Sex differences and shifts in body composition, physical activity, and total energy expenditure across a 3-month expedition

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Abstract

Objectives: An energetically demanding environment like a wilderness expedition can lead to potent stressors on human physiology and homeostatic balance causing shifts in energy expenditure and body composition. These shifts likely have consequences on overall health and performance and may potentially differ by sex. It is therefore critical to understand the potential differential body composition and energy expenditure changes in response to a novel and challenging environment in both males and female bodies.

Methods: Data were collected from 75 healthy individuals (female = 41; ages 18–53) throughout a 3-month long expedition in the American Rockies. Body mass, body fat, and lean muscle mass were measured before, during, and after the course. Physical activity intensity and energy expenditure were also measured in a subset of participants using the wGT3X-BT Actigraph wrist monitor and an accompanying Bluetooth heart rate monitor.

Results: Over the 3-month period, individuals initially experienced declines in body mass, body fat percentage, and lean muscle mass. Participants partially rebounded from these deficits to maintain overall body mass with a slight recomposition of body fat and lean muscle mass. Our data also demonstrated that sex moderated total energy expenditure, where females experienced a modest decline whereas males experienced an increase in energy expenditure from the beginning to the end of the course.

Conclusions: Understanding changes in energy storage in the body and variation in energy expenditure between sexes during a 3-month expedition has critical implications for maintaining health and performance in an energetically demanding environment where resources may be scarce.
INTRODUCTION

Energetically demanding environments, like backcountry, high altitude, or cold ecologies, can stress human physiology and homeostatic balance. Environmental stressors like hypoxia, cold stress, and increased physical activity play a role in determining how energy within the body is allocated and can also shape and influence physiology across multiple timescales. Indigenous or other long-term resident populations of extreme environments often demonstrate genetic adaptations to those conditions and/or exhibit phenotypic changes (i.e., emerging through developmental exposure) that facilitate their day-to-day functioning (Beall, 2014; Leonard, 2018). However, in the short-term, nonadapted sojourners can experience rapid physiological changes as they adjust to high altitude and extreme cold conditions, often resulting in relatively swift net negative outcomes (e.g., extreme weight loss) within the initial 2–3 week-long acclimatization period (Moran, 2008; Shvartz et al., 1974). Backcountry expedition settings are a good model for understanding such shorter-term acclimatization processes since individuals are exposed to an energetically demanding environment for a set period of time, have constrained access to resources, and often engage in intensive physical activity.

Energy expenditure has been shown to increase when individuals are first introduced to these settings, (Hattersley et al., 2020; Ocobock, 2016a; Pulfrey & Jones, 1996; Westerterp et al., 1992), though once acclimatized, bodies can potentially rebound from the increased energetic demands and return to their original baseline status. However, questions remain regarding differences in acclimatization, particularly when considering over a longer period of time beyond the first couple weeks and into several months. Past work in the area has considered certain individual differences as influences on acclimatization processes, including developmental exposures to challenging ecologies (e.g., high altitude) and age-based variation in physiological function in core processes (e.g., reduced vasoconstriction) (Castellani & Young, 2016; Frisancho, 2013; Moore et al., 2011). However, surprisingly few studies have modeled differences in acclimatization energetics based on by sex, which may play a contributing role in individual response to such conditions.

Much of the early literature on how bodies respond to environmental stressors in expedition settings was often limited by only looking at highly trained individuals, small sample sizes, but also, importantly, studying only male bodies and/or failing to consider how acclimatization-related responses may differ by sex (Butterfield et al., 1992; Consolazio et al., 1972; Tanner & Stager, 1998; Westerterp, 2001; Westerterp & Kayser, 2006). Yet, a small number of recent studies among both resident populations and acclimatizing individuals suggests that in energetically intensive domains male and female bodies may respond differently in how they expend energy and how body composition thus shifts (Ocobock, 2017; Sarma et al., 2020; Zaccagni et al., 2014).

Research has demonstrated notable changes in individual energy status and expenditure when individuals are on expeditions. Intensive backcountry expeditions are marked by increases in individuals’ energy expenditure reaching up to well over 4000 kcal day$^{-1}$ (Hattersley et al., 2020; Ocobock, 2016b; Pulfrey & Jones, 1996). Compared to adapted groups, sojourners to these challenging and physically intensive settings must acclimate to the dual burdens of everyday activity as well as novel and potentially harsh environmental stressors which may explain the initial increased energy expenditure (Frisancho, 2013; Moore et al., 1998). Further, when energetic demands increase to the point of a negative energy balance, the increased energetic cost is compensated for by drawing on stored energy deposits, like fat stores that serve as long-term energy reservoirs, or muscle mass, leading to a reconfiguration of body composition. Body mass fluctuation is more nuanced than the direct consumption/expenditure of calories and caloric intake and the macronutrient content consumed can help explain expenditure. However, the use of energy deposits and subsequent body composition changes can broadly point to energy expenditure exceeding energy intake and help infer energy status (Ocobock, 2020; Westerterp et al., 1992). When facing energy deficits, the body will preferentially burn fat stores and then begin to burn muscle (Ocobock, 2017) with likely functional implications for everyday activity. This has been seen in prior expeditionary research where individuals experienced a re-composition of body fat and muscle mass, though intriguingly, this re-composition differed by sex (Ocobock, 2017; Zaccagni et al., 2014).

Over the course of an expedition, Ocobock found that body fat attenuated muscle mass catabolism, and females especially benefitted from potential fat-protective effects. Females, who started with higher initial body fat, tended to gain muscle mass but lose fat whereas males, more often beginning at, or near, essential levels of body fat, tended to lose both (Ocobock, 2017). This work suggests that possessing a higher body fat percentage might spare muscle mass catabolism. This is particularly relevant for individuals in energetically demanding environments for long periods of negative energy balance, such as environments that require high vigilance, high altitude or cold ecologies, or even during intensive seasonal shifts due to changes in ecology, workloads, and/or eating practices. This also supports previous findings indicating a positive and protective effect of body fat against fat-free
mass break down (Ocobock, 2017; Reynolds et al., 1999; Zaccagni et al., 2014). Thus, sex differences in initial body composition distribution may determine subsequent changes in body composition when acclimatizing. Given that females tend to have on average higher body fat than males (Borrud et al., 2010; Bredella, 2017; Wells, 2007), this starting higher body fat may be protective against losses of lean muscle. Burning through fat and potentially muscle during an expedition could lead to poor individual performance but may also lead to other downstream negative health consequences related to depleted energy resources, such as fatigue or dysregulated immune function (Marconi et al., 2005; Muehlenbein et al., 2010).

