

Does hypoxia play a role in the development of sarcopenia in humans?

Mechanistic insights from the Caudwell Xtreme Everest Expedition

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ABSTRACT

Objectives: Sarcopenia refers to the involuntary loss of skeletal muscle and is a predictor of physical disability/mortality. Its pathogenesis is poorly understood, although roles for altered hypoxic signaling, oxidative stress, adipokines and inflammatory mediators have been suggested. Sarcopenia also occurs upon exposure to the hypoxia of high altitude. Using data from the Caudwell Xtreme Everest expedition we therefore sought to analyze the extent of hypoxia-induced body composition changes and identify putative pathways associated with fat-free mass (FFM) and fat mass (FM) loss.

Methods: After baseline testing in London (75m), 24 investigators ascended from Kathmandu (1,300m) to Everest base camp (EBC 5,300m) over 13 days. Fourteen investigators climbed above EBC, eight of whom reached the summit (8,848m). Assessments were conducted at baseline, during ascent and after one, six and eight week(s) of arrival at EBC. Changes in body composition (FM, FFM, total body water, intra- and extra-cellular water) were measured by bioelectrical impedance. Biomarkers of nitric oxide and oxidative stress were measured together with adipokines, inflammatory, metabolic and vascular markers.

Results: Participants lost a substantial, but variable, amount of body weight (7.3 ± 4.9 kg by expedition end; $p < 0.001$). A progressive loss of both FM and FFM was observed, and after eight weeks, the proportion of FFM loss was 48% greater than FM loss ($p < 0.008$). Changes in protein carbonyls ($p < 0.001$) were associated with a decline in FM whereas 4-hydroxynonenal ($p < 0.001$) and IL-6 ($p < 0.001$) correlated with FFM loss. GLP-1 ($r = -0.45$, $p < 0.001$) and nitrite ($r = -0.29$, $p < 0.001$) concentration changes were associated with FFM loss. In a multivariate model, GLP-1, insulin and nitrite were significant predictors of FFM loss while protein carbonyls were predicted FM loss.

Conclusions: The putative role of GLP-1 and nitrite as mediators of the effects of hypoxia on FFM is an intriguing finding. If confirmed, nutritional and pharmacological interventions targeting these pathways may offer new avenues for prevention and treatment of sarcopenia.

INTRODUCTION

Sarcopenia is defined as a significant loss of fat free mass (FFM). This can affect physical function and lead to an increased risk of physical disability and mortality¹. The pathogenesis of sarcopenia is likely to be multifactorial, and skeletal muscle hypoxia has been proposed as a causal factor for muscle wasting and reduced contractility²⁻⁴.

Weight loss has been widely reported in hypoxic chamber experiments and after sojourns at high altitude, with associations between magnitude of loss and both duration of exposure to hypoxia and level of hypoxemia⁵⁻⁷. Current evidence seems to point to an alteration of appetite control and consequent reduction of energy intake as a determinant of the weight loss, whereas energy expenditure (resting and dietary induced thermogenesis) seems to be less affected⁸. More than 60% of the weight lost is typically composed of FFM leading to a decline of muscle contractility and physical performance and, consequently, an individual's capacity to cope with extreme environmental conditions⁹.

Changes in appetite hormones [(leptin, ghrelin, glucagon like peptide 1 (GLP-1) and cholecystokinin K (CCK)] have been reported after exposure to hypoxia¹⁰⁻¹². In particular, the role of leptin and ghrelin as causal factors in the reduction of energy intake has attracted controversy after studies reported opposing associations of these appetite hormones with weight loss¹³⁻¹⁷. Recently, a decreased secretion of post-prandial GLP-1 was observed in healthy men exposed to normobaric hypoxia.¹⁸ Conversely, an *in vitro* study showed enhanced GLP-1 secretion after hypoxia-inducible factor-1 α (HIF-1 α) knockdown in human adipocytes¹⁹. To the best of our knowledge, the role of GLP-1 has never been investigated in humans exposed to prolonged hypobaric hypoxia.

A key role in the onset of these adaptive metabolic responses is played by inflammation and oxidative stress, which are enhanced under conditions of low oxygen availability^{7,20-22}. The consecutive disruption of intracellular redox balance and inflammation both contribute to skeletal muscle mobilization^{23,24}. Hypoxia disrupts the efficiency of the mitochondrial electron transport chain, inducing leakage of electrons to molecular oxygen and thereby generating reactive oxygen species (ROS)²⁵. Interleukin 1 (IL-1), interleukin 6 (IL-6) and C-reactive protein (CRP) are often upregulated during expeditions at high altitude²⁶, and mechanisms linked to skeletal muscle wasting include activation of HIF-1 α and NF- κ B catabolic pathways and inhibition of the anabolic mammalian target of rapamycin (mTOR) pathway²⁷⁻²⁹. Nitric oxide (NO) metabolism is also influenced by oxygen availability as

demonstrated by raised levels of nitrite and nitrate (markers of NO production) and cyclic guanosine monophosphate (cGMP, a biomarker of NO activity) during acclimatisation to high altitude³⁰.

Therefore, physiological data and plasma samples from the 2007 Caudwell Xtreme Everest (CXE) expedition³¹ could provide valuable mechanistic insights into the relationship between hypoxia and FFM loss whereby the extended duration at high altitude serves as a pathogenic model of sarcopenia. We first assess body composition changes (FM and FFM) and fluid shifts [total body water (TBW), intracellular (ICW) and extracellular water (ECW)] that occurred during the expedition. We then evaluate the association between changes in FM and FFM with a comprehensive panel of biomarkers of oxidative stress, inflammation, NO bioavailability, appetite control and intermediary metabolism to identify significant predictors of changes in FM and FFM during prolonged exposure to hypoxia. We hypothesized that changes in FFM would be associated with indices of oxidative stress and inflammation in this group of healthy individuals exposed to hypobaric hypoxia during the CXE study.

METHODS

The study was approved by the University College of London (UCL) Research Ethics Committee, in accordance with the Declaration of Helsinki. Verbal and written informed consent was obtained from all subjects. The study took place between January and June 2007.

Subjects: Twenty-four healthy participants (18 male; mean age 34.9y; range 19–59y) who were investigators on the CXE 2007 research expedition to Mount Everest participated in this study³¹. All participants were sea level natives free of cardiovascular or respiratory disease. Criteria for participation have been described in detail elsewhere³¹.

Study Protocol: The design and conduct of this study is described elsewhere³¹. Briefly, participants underwent baseline testing in London (altitude 75m) before travelling by plane to Kathmandu, Nepal (1,300m). From there they flew to Lukla (2,800m) on expedition day 1 and then trekked to Everest Base Camp (EBC; 5,300m), arriving on expedition day 13. The ascent profile, along with blood hemoglobin levels and oxygen saturations, is detailed in **Table S1 of the Online Supplementary Material**. Testing was conducted during the ascent in field laboratories at Kathmandu (1,300m; day -3 to 0), Namche (3,500m; day 4 to 6),

Pheriche (4,250m; day 9 to 10), and at EBC (5,300m; day 15 to 17, EBC week 1). The participants were divided into two subgroups, Group 1 (base-camp team) who subsequently remained at EBC for the duration of the expedition (n=10) and Group 2 (climbing team; n=14) who subsequently ascended above 5,300m, to a maximum of 8,848m on Mount Everest; measurements were repeated in both groups at week 6 and week 8. Ambient temperatures were well controlled during testing³¹.

Dietary intake: Three meals were provided per day along with ample provision of calorific snacks (chocolate, nuts, crisps, malt loaf, cheese, cured meat) *ad libitum*, guaranteeing access to plenty of carbohydrates and protein to cope with the increased energy cost of the walk /climb; fresh fruit and vegetable intake was low at altitudes above 3,500m. An ample supply of meals and snacks were maintained up to camp 2, beyond this hot food consisted of dehydrated meals whilst snacks remained available.

Peripheral oxygen saturation: SpO₂ was measured by an independent investigator on the morning of the same day that blood was analyzed, after 10 minutes of rest, using a pulse oximeter (Onyx 9500, Nonin, USA).

Anthropometry: Body weight (kg) was measured using mechanical Seca 761 scales (Seca, Birmingham, UK), which were hand-calibrated. An independent investigator recorded body weight to the nearest 0.5kg with the participant wearing base layers only. Height was measured using a portable stadiometer and recorded to the nearest 0.1cm.

