Of particular note, whilst it is generally incorporated well in all striated muscle, DHA was innately incorporated to higher relative percentages in the gastrocnemius compared to the soleus muscle and myocardium without any dietary intervention as well as in response to fish oil feeding, perhaps reflecting an adaptive response to the higher peak metabolic demand and fatigability of the predominant type II muscle fibres. The large changes in composition and function achieved with only small additions of fish oil to the diet suggests that DHA may be an essential component of striated muscle for optimal healthy function and that the failure to include regular fish or fish oil in the diet might lead to a deficiency condition reflected in susceptibility to muscle fatigue.

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Conflict of interest:

None.

Authorship:

R.H., G.E.P. and P.L.M. conceived and designed the research; R.H. collected and analysed the data; R.H. and P.L.M. analysed the data; and R.H., G.E.P., and P.L.M. interpreted the data and provided important intellectual content in the drafting of the manuscript. P.L.M. had primary responsibility for final content.

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668

669 **Table 1**: Dietary fatty acid composition for diets with different concentrations of fish oil

Diet:	**Control**	**LowFO**	**ModFO**
FO g/kg diet:	0	3.1	12.5
OO g/kg diet:	100	96.9	87.5
Fatty acid		(g/kg)	
14:0	0	0.1	0.4
16:0	10.4	10.7	11.6
18:0	2.8	2.9	3.1
18:1 (OA)	75.8	73.9	68.2
18:2 n-6 (LA)	8.3	8.1	7.5
18:3 n-3 (LNA)	0.5	0.5	0.5
20:4 n-6 (AA)	0.1	0.2	0.3
20:5 n-3 (EPA)	0	0.2	0.9
22:5 n-3 (DPA)	0	0.1	0.1
22:6 n-3 (DHA)	0	0.9	3.6
Σ n-6 PUFA	8.7	8.5	8.0
Σ n-3 PUFA	0.5	1.7	5.1
n-6/n-3 PUFA ratio	16.63	5.05	1.56
LA % en	1.92	1.87	1.72
EPA % en	0	0.05	0.20
DHA % en	0	0.20	0.83
Total fat % en	23.08	23.08	23.08

670

671 Control diet (0% fish oil); LowFO: 0.31% fish oil diet; ModFO: 1.25% (moderate) fish oil diet.
672 AA: arachidonic acid; DHA: docosahexaenoic acid; DPA: docosapentaenoic acid; EPA:
673 eicosapentaenoic acid; LA: linoleic acid; LNA: linolenic acid; OA: oleic acid; OO: olive oil;
674 PUFA: polyunsaturated fatty acid

675 Table 2. Percent fatty acid composition of membrane phospholipids of heart and hindlimb muscles from rats after dietary fish oil supplementation for
676 15 weeks