In addition, while it is well understood that males and females have differential basal metabolic rates largely due to relatively greater body and fat-free mass in males (Johnstone et al., 2005; Manini, 2010; Ocobock, 2020), it is less known how total energy expenditure may differ by sex during and after acclimatization. Beyond basic differences in body composition and basal metabolic rate, some previous research suggests that there are potential differences in how males and females respond to extreme physiological demands, for example, such as males having higher dependency on carbohydrate utilization and increases in the heart's stroke volume in expedition settings thus increasing energy expenditure during demanding activities (Braun et al., 2000; Hattersley et al., 2020; Pettit et al., 1999). However, when taken together, these findings do not yet show a conclusive pattern. Failing to account for differential energy expenditure due to sex in these settings, including how this relates to individual energy status could have critical implications in expedition settings, including requiring early withdrawal and a higher incidence for injury or illness, in a setting that may have very limited access to additional resources and assistance (Tanner & Stager, 1998; Westerterp et al., 1992; Zaccagni et al., 2014). It is therefore crucial to understand the potential body composition and energy expenditure changes in response to a novel and challenging environment, and the possible sources of individual variation given these functional consequences.

To help address these questions of acclimatization, inferred energetic status, and energy expenditure, we considered how adjusting to multiple stressors in a challenging backcountry environment impacted changes in body composition, physical activity levels, and total energy expenditure (TEE) as well as the potential sex differences thereof. Working with individuals participating in 3-month long expeditions through the American Rocky Mountains as a part of the National Outdoor Leadership School (NOLS), we assessed changes in body composition, particularly that of body mass, body fat, and lean muscle mass across the length of the expedition as individuals acclimatized to their environment. Following Ocobock’s earlier findings regarding sex differences in body composition changes on expeditions (also at NOLS), we predicted that there would be a difference between males and females in the pattern of changes in body mass, body fat, and lean muscle mass. For changes in energy expenditure, we predicted that when participants were first exposed to the stressors of the novel and challenging environment, their average TEE would increase while on the course.

2 | METHODS

2.1 | Participants

In this study healthy individuals (n = 75; ages 18–53), took part in one of ten ~90-day NOLS outdoor education courses occurring simultaneously between August–December of 2018. Six of these courses were designated as general fall semester courses, two were designed to train outdoor educators, and two were designed to train participants in wilderness medicine and search and rescue skills. Of these participants, 34 were male and 41 were female. To take part in a NOLS course, students had to be generally healthy with no debilitating illnesses or injuries that might impede their ability to complete the course. Students also had to be willing to comply to a rigorous code of conduct including abstaining from tobacco, alcohol, and illegal substances while on the course. In this study, 96% of students reported that they had at least some prior experience in backcountry settings, however, 92% reported that they had no experience on a NOLS expedition of this duration and intensity. The NOLS Research Review Board and the University of Notre Dame Institutional Review Board approved this study (IRB Protocol 18-02-4483), and participants gave written informed consent prior to participating.

2.2 | Field settings

NOLS is a US-based nonprofit organization that teaches leadership and wilderness skills while students live in the outdoors for an extended period of time. Expeditions included in this study traveled throughout the American West, spanning Wyoming, Utah, Colorado, and Nevada. During their expedition period, participants experienced altitudes of up to 13 804 ft and temperatures between −18.9 and 27.2°C. The typical schedule for a NOLS student would be to arrive in Lander, WY several days before they leave for their expedition to meet the other students on the course and instructors. Each course has,
on average, 13 students, with 3–4 instructors on each section. Each course went through four sections. Sections were focused on one of the following activities: hiking, mountaineering, canoeing, kayaking, climbing, canyoneering, and winter camping. An example course would be section 1 (hiking) followed by section 2 (canoeing) followed by section 3 (climbing) and finishing with section four (winter camping). These sections were dichotomously coded into “low” and “high” difficulty based on the intensity of activity (i.e., Activity Difficulty) established from rankings made by NOLS instructors and staff (Table 1). All students on the course went through at least one high difficulty section and at least one low difficulty section. Sections were predetermined by NOLS before courses began and were chosen based on season as well as logistical and permitting constraints (see Appendix S1, Table 1). The wilderness medicine course participants spent the first section of their course in a shared classroom and field setting to be certified as wilderness emergency medical technicians (wilderness EMTs) and were thus excluded from any activity or energy expenditure measurements during that section. In each section, students were required to follow a set curriculum where they learned and engaged in standardized wilderness and leadership-related skills and activities.

Data were collected at the transitions between the four-course sections. These transition collection points are referred to as checkpoints here on forward. Thus, collection took place precourse, midcourse checkpoint 1, midcourse checkpoint 2, midcourse checkpoint 3, and postcourse (see Figure 1).

2.3 Anthropicatic and body composition measurements

Energy status was inferred via measurements of body mass, body fat percentage, and lean muscle mass were made at each data collection checkpoint using the Tanita BC-558 Ironman Segmental Body Composition Monitor bioelectrical impedance scale (Tanita Corporation, Arlington Heights, IL). The athletic setting was chosen for these measurements due to the increased fitness achieved throughout courses and to maintain measurement consistency. The Tanita equations are unpublished. Measurements were taken in the morning before participants consumed a meal at each transition point to the next section, though due to logistical constraints, measurements could not be taken at a consistent time of day.

Of the total 346 observations, six observations for lean muscle mass and body fat were missing.