Body Composition: Bioelectrical impedance measurements were taken after a 10 min period of supine rest as the participant lay on a non-conducting air mattress with their arms away from their torso and their legs separated. Measurements were obtained before meals and after voiding. The participants wore base layers but removed shoes and socks. Aluminium electrodes were placed on the right side over the metacarpophalangeal joints and between the ulna-radial styloid processes of the wrist and over the metatarsal phalangeal joints and between the malleoli of the ankle. A hand-held, battery operated tetrapolar bioimpedance analyser (Bodystat® 1500) was used to apply currents at multiple frequencies of 5, 50, 100 and 200 kHz. Total body water and extracellular water were calculated by integral algorithms of the bioanalyser. We assumed that water contributed 73% to FFM at normal hydration status. Intracellular water was calculated as the difference between TBW and ECW. FM was calculated as the difference between body weight and FFM.

Blood sampling and sample analysis: All blood samples were taken prior to any exercise protocols scheduled for the day³¹ and drawn from the antecubital vein. Plasma was separated from blood cells by centrifugation of whole blood at 800xg for 15min and immediately frozen in 1ml aliquots in liquid nitrogen. Samples were stored for the duration of the expedition including their transport back to Kathmandu in liquid nitrogen, transported back to the UK on dry ice and kept at -40°C in a commercial cryostorage facility until analysis. *Sample analysis began approximately one year after start of biobanking (July 2007) and was completed within 22 months (Aug 2008-May 2010).*

Oxidative Stress Markers: Isoprostanes (8-iso-prostaglandin F-2α) and 4-hydroxy-2-nonenal (4-HNE) were quantified using direct competitive enzyme immunoassay (Assay Designs, Ann Arbor, MI) and ELISA (OxiSelect HNE-His Adduct ELISA kit, Cell Biolabs, San Diego, CA), respectively. Protein carbonyls (ProCO) were quantified following derivatization with dinitrophenylhydrazine using a commercial ELISA kit (OxiSelect STA-310; Cell Biolabs).

Nitric Oxide Biomarkers: NO metabolite concentrations were quantified immediately after thawing of frozen plasma aliquots in the presence of an excess of N-ethylmaleimide (NEM, in PBS; 10 mM final concentration). For nitrite/nitrate analysis, NEM-treated samples were deproteinized with ice-cold methanol (1:1 v/v), cleared by centrifugation and subjected to analysis by high pressure liquid chromatography using a dedicated nitrite/nitrate analyzer (ENO20, Eicom). Cyclic GMP was determined by commercial immunoassay kits (R&D Systems, Abingdon, UK; Biomedica, Vienna, Austria).

Inflammatory Markers: Interleukin-6, tumour necrosis factor (TNF-α) and *macrophage* migration inhibitory factor (MIF) were quantified using xMAP technology (Human-Cytokines-12-plex-panel, BioRad) on a Luminex/Bio-Plex-200 System with high-throughput fluidics (BioRad).

Glucose and Insulin: Plasma glucose levels were measured with the glucose oxidase method. Insulin levels were determined using the Bio-Plex-Pro-Human-Diabetes 12-plex panel (BioRad).

Metabolic Hormones and Adipokines: Adiponectin, adipisin, ghrelin, glucose-dependent insulinotropic polypeptide (GIP), GLP-1, glucagon, leptin, resistin, and visfatin were measured with the Bio-Plex Pro-Human-Diabetes multiplex immunoassay panels (BioRad). Epinephrine and Norepinephrine were quantified using a direct competitive enzyme immunoassay (Bi-CAT ELISA, Alpco Diagnostics, Salem, NH). Lactate concentrations were

determined colorimetrically by coupled enzymatic reactions using commercial assay kits (Sigma). Triiodothyronine (T3) was measured using the rat thyroid hormone panel Milliplex MAP kit (Millipore; there is no difference between rat and human T3).

Statistical Analysis: Data were described as means \pm SD. Data were log-transformed if not normally distributed (ΔSpO_2 , $\Delta 4\text{-HNE}$). T test for independent samples were used to compare characteristics between groups 1 and 2 at baseline and during the expedition. Linear mixed models for repeated measures were used to analyse whether there were significant changes in body composition during the expedition. Paired t test was used to test within-subject differences of FM and FFM and ECW and ICW at each phase. Pearson's correlation was used to evaluate significant associations between changes in body composition with metabolic, vascular and oxy-inflammatory biomarkers. For the correlation analysis, we applied the Bonferroni correction to account for the multiple comparisons, and only results with $p < 0.001$ were considered as statistically significant. Stepwise multiple linear regression was performed to identify significant metabolic predictors explaining the loss of FFM during the CXE expedition. Regression models include changes for significant biomarkers identified by the correlation analyses and measured during the different phases of the expedition ($n=138$). Analyses were conducted using SPSS-19 for Windows and Sigmaplot-11 for Windows. P value was set at <0.05 .

RESULTS

Baseline Characteristics: Twenty-four participants (14 climbing team and 10 base-camp team) completed the eight-week expedition. Participants were predominantly male (18/5), with mean age and BMI of 34.9 ± 9.2 years and 24.9 ± 2.8 kg/m². Baseline body composition characteristics were not significantly different between participants reaching the summit and those residing at basecamp (**Table 1**).

Body Composition: Participants lost a significant amount of weight, FM and FFM throughout the expedition (**Figure 1A**). Body weight change amounted to -7.3 ± 4.9 kg ($p < 0.001$) at the end of the expedition (**Figure 1B**), which was significantly higher in the climbing team compared to base-camp team (-4.3 ± 9.1 kg, $p = 0.04$, **Figure 2A**). Body weight changes showed remarkable inter-individual variability, with some participants losing >10 kg and others gaining a little in the climbers whereas variability of weight change was lower for the base-camp team (see **Figure S1 of the Online Supplementary Material** for details). Overall,

participants showed a progressive loss of both FM and FFM, but the proportion of FFM loss was 48% greater than FM loss ($p<0.008$) (**Figure 1B**). After eight weeks, the climbing team showed a greater loss of FFM ($p=0.03$, **Figure 2B**), whereas a significant difference in FM loss between the two groups was found after one ($p=0.02$) and six ($p=0.03$) weeks of the expedition (**Figure 2C**).

Participants also experienced a significant decline in TBW, ECW and ICW (**Figure 3A**). Changes in TBW were $-3.1\pm2.9L$, which accounted for $>60\%$ of FFM losses. The majority of TBW losses were accounted for by changes in ICW ($-2.2\pm1.7L$), which were significantly ($p=0.02$) greater than ECW ($-1.1\pm1.6L$) after eight weeks (**Figure 3B**).

Metabolic, vascular and oxy-inflammatory biomarkers: With one exception, all plasma biomarkers showed significant changes during the expedition ($p<0.001$); only ghrelin concentrations remained unchanged ($p=0.54$). Nitrite levels increased during the expedition, but a substantial drop was observed at eight weeks at high altitude. Similarly, after an initial rapid increase during the ascent, cGMP concentrations progressively declined during the remainder of the expedition. Changes were more distinct for nitrate, which showed levels below baseline in the last two weeks. ProCO (decline), 4-HNE (increase), 8-isoPGF (increase), IL-6 (increase) showed significant changes with prolonged exposure to hypoxia whereas minor changes were seen for CRP and TNF- α . Increases in concentration during the last two weeks of the expedition were seen with GLP-1, insulin, T3, adrenalin, glucagon, lactate, adiponectin, GIP, adipsin and visfatin. Conversely, a decline was observed for noradrenalin, leptin and resistin (see **Figure S2 of the Online Supplementary Material** for details).

Correlation Analyses: We evaluated the association between changes in body composition (weight, FFM and FM) with biomarkers of NO bioavailability, oxy-inflammatory stress, metabolic status and adipokines, and these results are detailed in **Table 2**. Lower SpO₂ was associated with a greater decrease in weight ($r=0.49$, $p<0.001$), FFM ($r=0.38$, $p<0.001$) and FM ($r=0.32$, $p<0.001$). Changes in nitrite concentrations were associated with significant changes in FFM ($r=-0.29$, $p<0.001$) but not with FM ($r=-0.03$, $p=0.68$). A decrease in ProCO was associated with greater losses of body weight ($r=0.55$, $p<0.001$), FFM ($r=0.42$, $p<0.001$) and FM ($r=0.40$, $p<0.001$). Conversely, weight ($r=-0.32$, $p<0.001$) and FFM ($r=-0.29$, $p<0.001$) losses were associated with an increase in 4-HNE concentrations. The only inflammatory biomarker associated with body composition changes was IL-6 (BW, $r=-0.47$; FM, $r=-0.29$; FFM, $r=-0.38$; $p<0.001$). Changes in FM were associated with adrenalin ($r=-0.32$, $p<0.001$)

and lactate ($r=-0.29$, $p<0.001$) whereas changes in FFM were associated with GLP-1 ($r=-0.47$, $p<0.001$), insulin ($r=-0.36$, $p<0.001$), glucagon ($r=-0.44$, $p<0.001$) and visfatin ($r=-0.41$, $p<0.001$).

