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RESEARCH ARTICLE

# Hypoxia-seeking behavior, metabolic depression and skeletal muscle function in an amphibious fish out of water

**Giulia S. Rossi* and Patricia A. Wright**


## ABSTRACT

Several animals enter a state of dormancy to survive harsh environmental conditions. During dormancy, metabolic depression can be critical for economizing on limited endogenous energy reserves. We used two isogenic strains (strain 1 and strain 2) of a self-fertilizing amphibious fish (*Kryptolebias marmoratus*) to test the hypothesis that animals seek hypoxic microhabitats that, in turn, accentuate metabolic depression during dormancy. Using custom-built tunnels that maintained a longitudinal $O_2$ gradient (hypoxic to normoxic), we assessed the $O_2$ preference of *K. marmoratus* during prolonged air exposure. In support of our hypothesis, we found that one isogenic strain (strain 2) spent more time in hypoxia compared with normoxia after 21 days in air. Prolonged air exposure in both strains resulted in lower $O_2$ consumption rates compared with active fish (35% depression), which was accentuated (51% depression) when fish were exposed to aerial hypoxia acutely. We then tested the hypothesis that chronic aerial hypoxia acclimation would protect endogenous energy reserves and skeletal muscle integrity, thereby maintaining locomotor performance, possibly owing to hypoxic hypometabolism. We found that air-acclimated fish from both strains were in poorer body condition relative to fish acclimated to aerial hypoxia. Furthermore, aerial hypoxia acclimation minimized glycogen usage (strain 1), lipid catabolism (strain 2) and white muscle atrophy (strain 2), as well as preserved terrestrial locomotor performance compared with fish in air (strain 2). Overall, our findings suggest that some *K. marmoratus* strains seek microhabitats that accentuate metabolic depression during dormancy, and that microhabitat $O_2$ availability may have significant implications for energy metabolism, and the structure and function of skeletal muscle. Furthermore, the differential responses between isogenic strains suggests that genetic factors also contribute to phenotypic differences in the emersion behavior and physiology of this species.


**KEY WORDS: Microenvironment, Hypoxic hypometabolism, Muscle phenotype, Energy reserves, Dormancy, Choice chamber**

## INTRODUCTION

Several animals enter a state of dormancy to survive harsh environmental conditions, including periods of prolonged cold or drought. During dormancy, animals remain inactive and have no external food supply; thus, a common feature of dormancy is the depression of metabolic rate to conserve limited endogenous energy reserves until the return of environmental conditions favorable for active life (for reviews, see Storey and Storey, 1990, 2012; Guppy and Withers, 1999). A true metabolic rate depression involves an active downregulation of cellular energy (ATP) turnover below the standard level (SMR; standard metabolic rate) (Storey, 2002), which supports only the essential homeostatic activities of cells and whole organisms (Hulbert and Else, 2004). Here, we use metabolic depression to describe a reduction in metabolic rate below the routine level (RMR; routine metabolic rate). The extent to which animals depress metabolic rate gives a proportional extension to the time they can survive using endogenous reserves (Storey and Storey, 1990; Boutilier et al., 1997). Consequently, a considerable metabolic depression is necessary for animals that remain dormant for many months (Hochachka and Guppy, 1987). For example, long-neck turtles (*Chelodina rugosa*) can survive seasonal droughts lasting 4–5 months by depressing metabolic rate by approximately 70% (Kennett and Christian, 1994), whereas African lungfish (*Protopterus aethiopicus*) can tolerate drought for years by depressing metabolic rate by 80–90% (Fishman et al., 1992).

Animals, both active and dormant, rely primarily on lipid and/or carbohydrate catabolism to satisfy energy (ATP) demands, while proteins are generally used as a fuel of last resort (Dark, 2005; McCue, 2010). For example, the common frog (*Rana temporaria*) was found to preferentially catabolize lipids during the first 40 days of hibernation, and progressively shifted to exclusive carbohydrate metabolism by 90 days (Donohoe et al., 1998). If dormant animals exhaust lipid and carbohydrate reserves, they must rely on protein catabolism to meet energy demands (Castellini and Rea, 1992; Caloin, 2004). However, extensive protein catabolism is problematic because it can result in skeletal muscle atrophy, which can be exacerbated by disuse during dormancy. Any muscle atrophy during dormancy is detrimental for animals upon arousal, when normal muscular activity must be resumed (Hudson and Franklin, 2002a,b). Impaired locomotor performance can threaten foraging ability, reproductive success, predator avoidance and, ultimately, survival.

Metabolic rate and fuel usage in dormant ectotherms will be affected by the microhabitat. For example, microhabitats with elevated temperatures can expedite substrate utilization and lead to skeletal muscle atrophy (Young et al., 2011). In contrast, microhabitat conditions that support metabolic depression may aid in skeletal muscle preservation. Hypoxic conditions, for example, have been reported to depress metabolism in a number of ectothermic animals (Boutilier et al., 1997; Hicks and Wang, 1999). For animals that remain dormant for extended periods of time, hypoxic hypometabolism would assist in skeletal muscle maintenance if it accentuates metabolic depression and protects endogenous energy reserves from premature exhaustion. Thus, do animals seek hypoxic microhabitats during dormancy that, in turn, maximally depress metabolic rate?

We used the amphibious mangrove rivulus (*Kryptolebias marmoratus*) to examine this question because they inhabit tropical mangrove swamps that desiccate for several months

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during the dry season. During seasonal droughts, *K. marmoratus* can survive out of water (emersed) for more than 60 days (Taylor, 1990; Turko et al., 2019), despite the inability to eat on land (Pronko et al., 2013). Although the definition of estivation is not clear cut, *K. marmoratus* remain largely inactive (Turko et al., 2017) and, like estivating animals, enter a hypometabolic state where RMR is depressed by more than 40% after 21 days in air (Turko et al., 2019). When on land, *K. marmoratus* are often found nestled within the termite tunnels of rotting logs (Taylor et al., 2008) that may be hypoxic (12–14% air saturation; Anderson and Ultsch, 1987). Several other ectothermic animals can similarly be found in potentially hypoxic habitats during periods of dormancy, including fish (Smith, 1931; Chew et al., 2004), amphibians (Ruibal and Hillman, 1981; Etheridge et al., 1990; Boutilier et al., 1997; Stewart et al., 2003; Booth 2006) and reptiles (Kennett and Christian, 1994; Markle and Chow-Fraser, 2017) that estivate/hibernate within subterranean burrows or beneath the ice of frozen lakes. Thus, we used *K. marmoratus* to test the hypothesis that animals seek hypoxic microhabitats during periods of dormancy that, in turn, accentuate metabolic depression. The hypoxic habitat hypothesis predicts that *K. marmoratus* will preferentially occupy hypoxic rather than normoxic microhabitats during periods of prolonged air exposure. Fish were placed in custom experimental choice chambers that maintained an $O_2$ gradient (normoxic to hypoxic) to determine the preferred $O_2$ level of fish out of water. If fish select hypoxic microhabitats when on land, then exposure to aerial hypoxia acutely should result in a more profound metabolic depression than results from aerial normoxia exposure. Thus, we measured the $O_2$ consumption rate of water- (control) and air-acclimated (21 days) fish in aerial normoxia, as well as the $O_2$ consumption rate of air-acclimated fish acutely exposed to aerial hypoxia. We then tested the hypothesis that chronic hypoxia acclimation in air would protect endogenous energy reserves and skeletal muscle integrity, thereby maintaining locomotor performance. The hypothesis predicts that *K. marmoratus* acclimated to aerial hypoxia will deplete energy stores more slowly, demonstrate less skeletal muscle atrophy and have better locomotor performance than fish acclimated to aerial normoxia, presumably owing to hypoxic hypometabolism. We measured the whole-body [glycogen] and lipid content in fish acclimated to water (control), air and aerial hypoxia for 21 days. The cross-sectional area of red and white muscle fibers was also measured, as well as terrestrial locomotor performance (tail-flip jumping).

## MATERIALS AND METHODS

### Experimental animals

All experimental fish ($n$=235, 0.088±0.002 g) were adult hermaphrodites of the self-fertilizing *Kryptolebias marmoratus* Poey 1880. We performed all experiments in duplicate on two isogenic strains: strain 1 (SLC8E, from St Lucie County, FL, USA) and strain 2 (50.91, from Twin Cayes, Papa Gabriel, Belize) (Tatarenkov et al., 2010). Prior to experiments, fish were individually maintained in 120 ml plastic holding cups (60 ml water, 15‰ salinity, 25°C) in the Hagen Aqualab at the University of Guelph on a 12 h:12 h light:dark cycle (Frick and Wright, 2002). Fish were fed live *Artemia* sp. nauplii three times weekly. All experimental procedures were approved by the University of Guelph Animal Care Committee (AUP 3891).