2.4 Energy expenditure and physical activity measurements

To look at acclimatization, we compared physical activity and TEE and the beginning and end of the course. Energy expenditure ($n = 31$, observations $= 39$) and physical activity measurements ($n = 46$, observations $= 62$) were taken early in the course (the last 10 days of the first section) and late in the course (the last 10 days of the fourth section) from a subset of the total participants (see Figure 1). From this subset, 16 individuals were measured for physical activity twice both early and late in the course and eight individuals were measured twice for TEE both early and late in the course. One participant had physiologically implausible TEE values and was removed from the analysis ($n = 31$, observations $= 38$). Using the Actigraph wGT3X-BT monitor, we calculated physical activity level using the Freedson VM3 Combination equations using all three axes of movement (X, Y, Z) via “counts” measured through accelerations (Sasaki et al., 2011). The Freedson VM3 combination equation delineates between individuals with epoch counts per minute that are over 2453 ($n = 16$; see Appendix S1) and

| Activity                          | Section         | Typical elevation | Month     | Average temperature |
|----------------------------------|-----------------|-------------------|-----------|---------------------|
| Low physical difficulty          | Lander          | 5400 ft           | Aug–Sep   | 6.1–27.2° C         |
|                                  | Wilderness EMT  | 5600 ft           | Sep–Oct   | 6.1–27.2° C         |
|                                  | Climbing        | 6500 ft           | Sep–Nov   | 13.9–32.2° C        |
|                                  | Canoeing        | 5300 ft           | Sep–Oct   | 0.5–25.0° C         |
|                                  | Kayaking        | 5300 ft           | Oct–Nov   | −5.5–16.7° C        |
| High physical difficulty         | Hiking          | 10 300 ft         | Sep–Oct   | −10.5–7.2° C        |
|                                  | Mountaineering  | 10 600 ft         | Sep       | −5.5–7.2° C         |
|                                  | Canyoneering    | 5800 ft           | Nov–Dec   | −7.7–12.2° C        |
|                                  | Winter camping  | 10 000 ft         | Dec       | −18.9–−10° C        |
individuals with epoch counts per minute under 2453 (see Appendix S1). Time spent in moderate-to-vigorous physical activity was calculated via counts per minute cut-points. The cut-points used to determine intensity of activity are as follows: light (0–2690 counts per minute), moderate (2691–6166 counts per minute); vigorous (6167–9642 counts per minute); very vigorous (9643–∞).

In this sample, participants only achieved activity intensity up to the moderate level. All Actigraph physical activity estimates were based on raw data at 10-s epochs. We used the flex-heart rate method to estimate TEE. TEE across a 24-h period was estimated based on up to 10 days of raw wear time data measured at 10-s epochs—all values reported are TEE over 24 h (i.e., TEE kcal day⁻¹). We used the formula derived by Hiilloskorpi and colleagues (see Appendix S1) to analyze heart rate data and calculate TEE (Hiilloskorpi et al., 2003). Using heart rate to estimate TEE is a standard technique in human energetics research; the utility of heart rate as a proxy measure for energy expenditure stems from the fact that there is a linear relationship between heart rate and energy expenditure (or oxygen consumption) over a large range of activity levels (Booyens & Hervey, 1960; Christensen et al., 1983). Though less accurate at very high levels of physical activity, on average as work or exercise levels increase, heart rate increases as a direct function of energy demands (Leonard, 2003; Ocobock, 2016b). In addition, the flex-heart rate method accounts for the variation when the linear relationship begins to break down (Leonard, 2003).

The average 24-h TEE of each participant was calculated using a custom script developed in Python based on the Hiilloskorpi flex-heart rate formula. First, missing data were replaced using interpolation when the period of missing data was less than 20 min (5.7% of all data); gaps in the data longer than 20 min were excluded from the analysis (9.7% of all data). Then, TEE was calculated for each 10 s epoch based on the participant’s sex and mass using relationships derived for low activity levels (heart rate <90 bpm) and high activity levels (heart rate ≥90 bpm) (Hiilloskorpi et al., 2003; see Appendix S1 for equations for light and heavy activity). Subsequently, we derived a representative 24-h TEE profile for each participant by averaging the calculated TEE in corresponding 10 s epochs across each day. We enforced a physiological lower bound for TEE replacing derived values below the estimated basal metabolic rate (BMR) with the BMR (Henry, 2005). We found that the Python code could more accurately identify and correct missing heart rate datapoints than by hand coding and could process each data file much faster (~1 min per file vs. ~3 h per file). A link to the Python script for download is provided in Appendix S1.

### 2.5 Statistical analysis

Heart rate analyses were run in Python version 3.7 and all statistical analyses were run in R and Stata version 14 (Stata Corporation, College Station, TX). We first used t-tests to assess raw changes in body mass, lean muscle mass, and body fat in both males and females. We then used linear mixed models to test for the interaction between time points on the course (precourse, checkpoint 1, checkpoint 2, checkpoint 3, postcourse) and sex to determine if sex moderated the relationship between time and body composition changes adjusting for age (model 1). We next used linear mixed models to estimate change in body composition over time without the interaction, adjusting for sex, and age (model 2). Finally, we ran the same linear mixed model also adjusting for the dichotomous variable categorizing activity difficulty (model 3). These models treated individuals nested within their course as a random intercept effect. Activity difficulty was not included in the interaction models due to collinearity since the final section of all courses, and thus final comparative time point, was ranked as high difficulty. All of these models used checkpoint 1 (i.e., after the
completion of the first section), as the comparison variable relative to the other sections of the course. Finally, we used linear mixed models to estimate change in TEE and percentage of time spent in moderate-to-vigorous activity (%MVPA) from the beginning to the end of the course. For moderation analyses with a significant interaction, we conducted pairwise comparisons to assess the significance and effect sizes for the relevant categorical variables (i.e., sex*time point). Since prior work in this group suggests that the flex-HR method may overestimate estimates of TEE of 3000 kcal day−1 or higher by ~17% (Ocobock, 2016b), in a posthoc analysis we ran the same interaction linear mixed model, follow up pairwise comparison, and female-only model for TEE with this additional correction.

3 | RESULTS

Participants were 23.03 (±6.17 SD) years old, on average (Table 2). We found that at the beginning of the course, females started with a mean 63.06 ± 9.73 kg in total body mass, 45.90 ± 5.59 kg in lean muscle mass, and 23.59% ± 6.67% body fat. Males began with mean of 76.82 ± 11.05 kg in total body mass, 63.13 ± 8.46 kg in lean muscle mass, and 13.45% ± 4.49% body fat (Table 3).

