Body size and its implications upon resource utilization during human space exploration missions

Jonathan P. R. Scott1,2*, David A. Green1,2,3, Guillaume Weerts2 & Samuel N. Cheuvront4

The purpose of this theoretical study was to estimate the effects of body size and countermeasure (CM) exercise in an all-male crew composed of individuals drawn from a height range representative of current space agency requirements upon total energy expenditure (TEE), oxygen (O2) consumption, carbon dioxide (CO2) and metabolic heat (Hprod) production, and water requirements for hydration, during space exploration missions. Using a height range of 1.50- to 1.90-m, and assuming geometric similarity across this range, estimates were derived for a four-person male crew (age: 40-years; BMI: 26.5-kg/m2; resting VO2 and VO2max: 3.3- and 43.4-mL/kg/min) on 30- to 1,080-d missions, without and with, ISS-like CM exercise (modelled as 2 × 30-min aerobic exercise at 75% VO2max, 6-d/week). Where spaceflight-specific data/equations were not available, terrestrial data/equations were used. Body size alone increased 24-h TEE (+ 44%), O2 consumption (+ 60%), CO2 (+ 60%) and Hprod (+ 60%) production, and water requirements (+ 19%). With CM exercise, the increases were + 29 to 32%, + 31%, + 35%, + 42% and + 23 to 33% respectively, across the height range. Compared with a ‘small-sized’ (1.50-m) crew without CM exercise, a ‘large-sized’ (1.90-m) crew exercising would require an additional 996-MJ of energy, 52.5 × 103-L of O2 and 183.6-L of water, and produce an additional 44.0 × 103-L of CO2 and 874-MJ of heat each month. This study provides the first insight into the potential implications of body size and the use of ISS-like CM exercise upon the provision of life-support during exploration missions. Whilst closed-loop life-support (O2, water and CO2) systems may be possible, strategies to minimize and meet crew metabolic energy needs, estimated in this study to increase by 996-MJ per month with body size and CM exercise, are required.

To sustain humans in space requires the construction of a protective habitat and the generation (and maintenance) of environmental conditions consistent with life. Any habitat, be it a transit vehicle, orbital outpost such as the International Space Station (ISS) in Low Earth Orbit, or future surface habitat, must not only protect crewmembers from the near vacuum of space, but also the extremes of temperature and other space-specific risks including radiation and micrometeorites. Furthermore, appropriate ‘life-support’ must be provided (i.e. oxygen [O2], water and food), in addition to the management/removal of the by-products of human metabolism (carbon dioxide [CO2], water vapour, metabolic heat, urine, and faeces). On ISS, the provision of life-support is achieved through a combination of supply (and regular re-supply) from the ground (e.g. the Russian ‘Progress’ expendable cargo and SpaceX’s ‘Dragon’ supply vehicles), and a range of on-board technologies that both manage the internal atmosphere and, increasingly, re-use or recycle by-products (e.g. splitting of CO2 to generate O2 and partially [70%] efficient recycling of urine for potable water)1,2.

However, future space exploration will once again require humans to venture beyond Low Earth Orbit3, rendering re-supply significantly more difficult, especially in the case of deep space (i.e. beyond the Lunar orbit) exploration missions. Moreover, in the short- to medium-term, exploration transit vehicles and lunar orbital (and possibly surface) habitats will be markedly smaller than ISS, which currently has a habitable volume of 338-m3 and typically sustains six, and transiently as many as 15, crew members. In contrast, the National Aeronautics

1KBR, 511147 Cologne, Germany. 2Space Medicine Team, European Astronaut Centre, European Space Agency, 51147 Cologne, Germany. 3Centre of Human and Applied Physiological Sciences, King’s College London, London SE1 1UL, UK. 4Sports Science Synergy, LLC, Franklin, MA 02038, USA. *email: jonathan.scott@esa.int
and Space Administration (NASA)’s ‘Orion’ Multi-purpose Crew Vehicle is designed to sustain a crew of four for up to 21-days in a habitable volume of only 8.95-m$^3$. Furthermore, the current concept of the Lunar Gateway or ‘Gateway’, formerly known as the Deep Space Gateway, a space station where crew may spend up to 30-d in a Cis-Lunar orbit, envisions just two habitation modules. As such, the influence of human metabolism (i.e. depletion of O$_2$ and accumulation of CO$_2$, heat and water vapour) on the internal atmosphere will potentially be more acute (i.e. depletion/accumulation will be more rapid within a smaller volume of air).