### Experimental protocol

Three series of experiments were conducted: (1) a behavioral experiment to determine the environmental $O_2$ preference of *K. marmoratus* out of water during a 21 day air exposure period, (2) a physiological experiment to determine whether acute aerial hypoxia exposure after 21 days in air accentuates the metabolic depression in *K. marmoratus*, and (3) a physiological experiment to determine whether chronic aerial hypoxia acclimation (21 days) slows substrate utilization compared with aerial normoxia acclimation (21 days), thereby preserving skeletal muscle integrity and locomotor performance (Fig. S1). Following experimentation, fish were weighed and the standard length was measured for determination of body condition (Fulton's $K$) as described by Froese (2006). When the partial pressure of $O_2$ ($P_{O_2}$) was not constant for the entire the experimental period (i.e. during choice chamber experiments and acute hypoxia exposure during $O_2$ consumption experiments), Fulton's $K$ was not measured.

#### Series 1

To determine whether *K. marmoratus* seek hypoxic microhabitats during periods of prolonged air exposure, we designed experimental choice chambers that maintained a $P_{O_2}$ gradient through which fish could move freely (Fig. S2). We constructed the choice chambers from 10 ml serological pipettes to mimic the termite tunnels in rotting logs that *K. marmoratus* inhabit in the wild (Taylor et al., 2008). The serological pipettes were halved to create semi-circlular tubes (21 cm long, 1 cm diameter), which were then fitted with a mesh bottom. A strip of water-soaked (15‰) filter paper (0.5 cm wide) was placed inside each tube, on top of the mesh to give fish a moist substrate for travel within the tube.

We measured the $P_{O_2}$ preference of *K. marmoratus* (strain 1, $n$=12; strain 2, $n$=23) within the choice chambers during the initial (days 1–2) and final (days 20–21) 48 h of a 21-day air exposure period. First, we randomly positioned fish in individual choice chambers, then introduced a $P_{O_2}$ gradient (10.1±0.4 to 19.9 ±0.1 kPa). The $P_{O_2}$ gradient was generated by placing the choice chambers over three side-by-side containers (1.5 litres) filled with water (15‰) (Fig. S2). We vigorously bubbled nitrogen into the container at one end to generate hypoxic air in the choice chamber above ('low $O_2$ zone'=10.1±0.4 kPa). In the container at the opposite end, we vigorously bubbled air to generate normoxic air in the choice chamber above ('high $O_2$ zone'=19.9±0.1 kPa). We bubbled both air and nitrogen into the middle container to generate an intermediate $P_{O_2}$ in the air above ('medium $O_2$ zone'=15.7±0.3 kPa). The $P_{O_2}$ in each zone was continuously measured during experimental trials using $O_2$-sensing optodes and a fibre-optic probe (Loligo Systems WITROX 4, Tjele, Denmark). The optodes were calibrated prior to experimentation using humidified atmospheric air (21 kPa $O_2$) and 2 mol $l^{-1}$ sodium sulphite (0 kPa $O_2$). Fish were video recorded within the choice chamber using a webcam (Logitech C905w, Newark, CA, USA). Following exposure to the $P_{O_2}$ gradient on days 1–2, the $P_{O_2}$ gradient was stopped, and fish were maintained in their choice chamber under normoxic conditions until re-exposure to the $P_{O_2}$ gradient during days 20–21. We did not reposition fish within the choice chambers before reintroduction of the $P_{O_2}$ gradient to minimize disturbance. For analysis, we calculated the proportion of time fish spent in each $O_2$ zone during both recording periods.

All behavioral tests were carried out across seven 21-day experimental trials (five fish per trial on average). To ensure that all experimental trials were carried out consistently, we began all trials between 12:00 and 16:00 h, in the same position within the same climate-controlled room (25°C, 12 h:12 h light:dark). The choice chamber was illuminated in the day with room lighting (no exterior windows), and at night with red light to minimize disturbance to the fish. The direction of the $O_2$ gradient (hypoxia

to normoxia) was randomly reversed (normoxia to hypoxia) between trials, and most of the trials contained fish from both strains. All videos were analysed by the same observer (G.S.R.).

### Series 2

A separate group of fish was acclimated for 21 days to one of two experimental treatments: water (control) or air. Control fish were maintained in water (15‰) and fed *Artemia* sp. nauplii three times weekly. Air acclimation was achieved by placing fish on moist filter paper (15‰) in 120 ml plastic holding cups, as previously described (Ong et al., 2007). The mass-specific rate of $O_2$ consumption was then measured in control (strain 1, $n$=10; strain 2, $n$=10) and air-acclimated (strain 1, $n$=8; strain 2, $n$=8) fish using closed-system respirometry. Fish were placed in custom glass micro-respirometry chambers (∼1 ml) containing a piece of wet filter paper that kept the environment moist during the experimental period. Fish were acclimated to the experimental chamber for a 2 h period in air, during which time the chamber was left open to maintain $P_{O_2}$ at approximately 21 kPa. A 2 h acclimation has previously been shown to be sufficient for *K. marmoratus* to recover from handling stress (Blanchard et al., 2019). Following the 2 h acclimation period, the chamber was sealed and the decline in $P_{O_2}$ was measured for 1 h using $O_2$-sensing optodes, which were calibrated weekly. To determine whether aerial hypoxia accentuates metabolic depression in *K. marmoratus*, an additional group of fish (strain 1, $n$=8; strain 2, $n$=8) held in air for 21 days was placed in micro-respirometry chambers that were continuously flushed with an air–$N_2$ mixture (approximately 9.3 kPa $O_2$; Wosthoff, Calibrated Instruments Inc., NY, USA) for 2 h prior to the 1 h measurement period. We attempted to measure $O_2$ consumption in fish acclimated to aerial hypoxia continuously for 21 days in preliminary experiments. However, we were unable to prevent re-oxygenation while transferring fish from their acclimation chambers to the micro-respirometry chambers, resulting in highly variable $O_2$ consumption measurements. We calculated $O_2$ consumption rates from the decline in $P_{O_2}$ over the 1 h measurement period in three consecutive 20 min intervals, standardized to body mass. There was no significant difference in $O_2$ consumption across the technical replicates (repeated-measures ANOVAs; $P$>0.05), thus, we report the average of the three $O_2$ consumption measurements. The $P_{O_2}$ in the $O_2$ consumption trials performed under normoxia started at 20.1±0.2 kPa and declined to 17.8±0.3 kPa by the end of the measurement period. The $P_{O_2}$ in the $O_2$ consumption trials performed under aerial hypoxia started at 9.3 ±0.2 kPa and declined to 8.4±0.2 kPa. The $P_{O_2}$ in all trials remained above the lower aerial critical oxygen tension ($P_{crit}$) for *K. marmoratus* strain 1 (SLC8E) and strain 2 (50.91) (Blanchard et al., 2019). All $O_2$ experiments were conducted at 25°C, and between 12:00 and 18:00 h to minimize the effects of diel metabolic rhythms (Rodela and Wright, 2006). Control fish were fasted for at least 48 h prior to use in experiments, which is more than sufficient time to ensure that metabolic rate returns to baseline levels post-feeding (Sutton et al., 2018). We also measured $O_2$ consumption in a group of fish that had been fasted for 21 days in water (fasted controls) to determine whether the inability to eat on land plays a significant role in metabolic depression in normoxic air.

### Series 3

#### Energy reserves

An additional group of fish was exposed for 21 days to one of three experimental treatments – control, air or aerial hypoxia – for analysis of whole-body [glycogen] and lipid content. Aerial hypoxia acclimation was achieved by placing air-exposed fish in an incubator (Innova 4230, New Brunswick Scientific, NJ, USA) that was maintained at approximately 8.2 kPa $O_2$ using an air–$N_2$ mixture (25°C, 12 h:12 h light:dark). Following acclimation, fish were immediately euthanized via cold-water immersion, and either snap-frozen in liquid nitrogen for [glycogen] determination (strain 1, $n$=22; strain 2, $n$=21), or dried (48 h at 60°C) for lipid analysis (strain 1, $n$=22; strain 2, $n$=23). Whole-body [glycogen] was measured enzymatically (Bergmeyer et al., 1974), and lipid content was measured by chloroform extraction (Junior and Peixoto, 2013).