Stepwise Multiple Regression: FFM losses were predictive of changes in GLP-1 ($B\pm SE$, -0.006 ± 0.001 , $p<0.001$), insulin ($B\pm SE$, 0.002 ± 0.001 , $p=0.01$) and nitrite ($B\pm SE$, -4.7 ± 2.2 , $p=0.03$) in a fully adjusted multivariate model. Changes in ProCO ($B\pm SE$, 0.16 ± 0.07 , $p=0.03$) were instead the only predictor of FM changes (**Table 3**).

DISCUSSION

Summary of Main Findings: Our analyses explored whether data from healthy humans exposed to hypobaric hypoxia at high altitude could provide mechanistic clues into the pathogenesis of sarcopenia and identify potential physiological targets for intervention to preserve FFM in humans. First, we demonstrated a significant direct association between lower oxygen saturations and loss of FM and FFM. The correlation analyses identified two distinct groups of biomarkers: 1) *compensatory* – loss of FM and FFM was associated with increased biomarker concentrations; and 2) *synergistic* – loss of FM and FFM was associated with decreased biomarker concentrations. The former includes nitrite, 4-HNE, IL-6, GLP-1, insulin, adrenalin, glucagon and visfatin, whereas the only biomarker to show synergistic changes with FM and FFM was ProCO. The multivariate analyses provide further support for the role of GLP-1, nitrite and insulin as mediators of FFM loss, whereas the only predictor of FM loss were changes in ProCO concentrations.

Body composition: Data from previous studies have shown that the extent and rate of weight loss is correlated with the rate, extent and duration of the exposure to hypoxia^{5,6,32-34}, but the factors involved in the onset and maintenance of this remain undetermined. Variability in the magnitude of weight loss in the face of a consistent exposure (rate, extent and duration) to hypobaric hypoxia in our participants is striking and consistent with previous reports^{5-7,34}. This variability in response to a consistent stimulus provided the signal on which our analysis is based. Since rate, extent and duration of the hypoxic stress experienced during this expedition were virtually identical for all members of the climbing and laboratory team the variability in response between the two groups must therefore be due to either genetic or epigenetic differences in metabolic phenotype. Differences in FM loss were particularly striking (Fig. 2C) inviting speculation about differential fatty acid

handling, regulation of fat synthesis and lipolysis or a combination of these factors between individuals with different levels of prior high altitude experience (criteria for inclusion in the climbing team included previous event-free ascents above 6,500m and over 8,000m for summit climbers, whereas members of the laboratory staff must have had event-free exposure to altitudes >4,000m³¹). Since those differences appear to resurface upon a subsequent hypoxic challenge already at moderate altitudes (i.e. during the early phase of this study before separation of the Core Team into EBC laboratory staff and climbers) and are therefore related to the process of acclimatization to hypoxia this aspect of metabolic regulation would seem to merit further study.

Processes regulating appetite and energy intake along with hypoxia-induced suppression of skeletal muscle protein synthesis seem to have a more prominent role than energy expenditure *per se* in driving weight loss⁸. We could not directly test the specific contribution of these two components to the individual changes in energy balance during the expedition, but the significant association of satiety hormones (insulin, GLP-1) with FFM loss and the greater body composition changes in climbers may indicate that both sides of the energy balance equation (lower energy intake and increased physical activity/energy expenditure, in particular in the climbing group) could be involved. Alternatively, hypoxia may directly suppress protein synthesis via the mTOR/Akt pathways. However, none of these factors on their own can possibly account for the observed differences in weight loss between laboratory and climbing team (Fig. 2) as both groups adhered to the exact same ascent profile until reaching EBC.

Weight losses of 2.4 – 5.0 kg have been reported during expeditions to altitudes above 5,000m (duration: 14-47 days)^{5,7,33,35}. The use of hypoxic chambers, where food intake, temperature and exercise were controlled in two independent studies, resulted in average weight loss ranging from 5.0 to 7.4kg in subjects exposed to hypobaric hypoxia (simulated altitude of 8,848m) over 38 days^{32,36}, which are comparable to the mean weight loss observed in our cohort.

Our study showed that the FFM loss contributed to more than 50% of total weight lost, which clearly deviates from the Forbes's theory which states that approximately one-fourth of weight loss will be FFM (i.e., $\Delta\text{FFM}/\Delta\text{Weight} = \sim 0.25$) with the remaining three-fourths fat mass^{37,38}. The average water content of FFM is about 73% and therefore it is not surprising that TBW accounted for the majority of FFM losses³⁹; however, the higher loss of ICW

compared to ECW indicates a highly catabolic state and mobilisation of metabolically active body cell mass⁴⁰. These changes in body composition have been a common observation in studies conducted at high altitude and it could represent an adaptive protective mechanism under conditions of reduced oxygen availability⁹. Murray & Montgomery have advanced the hypothesis that free amino acids and ketone bodies may act as both substrates and metabolic modulators to protect cells from the hypoxic challenge by improving mitochondrial efficiency, activating ATP-sensitive potassium channel and reducing the production of reactive oxygen species⁴¹. The Operation Everest II chamber study reported a 2.5kg loss of FM and a 4.9kg loss of FFM³² which are similar to the changes reported in our study. Despite the significant difference in physical exertion, this similarity in body composition changes would seem to provide further support for the role of hypoxia as a key factor in the pathogenesis of sarcopenia.

Oxidative stress and inflammation: Oxidative stress, chronic inflammation, and mitochondrial dysfunction all play important roles in muscle atrophy⁴². The interaction of these factors may converge on several intracellular signaling pathways, which affect the balance between protein synthesis and breakdown, and induce apoptosis, underpinning the primary pathology of significant muscle mass loss⁴³. This model implies a predominant, damaging role of ROS on skeletal muscle, but the physiological signalling roles of ROS and NO generated during muscle contractile activity cannot be dismissed⁴⁴. In skeletal muscle, NAD(P)H oxidases and nitric oxide synthases are the main producers of superoxide (O_2^-) and NO, respectively, which may interact with each other to form the potent oxidant, peroxynitrite ($ONOO^-$)⁴⁵. However, the ROS that seems to play a major signalling role in the muscle is hydrogen peroxide (H_2O_2)^{44,46}. These reactive species are characterised by different chemical properties which may activate a number of transcription factors (NF- κ B, AP-1, HSF-1 and Nrf2), modify protein activities and potentially induce downstream redox effects such as stimulation of cytoprotective and metabolic mechanisms such as autophagy, muscle repair and mitochondrial biogenesis⁴⁴⁻⁴⁶.

The univariate correlations show a significant association between loss of FFM and plasma 4-HNE concentrations, suggesting the involvement of oxidative stress (contributing to lipid oxidation) in muscle mobilisation. ProCO was the only significant predictor of FM loss in the multivariate model. Plasma levels of ProCO are a measure of protein oxidation promoted by ROS but, counter intuitively, the concentrations of ProCO progressively decreased with FM

mobilisation. This might be explained by a predominant utilisation under these conditions of proteins as a metabolic fuel; alternatively, skeletal muscle turnover may be enhanced to supply specific amino acids for which there is a higher demand in hypoxia⁴¹. Another reason for the relatively greater muscle loss in the context of the elevated inflammatory response may be that the amino acid content of acute phase proteins is very different to that of normally produced transport and structural proteins (and indeed to that provided in most diets)⁴⁷. Acute phase proteins have a particularly high phenylalanine, tyrosine and tryptophan content; for example, the phenylalanine content of acute-phase proteins is 105g/kg versus 40g/kg in muscle, meaning that to build 100 g of acute-phase protein one would need about $100 \times 105 / 40$ g of protein substrate from food or catabolism.

IL-6 concentrations were significantly elevated, and this was the only pro-inflammatory marker associated with changes in FFM and FM. The physiological role of IL-6 as either a pro-inflammatory cytokine or adaptive myokine is still controversial⁴⁸, and our study was not suited to distinguish between these roles. However, we speculate that these two physiological functions may not be mutually exclusive but rather be part of the same adaptive process; the inflammatory response could be part of an immune, protective change induced by the hypoxic stress whereas the myokine metabolic action could be involved in the enhancement of muscular efficiency as part of the response to increased energetic demands of the remaining muscle fibres, aimed at compensating FFM loss.