3.1 | Body composition changes

Body mass and body fat. By the end of the course, when assessing raw body composition change values from before the course, females had a significant 1.25% average loss in body fat (p < .05) and a small nonsignificant mean increase of 0.98 kg in total body mass (p > .50). Similarly, males had a significant 1.66% average loss in body fat (p < .05) and a nonsignificant mean decrease of 0.52 kg in total body mass (p > .50; see Table 3 and Figure 2). Across all time points, we found that females, on average, had significantly lower body mass and greater body fat compared to males (all p < .01; Table 3). Using linear mixed models, we observed that in the beginning of the expedition when individuals were initially adjusting to their environment (precourse to checkpoint 1), all individuals experienced a significant loss in body mass and body fat (p < .05; see Tables 4 and 5, model 2) adjusting for sex and age. When adjusting for sex and age, we found that after this initial adjustment period, there was a significant increase in body mass through the rest of the course (checkpoint 1 to checkpoint 2, checkpoint 3, and postcourse; Table 4, model 2) and a brief significant increase in body fat in the middle sections of the course (checkpoint 1 to checkpoint 2 and checkpoint 3; Table 5, model 2). When also adjusting for activity difficulty, we found that individuals experienced a significant increase in body mass throughout the course following the first section (checkpoint 1 to checkpoint 2, checkpoint 3, and postcourse; Table 4, model 3) but there was no significant change in body fat following the first section (Table 5, model 3). Following these linear mixed models, we found that sex did not significantly moderate changes in either body mass or body fat across the duration of the course (all p > .2; see Tables 4 and 5, models 1).

Lean muscle mass. From before the course to after, females had an average increase of 0.83 kg in lean muscle mass whereas males had a mean increase of 2.02 kg in lean muscle mass (all p > .20; see Table 3 and Figure 2). Across all time points, we found that females, on average, had significantly lower lean muscle mass compared to males (Table 3; p < .05). When adjusted for age (Table 6), sex did not moderate changes in lean muscle mass. Further, there were no significant changes across any of the time points in lean muscle mass when adjusting for sex and age (Table 6, model 2). However, when adjusting for sex, age, and activity difficulty, a significant increase in

| TABLE 2  | Descriptive statistics |
|-------------|------------------------|
| **Mean ± SD** |                        |
| Age         | 23.03 ± 6.17           |
| Sex         |                        |
| Males       | 43.06%                 |
| Females     | 56.94%                 |
| Ethnicity   |                        |
| Asian       | 4.22%                  |
| Native Hawaiian or other Pacific Islander | 1.40% |
| Black or African American | 2.82% |
| White       | 83.10%                 |
| Other       | 2.82%                  |
| Multiple Categories/Mixed | 5.63% |
| Highest Education Level |                 |
| GED         | 1.35%                  |
| High school diploma | 36.49% |
| Some college | 29.73% |
| College degree or higher | 32.43% |
| Group size  | 13.15 ± 1.9            |
| %MVPA       | 25.60% ± 10.36%        |
| average energy expenditure/hr | 279.00 ± 147.37 kCal |
| TEE (24 h)  | 4345.39 ± 1806.26 kCal |
muscle mass was seen in checkpoint 2 and 3 when compared to checkpoint 1 (Table 6, model 3).

3.2 Physical activity and energy expenditure

In our models for %MVPA, individuals spent 26.6% ± 11.4% of time in moderate to vigorous physical activity early in the course and 24.8% ± 9.6% late in the course (see Figure 3). When adjusting for relevant covariates, there was no significant change in %MVPA from earlier in the course to later in the course and sex did not moderate any differences in %MVPA (all \( p > .7 \)).

We found that all individuals had a mean TEE of 4311.47 ± 1706.90 kcal day\(^{-1}\) early in the course and 4410.62 ± 2055.63 kcal day\(^{-1}\) later in the course (see Figure 3). When correcting for body mass in males and females, we observed that TEE in males per kilogram was on average 75.54 kcal day\(^{-1}\) kg\(^{-1}\) in the first section and 85.44 kcal day\(^{-1}\) kg\(^{-1}\) in the last section of the course and TEE in females per kilogram was on average 51.81 kcal day\(^{-1}\) kg\(^{-1}\) in the first section of the course and 46.97 kcal day\(^{-1}\) kg\(^{-1}\) in the last section of the course. Sex was a significant main effect predicting energy expenditure and there was also a significant interaction for time point on the course x sex (\( p < .05 \); Table 7). In a follow up pairwise comparison, we found that the rate of increase is significantly positive in males when comparing early to later in the course (\( p < .05 \)) but not significant in females (\( p > .40 \)). When considering females alone in a separate model, they experienced a statistically significant decline in TEE from the beginning of the course to the end of the course (\( p < .05 \)). Comparatively, when considering males alone in a separate model, they had an increase in TEE from the beginning of the course to the end (see Figure 3), though this was not statistically significant (\( p = .08 \)). In the posthoc analysis correcting for potential flex-HR overestimation of TEE, these patterns remained consistent. Activity difficulty was not included in these models due to collinearity with time point given that all section 4 activities were ranked to be of highest physical difficulty. When only considering participants measured for TEE, we found that adjusting for sex and age, body mass and lean muscle mass significantly increased (\( p < .05 \)) in the last section of the course compared the first section.

4 DISCUSSION

In this study, we analyzed how body composition, physical activity, and energy expenditure changed across the length of a 3-month expedition in a highly challenging
and energetically demanding environment. Prior research in expedition-like settings have revealed how these kinds of environments can lead to rapid and substantial changes to energy status and expenditure, though there is less known about how sex may influence these outcomes (Butterfield et al., 1992; Consolazio et al., 1972; Tanner & Stager, 1998; Westerterp, 2001; Westerterp & Kayser, 2006). Our findings demonstrated that while body composition and energy expenditure are, unsurprisingly, distinctly varied by sex, how body composition changes during and after acclimatizing is generally similar between males and females. In contrast, how energy expenditure changes across the length of a 3-month expedition period may differ by sex. Assessing how sex could shape changes in energy status and expenditure in a backcountry expedition setting can help us better understand the nuances of acclimatizing to an energetically demanding environment or a novel energetic challenge. These nuances are critical when considering the parameters and resources required when preparing individuals for similar energy intensive circumstances. Beyond other expeditionary environments, this preparation may also be relevant for groups experiencing broadly related conditions, such as on military or humanitarian missions in austere settings, firefighters in prolonged precarious circumstances (e.g., wildfires), or those experiencing unexpected rapid human movement (e.g., forced migration).