#### Muscle histology

We measured the size (cross-sectional area) of red and white muscle fibers in another group of fish under control, air or aerial hypoxia conditions for 21 days (strain 1, $n$=22; strain 2, $n$=22). Following acclimation, fish were euthanized via immersion in MS-222 (500 mg $l^{-1}$). A ∼3 mm transverse steak immediately anterior to the dorsal fin was removed, coated in embedding medium (Shandon Cryomatrix™, Fisher Scientific, Hampton, NH, USA), frozen in liquid nitrogen-cooled isopentane and stored at −80°C. Frozen muscle steaks were then cut into 8 µm transverse sections in a cryostat (Leitz Cryostat Microtome, Labequip Ltd, Markham, ON, Canada) at −20°C, mounted on Superfrost Plus slides (Fisher Scientific) and stored at −80°C until staining. Red muscle staining and analysis was performed as previously described by Rossi et al. (2018). White muscle analysis was performed as described by Rossi et al. (2019a). Control and air-acclimated fish used for muscle phenotyping were previously used for $O_2$ consumption measurements.

#### Jumping performance

We compared the terrestrial locomotor performance in a final group of control, air-acclimated and aerial hypoxia-acclimated fish (21 days; strain 1, $n$=23; strain 2, $n$=23), as previously described (Rossi et al., 2019a; McFarlane et al., 2019). Briefly, fish were encouraged to jump via gentle prodding with a clicker ballpoint pen until exhausted, i.e. unresponsive to prodding. The jumping trials were video recorded and analyzed to quantify the distance of the longest jump (in body lengths) and the number of jumps fish performed before reaching exhaustion (Brunt et al., 2016).

### Statistical analysis

We determined the preferred $O_2$ zone of *K. marmoratus* during days 1–2 and days 20–21 using methods for compositional data, because the proportion of time fish spend in any one $O_2$ zone is dependent upon the time spent in other $O_2$ zones. All proportions were isometric log-ratio (ILR) transformed and then analysed using an ordinary least squares (OLS) regression. We subsequently back-transformed the coefficients for meaningful interpretation of the results (van den Boogrart and Tolosana-Delgado, 2013).

To determine the effects of strain and experimental treatment on $O_2$ consumption, body condition, lipid content, muscle phenotype and jumping performance, we used two-way ANOVAs. When a significant main effect of treatment was detected, a Tukey's *post hoc* test was used to identify which treatment groups differed (all reported $P$-values are adjusted for multiple comparisons). When a significant strain×treatment interaction was detected (glycolytic fiber size, number of jumps), the data were divided by strain and analysed using a one-way ANOVA, followed by a Tukey's *post hoc* test. The [glycogen] of strain 2 control and air-acclimated fish was compared using a two-sided $t$-test; the aerial hypoxia group was excluded from the analysis because the [glycogen] in five of six fish was below detectable limits. A one-way ANOVA was used to compare the

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[glycogen] of strain 1 fish across treatment groups, followed by a Tukey's *post hoc* test. Owing to the limitations of merely presenting *P*-values (Halsey et al., 2015; Halsey, 2019), we supplemented the *P*-values from all *post hoc* comparisons with an effect size calculation (Cohen's *D*; *d*-value) for each strain (strain 1=$d_1$; strain 2=$d_2$) to indicate the magnitude of the effect between treatment groups. When $d<0.5$, the treatment effect is relatively small and inconsequential, whereas $d>0.5$ indicates that the treatment effect is biologically meaningful (Sullivan and Feinn, 2012). Prior to analysis, we assessed all data for normality and homogeneity of variance; when data did not meet these parametric test assumptions, they were appropriately transformed. All analyses were performed using RStudio (version 1.1.447).

## RESULTS

### Environmental $O_2$ preference

The proportion of time strain 2 fish spent in each $O_2$ zone during days 1–2 was equally distributed (OLS: $P=0.63$; Fig. 1). However, strain 2 fish showed a preference for the low $O_2$ zone by the end of the air exposure period (OLS: $P=0.02$): fish spent 53±7% of the time in the low $O_2$ zone, and only 26±5% and 21±6% in the medium and high $O_2$ zones, respectively (Fig. 1). The time strain 1 fish spent in each $O_2$ zone was equally distributed during days 1–2 (OLS: $P=0.15$) and days 20–21 (OLS: $P=0.80$) (data not shown).

### $O_2$ consumption and body condition

The mass-specific rate of $O_2$ consumption in *K. marmoratus* was significantly influenced by the experimental treatment (two-way ANOVA: $P<0.001$) but not by strain (two-way ANOVA: $P=0.76$; Fig. 2A). We found that control fish had significantly higher $O_2$ consumption rates than both air- and aerial hypoxia-acclimated fish (Tukey: $P<0.001$, $d_1=1.5$, $d_2=1.0$; $P<0.001$, $d_1=2.2$, $d_2=1.7$). Air-acclimated fish also had higher $O_2$ consumption rates than aerial hypoxia-acclimated fish (Tukey: $P=0.01$, $d_1=1.5$, $d_2=1.4$). In contrast, the $O_2$ consumption rate between fasted controls and air-acclimated fish was not significantly different in either strain (two-way ANOVA: $P=0.19$, $P=0.36$; Fig. S3). We found that the experimental treatment affected body condition (two-way ANOVA: $P<0.001$) but the strain did not (two-way ANOVA: $P=0.30$; Fig. 2B). The body condition of air-acclimated *K. marmoratus* was lower than that of control and aerial hypoxia-acclimated fish (Tukey: $P<0.001$, $d_1=0.7$, $d_2=0.8$; $P=0.01$, $d_1=0.5$, $d_2=0.6$). We found no significant difference in the body condition of control and aerial hypoxia-acclimated fish (Tukey: $P=0.39$, $d_1=0.3$, $d_2=0.3$).

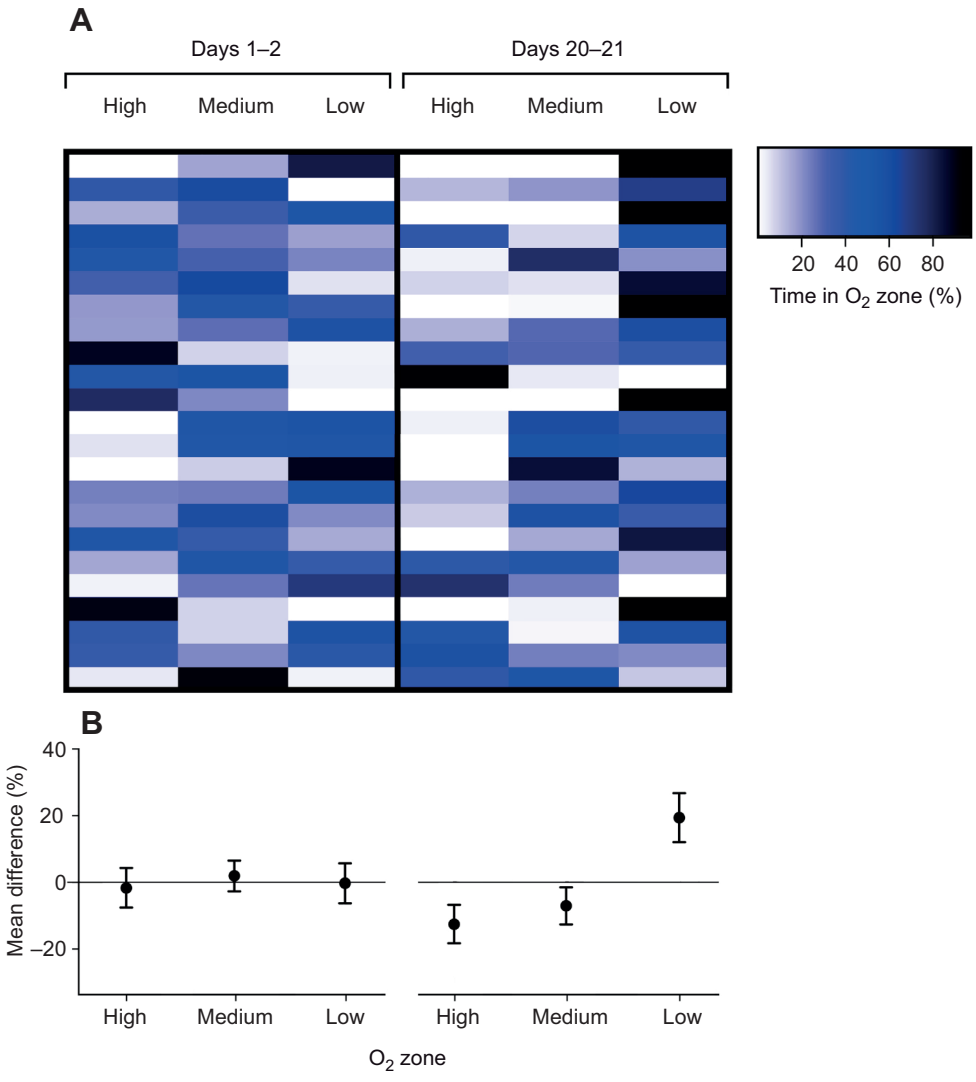


**Fig. 1. The $O_2$ preference of *Kryptolebias marmoratus* during prolonged air exposure.** (A) Heat map representing the percentage of time spent in the high, medium and low $O_2$ zones by *Kryptolebias marmoratus* (strain 2; $n=23$) during the first (days 1–2, left) and final (days 20–21, right) 48 h of a 21-day air exposure period. Each row represents an individual and each column represents an $O_2$ zone. (B) The percentage mean difference between the observed time *K. marmoratus* spent in each $O_2$ zone during days 1–2 (left) and days 20–21 (right) and the expected time assuming *K. marmoratus* demonstrated no $O_2$ zone preference (one-third per zone). Error bars denote the ±s.e.m. of each $O_2$ zone. Strain 1 fish demonstrated no $O_2$ zone preference during days 1–2 or days 20–21 (data not shown).