A short exposure to a 4,200m simulated altitude increased IL-6 concentrations with and without exercise⁴⁹. In 48 trekkers studied over a 6-week ascent up to 5,129m, IL-6 and IL-17a levels were found to be significantly higher at high altitude than at sea level, and exercise led to a further significant increase in IL-6 but not IL-17 levels⁵⁰. While IL-6 seems to be critically involved in hypoxia-induced adaptive changes in muscle metabolism⁵¹ it remains to be established whether these responses have also a defined role in the pathogenesis of sarcopenia.

Nitric oxide: Nitrite and cGMP concentrations progressively increased during the ascent and showed a slight decline after eight weeks, but concentrations did not drop below baseline. Changes in nitrate concentrations were more defined and a substantial decrease compared to baseline was observed after six weeks. Levett *et al*³⁰ have previously explored part of these responses and interpreted them as being indicative of an enhanced conversion of nitrate into nitrite and NO as a consequence of prolonged hypoxic exposure. The novel

finding of the current analysis is the significant association between FFM loss and circulating nitrite concentrations. Again, this could be part of an orchestrated compensatory response to enhance muscular energy efficiency under conditions of low oxygen availability and reduced muscle mass. This hypothesis is supported by the role of NO in mitochondrial biogenesis and efficiency⁵² as demonstrated by the enhanced Phosphate/Oxygen Ratio in skeletal muscle after supplementation with dietary nitrate⁵³. In addition, inorganic nitrate supplementation in participants exposed to normobaric hypoxia increases exercise performance and reduces oxygen consumption, effects which were significantly correlated with post-supplementation plasma nitrite concentrations⁵⁴. Of note, skeletal muscle has recently been proposed to act as endogenous nitrate reservoir; thus, the increase in circulating nitrite may be secondary to the reduction of released nitrate⁵⁵.

Metabolic responses: GLP-1 is an incretin hormone secreted by L-cells in the small intestine in response to eating and is involved in the regulation of glucose levels, gastric emptying and appetite⁵⁶. GLP-1 also appears to cause insulin-independent vasodilation and potently stimulates NO synthase phosphorylation in endothelial cells⁵⁷. Moreover, GLP-1 recruits muscle microvasculature, which is associated with increased muscle glucose utilisation, plasma NO metabolite concentrations, muscle interstitial oxygenation as well as insulin clearance and uptake⁵⁸. Our results clearly highlight the pleiotropic effects of hypoxia on multiple metabolic pathways. FM mobilisation was associated with increased concentrations of counter-regulatory hormones such as adrenalin and lactate as they are linked to activation of β -oxidation and anaerobic metabolism. In a previous analysis, we demonstrated a significant association between adrenalin and insulin sensitivity²⁰, suggesting an activation of lipolytic pathways to satisfy enhanced energy demands. By contrast, FFM loss was associated with increases in GLP-1, insulin and glucagon concentrations. GLP-1 was the strongest predictor of FFM loss in the multivariate model. This finding could have significant treatment potential for the reduction of FFM loss under hypoxic conditions, which might be achieved with the help of dipeptidyl peptidase-IV (DPP-IV) inhibitors or GLP-1 analogues such as exendin-4, a pharmacological approach now commonly used for diabetes treatment. Increases in GLP-1 may represent a compensatory response to FFM loss to enhance vascular/metabolic coupling in the muscle via a synergistic effect on NO and insulin signalling pathways. Consistent with this notion, exendin-4 improved islet transplantation outcome by rescuing pancreatic islets from hypoxia-induced

oxidative stress⁵⁹. Exendin-4 has also been shown to activate Nrf2, a transcription factor that plays a central role in orchestrating cellular anti-oxidative defence and redox homeostasis, providing a potential mechanistic explanation for the anti-inflammatory effects of GLP-1 and its agonists⁶⁰. Curiously, GLP-1 concentrations did not change in healthy, young men exposed to normobaric hypoxia for ten days⁶¹, potentially highlighting fundamental differences between the effects of normobaric and hypobaric hypoxia on human physiology⁶².

We have previously described the development of increased insulin resistance with prolonged exposure to hypobaric hypoxia²⁰. However, the multivariate model reported in the present study suggests a concomitant decline of FFM and insulin concentrations during the expedition. This result is not surprising considering that, after accounting for other regulatory factors, it would be favourable in hypoxic conditions to reduce the anabolic drive and enhance tissue mobilization and energy release. In general, insulin levels tend to be increased during prolonged exposure to hypoxia^{63,64} whereas low levels of insulin have been reported in studies with short hypoxic exposure and modest altitudes⁶⁵.

Adipokines: Visfatin concentrations were significantly associated with FFM loss in the univariate correlation analyses, but visfatin was not a significant predictor in the multivariate model. This adipokine is produced by adipocytes and macrophages infiltrating adipose tissue but also generated in the liver and skeletal muscle⁶⁶. Secretion of visfatin is stimulated by inflammation and has insulin-mimetic effects such as: increased glucose uptake in adipocytes and myocytes, suppression of hepatic glucose release, and lipogenesis⁶⁷. Ours is the first study to investigate the association between hypoxia and visfatin in humans; previous *in vitro* studies have shown an upregulation of visfatin gene expression in adipocytes through the activation of the HIF-1 α pathway secondary to hypoxia^{68,69}.

Strengths and limitations: The main strengths of our current study are represented by the number of subjects that participated in the eight-week expedition, the consistency of hypoxic exposure pattern and variability of response in the face of this consistent stimulus; (thereby providing an important physiological signal), the depth and richness of physiological phenotyping, and the comprehensive nature of our biomarker profiling. Another strength lies in the use of multiple biomarkers of oxidative stress to explore the relationship between hypoxia and FFM loss, which is unprecedented and uncommon for

field studies. More often than not, oxidative stress markers are used interchangeably with little consideration as to their specificity, biological half-life and the nature of the oxidative insult they represent. However, our study is not without limitations. The use of BIA for the assessment of body composition at high altitude has been challenged as changes in hydration may influence the accuracy of measurements^{70,71}. However, the study used multi-frequency BIA which allows the measurement of intra- and extra-cellular compartments. Secondly, plasma osmolality during the expedition did not change, which rules out the potential interference of changes in hydration status on BIA measurements (**Table S2 of the Online Supplementary Material**). Skinfold thickness was also measured during the expedition to assess body composition changes, but the results obtained using this method were unreliable and have therefore not been included in this report. Finally, the generalizability of these results to the general population is limited and therefore results should be interpreted with caution. However, the primary aim of the study was to provide clues as to the effects of prolonged hypoxia on loss of FFM and identify potential mechanisms involved in the development of sarcopenia.

Implications for future research: Changes in GLP-1 and nitrite concentrations are significantly correlated (**Figure S3 of the Online Supplementary Material**), and both are significant predictors of FFM loss. These changes are likely to represent integrated compensatory responses to increase blood flow, delivery of nutrients and overall tissue metabolic capacity. The effects of these pathways on skeletal muscle structure and performance could be tested in future animal and human studies with exposure to normoxia and hypoxia and supplementation with, for example, incretins (or DPP-IV inhibitors) and dietary nitrate. Specifically we offer candidate mechanisms that can be further evaluated in patient groups where sarcopenia is common including older patients and critically ill patients, or in those susceptible to hypoxia as a result of cardiovascular or pulmonary disease.

CONCLUSIONS

Exposure to hypobaric hypoxia resulted in a significant FFM loss that was associated with increased levels of biomarkers of the NO pathway (nitrite), markers of oxidative stress (4-HNE), inflammation (IL-6) and metabolic efficiency (GLP-1, insulin). The putative role of GLP-1 and nitrite as mediators of the effects of hypoxia on FFM is an important finding. If

confirmed, nutritional and pharmacological interventions targeting GLP-1 and the Nitrite-Nitric Oxide pathways could represent promising strategies to prevent loss of skeletal muscle at high altitude and in susceptible patient groups.

Author contributions

M.P.W.G. and M.F. are the guarantors of this work and, as such, had full access to all the data in the study and take responsibility for the integrity of the data and the accuracy of the data analysis. L.W., M.S., M.P.W.G., M.F. wrote the manuscript and researched data; H.L.R., C.A.L., K.M. researched data; H.E.M., M.G.M., M.A.S. contributed to discussion and reviewed/edited manuscript; B.O.F., M.K., D.S.M., D.Z.H.L. researched data, contributed to discussion and reviewed/edited manuscript.