	Tissue:	Gastrocnemius			Soleus			Left Ventricle		
	Diet:	Control	LowFO	ModFO	Control	LowFO	ModFO	Control	LowFO	ModFO
Fatty acid:			**(0.31%)**	**(1.25%)**		**(0.31%)**	**(1.25%)**		**(0.31%)**	**(1.25%)**
16:0	§	^{b}15.70 ± 0.83	^{a}20.39 ± 0.97*	^{a}21.98 ± 2.18*	^{c}9.83 ± 0.56	^{b}15.57 ± 0.63*	^{a}17.95 ± 0.68*	^{c}9.59 ± 0.18	^{c}11.57 ± 0.21	^{b}12.36 ± 0.10
16:1	@	^{a}0.63 ± 0.04	^{a}0.71 ± 0.08	^{a}0.88 ± 0.17	^{a}0.75 ± 0.09	^{ab}0.68 ± 0.09	^{a}0.62 ± 0.05	^{b}0.36 ± 0.02	^{b}0.37 ± 0.04	^{b}0.31 ± 0.02
18:0	§	^{c}16.15 ± 0.76	^{c}15.83 ± 0.58	^{c}15.49 ± 0.66	^{b}18.77 ± 0.45	^{b}18.17 ± 0.65	^{a}19.98 ± 0.82	^{a}20.49 ± 0.13	^{a}19.88 ± 0.24	^{a}20.30 ± 0.36
ΣSFA	§	^{a}36.40 ± 1.06	^{a}38.84 ± 1.27	40.30 ± 2.54	^{b}32.94 ± 0.73	^{ab}35.79 ± 0.51	40.23 ± 1.41*	^{b}30.11 ± 0.12	^{b}33.46 ± 0.13	34.91 ± 0.30
18:1	ø	^{b}10.32 ± 0.48	^{ab}12.81 ± 0.57*	^{b}11.94 ± 0.32*	^{a}14.96 ± 1.08	^{a}15.87 ± 0.68	^{b}14.19 ± 0.64	^{a}13.43 ± 0.21	^{b}11.26 ± 0.20*	^{b}10.28 ± 0.29*
ΣMUFA	ø	^{b}12.14 ± 0.48	^{ab}13.87 ± 0.61	13.19 ± 0.50	^{a}17.72 ± 1.29	^{a}16.99 ± 0.64	15.11 ± 0.62	^{b}13.79 ± 0.20	^{b}12.06 ± 0.20	11.01 ± 0.31
18:2n-6	#	19.66 ± 0.85	16.80 ± 0.74	15.09 ±1.03*	20.68 ± 0.55	18.78 ± 0.54	17.59 ± 0.26*	21.17 ± 0.39	19.25 ± 0.71	18.08 ± 0.32*
20:3n-6	ø	^{a}0.78 ± 0.03	^{b}0.51 ± 0.03*	^{b}0.51 ± 0.04*	^{a}0.80 ± 0.02	^{a}0.63 ± 0.07*	^{a}0.67 ± 0.01	^{b}0.55 ± 0.02	^{b}0.51 ± 0.04	^{b}0.53 ± 0.02
20:4n-6	§	^{b}15.85 ± 0.53	^{b}11.47 ± 0.93*	^{b}7.01 ± 1.06*†	^{b}16.37 ± 0.41	^{b}13.61 ± 0.81*	^{b}9.36 ± 0.61*	^{a}24.04 ± 0.37	^{a}18.41 ± 0.45*	^{a}15.65 ± 0.55*
22:4n-6	#	^{b}0.39 ± 0.09	0.19 ±0.05	0.03 ± 0.03*	^{a}0.66 ± 0.06	0.31 ± 0.08*	0.06 ± 0.06*†	^{a}0.70 ± 0.04	0.32 ± 0.03*	0.12 ± 0.01*†
22:5n-6	@	^{b}1.39 ± 0.11	0.35 ± 0.04*	0.40 ± 0.01*	^{b}1.24 ± 0.08	0.41 ± 0.05*	0.23 ± 0.08*	^{a}2.07 ± 0.10	0.62 ± 0.04*	0.57 ± 0.03*
Σ n-6 PUFA	§	^{b}41.23 ± 0.94	^{b}28.99 ± 0.99*	^{c}22.97 ± 1.59*†	^{b}42.92 ± 1.10	^{b}33.27 ± 1.23*	^{b}27.72 ± 0.81*†	^{a}48.54 ± 0.23	^{a}38.83 ± 0.56*	^{a}34.88 ± 0.67*†
20:5n-3		n.d.	0.16 ± 0.04*	0.36 ± 0.10*†	n.d.	0.06 ± 0.04	0.29 ± 0.07*	n.d.	0.05 ± 0.01	0.37 ± 0.04*†
22:5n-3		^{a}0.87 ± 0.05	0.86 ± 0.06	^{b}0.85 ± 0.09	^{b}0.71 ± 0.03	0.95 ± 0.06*	^{a}1.01 ± 0.08*	^{b}0.68 ± 0.04	0.79 ± 0.05	^{b}0.91 ± 0.04*
22:6n-3	#	^{a}9.26 ±0.74	^{a}19.89 ± 0.36*	^{a}24.25 ± 1.03*†	^{b}5.14 ± 0.23	^{b}14.27 ± 0.65*	^{b}18.04 ± 1.40*	^{b}6.62 ± 0.34	^{b}16.84 ± 0.38*	^{b}20.35 ± 0.68*
Σ n-3 PUFA	§	^{a}9.75 ± 0.63	^{a}18.30 ± 0.30*	^{a}22.33 ± 1.02*†	^{b}5.62 ± 0.21	^{b}13.35 ± 0.63*	^{b}16.93 ± 1.30*	^{b}7.30 ± 0.34	^{b}15.65 ± 0.35*	^{b}19.21 ± 0.60*