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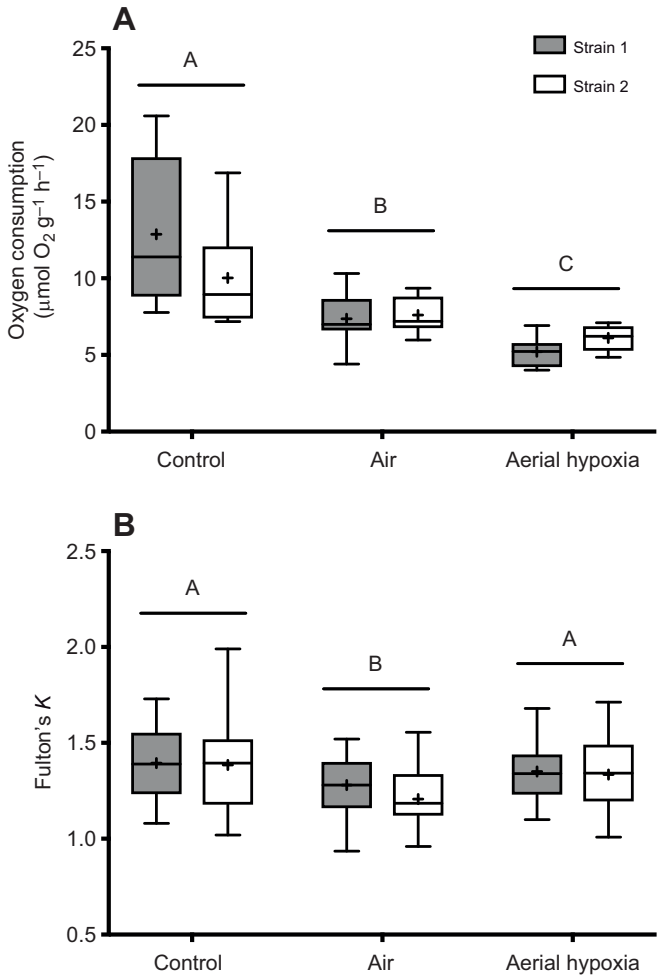


**Fig. 2. The effect of aerial normoxia and aerial hypoxia exposure on the metabolic rate and body condition of *K. marmoratus*.** (A) The mass-specific rate of $O_2$ consumption in water (control; strain 1, $n$=10; strain 2, $n$=10) and air-acclimated *K. marmoratus* under aerial normoxia (~21 kPa; strain 1, $n$=8; strain 2, $n$=8), as well as the $O_2$ consumption rate of air-acclimated (21 days) fish acutely exposed to aerial hypoxia (~9.4 kPa; strain 1, $n$=8; strain 2, $n$=8). (B) The body condition (Fulton's $K$) of *K. marmoratus* acclimated to water (control; strain 1, $n$=33; strain 2, $n$=32), air (strain 1, $n$=30; strain 2, $n$=32) and aerial hypoxia (strain 1, $n$=29; strain 2, $n$=28) for 21 days. Different uppercase letters indicate significant differences between experimental treatments. Means are shown as crosses within the box.

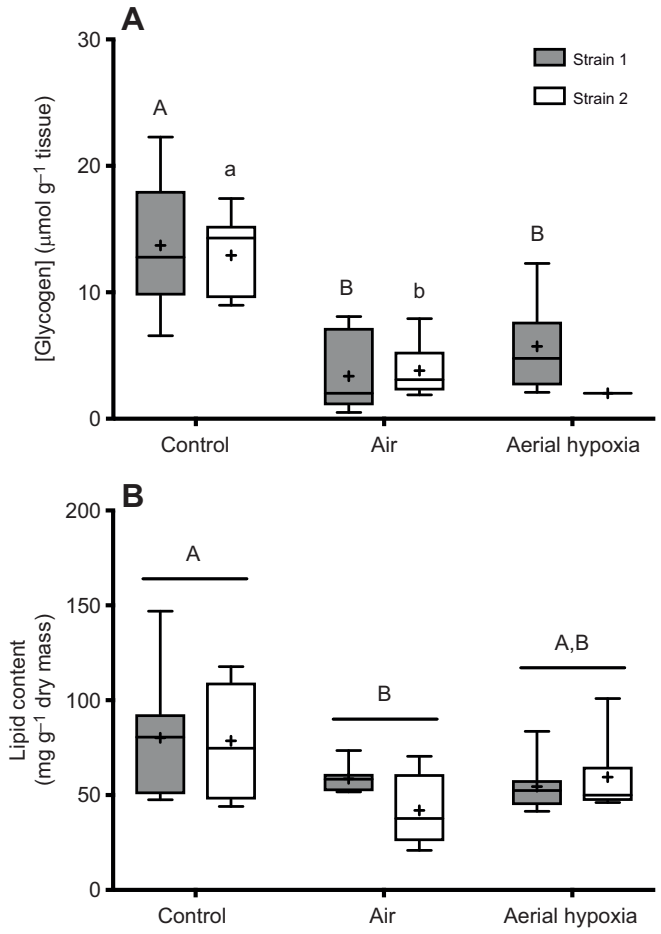


**Fig. 3. The effect of aerial normoxia and aerial hypoxia acclimation on metabolic fuel use in *K. marmoratus*.** (A) The whole-body [glycogen] of control (strain 1, $n$=7; strain 2, $n$=7) and air- (strain 1, $n$=7; strain 2, $n$=8) and aerial hypoxia-acclimated (strain 1, $n$=7; strain 2, $n$=6) *K. marmoratus*. Different uppercase and lowercase letters denote significant differences in the [lactate] of strain 1 and strain 2 fish, respectively, across treatment groups. (B) The whole-body lipid content of control (strain 1, $n$=8; strain 2, $n$=8) and air- (strain 1, $n$=7; strain 2, $n$=8) and aerial hypoxia-acclimated (strain 1, $n$=7; strain 2, $n$=7) fish. Different uppercase letters indicate significant differences between experimental treatments. Means are shown as crosses within the box.

### Energy reserves

The [glycogen] of strain 1 fish differed significantly across treatment groups (one-way ANOVA: $P$<0.001; Fig. 3A). We found that control fish had a higher [glycogen] than those acclimated to air and aerial hypoxia (Tukey: $P$<0.001, $d_1$=1.2; $P$=0.004, $d_1$=0.9). Although the [glycogen] of air- and aerial hypoxia-acclimated fish did not differ significantly (Tukey: $P$=0.39), there was a meaningful trend towards reduced glycogen usage in aerial hypoxia-acclimated fish, which catabolized 17% less glycogen than fish acclimated to air ($d_1$=0.7). Similarly, in strain 2 fish, the control group had a higher [glycogen] than the air-acclimated group ($t$-test: $P$<0.001, $d_2$=3.3), but glycogen was undetected in the aerial hypoxia group (Fig. 3A). The lipid content of *K. marmoratus* was significantly influenced by the experimental treatment (two-way ANOVA: $P$=0.002) but not by strain (two-way ANOVA: $P$=0.20; Fig. 3B). We found that air-exposed fish had a lower lipid content than control fish (Tukey: $P$=0.001, $d_1$=0.9, $d_2$=1.5). There was no significant difference in the lipid content of control and aerial hypoxia-acclimated fish (Tukey: $P$=0.41), but the effect sizes imply that both strains catabolized lipids under aerial hypoxia ($d_1$=1.0, $d_2$=0.9). Similarly, there was no significant difference in the lipid content of air- and aerial hypoxia-acclimated fish ($P$=0.05), but effect size implies that the use of 23% fewer lipids by strain 2 fish acclimated to aerial hypoxia may be biologically important ($d_1$=0.4, $d_2$=0.8).