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FIGURE LEGENDS

Figure 1: Changes (Δ) in body weight, fat mass (FM) and fat-free mass (FFM) during the expedition. Data are presented as absolute values (Fig 1a) and as changes (Δ) relative to baseline measured at sea level (London, Fig 1b). Linear mixed models for repeated measures were used to analyse whether there were significant changes in body composition during the expedition for both sets of data. Paired t-test was used to test for differences in losses of FM and FFM at each phase (Fig 1b).

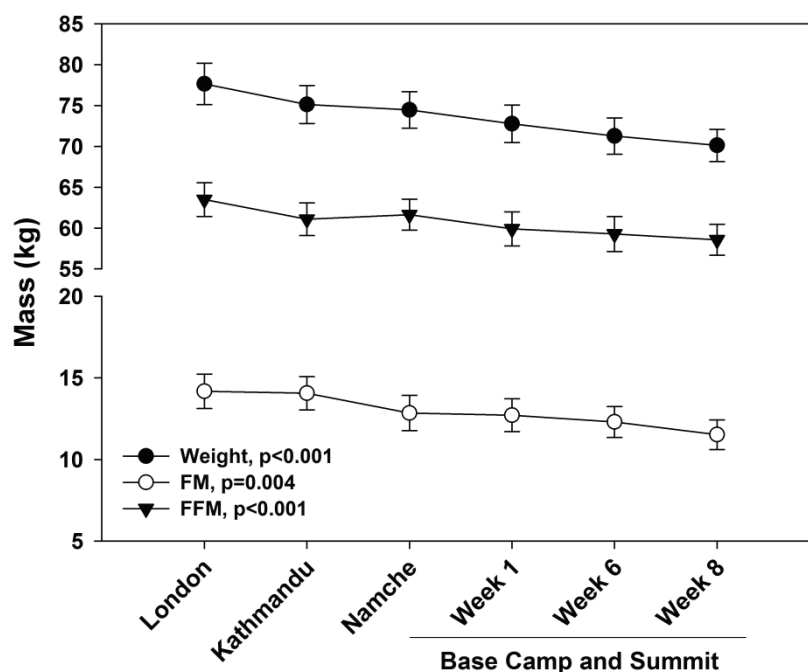
Figure 2: Changes (Δ) in body weight (A), fat-free mass (FFM, B) and fat mass (FM, C) during the expedition in individuals attempting to/reaching the summit (climbers) or residing at Everest Base Camp. Data were expressed relative to sea level (London). Linear mixed models for repeated measures were used to analyse whether there were significant changes in body composition during the expedition. Independent t-test was used to test for differences in losses of weight, FM and FFM between the two groups at each phase.

Figure 3: Changes (Δ) in total body water (TBW), extracellular (ECW) and intracellular (ICW) water during the expedition. Data are presented as absolute values (Fig 3a) and as changes (Δ) relative to baseline measured at sea level (London, Fig 3b). Linear mixed models for repeated measures were used to analyse whether there were significant changes in body composition during the expedition for both sets of data. Paired t-test was used to test for differences in losses of ECW and ICW at each phase (Fig 3b).

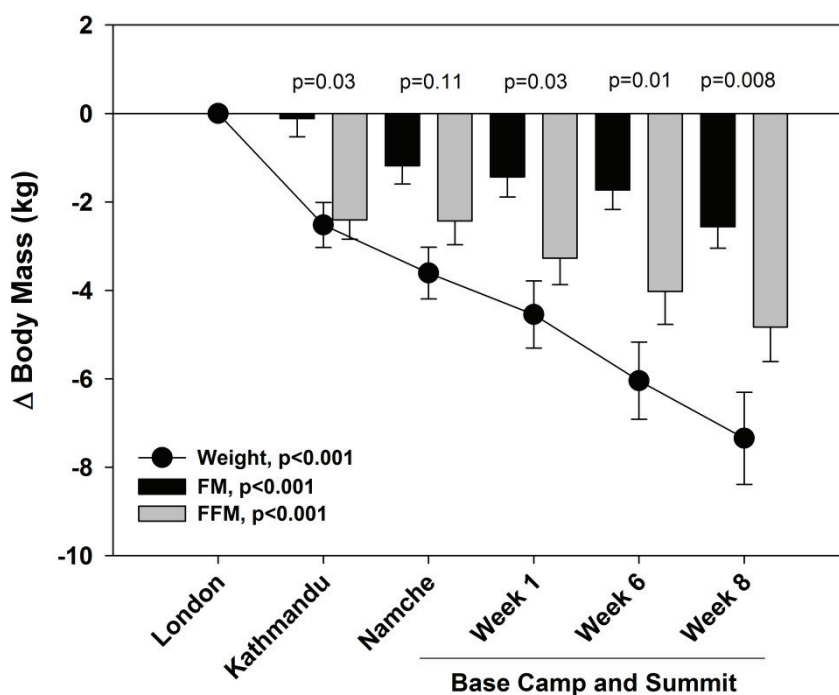
Table 1: Body composition characteristics of the CXE 2007 Expedition Team and comparison between team members climbing above Everest Base Camp/reaching the summit (climbers) and members residing at Everest Base Camp at the beginning of the expedition.

	All	Climbers	Base Camp	p
N	24	14	10	-
Gender (M/F)	18/6	12/2	6/4	-
Age, years	34.9±9.2	35.7±6.8	33.8±12.1	0.62
Weight, kg	77.6±12.4	80.7±13.3	72.2±9.5	0.08
Height, cm	176.2±6.8	178.4±5.9	172.7±7.2	0.07
Body Mass Index, kg/m²	24.9±2.8	25.2±3.2	24.1±2.2	0.80
Fat mass, kg	14.1±5.1	14.8±5.6	13.2±4.5	0.45
Fat free mass, kg	63.4±10.1	66.5±9.3	59.2±10.1	0.08
Total body water, L	45.4±7.1	47.4±6.4	42.6±7.5	0.10
Extracellular water, L	19.1±2.3	19.8±2.2	18.1±2.3	0.08
Intracellular water, L	26.0±4.6	27.2±1.1	24.2±4.8	0.12

Data are presented as means±SD. N= number of subjects; M= Male; F= Female; Mann-Whitney test was used to determine differences between the two groups.



a



b

Figure 1: Overall participant mean changes (\pm s.e) in body weight, fat mass (FM) and fat free mass (FFM) during the expedition. Data are presented as absolute values (Fig 1a) and as changes (Δ) relative to baseline measured at sea level (London, Fig 1b). Linear mixed models for repeated measures were used to analyse whether there were significant changes in body composition during the expedition for both sets of data. Paired t test was used to test for differences in losses of FM and FFM at each phase (Fig 1b).