When selecting astronauts for missions to ISS, body ‘size’ is not currently a significant operational consideration. The only anthropometric requirement is that applicants’ stature falls within a specified range (1.495- to 1.905-m; 58.9” to 74.8”) but this is purely for compatibility with existing hardware, not least the “Kazbek” seat pan liner of the Soyuz transit vehicle. As a result of the relative ease of supply/re-supply and large habitable volume of ISS, the effect of body size on provision of life-support, including the removal of metabolic by-products for the six-person crew is small. That said, even with a nominal ISS crew of six, CO$_2$ levels generally range between 0.3 and 0.7% CO$_2$ (2.3- to 5.3-mmHg) with a mean of 0.5% CO$_2$ equivalent to 16 times that in ambient air at sea level. Furthermore, CO$_2$ levels are location-specific depending on the presence of crew members and the relative efficacy of ventilation fans required to reduce expired air bubbling due to the absence of natural convection, with hourly means of up to 0.7% CO$_2$ reported. This increased ambient concentration of CO$_2$ (and the resulting hypercapnia) is proposed to be a contributor to the high prevalence of headache and the spaceflight-associated neuro-ocular syndrome observed in ISS astronauts. Interestingly, recent evidence suggests that pre-flight body weight and anthropometrics (chest and waist circumference) may predict microgravity-induced ocular changes associated with this syndrome.

In contrast, it is well established that human (basal) metabolism is, in absolute terms, proportional with body size, reflected in larger individuals possessing higher resting O$_2$ consumption (VO$_2$) as well as CO$_2$ (VCO$_2$) and metabolic heat production. Likewise, assuming equal aerobic fitness (maximal oxygen uptake [VO$_2$max] relative to body mass), larger individuals will require a greater amount of energy, and thus consume more O$_2$ and produce more CO$_2$ and metabolic heat, than smaller people at the same relative exercise intensity (e.g. 75% VO$_2$max). Although minute-to-minute these differences may be relatively small, when accumulated over the course of a space mission, they could become substantial, particularly if, as is the case on ISS, regular exercise is performed. In fact, whilst life-support resource constraints are features of other closed (i.e. artificially sustained) environments, such as submarines and polar bases, they are not associated with the high levels of countermeasures (CM) exercise performance in space necessitated to mitigate (to some degree) the deleterious effects of microgravity. Thus, future human space exploration missions may well present the ‘perfect storm’, combining high levels of exercise performance (and thus metabolic cost) in conditions of extreme life-support constraint.

As such, the purpose of this theoretical study was to estimate the effect of body size and CM exercise in a crew of four composed of individuals drawn from a height range representative of space agency requirements upon total energy expenditure (TEE), O$_2$ consumption, CO$_2$ and metabolic heat production, and water requirements for hydration, during exploration missions of increasing duration. With physiological differences between males and females in terms of body composition and metabolism, and responses to the spaceflight environment, this initial study focused only on males. In addition, as the operational approach to the use of in-flight CM exercise during exploration missions is yet to be confirmed, to explore the effects of body size and CM exercise, this paper considered two hypothetical scenarios:

1. Male crew living in microgravity, but performing no in-flight CM exercise;
2. Male crew living in microgravity and performing CM exercise comparable in volume to that currently employed on ISS.

Results

Characteristics of theoretical astronaut population. Based on the study assumptions and calculations used, the characteristics of the theoretical male astronaut populations are shown in Table 1.

Total energy expenditure, O$_2$ consumed, CO$_2$ and metabolic heat produced, and fluid lost through sweating, during a single bout (30-min at 75% VO$_2$max) of CM exercise are shown in Table 2.

| 24-h values for TEE, O$_2$ consumed, and CO$_2$ metabolic heat and sweat produced by the theoretical populations, without and with CM exercise, are shown in Table 3. Body size alone increased 24-h TEE (+ 44%), O$_2$ consumption (+ 60%), CO$_2$ production (+ 60%), heat production (+ 60%) and water requirements (+ 19%). With CM exercise, the increases were + 29–32%, + 31%, + 25%, + 42% and + 23–33% across the body size range.