### Muscle phenotype

Both the experimental treatment and the strain affected the size of red muscle fibers in *K. marmoratus* (two-way ANOVA: $P$=0.007, $P$=0.04; Fig. 4A). We found that air-exposed fish had significantly larger red muscle fibers than control fish (Tukey: $P$=0.005, $d_1$=1.3, $d_2$=1.0). Although there was no significant difference in the size of red muscle fibers between air- and aerial hypoxia-acclimated fish (Tukey: $P$=0.12), in strain 1 fish there was a trend towards smaller fibers in aerial hypoxia than in air ($d_1$=1.3, $d_2$=0.3). Similarly, we found no significant difference in the size of red muscle fibers

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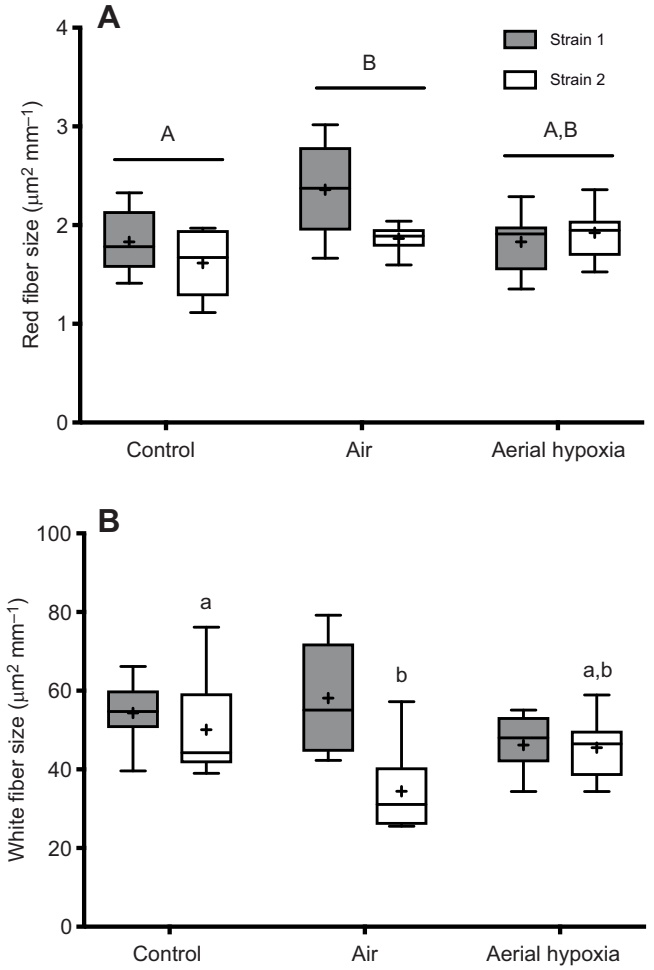


**Fig. 4. The effect of aerial normoxia and aerial hypoxia acclimation on the skeletal musculature of *K. marmoratus*.** (A) The red muscle fiber size of control (strain 1, *n*=8; strain 2, *n*=8) and air- (strain 1, *n*=7; strain 2, *n*=8) and aerial hypoxia-acclimated (strain 1, *n*=8; strain 2, *n*=7) *K. marmoratus*. Different uppercase letters indicate significant differences between experimental treatments. Strain 1 and strain 2 were significantly different from each other. (B) The white muscle fiber size of control (strain 1, *n*=8; strain 2, *n*=8) and air- (strain 1, *n*=7; strain 2, *n*=8) and aerial hypoxia-acclimated (strain 1, *n*=7; strain 2, *n*=7) fish. Different lowercase letters indicate significant differences between the white muscle fibers of strain 2 fish across experimental treatments. There was a significant strain×treatment interaction. Means are shown as crosses within the box.

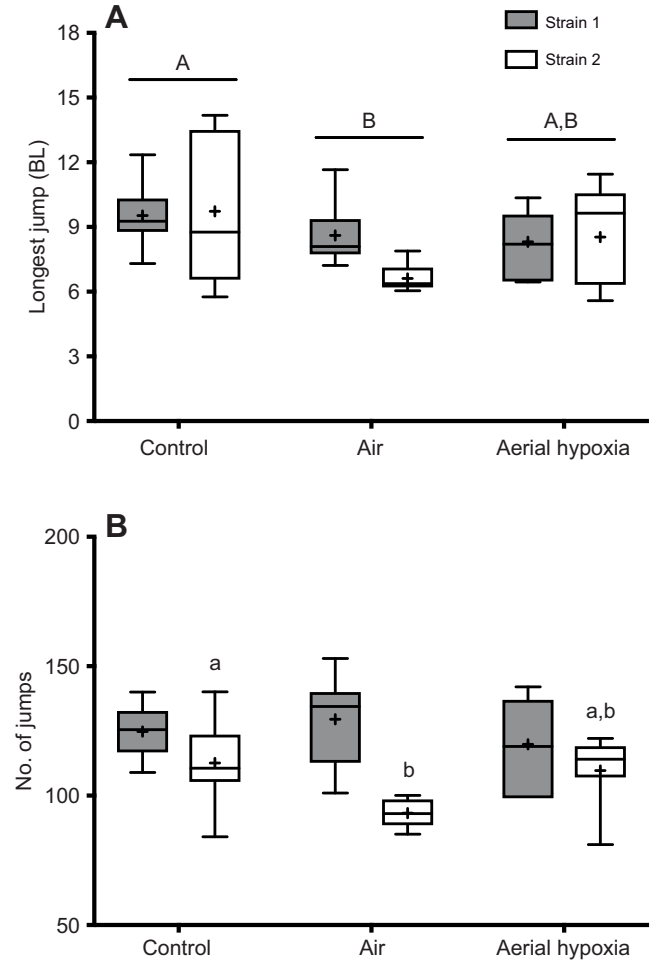


**Fig. 5. The effect of aerial normoxia and aerial hypoxia acclimation on the terrestrial locomotor performance of *K. marmoratus*.** (A) The longest jump performed (in body lengths, BL) by control (strain 1, *n*=8; strain 2, *n*=8) and air- (strain 1, *n*=8; strain 2, *n*=8) and aerial hypoxia-acclimated (strain 1, *n*=7; strain 2, *n*=7) *K. marmoratus*. Different uppercase letters indicate significant differences between experimental treatments. (B) The number of jumps performed by control (strain 1, *n*=8; strain 2, *n*=8) and air- (strain 1, *n*=8; strain 2, *n*=8) and aerial hypoxia-acclimated (strain 1, *n*=7; strain 2, *n*=7) fish before exhaustion. Different lowercase letters indicate significant differences between the number of jumps performed by strain 2 fish across experimental treatments. There was a significant strain×treatment interaction. Means are shown as crosses within the box.

between control and aerial hypoxia-acclimated fish (Tukey: $P$=0.43), though strain 2 fish acclimated to aerial hypoxia had 15% larger fibers than control counterparts, which may be biologically meaningful ($d_1$=0.0, $d_2$=1.0). The size of the white muscle fibers in strain 1 and strain 2 fish was differentially affected by the experimental treatment, as evident by a significant strain×treatment interaction (two-way ANOVA interaction: $P$=0.01; Fig. 4B). The size of white muscle fibers did not differ across treatments in strain 1 fish (one-way ANOVA: $P$=0.12) but differed in strain 2 fish (one-way ANOVA: $P$=0.03). Strain 2 fish acclimated to air had significantly smaller white muscle fibers than control fish (Tukey: $P$=0.02, $d_2$=1.3). We found no significant difference in the size of white muscle fibers between control and aerial hypoxia-acclimated fish ($P$=0.70, $d_2$=0.4). We found no significant difference in the size of white muscle fibers between air- and aerial hypoxia-acclimated fish (Tukey: $P$=0.15), but there was a meaningful trend towards larger white muscle fibers in aerial hypoxia-acclimated fish, which were 24% larger than those of fish in air ($d_2$=1.2).