### 4.1 Sex differences in body composition changes

Following typical sex-distribution in human body composition (Wells, 2007), we found that females on average had significantly lower body mass, lower lean muscle mass, and higher body fat compared to males at all time points on the course. Participants of both sexes experienced overall declines in body fat as well as rebounds in body mass across the course. Given the energetically demanding conditions of the expedition-setting, it might be expected that there would be dramatic losses in body mass, body fat, and lean muscle mass, particularly if at least some individuals failed to consume enough rations to meet the daily energetic costs on the course. However, the relatively stable patterns we observed suggest that...
individuals may be avoiding a substantial negative energy balance and successfully acclimatizing to these conditions over the course duration.

At the end of the course, we found that there was no significant difference in participants’ body mass or lean muscle mass compared to before they started, but that they did experience a significant loss in body fat. These data showed that after initial losses in body mass (~0.45 kg) and body fat (2%), individuals were able to partially rebound over the length of their course, regaining any lost body mass and some body fat, though body fat was lost once more during the last section of the course. Lean muscle mass remained consistent throughout. The observed decreases in both body mass and body fat as individuals acclimatized to the course stressors in the first section (precourse to checkpoint 1) potentially reflect a negative energy balance where individuals were likely drawing on internal energy stores. The later patterns suggest that individuals eventually attained a positive energy balance to regain these lost stores. The lower body fat postcourse, commensurate to the initial loss in body fat, suggests that fat stores were spent once more to accommodate expeditionary energetic stresses in the final section. However, loss of lean muscle mass was prevented and (nonsignificantly) increased on average 2.5%, likely contributing to the overall body mass increase. When adjusting for activity difficulty in addition to sex and age, there was a steady increase in body mass and lean muscle in the middle of the course after the first section, but no significant change in body fat throughout the course. This suggests that the difficulty of the activities during each section of the course played a role in explaining at least losses in body fat. After the first section of the course, the middle sections may have provided a respite where individuals were back in an energy surplus and could regain lost body fat. Contrary to our prediction, however, we did not find that sex moderated changes in body mass, body fat, or lean muscle mass.

Most prior work assessing changes to body composition in similar but non-NOLS settings (i.e., mountaineering, backpacking, etc.) are limited to shorter-term expeditions, that last a couple weeks (Hamad & Travis, 2006; Zaccagni et al., 2014). However, across the course of ~3 months, if a population has acclimatized to their surroundings environment and has ample nutrition, they would likely return to their starting body mass and potentially exhibit readjusted body fat and lean muscle, as we see here. The rebounded body mass and redistribution of body fat and lean muscle suggests that study participants may have avoided some of the negative health and performance outcomes related to

| Table 4 Predicting change in weight (kg) from time point (compared to midcourse checkpoint 1—observations = 346) |
| Model 1 | Coefa 95% CI | p | Model 2 | Coef 95% CI | p | Model 3 | Coef 95% CI | p |
|---------|--------------|---|---------|--------------|---|---------|--------------|---|
| Main effects |
| Time pointb |
| Precourse | 0.65 (−0.12, 1.42) | .098 | 0.82 (0.23, 1.41) | .006 | 0.33 (−0.37, 1.04) | .356 |
| Checkpoint 2 | 1.64 (0.86, 2.42) | .001 | 1.54 (0.95, 2.14) | .001 | 1.21 (0.56, 1.86) | .001 |
| Checkpoint 3 | 1.70 (0.91, 2.49) | .001 | 1.57 (0.97, 2.17) | .001 | 1.40 (0.78, 2.01) | .001 |
| Postcourse | 1.01 (0.22, 1.80) | .012 | 0.82 (0.22, 1.42) | .008 | 1.00 (0.38, 1.61) | .001 |
| Sex (male)c | 13.70 (9.24, 18.16) | .001 | 13.59 (9.19, 17.99) | .001 | 13.61 (9.22, 18.00) | .001 |
| Interaction terms |
| Time point × sex |
| Precourse × sex | 0.40 (−0.79, 1.59) | .507 | − | − | − | − |
| Checkpoint 2 × sex | −0.24 (−1.45, 0.96) | .693 | − | − | − | − |
| Checkpoint 3 × sex | −0.31 (−1.52, 0.90) | .617 | − | − | − | − |
| Postcourse × sex | −0.44 (−1.65, 0.76) | .471 | − | − | − | − |
| Covariates |
| Age | 0.16 (−0.20, 0.51) | .388 | 0.16 (−0.20, 0.51) | .390 | 0.16 (−0.20, 0.51) | .390 |
| Activity difficulty | −0.67 (−1.22, −0.12) | .017 |

Note: bold values indicate p-value < 0.05.
aCoef and 95% CI from Linear Mixed Models.
bComparison for variables compared to checkpoint 1.
cSex: 1 = male; 0 = female.
loss of strength and stamina that can accompany rapid and sustained weight loss in such settings. While past research in expedition settings have demonstrated that lean muscle mass tends to decline, often at substantial rates, and is exacerbated by concurrent intensive loss in body fat (Hoppeler et al., 1990; Tschöp & Morrison, 2001; Zaccagni et al., 2014). Our results instead show that across all individuals, lean muscle maintenance and even a transient gain when adjusting for section difficulty. These findings differ from earlier research with NOLS students on similar 90-day courses, where individuals experienced substantial and significant losses in body mass and body fat, particularly in ways that differed by sex (i.e., men lost substantial lean mass when in similar conditions; Ocobock, 2017). These differences were possibly due to higher energy availability during the course in the present study as well as a key difference in the populations’ essential fat profiles.

Comparatively, in the present study, only 2.7% of this group were at a critically low fat-mass at any point during the expedition. Further, in response to Ocobock’s work in 2013, NOLS altered the food rations for all participants to include macronutrient-dense snack foods that students preferred to eat and initiated an education campaign to teach instructors how to explain complete proteins and coach students to eat all their rations (particularly the less popular protein-rich foods like powdered milk and eggs). This likely had an impact on overall energy balance and increased individual energy intake even in light of the potential appetite suppressant effects of expeditionary activity. The changes in expeditionary diet and education instituted by NOLS following Ocobock’s study may have led to a higher energy availability during the course for all individuals. Since extensive fat mass loss to the point of reaching essential fat levels puts muscle mass at risk, the minimal fat loss in this sample allowed for rebounds in body mass and fat as well as muscle maintenance and even gain despite section difficulty. Our findings suggest that with minimized negative energy balance across the acclimatization period, deleterious body mass and muscle mass loss can be protected against, even under intensive expedition