Energy expenditure. For a four-person all-male crew without, and with, the performance of CM exercise, body size increased TEE from 1,074-MJ for a ‘small-sized’ (1.50-m) crew to 1,548-MJ for a ‘large-sized’ (1.90-m) crew during a 30-d mission, and from 38,659-MJ to 55,742-MJ during a 1,080-d mission (Fig. 1). For a 30-d mission, CM exercise alone increased TEE by 966-MJ per month (Table 4).

Oxygen consumption. For a four-person all-male crew without, and with, the use of CM exercise, body size increased total O$_2$ consumed from 47.6×10$^{-3}$-L for a ‘small-sized’ (1.50-m) crew to 76.4×10$^{-3}$-L for a ‘large-sized’ (1.90-m) crew during a 30-d mission, and from 1,714×10$^{-3}$-L to 2,749×10$^{-3}$-L during a 1,080-d mission (Fig. 2). For a 30-d mission, CM exercise alone increased O$_2$ consumed by 14.8×10$^{-3}$-L for a small-sized crew and by 23.8×10$^{-3}$-L for a large-sized crew, and by 533×10$^{-3}$-L and 856-L for a 1,080-d mission. Compared with
Table 1. Characteristics of the theoretical astronaut populations. BM body mass; BSA body surface area; \( VO_{2\text{max}} \) maximal rate of oxygen uptake. RMR resting metabolic rate, NEAT non-exercise activity thermogenesis, \( VO_2 \) rate of oxygen consumption, \( VCO_2 \) rate of carbon dioxide production, CM countermeasure, EE energy expenditure, \( M_{\text{prod}} \) rate of metabolic heat production, SR sweat rate. See main text for definition of assumptions.

| Stature (m) | 1.50 | 1.60 | 1.70 | 1.80 | 1.90 |
|------------|------|------|------|------|------|
| BM (kg)    | 59.6 | 67.8 | 76.6 | 85.9 | 95.7 |
| BSA (m²)   | 1.54 | 1.71 | 1.88 | 2.06 | 2.24 |
| \( VO_{2\text{max}} \) (L/min) | 2.59 | 2.94 | 3.32 | 3.73 | 4.15 |
| Rest       |      |      |      |      |      |
| RMR (MJ/d) | 5.78 | 6.44 | 7.13 | 7.85 | 8.60 |
| NEAT (MJ/d)| 2.31 | 2.58 | 2.85 | 3.14 | 3.44 |
| \( VO_2 \) (L/min) | 0.197 | 0.224 | 0.253 | 0.283 | 0.316 |
| \( VCO_2 \) (L/min) | 0.155 | 0.176 | 0.199 | 0.223 | 0.249 |
| Basal \( M_{\text{prod}} \) (kJ/s) | 65.7 | 74.8 | 84.4 | 94.7 | 105.5 |
| Basal fluid needs (L/d) | 2.63 | 2.74 | 2.86 | 2.99 | 3.13 |
| CM exercise @ 75% \( VO_{2\text{max}} \) |      |      |      |      |      |
| \( VO_2 \) (L/min) | 1.94 | 2.21 | 2.49 | 2.79 | 3.11 |
| \( VCO_2 \) (L/min) | 1.74 | 1.98 | 2.24 | 2.51 | 2.80 |
| EE (kcal/min) | 9.6 | 10.9 | 12.3 | 13.8 | 15.4 |
| \( M_{\text{prod}} \) (kJ/s) | 667 | 759 | 857 | 960 | 1,070 |
| SR (mL/min) | 10.1 | 11.7 | 13.4 | 15.2 | 17.1 |

Table 2. Estimated total energy expenditure (EE), oxygen (\( O_2 \)) consumed, and carbon dioxide (\( CO_2 \)), metabolic heat (\( H_{\text{prod}} \)) and sweat produced, during a single bout (30-min at 75% \( VO_{2\text{max}} \)) of countermeasure exercise by a theoretical male crew member. See main text for definition of assumptions.