### Jumping performance

The longest jump *K. marmoratus* could perform was affected by the experimental treatment (two-way ANOVA: $P$=0.04), but strain had no effect (two-way ANOVA: $P$=0.06; Fig. 5A). The longest jump air-acclimated fish could perform was shorter compared with that of control fish (Tukey: $P$=0.03, $d_1$=1.5, $d_2$=1.3). There was no significant difference in longest jump length between control and aerial hypoxia-acclimated fish (Tukey: $P$=0.54), but in strain 1 the effect size implies that the longest jump fish could perform in aerial hypoxia was shorter than under control conditions ($d_1$=0.8, $d_2$=0.4). Similarly, we found no significant difference in the longest jump length between air- and aerial hypoxia-acclimated fish (Tukey: $P$=0.29), but there was a meaningful trend towards longer jumps by

strain 2 fish in aerial hypoxia, which were 20% longer than jumps in air ($d_1$=0.2, $d_2$=1.1). We found that the number of jumps strain 1 and strain 2 fish could perform before exhaustion was differentially affected by treatment (two-way ANOVA interaction: $P$=0.05; Fig. 5B). Strain 1 fish jumped the same number of times regardless of treatment (one-way ANOVA: $P$=0.46). However, the number of jumps strain 2 fish performed differed across treatments (one-way ANOVA: $P$=0.01): air-acclimated fish jumped fewer times than control fish (Tukey: $P$=0.02, $d_2$=1.6). There was no significant difference between the number of jumps performed by air- and aerial hypoxia-acclimated fish (Tukey: $P$=0.05), but the effect size implies that the 20% more jumps performed by strain 2 fish acclimated to aerial hypoxia may be biologically important ($d_2$=1.6).

## DISCUSSION

We used *K. marmoratus* to test the hypothesis that animals seek hypoxic microhabitats that, in turn, accentuate metabolic depression during dormancy. In support of our hypothesis, we found that one isogenic strain spent more than double the amount of time in hypoxia compared with normoxia after 21 days in air. Furthermore, prolonged air exposure in both strains resulted in lower $O_2$ consumption rates compared with active fish (35% depression), which was accentuated (51% depression) when fish were exposed to aerial hypoxia acutely. The fact that fish exposed to aerial hypoxia demonstrated lower $O_2$ consumption rates than air-exposed fish (which were fasted and inactive) is suggestive of active metabolic rate depression, particularly because $O_2$ consumption measurements were obtained above $P_{crit}$ for *K. marmoratus* in air (Blanchard et al., 2019), indicating that this was not simply an oxy-conforming response. We also tested the hypothesis that chronic hypoxia exposure in air would protect endogenous energy reserves and skeletal muscle integrity, thereby maintaining locomotor performance, possibly owing to hypoxic hypometabolism. We found that air-acclimated fish from both strains were in poorer body condition relative to control fish and those acclimated to aerial hypoxia. Air-acclimated fish demonstrated considerable glycogen and lipid catabolism (both strains), white muscle atrophy (strain 2 only) and poorer terrestrial locomotion compared with control fish (strain 2 only). However, aerial hypoxia acclimation reduced glycogen usage by 17% in strain 1 fish, and spared lipids and white muscle protein in strain 2 fish by 23% and 22%, respectively. Furthermore, aerial hypoxia acclimation maintained the terrestrial locomotor performance of strain 2 fish compared with air acclimation (22% farther longest jump, 20% more jumps). Overall, our findings demonstrate that *K. marmoratus* seek microhabitats that, in turn, accentuate metabolic depression, and that microhabitat $O_2$ availability can have significant implications for substrate utilization, and the structure and function of skeletal muscle.

### Microhabitat selection and $O_2$ consumption

We showed that *K. marmoratus* (strain 2) seek hypoxic microhabitats after prolonged air exposure, and one possible benefit is an accentuation of metabolic depression. Our laboratory findings are consistent with the observed habitat preference of *K. marmoratus* in the wild, as fish are often found within decaying mangrove logs (Taylor et al., 2008), which are likely hypoxic (Anderson and Ultsch, 1987). Although strain 1 fish did not seek hypoxia on land, they catabolized less of their metabolic fuel stores (glycogen and some lipids) after 21 days in air compared with strain 2 fish (glycogen, lipids and muscle protein). This was an interesting finding because the absolute rate of $O_2$ consumption was not significantly different between strains after 21 days in air. One possible explanation for the differential fuel use relates to the rate of metabolic depression. For instance, if strain 1 fish depressed metabolic rate to the air-acclimated (21 day) value several days before strain 2 fish, this would likely result in considerable energy savings. Thus, strain 2 fish may face greater pressure to seek low $O_2$ microhabitats during seasonal droughts that accentuate metabolic depression and preserve their remaining energy stores. Alternatively, there are several other reasons why *K. marmoratus* may be found in hypoxic microhabitats in the wild, not just as a strategy to reduce $O_2$ consumption. For example, the decaying logs in which *K. marmoratus* are found may contain more moisture that would protect fish from dehydration and help survival. Overall, the microhabitat conditions that mediate microhabitat selection strategies in dormant taxa are poorly understood, but this remains an exciting avenue for future investigation.

Prolonged air exposure in both strains resulted in lower $O_2$ consumption rates compared with active fish, which was accentuated when fish were exposed to aerial hypoxia acutely. Microhabitat $O_2$ availability has similarly altered the extent of metabolic depression in other dormant animals. For example, hibernating frogs (*Rana temporaria*) exposed to chronic aquatic hypoxia exhibited a 75% suppression of metabolic rate (Donohoe and Boutilier, 1998), whereas those in normoxic water only depressed metabolism by approximately 50% (Donohoe et al., 1998). It is unknown whether hypoxic hypometabolism would persist in *K. marmoratus* with chronic hypoxia exposure in air. However, in many fishes acclimated to chronic hypoxia (weeks to months), $O_2$ consumption remained low over time (e.g. Kerstens et al., 1979; Timmerman and Chapman, 2004). We recently showed that the green-striped burrowing frog (*Cyclorana alboguttata*) also selects environmental hypoxia, which consistently accentuated metabolic depression by ∼30% throughout the first 7 weeks of estivation (Rossi et al., 2020). Taken together, we suggest that the microhabitats occupied by animals during dormancy can have a profound impact on the physiological strategies used to tolerate environmental extremes.

### Endogenous fuel usage

The pattern of metabolic fuel use differed between *K. marmoratus* strains. Strain 1 fish catabolized 75% of their glycogen stores after 21 days in air, but only 58% after 21 days in aerial hypoxia. Glycogen stores are considered to be the primary source of metabolic fuel for fish experiencing hypoxia (Hochachka and Somero, 1984). Thus, glycogen preservation under aerial hypoxia suggests that strain 2 fish may be reducing their overall ATP demand. In contrast, strain 2 fish catabolized glycogen, lipids and presumably protein (given the white muscle fiber atrophy) in air. Aerial hypoxia acclimation attenuated lipid usage in this strain by 23%, and spared muscle protein. These findings are consistent with that from overwintering goldfish (*Carassius auratus*), in which lipid oxidation is constrained under extreme hypoxia in favor of anaerobic glycolysis (Hochachka and Somero, 1984). Accordingly, the [glycogen] of most strain 2 fish was undetectable after aerial hypoxia acclimation. A recent study from our laboratory also demonstrated considerable glycogen and lipid catabolism in three isogenic strains of *K. marmoratus* (50.91, SLC8E and HON9) after 21 days of air exposure (Turko et al., 2019). Interestingly, both our study and that of Turko et al. (2019) found that strain 2 (50.91) fish catabolized 20–25% more of their lipid reserves than strain 1 (SLC8E) fish after air exposure despite the same rate of $O_2$ consumption between the two strains after 21 days in air. The rate at

which metabolic depression is achieved between *K. marmoratus* strains may explain the discrepancy in substrate use, but this hypothesis warrants further investigation. Overall, our findings suggest that *K. marmoratus* strains can employ different behavioral and physiological strategies to prevent the premature exhaustion of endogenous energy reserves during prolonged air exposure. Furthermore, the differential responses between isogenic strains suggest that genetic factors contribute to phenotypic differences in the behavior and physiology of *K. marmoratus*.

### Muscle phenotype and locomotion

The integrity of skeletal muscle in *K. marmoratus* can be critical for survival. Like most fish, *K. marmoratus* rely on their skeletal musculature to power the locomotor movements required for accomplishing essential daily tasks (e.g. predator avoidance, prey capture). Air exposure resulted in the hypertrophy of red muscle fibers in *K. marmoratus*, which we have previously demonstrated is the result of the higher $O_2$ availability in atmospheric air relative to water (Rossi et al., 2018). In contrast, strain 2 fish demonstrated atrophy of their white muscle fibers after air acclimation, suggesting that the greater substrate utilization by these fish may have led to protein catabolism. Consequently, strain 2 fish demonstrated poorer locomotor performance (shorter longest jump, fewer jumps performed) after air acclimation. In support of our hypothesis, the skeletal muscle integrity and locomotor performance of *K. marmoratus* was maintained after 21 days on land with chronic aerial hypoxia exposure. Previous studies have demonstrated that a profound metabolic depression during dormancy can preserve skeletal muscle structure and function (for review, see Hudson and Franklin, 2002a). For example, the frog *C. alboguttata* depresses metabolic rate by up to 80% during estivation (Kayes et al., 2009; Young et al., 2011) and exhibited no skeletal muscle atrophy after several months (Hudson and Franklin, 2002b). Any changes in the skeletal musculature of dormant animals that negatively impact locomotor performance can threaten foraging ability, reproductive success, predator avoidance and, ultimately, survival.