ΣPUFA	@	[b]51.45 ± 0.89	[b]47.29 ± 0.76	[b]45.31 ± 2.16	[b]49.34 ± 1.07	[b]46.62 ± 1.36	[b]44.66 ± 1.81	[a]56.10 ± 0.15	[a]54.49 ± 0.27	[a]54.08 ± 0.47
n-6/n-3 ratio	#	[b]4.33 ± 0.34	[b]1.59 ± 0.08*	1.03 ± 0.07*	[a]7.71 ± 0.43	[a]2.51 ± 0.14*	1.68 ± 0.12*	[a]6.72 ± 0.34	[a]2.49 ± 0.09*	1.83 ±0.09*
PI	ø	136 ± 3	[a]156 ± 2*	[a]162 ± 7*	125 ± 1	[b]143 ± 4*	[b]147 ± 7 *	134 ± 2	[a]166 ±2*	[a]173 ± 2*

Σ SFA = sum of saturated fatty acids; Σ MUFA = sum of monounsaturated fatty acids; Σ PUFA = sum of polyunsaturated fatty acids; PI = peroxidisability index (Peroxidisability index was calculated from the formula: (% dienoic acids × 1) + (% trienoics × 2) + (% tetraenoics × 3) + (% pentaenoics × 4) + (% hexaenoics × 5).[28] . Values are mean ± SEM. n= 4-6 per group. Within tissues (between diets): *p<0.05 vs. control diet (Table 2); †p<0.05 vs. LowFO diet. Between tissues (within diets): Values sharing a common letter superscript are not significantly different to other tissues within that diet. Overall between tissues (all diet groups combined): § p<0.05 LV ≠ sol ≠ gastroc; # p<0.05 gastroc ≠ sol, LV; ø p<0.05 sol ≠ gastroc, LV; @ p<0.05 LV ≠ sol, gastroc.

684 Table 3. Effect of dietary FO on time (s) to decline to 50% of maximum for contraction and relaxation
685 parameters of first and 25th (last) contractions in repetitive 5s burst stimulation.

		Contraction peak force		Contraction rate +dT/dt max		Relaxation rate -dT/dt max	
DIET		First	Last	First	Last	First	Last
Control	n=6	62 ±10s	35 ± 7s	48 ± 2s	33 ±5s	26 ±4s	18 ±2s
Low FO	n=4	*110 ±15s	*61 ± 8s	*94 ±13s	*51 ±8s	*35 ±5s	21 ±3s
ModFO	n=7	*117 ±14s	*62 ±11s	*96 ±12s	*56 ±9s	*37 ±3s	*25 ±3s

686 * P<0.05 vs control diet.