| Stature (m) | 1.50 | 1.60 | 1.70 | 1.80 | 1.90 |
|------------|------|------|------|------|------|
| EE (MJ)    | 1.28 | 1.45 | 1.64 | 1.84 | 2.05 |
| \( O_2 \) (L) | 61.7 | 70.2 | 79.3 | 88.9 | 99.0 |
| \( CO_2 \) (L) | 55.4 | 63.1 | 71.2 | 79.8 | 88.9 |
| \( H_{\text{prod}} \) (kJ) | 1,200 | 1,366 | 1,542 | 1,729 | 1,926 |
| Sweat (mL) | 303 | 350 | 401 | 455 | 513 |

Table 3. 24-h values for theoretical male astronaut populations without, and with, the use of ISS-like countermeasure (CM) exercise (modelled as two bouts of 30-min of cycle ergometry at 75% \( VO_{2\text{max}} \)). TEE, total energy expenditure, \( O_2 \) total oxygen consumed, \( CO_2 \) total carbon dioxide produced, \( H_{\text{prod}} \) total metabolic heat produced. Numbers in brackets indicate the difference (%) between data without, and with CM exercise. See main text for definition of assumptions.

| Stature (m) | 1.50 | 1.60 | 1.70 | 1.80 | 1.90 |
|------------|------|------|------|------|------|
| No exercise |      |      |      |      |      |
| TEE (MJ)   | 8.9  | 9.9  | 10.8 | 11.9 | 12.9 |
| \( O_2 \) (L) | 397 | 451 | 510 | 571 | 636 |
| \( CO_2 \) (L) | 313 | 356 | 401 | 450 | 501 |
| \( H_{\text{prod}} \) (MJ) | 5.7 | 6.5 | 7.3 | 8.2 | 9.1 |
| Water requirements (L) | 2.63 | 2.74 | 2.86 | 2.99 | 3.13 |
| CM exercise |      |      |      |      |      |
| TEE (MJ)   | 11.9 (+29) | 12.8 (+29) | 14.1 (+30) | 15.5 (+31) | 17.0 (+32) |
| \( O_2 \) (L) | 494 (+31) | 562 (+31) | 634 (+31) | 711 (+31) | 792 (+31) |
| \( CO_2 \) (L) | 423 (+35) | 482 (+35) | 544 (+35) | 610 (+35) | 679 (+35) |
| \( H_{\text{prod}} \) (kJ) | 8.1 (+42) | 9.2 (+42) | 10.4 (+42) | 11.6 (+42) | 13.0 (+42) |
| Water requirements (L) | 3.23 (+23) | 3.44 (+26) | 3.67 (+28) | 3.90 (+30) | 4.16 (+33) |
a small-sized crew performing no CM exercise, a large-sized crew performing ISS-like CM exercise require an additional $52.5 \times 10^3$-L of O$_2$ per month (Table 4). 

**Carbon dioxide production.** For a four-person all-male crew without, and with, the use of CM exercise, body size increased total CO$_2$ production from $37.5 \times 10^3$-L for a ‘small-sized’ (1.50-m) crew to $62.2 \times 10^3$-L for a ‘large-sized’ (1.90-m) crew during a 30-d mission, and from $1,350 \times 10^3$-L to $2,166 \times 10^3$-L during a 1,080-d mission (Fig. 3). For a 30-d mission, CM exercise alone increased CO$_2$ production by $13.3 \times 10^3$-L for a small-sized crew and by $21.3 \times 10^3$-L for a large-sized crew, and by $479 \times 10^3$-L and $768 \times 10^3$-L for a 1,080-d mission. Compared with a small-sized crew performing no CM exercise, a large-sized crew performing ISS-like CM exercise produce an additional $44.0 \times 10^3$-L of CO$_2$ per month (Table 4).
Heat production. For a four-person all-male crew without, and with, the performance of CM exercise, body size increased total Hprod from 681.6-MJ for a ‘small-sized’ crew (1.50-m) to 1,093.6-MJ for a ‘large-sized’ (1.90-m) crew during a 30-d mission, and from 24,539- to 39,371-MJ during a 1,080-d mission (Fig. 4). For a 30-d mission, CM exercise alone increased total Hprod by 288.1-MJ for a small-sized crew and by 462.2-MJ for a large-sized crew, and by 10,371-MJ and 16,640-MJ for a 1,080-d mission. Compared with a small-sized crew performing no CM exercise, a large-sized crew performing ISS-like CM exercise produce an additional 874.2-MJ of heat per month (Table 4).