### Perspectives

We demonstrated that some *K. marmoratus* strains seek hypoxic microhabitats during prolonged air exposure, and that acute hypoxia exposure accentuates metabolic depression on land. Interestingly, previous studies from our laboratory have showed that *K. marmoratus* avoids aquatic hypoxia by emersing (Regan et al., 2011; Livingston et al., 2018). How is this behavioral pattern regulated? In other words, what mechanisms allow animals to avoid hypoxia during active periods, but favor hypoxic microhabitats during dormancy? Elucidating the physiological mechanisms modulating behavioral responses to hypoxia in dormant animals will be a fruitful avenue for future investigation.

Although we focused on environmental hypoxia in this study, there are numerous other abiotic factors that may interact with hypoxia to enhance metabolic depression in dormant animals. For example, the subterranean burrows of hibernating hamsters (*Mesocricetus auratus*) can be extremely hypoxic and hypercapnic (Kuhnen, 1986). Similarly, in mangrove swamps, low $O_2$ environments are often accompanied by hydrogen sulphide ($H_2S$) (Rossi et al., 2019b). If the microhabitats occupied by *K. marmoratus* during the dry season are both hypoxic and $H_2S$-rich, we might expect a more profound metabolic depression, as $H_2S$ inhibits oxidative phosphorylation in *K. marmoratus* (Cochrane et al., 2019). Although laboratory studies are valuable for evaluating the physiological mechanisms involved in metabolic depression during dormancy, understanding how microhabitat conditions alter physiological responses is critical.

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#### Competing interests

The authors declare no competing or financial interests.

#### Author contributions

Conceptualization: G.S.R., P.A.W.; Methodology: G.S.R., P.A.W.; Validation: G.S.R., P.A.W.; Formal analysis: G.S.R.; Investigation: G.S.R.; Data curation: G.S.R.; Writing - original draft: G.S.R.; Writing - review & editing: G.S.R., P.A.W.; Visualization: G.S.R.; Supervision: P.A.W.; Funding acquisition: G.S.R., P.A.W.

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#### Supplementary information

Supplementary information available online at
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#### References

**Anderson, J. F. and Ultsch, G. R.** (1987). Respiratory gas concentrations in the microhabitats of some Florida arthropods. *Comp. Biochem. Physiol.* **88**, 585-588. doi:10.1016/0300-9629(87)90086-7

**Bergmeyer, H. U., Berndt, E., Schmidt, F. and Stork, H.** (1974). D-Glucose: determination with hexokinase and glucose-6-phosphate dehydrogenase. In *Methods of Enzymatic Analysis*, 2nd edn (ed. H. U. Bergmeyer), pp. 1196-1201. New York: Academic Press.

**Blanchard, T. S., Whitehead, A., Dong, Y. W. and Wright, P. A.** (2019). Phenotypic flexibility in respiratory traits is associated with improved aerial respiration in an amphibious fish out of water. *J. Exp. Biol.* **222**, jeb186486. doi:10.1242/jeb.186486

**Booth, D. T.** (2006). Effect of soil type on burrowing behavior and cocoon formation in the green-striped burrowing frog, *Cyclorana alboguttata*. *Can. J. Zool.* **84**, 832-838. doi:10.1139/z06-062

**Boutilier, R. G., Donohoe, P. H., Tattersall, G. J. and West, T. G.** (1997). Hypometabolic homeostasis in overwintering aquatic amphibians. *J. Exp. Biol.* **200**, 387-400.

**Brunt, E. M., Turko, A. J., Scott, G. R. and Wright, P. A.** (2016). Amphibious fish jump better on land after acclimation to a terrestrial environment. *J. Exp. Biol.* **219**, 3204-3207. doi:10.1242/jeb.140970

**Chew, S. F., Chan, N. K., Loong, A. M., Hiong, K. C., Tam, W. L. and Ip, Y. K.** (2004). Nitrogen metabolism in the African lungfish (*Protopterus dolloi*) aestivating in a mucus cocoon on land. *J. Exp. Biol.* **207**, 777-786. doi:10.1242/jeb.00813

**Caloin, M.** (2004). Modeling of lipid and protein depletion during total starvation. *Am. J. Physiol.* **287**, E790-E798. doi:10.1152/ajpendo.00414.2003

**Castellini, M. A. and Rea, L. D.** (1992). The biochemistry of natural fasting at its limits. *Experientia.* **48**, 575-582. doi:10.1007/BF01920242

**Cochrane, P. V., Rossi, G. S., Tunnah, L., Jonz, M. G. and Wight, P. A.** (2019). Hydrogen sulphide toxicity and the importance of amphibious behaviour in a mangrove fish inhabiting sulphide-rich habitats. *J. Comp. Physiol. B.* **189**, 223-235. doi:10.1007/s00360-019-01204-0

**Dark, J.** (2005). Annual lipid cycles in hibernators: integration of physiology and behaviour. *Annu. Rev. Nutr.* **25**, 469-497. doi:10.1146/annurev.nutr.25.050304.092514

**Donohoe, P. H. and Boutilier, R. G.** (1998). The protective effects of metabolic rate depression in hypoxic cold submerged frogs. *Respir. Physiol.* **111**, 325-336. doi:10.1016/S0034-5687(97)00125-4

**Donohoe, P. H., West, T. G. and Boutilier, R. G.** (1998). Respiratory, metabolic and acid-base correlates of aerobic metabolic rate reduction in overwintering frogs. *Am. J. Physiol.* **43**, R704-R710. doi:10.1152/ajpregu.1998.274.3.R704

**Etheridge, K.** (1990). The energetics of estivating sirenid salamanders (*Siren lacertina* and *Pseudobranchus striatus*). *Herpetologica* **46**, 407-414.

**Fishman, A. P., Galante, R. J., Winokur, A. and Pack, A. I.** (1992). Estivation in the African lungfish. *Proc. Am. Philos. Soc.* **136**, 61-72.

**Frick, N. T. and Wright, P. A.** (2002). Nitrogen metabolism and excretion in the mangrove killifish *Rivulus marmoratus* II. Significant ammonia volatilization in a teleost during air exposure. *J. Exp. Biol.* **205**, 91-100.

**Froese, R.** (2006). Cube law, condition factor and weight-length relationships: history, meta-analysis and recommendations. *J. Appl. Ichthyol.* **22**, 241-253. doi:10.1111/j.1439-0426.2006.00805.x

**Guppy, M. and Withers, P.** (1999). Metabolic depression in animals: physiological perspectives and biochemical generalizations. *Biol. Rev.* **74**, 1-40. doi:10.1017/S0006323198005258

**Halsey, L. G.** (2019). The reign of the *P*-value is over: what alternative analyses could we employ to fill the power vacuum? *Biol. Lett.* **15**, 20190174. doi:10.1098/rsbl.2019.0174

**Halsey, L. G., Curran-Everett, D., Vowler, S. L. and Drummond, G. B.** (2015). The fickle *P* value generates irreproducible results. *Nat. Methods* **12**, 179-185. doi:10.1038/nmeth.3288

**Hicks, J. W. and Wang, T.** (1999). Hypoxic hypometabolism in the anesthetized turtle, *Trachemys scripta*. *Am. J. Physiol. Regul. Integr. Comp. Physiol.* **277**, R18-R23. doi:10.1152/ajpregu.1999.277.1.R18

**Hochachka, P. W. and Guppy, M.** (1987). *Metabolic Arrest and Control of Biological Time*. Cambridge: Harvard University Press.

**Hochachka, P. W. and Somero, G. N.** (1984). *Biochemical Adaptation*. Princeton: Princeton University Press.

**Hudson, N. J. and Franklin, C. E.** (2002a). Maintaining muscle mass during extended disuse: aestivating frogs as a model species. *J. Exp. Biol.* **205**, 2297-2303.