| Model 1 | Model 2 | Model 3 |
|--------|--------|--------|
| Coef | 95% CI | p | Coef | 95% CI | p | Coef | 95% CI | p |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Time point^c | | | | | | | | | |
| Precourse | 0.01 (0.005, 0.03) | .005 | 0.01 (0.006, 0.02) | .001 | 0.004 (−0.006, 0.01) | .452 |
| Checkpoint 2 | 0.01 (0.005, 0.03) | .004 | 0.01 (0.003, 0.019) | .005 | 0.005 (−0.004, 0.01) | .290 |
| Checkpoint 3 | 0.01 (0.0002, 0.02) | .047 | 0.01 (0.0005, 0.02) | .049 | 0.004 (−0.003, 0.01) | .269 |
| Postcourse | 0.003 (−0.008, 0.01) | .581 | −0.001 (−0.01, 0.01) | .879 | 0.003 (−0.005, 0.01) | .433 |
| Sex (male)^d | −0.10 (−0.12, −0.07) | .001 | −0.10 (−0.13, −0.08) | .001 | −0.10 (−0.13, −0.08) | .001 |

Note: bold values indicate p-value < 0.05.
^aCoef and 95% CI from Linear Mixed Models.
^bBody fat percentage values are presented as decimals (0.01 = 1%).
^cComparison for variables compared to CP1.
^dSex: 1 = male; 0 = female.
Conditions. They also highlight the importance of adequate energy availability, which can inform preparing individuals for similar energetically demanding conditions, such as in high altitude/cold environments or climate-devastated regions, with the aim to protect health and performance. If additional energy availability can buffer against substantial and sustained body mass and lean muscle mass loss, it can potentially prevent consequences associated thereof, from decreased capacity of major activity and reduced bone density due to muscle

| TABLE 6 Predicting change in lean muscle mass from time point (observations = 340) |
|---------------------------------|-----------------|-----------------|-----------------|
|                                 | Model 1         | Model 2         | Model 3         |
|                                 | Coef\(a\) 95% CI | \(p\)           | Coef\(b\) 95% CI | \(p\)         | Coef\(b\) 95% CI | \(p\)         |
| Main effects                    |                 |                 |                 |
| Time point\(b\)                |                 |                 |                 |
| Precourse                      | -0.54 (-1.57, 0.49) | .305           | -0.47 (-1.24, 0.31) | .238      | 0.03 (-0.89, 0.96) | .943         |
| Checkpoint 2                   | 0.74 (-0.27, 1.76) | .150           | 0.52 (-0.25, 1.29) | .188      | 0.85 (0.01, 1.69) | .047         |
| Checkpoint 3                   | 0.49 (-0.53, 1.51) | .348           | 0.64 (-0.13, 1.41) | .105      | 0.81 (0.02, 1.60) | .043         |
| Postcourse                     | 0.36 (-0.66, 1.38) | .493           | 0.24 (-0.54, 1.02) | .543      | 0.05 (-0.74, 0.85) | .899         |
| Sex (male)\(c\)               | 17.63 (14.52, 20.73) | **.001**       | 17.57 (14.62, 20.51) | **.001** | 17.54 (14.59, 20.49) | **.001**     |
| Interaction terms              |                 |                 |                 |
| Time point \times sex          |                 |                 |                 |
| Precourse \times sex           | 0.16 (-1.40, 1.72) | .839           | -            | -            | -            | -            |
| Checkpoint 2 \times sex        | -0.53 (-2.09, 1.02) | .501           | -            | -            | -            | -            |
| Checkpoint 3 \times sex        | 0.34 (-1.22, 1.90) | .673           | -            | -            | -            | -            |
| Postcourse \times sex          | -0.27 (-1.84, 1.30) | .732           | -            | -            | -            | -            |
| Covariates                      |                 |                 |                 |
| Age                             | 0.14 (-0.10, 0.38) | .248           | 0.14 (-1.00, 0.38) | .250      | 0.14 (-0.10, 0.38) | .257         |
| Activity difficulty             | 0.69 (-0.02, 1.40) | .057           | -            | -            | -            | -            |

Note: bold values indicate \(p\)-value < 0.05.
\(a\)Coef and 95% CI from Linear Mixed Models.
\(b\)Comparison for variables compared to CP1.
\(c\)Sex: 1 = male; 0 = female.

**FIGURE 3** Interaction model of checkpoint by sex in predicting TEE (kCal/day) via flex-HR. Sex moderated the change in average EE from the beginning to the end of the course \((p < .05)\): Females have a modest negative slope whereas males have comparatively increasing average EE from the beginning to the end of the course. See Table 7 for the linear mixed model. The lines represent male and female slopes estimating the fixed portion in the linear prediction for a linear mixed model.
deterioration to deleterious effects on immune system and cognitive function associated with excessive body mass and fat loss (Kell et al., 2001; Khodaee et al., 2015; Vermeiren et al., 2016; Yamaner et al., 2015).

4.2 Physical activity intensity and energy expenditure during the course

Physical activity intensity. There was no significant difference in individual's average %MVPA between early and late in the course. Though the ecological conditions may have changed across the different sections and the final section was consistently ranked as more physically intensive and difficult, our findings suggest that the intensity of activity did not change in any significant way (as discernable via our measures). The lack of difference in %MVPA is surprising due to anecdotal reports about the intensity of the final sections (i.e., winter camping sections) from students participating in NOLS courses. Participants reported that they perceived these final sections as harder and more activity intensive than earlier sections given the additional work needed, including setting up camp in the snow or cross-country skiing from site to site. These findings may indicate the early sections of the courses, including hiking and mountaineering sections, could potentially have been equally physically intensive as later canyoneering or winter camping sections. Further, the relatively consistent %MVPA during the first and last sections and the energy status rebounds in the middle sections (i.e., increases in body mass and fat) support the notion that the first and last sections of the courses were likely more physically intense than the middle sections of the courses. Future studies in this setting would benefit from routine measurement of %MVPA across the entire expedition to capture these potential differences. Alternatively, because we measured physical activity using the Actigraph via tri-axial motion, these findings may demonstrate that there is not enough variation in motion across all axes during the different conditions (terrains/activities/etc.) to distinguish significantly different activity intensity at the beginning and end of the course.