Water requirements for hydration. For a four-person all-male crew without, and with, the performance of CM exercise, body size increased total fluid needs from 315-L for a ‘small-sized’ (1.50-m) crew to 376-L for a ‘large-sized’ (1.90-m) crew during a 30-d mission, and from 11,350- to 13,530-L during a 1,080-d mission (Fig. 5). For a 30-d mission, CM exercise alone increased water requirements by 72.7-L for a small-sized crew and to 123.1-L for a large-sized crew, and by 2,618-L and 4,432-L for a 1,080-d mission. Compared with a small-sized crew performing no CM exercise, a large-sized crew performing ISS-like CM exercise require an additional 183.6-L water per month for hydration (Table 4).

Discussion

Based on our assumptions and methodological approach, the main findings of this study are that increasing theoretical male astronaut population height from 1.50- to 1.90-m increases resting 24-h TEE by + 44%, O2 consumed (+ 60%), CO2 (+ 60%) and metabolic heat (+ 60%) produced, and water required for hydration (+ 19%). Furthermore, performance of ISS-like CM exercise increases TEE (+ 29 to 32%), O2 consumed (+ 31%), CO2 (+ 35%) and metabolic heat (+ 42%) produced, and water requirements (+ 23 to 33%). For a four-person all-male crew, together, these differences translate in absolute terms to an additional 996-MJ energy, 52.5 × 10³-L of O2, 44.0 × 10³-L of CO2, 874-MJ of heat and 183.6-L of water per month.

In the early phase of ISS operations, crew received 1.8-kg/person/d of food, but mission guidelines state that the energy provided should be according on the estimated energy needs of the crewmember, based on body weight and height19. The estimations in this study suggest increasing theoretical male astronaut population body size alone increases the 24-h TEE requirement by 4.0-MJ/d (956-kcal). Based on the nutritional information from commercially-available, thermostabilized ‘ready-to-eat’ food analogous to current space food (Brown rice with chicken and vegetables: weight 250-g, energy: 365-kcal [1.53-MJ]; energy density: 1.46-kcal/g; volume: 340-cm³)18, the additional 55,742-MJ required for a 1,080-d mission with four male crew translates to 2,795-kg

**Figure 2.** Total oxygen consumption (× 10³-L) without (left panel) and with (right panel) countermeasure exercise during exploration missions of 30-, 90-, 180-, 360-, 720- and 1,080-d for a four-person crew based on theoretical male astronaut populations with statures of 1.50-m (broken grey line, filled circles), 1.60-m (solid grey line, open circles), 1.70-m (broken black line, filled circles), 1.80-m (solid black line, open circles) and 1.90-m (solid black line, filled circles).
of food. Although a number of science experiments have grown food in space, they are currently limited to small amounts of low-calorie salad crops. Thus, until a sufficient volume of high caloric-density food can be produced in space, the only option for future exploration missions is to launch food with the crew, potentially supplemented by additional supply missions, with significant implications for launch mass and mission architectures, and, when flown with the crew, on-board storage. For instance, based on the volume of a single 1.53-MJ portion of thermostabilized ‘ready-to-eat’ food, the additional food required for a 1,080-d mission would occupy a volume of 3.8-m3.