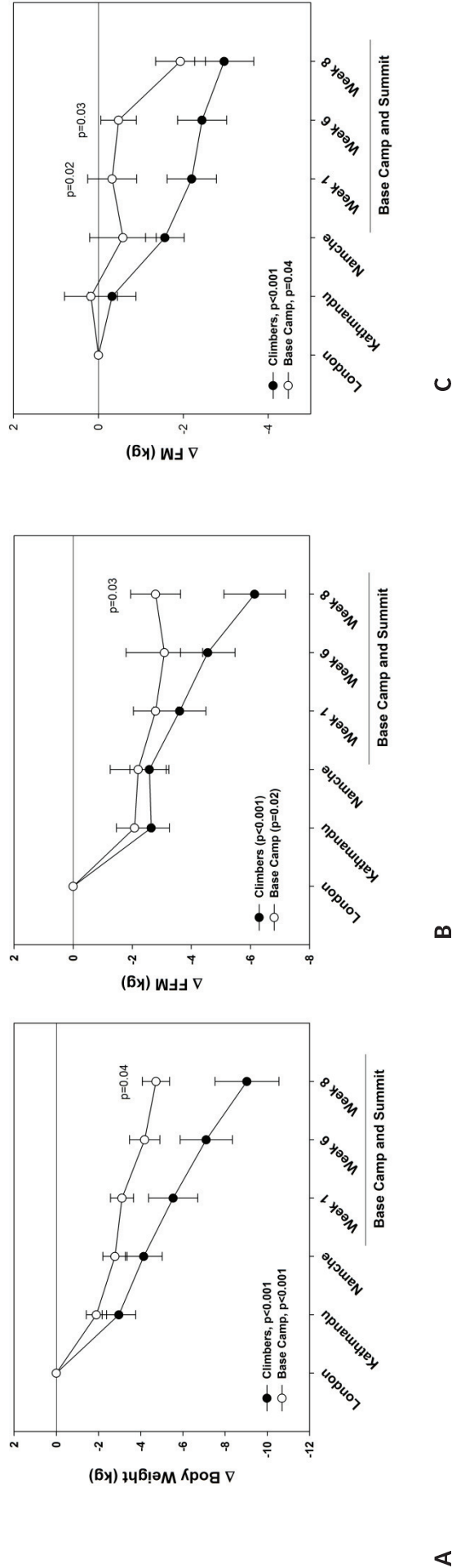
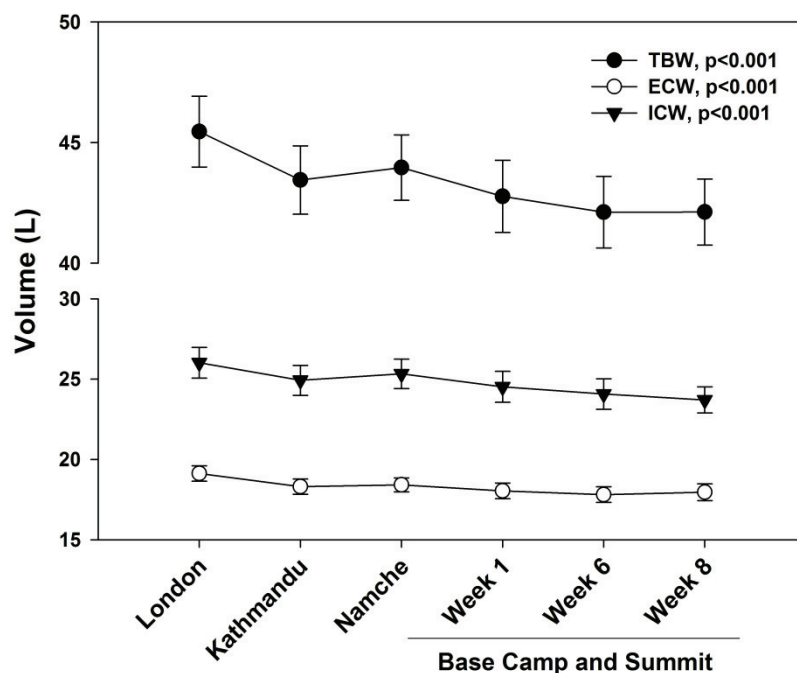
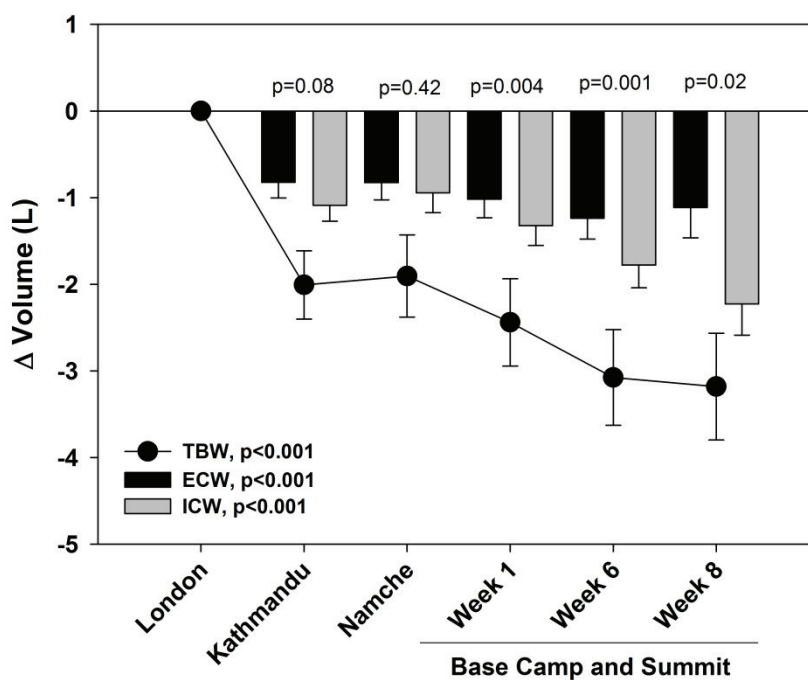


Figure 2: Mean changes (\pm s.e) in body weight (A), fat free mass (FFM, B) and fat mass (FM, C) during the expedition in individuals attempting to/reaching the summit (climbers) or residing at Everest Base Camp. Data were expressed relative to sea level (London). Linear mixed models for repeated measures were used to analyse whether there were significant changes in body composition during the expedition. Independent t-test was used to test for differences in losses of weight, FM and FFM between the two groups at each phase.



a



b

Figure 3: Mean changes (\pm s.e.) in total body water (TBW), extracellular (ECW) and intracellular (ICW) water during the expedition. Data are presented as absolute values (Fig 3a) and as changes in volume (Δ) relative to baseline measured at sea level (London, Fig 3b). Linear mixed models for repeated measures were used to analyse whether there were significant changes in body composition during the expedition for both sets of data. Paired t-test was used to test for differences in losses of ECW and ICW at each phase (Fig 3b).

Table 2: Correlation between changes (Δ) in body components with changes in biomarkers of oxygen exposure and biomarkers of nitric oxide (NO) activity, oxidative stress, inflammation and metabolism (N=138).

		Δ BW	Δ FM	Δ FFM
Hypoxia	Δ SPO ₂	0.49 (p<0.001)	0.32 (p<0.001)	0.38 (p<0.001)
NO Pathway	Δ NO ₂ ⁻	-0.30 (p<0.001)	-0.09 (p=0.27)	-0.29 (p<0.001)
	Δ NO ₃ ⁻	-0.09 (p=0.26)	0.004 (p=0.96)	0.13 (p=0.11)
	Δ cGMP	-0.04 (p=0.58)	-0.03 (p=0.68)	-0.04 (p=0.61)
Oxidative Stress	Δ ProCO	0.55 (p<0.001)	0.40 (p<0.001)	0.42 (p<0.001)
	Δ 4-HNE	-0.32 (p<0.001)	-0.22 (p=0.009)	-0.29 (p<0.001)
	Δ isoPGF	-0.12 (p=0.15)	-0.10 (p=0.25)	-0.10 (p=0.26)
Inflammation	Δ IL-6	-0.47 (p<0.001)	-0.29 (p<0.001)	-0.38 (p<0.001)
	Δ CRP	-0.03 (p=0.71)	-0.06 (p=0.44)	-0.03 (p=0.72)
	Δ TNF- α	-0.06 (p=0.49)	0.13 (p=0.13)	-0.16 (p=0.07)
Metabolic	Δ GIP	-0.14 (p=0.08)	0.11 (p=0.17)	-0.21 (p=0.01)
	Δ Ghrelin	-0.33 (p<0.001)	-0.24 (p=0.004)	-0.26 (p=0.002)
	Δ GLP-1	-0.53 (p<0.001)	-0.27 (p=0.003)	-0.47 (p<0.001)
	Δ Insulin	-0.44 (p<0.001)	-0.27 (p=0.003)	-0.36 (p<0.001)
	Δ T3	-0.10 (p=0.24)	-0.18 (p=0.02)	-0.005 (p=0.95)
	Δ Adrenalin	-0.29 (p<0.001)	-0.32 (p<0.001)	-0.17 (p=0.05)
	Δ Nor-adrenalin	0.20 (p=0.02)	0.10 (p=0.26)	0.22 (p=0.01)
	Δ Glucagon	-0.48 (p<0.001)	-0.21 (p=0.01)	-0.44 (p<0.001)
	Δ Lactate	-0.22 (p=0.01)	-0.29 (p<0.001)	-0.10 (p=0.22)
Adipokines	Δ Leptin	0.14 (p=0.09)	0.02 (p=0.74)	0.17 (p=0.04)
	Δ Resistin	-0.15 (p=0.07)	-0.02 (p=0.80)	-0.15 (p=0.07)
	Δ Visfatin	-0.45 (p<0.001)	-0.23 (p=0.02)	-0.41 (p<0.001)
	Δ Adiponectin	-0.04 (p=0.57)	0.06 (p=0.46)	-0.09 (p=0.24)
	Δ Adipsin	-0.08 (p=0.31)	-0.06 (p=0.44)	-0.10 (p=0.23)

Coefficients of correlations r are shown (p value). We applied the Bonferroni correction to the correlation analysis to account for multiple comparisons, and only results with $p<0.001$ were considered as statistically significant (highlighted in bold). BW: body weight; FM: fat mass; FFM: fat free mass; SPO₂: oxygen saturation; NO₂⁻: nitrite; NO₃⁻: nitrate; cGMP: cyclic guanylate monophosphate; ProCO: protein carbonyls; 4-HNE: 4-hydroxynonenal; isoPGF: 8-iso-15(S)-Prostaglandin F_{2 α} ; IL-6: interleukin 6; CRP: C-reactive protein; TNF- α : tumour necrosis factor α ; GIP: gastric inhibitory polypeptide; GLP-1: glucagon-like peptide 1; T3: triiodothyronine.