**Hudson, N. J. and Franklin, C. E.** (2002b). Effect of aestivation on muscle characteristics and locomotor performance in the Green-striped burrowing frog, *Cyclorana alboguttata*. *J. Comp. Physiol. B.* **172**, 177-182. doi:10.1007/s00360-001-0242-z

**Hulbert, A. J. and Else, P. L.** (2004). Basal metabolic rate: history, composition, regulation, and usefulness. *Physiol. Biochem. Zool.* **77**, 869-876. doi:10.1086/422768

**Junior, R. S. L. and Peixoto, P. E. C.** (2013). Males of the dragonfly *Diastatops obscura* fight according to predictions from game theory models. *Anim. Behav.* **85**, 663-669. doi:10.1016/j.anbehav.2012.12.033

**Kayes, S. M., Cramp, R. L., Hudson, N. J. and Franklin, C. E.** (2009). Surviving the drought: burrowing frogs save energy by increasing mitochondrial coupling. *J. Exp. Biol.* **212**, 2248-2253. doi:10.1242/jeb.028233

**Kennett, R. and Christian, K.** (1994). Metabolic depression in estivating long-neck turtles (*Chelodina rugosa*). *Physiol. Zool.* **67**, 1087-1102. doi:10.1086/physzool.67.5.30163883

**Kerstens, A., Lomholt, J. P. and Johansen, K.** (1979). The ventilation, extraction and uptake of oxygen in undisturbed flounders, *Platichthys flesus*: responses to hypoxia acclimation. *J. Exp. Biol.* **83**, 169-179.

**Kuhnen, G.** (1986). $O_2$ and $CO_2$ concentrations in burrows of euthermic and hibernating golden hamsters. *Comp. Biochem. Physiol. A.* **84**, 517-522. doi:10.1016/0300-9629(86)90359-2

**Livingston, M. D., Bhargav, V. V., Turko, A. J., Wilson, J. M. and Wright, P. A.** (2018). Widespread use of emersion and cutaneous ammonia excretion in aplocheiloid killifishes. *Proc. R. Soc. B.* **285**, 20181496. doi:10.1098/rspb.2018.1496

**Markle, C. E. and Chow-Fraser, P.** (2017). Thermal characteristics of overwintering habitats for the Blanding's turtle (*Emydoidea blandingii*) across three study areas in Ontario, Canada. *Herpetol Conserv Biol* **12**, 241-251.

**McCue, M. D.** (2010). Starvation physiology: reviewing the different strategies animals use to survive a common challenge. *Comp. Biochem. Physiol. A.* **156**, 1-18. doi:10.1016/j.cbpa.2010.01.002

**McFarlane, W., Rossi, G. S. and Wright, P. A.** (2019). Amphibious fish 'get a jump' on terrestrial locomotor performance after exercise training on land. *J. Exp. Biol.* **222**, jeb213348. doi:10.1242/jeb.213348

**Ong, K. J., Stevens, E. D. and Wright, P. A.** (2007). Gill morphology of the mangrove killifish (*Kryptolebias marmoratus*) is plastic and changes in response to terrestrial air exposure. *J. Exp. Biol.* **210**, 1109-1115. doi:10.1242/jeb.002238

**Pronko, A. J., Perlman, B. M. and Ashley-Ross, M. A.** (2013). Launches, squiggles and pounces, oh my! The water-land transition in mangrove rivulus (*Kryptolebias marmoratus*). *J. Exp. Biol.* **216**, 3988-3995. doi:10.1242/jeb.089961

**Regan, K. S., Jonz, M. G. and Wright, P. A.** (2011). Neuroepithelial cells and the hypoxia emersion response in the amphibious fish Kryptolebias marmoratus. *J. Exp. Biol.* **214**, 2560-2568. doi:10.1242/jeb.056333

**Rodela, T. M. and Wright, P. A.** (2006). Metabolic and neuroendocrine effects on diurnal urea excretion in the mangrove killifish *Rivulus marmoratus*. *J. Exp. Biol.* **209**, 2704-2712. doi:10.1242/jeb.02289

**Rossi, G. S., Turko, A. J. and Wright, P. A.** (2018). Oxygen drives skeletal muscle remodeling in an amphibious fish out of water. *J. Exp. Biol.* **221**, jeb180257. doi:10.1242/jeb.180257

**Rossi, G. S., Tunnah, L., Martin, K. E., Turko, A. J., Taylor, D. S., Currie, S. and Wright, P. A.** (2019a). Mangrove fishes rely on emersion behavior and physiological tolerance to persist in sulfidic environments. *Physiol. Biochem. Zool.* **92**, 316-325. doi:10.1086/703117

**Rossi, G. S., Cochrane, P. V., Tunnah, L. and Wright, P. A.** (2019b). Ageing impacts the scope for phenotypic flexibility in an air-acclimated amphibious fish. *J. Comp. Physiol. B* **189**, 567-579. doi:10.1007/s00360-019-01234-8

**Rossi, G. S., Cramp, R. L., Wright, P. A. and Franklin, C. E.** (2020). Frogs seek hypoxic microhabitats to accentuate metabolic depression during dormancy. *J. Exp. Biol.* 223, jeb218743

**Ruibal, R. and Hillman, S.** (1981). Cocoon structure and function in the burrowing frog *Pternohyla fodiens*. *J. Herpetol.* **15**, 403-408. doi:10.2307/1563529

**Smith, H. W.** (1931). Observations of the African lung-fish, *Protopterus aethiopicus*, and on evolution from water to land environments. *Ecology* **12**, 164-18. doi:10.2307/1932938

**Stewart, E. R., Reese, S. A. and Ultsch, G. R.** (2003). The physiology of hibernation in Canadian leopard frogs (*Rana pipiens*) and bullfrogs (*Rana catesbeiana*). *Physiol. Biochem. Zool.* **77**, 65-73. doi:10.1086/378921

**Storey, K. B.** (2002). Life in the slow lane: molecular mechanisms of estivation. *Comp. Biochem. Physiol. A.* **133**, 733-754. doi:10.1016/S1095-6433(02)00206-4

**Storey, K. B. and Storey, J. M.** (1990). Metabolic rate depression and biochemical adaptation in anaerobiosis, hibernation and estivation. *Quart. Rev. Biol.* **65**, 145-174. doi:10.1086/416717

**Storey, K. B. and Storey, J. M.** (2012). Aestivation: signaling and hypometabolism. *J. Exp. Biol.* **215**, 1425-1433. doi:10.1242/jeb.054403

**Sullivan, G. M. and Feinn, R.** (2012). Using effect size—or why the p value is not enough. *J. Grad. Med. Educ.* **4**, 279-282. doi:10.4300/JGME-D-12-00156.1

**Sutton, A. O., Turko, A. J., McLaughlin, R. L. and Wright, P. A.** (2018). Behavioural and physiological responses of an amphibious, euryhaline mangrove fish to acute salinity exposure. *Copeia* **106**, 305-311. doi:10.1643/CP-17-665

**Tatarenkov, A., Ring, B. C., Elder, J. F., Bechler, D. L. and Avise, J. C.** (2010). Genetic composition of laboratory stocks of the self-fertilizing fish *Kryptolebias marmoratus*: a valuable resource for experimental research. *PLoS ONE* **5**, e12863. doi:10.1371/journal.pone.0012863

**Taylor, D. S.** (1990). Adaptive specializations of the cyprinodont fish *Rivulus marmoratus*. *Fla. Sci.* **53**, 239-248.

**Taylor, D. S., Turner, B. J., Davis, W. P. and Chapman, B. B.** (2008). A novel terrestrial fish habitat inside emergent logs. *Am. Nat.* **171**, 263-266. doi:10.1086/524960

**Timmerman, C. M. and Chapman, L. J.** (2004). Behavioral and physiological compensation for chronic hypoxia in the sailfin molly (*Poecilia latipinna*). *Physiol. Biochem. Zool.* **77**, 601-610. doi:10.1086/421754

**Turko, A. J., Kültz, D., Fudge, D., Croll, R. P., Smith, F. M., Stoyek, M. R. and Wright, P. A.** (2017). Skeletal stiffening in an amphibious fish out of water is a response to increased body weight. *J. Exp. Biol.* **220**, 3621-3631. doi:10.1242/jeb.161638

**Turko, A. J., Doherty, J. E., Yin-Liao, I., Levesque, K., Kruth, P., Holden, J. M., Earley, R. L. and Wright, P. A.** (2019) Prolonged survival out of water is linked to a generally slow pace of life in a selfing amphibious fish. *J. Exp. Biol.* 222, jeb209270. doi: 10.1242/jeb.209270

**Van den Boogaart, K. G. and Tolosana-Delgado, R.** (2013). *Analyzing Compositional Data with R*. Berlin, Heidelberg: Springer.

**Young, K. M., Cramp, R. L., White, C. R. and Franklin, C. E.** (2011). Influence of elevated temperature on metabolism during aestivation: implications for muscle disuse atrophy. *J. Exp. Biol.* **214**, 3782-3789. doi:10.1242/jeb.054148