Energy expenditure. We found that across all individuals, there was no significant difference in TEE (kcal day\(^{-1}\)) from early to later in the course. Recent research by Ocobock (2016a, 2020) in similar expedition settings suggests that as relative “newcomers” to this kind of highly challenging environment, the continuous exposure to high levels of physical activity while undergoing novel and intense ecological stress, leads to sustained total energy expenditure at very high levels, well over \(~4000\) kcal day\(^{-1}\), over weeks and months without any tapering of energetic costs (Ocobock, 2016a, 2020). Averaging across, subjects in our study maintained estimated TEE at \(\sim4000\)–\(6000\) kcal day\(^{-1}\) from early to late in the course. While our estimates cannot take into account changes in physical fitness, such as reduced energetic cost per hour or cost per mile while hiking, elevated TEE at these levels at the beginning and end of the course seen across all individuals is comparable to other intensive expedition settings (Hattersley

### Table 7 Predicting change in TEE (flex-HR kCal/day) from time point (n = 38)

|                        | Model 1 |               | p     | Model 2 |               | p     |
|------------------------|---------|---------------|-------|---------|---------------|-------|
|                        | Coefa   | 95% CI        |       | Coef    | 95% CI        |       |
| Main effects           |         |               |       |         |               |       |
| Time pointb            |         |               |       |         |               |       |
| Postcourse             | -361.07 | (-1257.33, 535.20) | .430  | 316.59  | (-370.55, 1003.73) | .367  |
| Sex (male)c            | 3236.11 | (2245.67, 4226.54) | .001  | 3583.23  | (2664.08, 4502.38) | .001  |
| Interaction terms      |         |               |       |         |               |       |
| Time point × sex       |         |               |       |         |               |       |
| Postcourse × sex       | 1446.90 | (145.88, 2747.92) | .029  | –       | –              | –     |
| Covariates             |         |               |       |         |               |       |
| Age                    | -46.98  | (-158.60, 64.64) | .409  | -48.17  | (-164.25, 67.92) | .416  |
| Body fat%              | 7481.29 | (1518.52, 13444.05) | .014  | 7019.08  | (773.44, 13264.72) | .028  |

Note: bold values indicate p-value < 0.05.

aCoef and 95% CI from Linear Mixed Models.
bComparison for variables compared to checkpoint 1.
cSex: 1 = male; 0 = female.
et al., 2020; Ocobock, 2016a). While possible that the unmeasured middle sections of the course may have had declines in TEE, particularly given the rebounds in body mass and body fat, and even gains in lean muscle mass when adjusted for activity difficulty, these data show that over ~3 months, TEE levels still reach elevated levels, even well after initial acclimatization. These sustained levels of TEE are much higher than what would be estimated given assumptions of human energy expenditure. For example, the Constrained Energy Expenditure model predicts that energy expenditure eventually attenuates over time to a range of ~2500 kcal day$^{-1}$ as the body brings itself to an evolved, relatively restricted range of total energy expenditure, even as physical activity demands persist (Pontzer, 2015a, 2015b; Pontzer et al., 2016). However, given that individuals were regularly changing activities, it is not unreasonable for TEE estimates to remain high. In addition, the regular change in ecological conditions/temperature that could not be controlled for in this study, and the associated changes in individual thermoregulation thereof, could have also contributed to the relatively high TEE observed in participants. In contrast, research on trained individuals doing the same intensive activity (i.e., running) every day without substantial environmental change demonstrated comparably high TEE followed by an eventual attenuation in expenditure (Thurber et al., 2019). Our findings potentially shed light on the differences in TEE between habitual activity over a long period of time by trained individuals versus habitually high physical activity levels and TEE but doing nonhabitual activity by untrained individuals.

Notably, our data did show that sex moderated the change in TEE. Females demonstrated a modestly negative slope whereas males exhibited comparatively increasing TEE from the beginning to the end of course. In the pairwise-comparison following the significant interaction of sex and time point and adjusting for relevant covariates, we found that males, on average, expended significantly more energy (+1085.83 kcal day$^{-1}$, ~13.10% increase) later in the course than they did early in the course. In contrast, females, on average, expended less energy, spending 361.07 kcal day$^{-1}$ less late in the course compared to earlier in the course, though this decline was not significant.

Particularly when adjusted for total body mass, these findings introduce a potential sex-driven nuance in how average energy is spent across the length of a course. Given the baseline differences in BMR and body composition, understanding how sex may influence energy expenditure during and after acclimatization is of particular interest. Males and females differ in starting stored energy reserves and metabolic mechanisms and these differences are then potentially exacerbated through the acclimatization period and thereafter. These findings support the need to generate a series of new hypotheses to further explore and test how sex may moderate energy expenditure in extreme and energetically demanding conditions. While these differences could possibly hint to behavioral rather than physiological differences between males and females, where males may spend more time in intensive activity at the end of course and thus spend more energy per hour, this is unlikely. Given that there was no significant difference in activity intensity between males and females at any timepoint, this would suggest that differences in TEE were not due to physical activity, notwithstanding any limitations in our measurements.

Our data demonstrate a slight decline in TEE in females when comparing early to late in the course. This could be a reflection of energy expenditure levels reaching a constrained energy asymptote as theorized by Pontzer (Pontzer et al., 2016). However, female TEE levels later in the course are still relatively more elevated than what would be expected if constrained, averaging well over ~2500 kcal day$^{-1}$. This alternatively reflects a training or acclimatization effect in females resulting in greater efficiency by the end of the course.

Compared to earlier studies in this setting, these data indicate a population that is in energetic flux rather than in a negative energy balance. This additional energy availability likely changes the observed energy status and expenditure in this group since it protects against substantial body fat and lean muscle breakdown. In the previous population, where males were reaching essential fat levels and losing body fat and muscle, TEE was comparable to female TEE. Here, we potentially see that with enough energy availability and fat to protect against muscle catabolism, males exhibit even higher TEE. In comparison, possibly after initial losses in energy stores, female bodies may buffer against future losses by not ramping up TEE even as energetic resources are available. This could support a possible buffering capacity female bodies have in response to energetically demanding environments. Prior research has posited the benefits of higher body fat percentage of female bodies as protective under energetically demanding conditions like famine or cold stress (Castellani & Young, 2016; McArdle et al., 1984; Norgan, 1996; Toner et al., 1986; Wells, 2007), but our data may point to differences in how energy is allocated and expended as well. This buffering mechanism seen in female bodies in a challenging environment is likely the result of evolutionary processes. Maintaining energetic stores, is necessary for fertility and beneficial to ongoing fetal growth and lactation (Ellison, 2017; Jasienska, 2009; Vitzthum, 2008; Wells & Stock, 2007). This has in turn shaped human sexual dimorphism in body composition.
where females tend to have greater body fat on average (Wells, 2007). Though it is important to note that while these reproductive needs may have shaped our species through evolution, in these kinds of energy intensive settings in particular, female bodies do more than just reproduce—it is worthwhile thinking of how these buffering capacities may play a role in everyday function when states like pregnancy and lactation are unlikely and even unwanted. This also speaks to the seemingly contradictory evidence between male and female energy expenditure in expedition settings—in intensive, yet energy replete settings, untrained male bodies may continue to spend energy as resources are available, while untrained female bodies may continue to be more conservative in energy expenditure to prepare and adjust for potential future energy deficiencies.