Table 3: Stepwise multiple linear regression to identify significant metabolic predictors explaining the loss of FFM and FM during the Caudwell Xtreme Everest Expedition.

Dependent Variable: Δ FFM ($R^2= 0.34$)

	B	SE	P
Constant	-1.47	0.31	<0.001
Δ GLP-1	-0.006	0.001	<0.001
Δ Insulin	0.002	0.001	0.01
Δ NO ₂ ⁻	-4.7	2.2	0.03

Dependent Variable: Δ FM ($R^2= 0.23$)

Δ ProCO	0.16	0.07	0.03
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Regression models include changes for significant biomarkers identified by the correlation analyses and measured across the different study expedition phases (N=138). Dependent variable is change in FFM. Independent variables in the FFM model were changes in SPO₂, nitrite (NO₂⁻), cyclic guanosine mono phosphate (cGMP), protein carbonyls (ProCO), interleukin 6 (IL-6), glucagon, visfatin, 4-hydroxynonenal (4-HNE) and glucagon-like peptide 1 (GLP-1). Independent variables in the FM model were changes in SPO₂, protein carbonyl (ProCO), interleukin 6 (IL-6), adrenalin and lactate.

Table S1: Ascent profile and residence at high altitude of the team remaining at Everest Base Camp (EBC, N=10) and those climbing higher (Climbers, N=14)*. Information on altitude (m), barometric pressure (mmHg) and inspired partial pressure of oxygen (PIO₂, mmHg) is reported for each phase. Hemoglobin concentrations (g/dl) and arterial oxygen saturation (SaO₂, %) are reported in each group during the different phases of the expedition.

	Phase/Location	Altitude (m)	Barometric Pressure (mmHg)	PIO ₂ (mmHg)	Hb (g/dl)	SaO ₂ (%)	Plasma Samples for Biomarker Assessment
Ascent to EBC	Day 0 EBC lab team Climbers	Baseline (London)	754	148.0	13.3 (0.8) 14.2 (0.7)	98.0 (0.8) 97.9 (1.1)	✓
	Day 1 EBC lab team Climbers	Kathmandu	650	126.2	14.2 (0.8) 14.8 (0.8)	96.6 (1.7) 95.9 (1.3)	✓
	Day 3 EBC lab team Climbers	Namche	505	95.4	14.7 (0.7) 16.0 (1.1)	91.0 (5.7) 90.6 (2.1)	✓
	Day 7 EBC lab team Climbers	Pheriche	461	86.7	15.0 (1.1) 15.8 (0.8)	87.0 (4.4) 87.4 (2.3)	✓
	Day 12 EBC lab team Climbers	Arrival at EBC	404	74.7	-	-	-
	Day 19 (Week 1) EBC lab team Climbers	EBC	404	74.7	16.9 (1.7) 17.9 (1.5)	77.1 (6.3) 82.6 (4.1)	✓
High Altitude	Day 38 (Week 3) EBC lab team Climbers	EBC Camp 2	404 350	74.7 63.4	17.7 (1.1) 19.2 (2.0)	84.1 (5.0) 75.9 (6.4)	-
	Day 56 (Week 6) EBC lab team Climbers	EBC	404	74.7	17.3 (1.7) 18.5 (1.1)	82.8 (5.4) 85.6 (3.9)	✓
	Day 62 (Week 7) EBC lab team Climbers	EBC Summit	404 253	74.7 42.8	-	-	-
	Day 70 (Week 8) EBC lab team Climbers	EBC	404	74.7	17.7 (1.4) 19.4 (1.2)	84.3 (8.1) 87.2 (3.8)	✓

*Fourteen subjects participated in this part of the expedition of whom 8 reached the summit of Everest; 2 subjects were excluded because biomarker data were missing and therefore 12 subjects from this group were included in the final analysis. All subjects followed an identical trekking profile during their ascent to EBC and, to standardize hypoxic exposure, were prevented from excursions of more than 300 vertical metres from the group altitude at any time. For Group 1 (EBC laboratory staff), excursions were limited to within 500 vertical metres of the EBC altitude for the duration of the expedition. The climbing team (n = 14) followed an identical ascent profile until the completion of all testing at Camp 2 (6,400 m) including identical acclimatisation outings. Group 1 was not exposed to supplemental oxygen for the duration of the expedition. Group 2 was not exposed to any supplemental oxygen until the completion of testing at Camp 2. All climbers used supplemental oxygen at flow rates of 2-4 l/min for the summit climb above Camp 3 (7,100 m) and at 0.5 l/min whilst sleeping at and above Camp 3. Testing was repeated at the end of the expedition (immediately prior to departure) for all climbers at EBC (days 66 to 71).

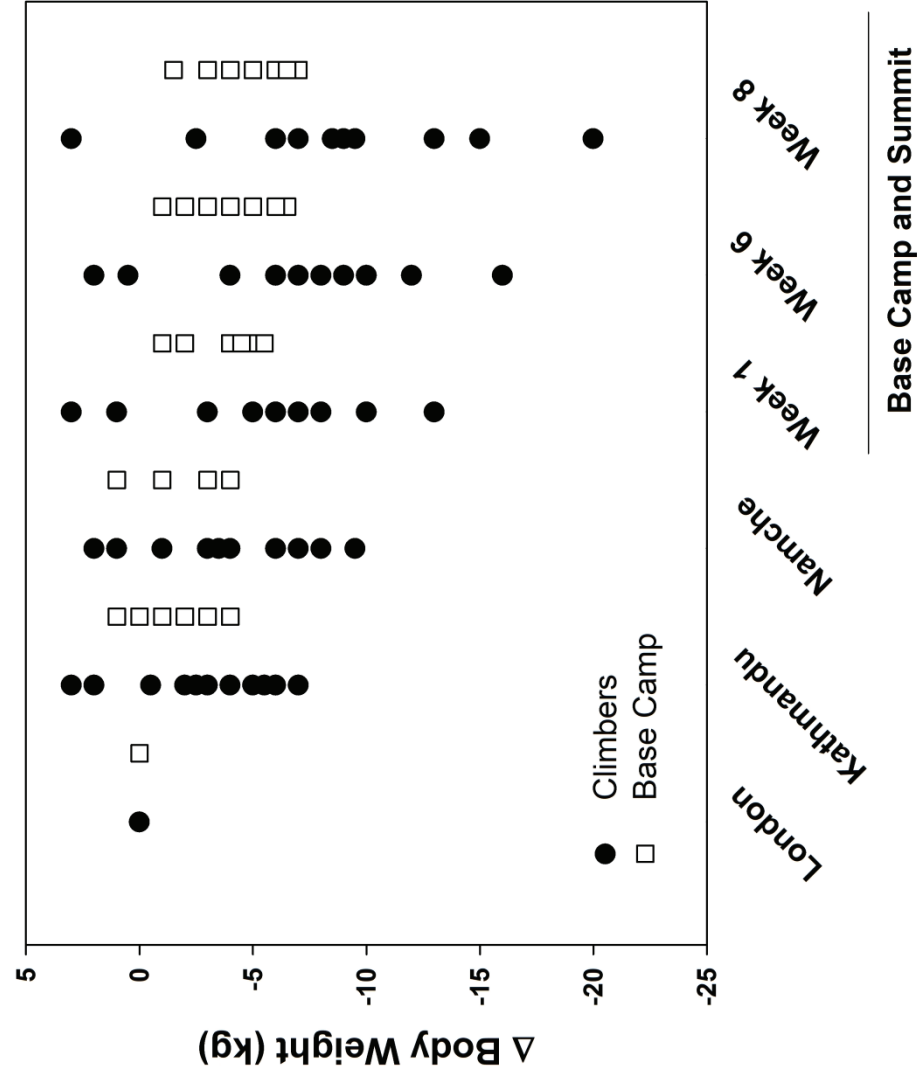


Figure S1: Individual changes in body weight during the expedition in climbers and base camp residents