687

688 **Figure Legends:**

689 **Figure 1.** Typical experimental trace from the contracting rat hindlimb illustrating force
690 development during a 5 min stimulation protocol (5Hz, 5s duty cycle) with (inset) one 5s burst
691 expanded to show the key derived measures of force and rate of force development (+/-
692 dT/dt_{max}).
693
694 **Figure 2.** Effect of diet on force production ($N.100g^{-1}$ muscle mass) of gastrocnemius/ soleus/
695 plantaris muscle bundle during repeated burst (5Hz, 5s duty-cycle) stimulation for 5 min. (a)
696 Force of the first contraction in each burst; (b) Force of the 25th (last) contraction in each burst.
697 Horizontal broken lines represent 50% of maximum contraction. (See Figure 1 for illustration)
698 Arrows (solid = control diet; broken = FO diets) show coincidence of the (a) first and (b) 25th
699 contraction in a burst with its decline to below 50% of maximum. Bars represent mean ± SEM.
700 Filled bars: Control diet n=6; Shaded bars: LowFO diet n=4; Open bars: ModFO diet n=7. *
701 LowFO, ModFO different to control, $p< 0.05$.
702
703 **Figure 3.** Effect of diet on differences in developed force ($N.100g^{-1}$ muscle mass) within bursts
704 (below axis) and recovery between bursts (above axis) of (5Hz, 5s duty-cycle) stimulation over 5
705 min. Within burst changes represents short-term fatigue over 5s. Between bursts represents
706 recovery of contractile force in the first contraction of a new burst relative to the 25th (last)
707 contraction of the previous before. (See Figure 1 for illustration) Bars represent mean ± SEM.
708 Filled bars: Control diet n=6; Shaded bars: LowFO diet n=4: Open bars: ModFO diet n=7. †
709 LowFO, ModFO different to control, $p< 0.02$; * LowFO, ModFO different to control, $p< 0.05$.
710
711 **Figure 4.** Effect of diet on maximum rate of force development ($dT.dt^{-1}_{max}$ above axis) and
712 maximum rate of force decline ($-dT.dt^{-1}_{max}$ below axis) in individual contractions ($N.100g^{-1}.s^{-1}$)
713 during repeated burst (5Hz, 5s duty-cycle) stimulation for 5 min. (a): first contraction; (b): 25th
714 (last) contraction in each 5s burst. (See Figure 1 for illustration) Horizontal broken lines
715 represent 50% of maximum. Filled symbols: Control diet n=6; shaded symbols: LowFO diet
716 n=4; open symbols: ModFO diet n=7. Symbols and bars represent mean ± SEM. † ModFO
717 different to control, $p< 0.02$; * LowFO, ModFO different to control, $p< 0.05$.