These modest sex differences may have important implications for strategizing how to best situate mixed-sex groups in extreme environment settings, particular in what energy budgets should be anticipated and costs thereof as individuals acclimatize over an extended period of time. In addition, here, sex is categorized dichotomously into two groups based on participant response. The variable of sex in humans is far more varied than two discrete categories (DuBois & Shattuck-Heidorn, 2021; Fausto-Sterling, 2012) and while we report the averages of the two groups, we currently do not know if the acclimatization process would further differ across the spectrum of sex. In addition, while male and female are important categories, training and background also shape performance and acclimatization, for example, highly trained elite females cannot be compared to males that are expedition novices (Bassami et al., 2007; Trapp et al., 2007; Westerterp, 2017). Our work here, however, demonstrates some important variation between sex in untrained individuals. This may begin to expand on the similarities and differences across individual bodies that are salient and relevant to potential functional outcomes.

**Limitations.** Because of field-based time restrictions, we were unable to collect exact energy intake and there was only a rough estimate of the foods consumed (energy) all participants had access to. All participants took a standard amount of food with them on each section of the expedition, within the cook groups (usually groups of 3–4) and there was general variation in what percentage of total food as well as individual preferences in the content of what people ate. This data was collected but not reported reliably, which is a known problem for self-reported energy intake data (Schoeller, 1995; Snodgass et al., 2006). However, through consistent measurements of body composition and the changes throughout the course, here we infer energy status (Ellison, 2003; Ocobock, 2020; Thurber et al., 2019). Future work testing these changes in similar settings or assessing the specific impact of energy intake could benefit from measuring specific caloric and macronutrient consumption.

Our study design also captured actigraphy data, including physical activity intensity and total energy expenditure data from a subset of the entire population at the beginning and ending of the course to specifically look at acclimatization at the beginning and end of exposure to such an environment. However, given that our findings suggest that the middle sections may have been less physically and energetically intense, it would be worthwhile to capture these sections in future studies. The activities during the first and last sections were programmed into the NOLS curriculum to facilitate specific skill-development, and thus the activity intensity and TEE may have been greater at the beginning and end of the course based on the requirements needed for course logistics. However, during the sections there was between-individual variation that we were able to capture to estimate physical activity intensity and TEE. Since estimates of physical activity intensity are based on motion, our measurements do not account for factors like increased fitness gains. We adjusted for the kinds of activities and how strenuous they are by accounting for their difficulty in the models. However, since our measures were estimates of TEE and heart rate data were not calibrated to a treadmill test, we recommend more research is required to parse out the specific relationship between physical activity intensity and TEE when individuals are acclimatizing. We recommend further research is needed to measure activity and energy expenditure at multiple points throughout an exposure/expedition period, across a greater number of individuals, as well as more robust measures of individual changes in fitness in order to ascertain specific and precise changes in physical fitness, strength, and fatigue. Finally, this study would have benefited from collecting energetic data via the Doubly-Labeled Water (DLW) method, largely accepted as the gold-standard for all TEE measurements (Dugas et al., 2011), though our work here shows a potential for using a relatively less cumbersome method to estimate TEE. However, it is important to note that while the average error for the flex-HR method is relatively small, it can overestimate individual TEE up to 17% particularly at higher levels of energy expenditure (i.e., >3000 kcal day$^{-1}$) (Leonard, 2003; Ocobock, 2016b). If our flex-HR estimates were inflated for higher values, it would suggest that TEE on average across the whole group would be slightly lower than seen in other shorter-term expedition settings, though still higher than the constrained level ~ 2500 kcal day$^{-1}$ (Hattersley et al., 2020; Pontzer et al., 2016). Post-hoc analysis suggests that this overestimation does not seem to impact the patterns of
difference between male and female TEE observed in this data set. Regardless, future research would benefit in measuring a larger percentage of the total sample size and include DLW measurements in order to increase statistical power, model accuracy, and measurement precision.

5 | CONCLUSION

In conclusion, we found that over the course of a 3-month-long expedition, individuals first experienced significant declines in body mass and body fat but were able to partially rebound back from these deficits over time increasing overall body mass, briefly increasing in lean muscle, but maintaining lowered fat mass. Even with significantly different starting points in body mass, body fat, and lean muscle mass, there were no significant differences in patterns of body composition change between the sexes. However, sex moderated the difference in TEE from the beginning to the end of the course where females experienced a modest decline and males experienced an increase in TEE suggesting that when assessing if TEE is constrained or continually increasing, there may be sex-specific nuances. Our data suggest that across many relatively untrained individuals there may be a difference in how total energy expenditure changes while acclimatizing to extreme environment exposure. These findings are important for our understanding of how energy is spent and stored and the sex-specific nuances in these changes and have critical implications for how to maintain a healthy body composition in order to function and perform in an energetically demanding environment where resource (and energy) availability may be scarce.

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AUTHOR CONTRIBUTIONS

Mallika Sarma: Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; project administration; resources; software; supervision; validation; visualization; writing-original draft; writing-review & editing. Cara Ocobock: Conceptualization; formal analysis; funding acquisition; methodology; resources; writing-original draft; writing-review & editing. Sarah Martin: Investigation; project administration; writing-review & editing. Shannon Rochelle: Investigation; project administration; resources; writing-review & editing. Brendan Croom: Data curation; formal analysis; writing-review & editing. Lee Gettler: Conceptualization; formal analysis; funding acquisition; methodology; resources; supervision; writing-original draft; writing-review & editing.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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**SUPPORTING INFORMATION**

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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