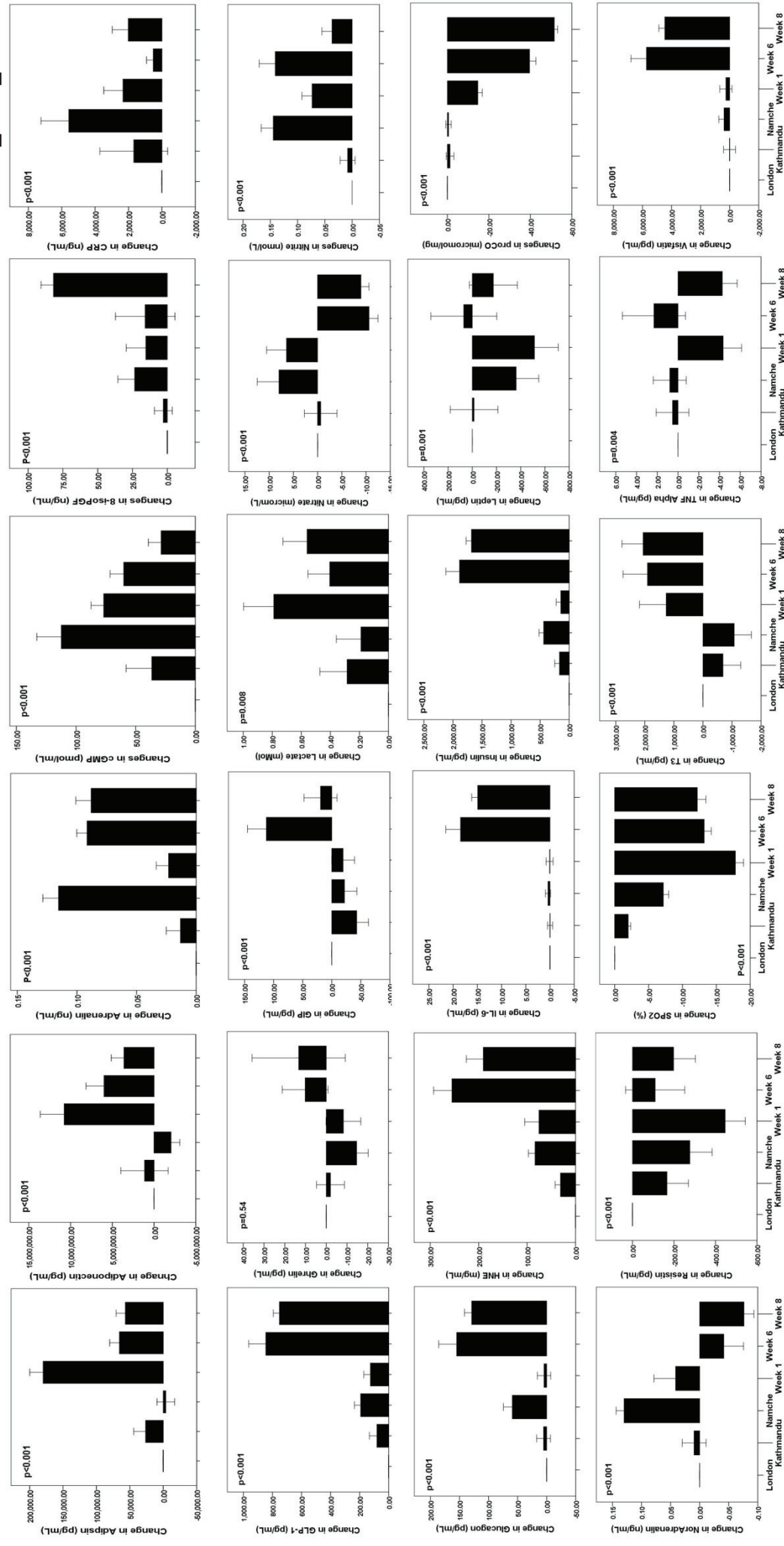


Figure S2: Panel showing mean changes (± s.e.) in metabolic biomarkers measured during the Caudwell expedition. Data were expressed relative to sea level (London). Linear mixed models for repeated measures were used to analyse whether there were significant changes in body composition during the expedition.

Table S2: Plasma osmolality (mOsm/kg) measured during the expedition

Altitude	Mean	St. Dev
London (75m)	292.9	5.8
Kathmandu (1300m)	292.7	9.4
Namche (3500m)	292.7	9.6
Pheriche (4250m)	286.9	13.8
Everest Base Camp Week 1 (5300m)	289.7	12.3
Everest Base Camp Week 6 (5300m)	285.3	13.7
Everest Base Camp Week 8 (5300m)	291.1	12.5

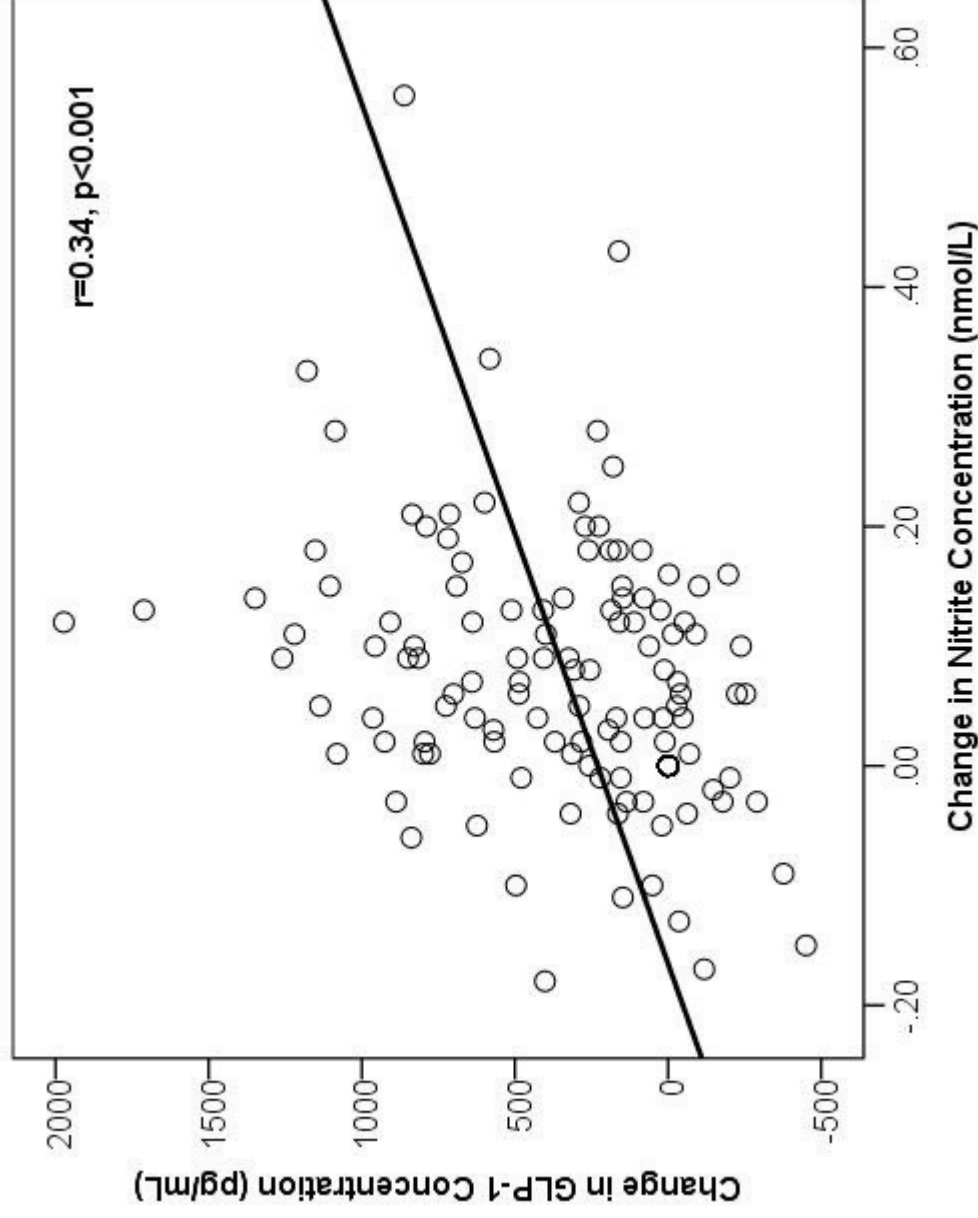


Figure S3: Correlation between changes in plasma concentrations of nitrite and GLP-1 during the expedition (N=138).