718

719

Figure 1

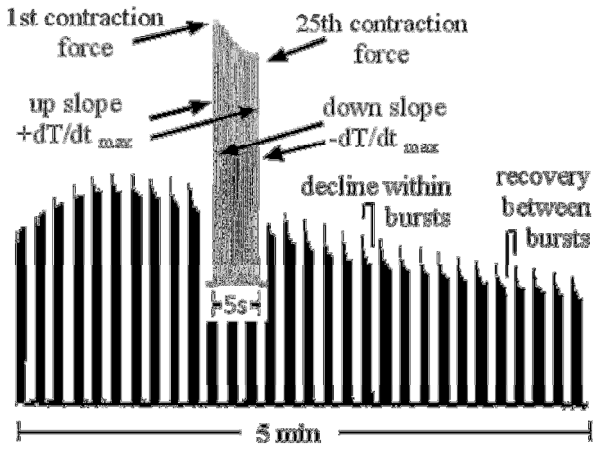

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Figure 2

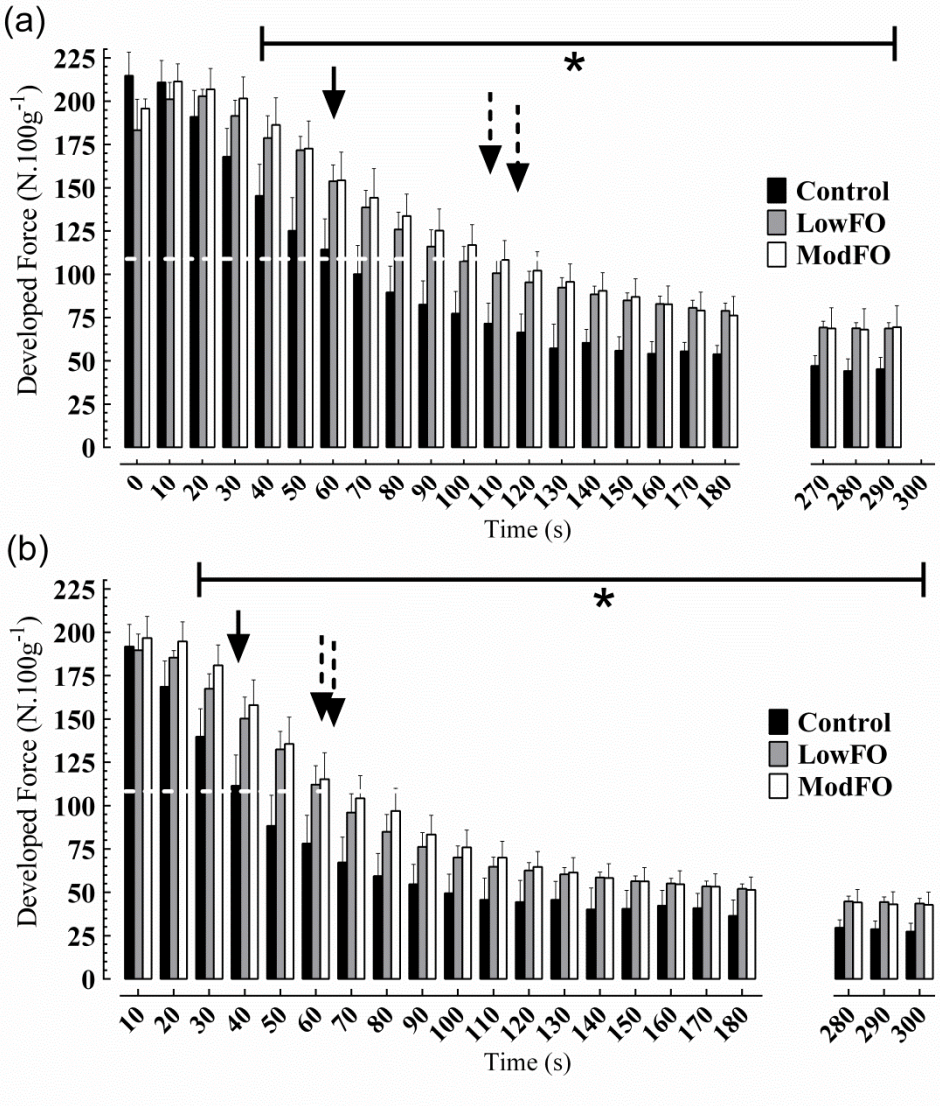

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Figure 3

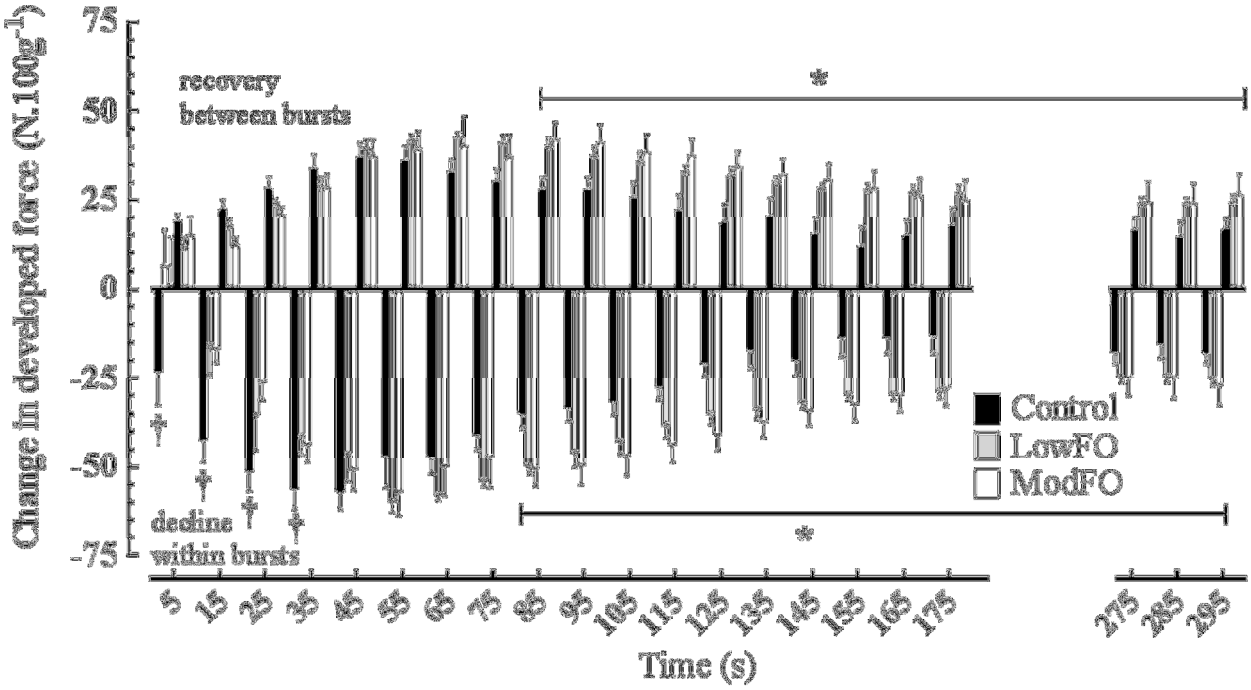

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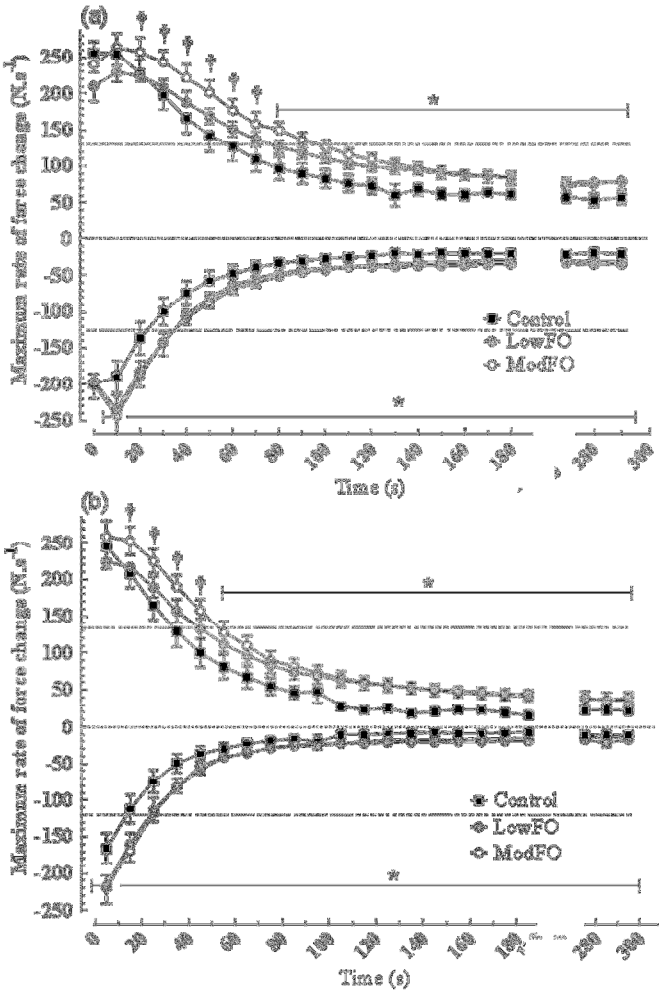
Figure 4



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