Food and its packaging, in addition to human waste, are predicted to be greatest contributors to exploration mission waste. Ewert and Broyan estimated that, for a 1-year mission (1,460-human days), a crew of four would need approximately 2,250-kg of food within 400-kg of packaging, with human waste estimated at 400-kg requiring a further 0.7-m3 of storage. Within the Gemini (space programme) food system, bite-size cubes of meat, fruit, dessert, and bread products were engineered to deliver 21.3-kJ/g (5.1-kcal/g), with the complete system offering approximately 2,890-kcal in 0.73-kg of packaged food. However, the in-flight acceptability of these cubes quickly declined resulting in many returning uneaten. Reductions in mass and volume are possible by increasing the proportion of energy from fat (currently up to 35% of total energy intake per NASA dietary guidelines), reducing water content and reducing reliance on energy ‘dilute’ foods such as beverages and vegetables. In ISS food, water contributes nearly 60% of total food weight, without any caloric value, resulting in thermostabilized pouches accounting for 65% of mass whilst providing only 30% of total calories. Stoklosa reports that a 10% decrease in water and an increase in energy sourced from fat to 35%, yielded a mass saving of 22% (321-g/d). Substitution of standard menu items with one ‘meal replacement bar’ (400-kcal per 100-g bar) per crewmember, per day, saved 17% (240-g/d), whilst combining the two approaches saved 36% (529-g/d). However, both increasing fat and decreasing water content may negatively impact acceptability, while reducing reliance on energy dilute foods may also impact on the delivery of appropriate nutrients.

Exercise is the cornerstone of the ISS CM programme and is likely to remain so on future exploration missions until an efficacious (across multiple physiological systems), safe and practical alternative is found. As such, the provision of food for exploration missions will need to account for the higher energy expenditure to ensure energy balance is maintained, or body mass/fat losses are at least managed within acceptable limits. Although not measured directly, estimations in the present study suggest that current ISS CM exercise increases 24-h energy expenditure by between 2.6- and 4.1-MJ/d for theoretical male astronauts of 1.50-m and 1.90-m.

**Figure 3.** Total carbon dioxide production (× 103-L) without (left panel) and with (right panel) countermeasure exercise during exploration missions of 30-, 90-, 180-, 360-, 720- and 1,080-d for a four-person crew based on theoretical male astronaut populations with statures of 1.50-m (broken grey line, filled circles), 1.60-m (solid grey line, open circles), 1.70-m (broken black line, filled circles), 1.80-m (solid black line, open circles) and 1.90-m (solid black line, filled circles).
Based on the nutritional information from the commercially-available food used above, this would equate to a further 360- to 470-g of food per person, per day. Combined with the effect of increasing body size, CM exercise could require an additional 4,598- to 5,688-kg of food, occupying 6.2–7.7-m³, for a four-person all-male crew during a 1,080-d mission.

The current ISS CM exercise programme of 12 sessions/week of aerobic and resistance exercise, results in approximately 75-min (30-min aerobic, 45-min resistance) of exercise per day. However, High Intensity Interval Training (HIIT) or Sprint Interval Training (SIT), which involve much shorter (although higher intensity) periods of activity than traditional aerobic exercise, may offer alternative strategies to effectively stimulate the cardiorespiratory system and, by significantly reducing the total duration of exercise, could also reduce total energy expenditure. Despite higher intensities, HIIT and SIT protocols result in 100–250-kcal less energy expenditure compared with 40-min of cycling at 60–65% VO₂max. Further energy expenditure savings might also be made by reducing the number of intervals/sprints. ISS resistance exercise is based on the traditional approach of ‘multiple sets of multiple repetitions’, but recent evidence suggests that, while multiple sets may be optimal, significant benefits may be achieved from only a single set. Alternative forms of exercise might also be effective in reducing energy expenditure. For instance, just 3- to 4-min of high-intensity jumping (comprising of approximately 50 jumps) six times per week using a supine pressure-cylinder-based sled was evaluated as a CM exercise during a long-term bed rest study. This CM reportedly prevented bed rest-induced reductions in tibial bone mineral density and content, and muscle strength, suggesting that it could be an effective alternative to resistance exercise. Moreover, jumping also prevented the bed rest-induced decrease in VO₂max and results in comparable acute responses to running/cycling HIIT. Therefore, although the energy expenditure associated with the jumping protocol is yet to be quantified, short duration (less than 25-min per week), sled-based jumping could conceivably replace both aerobic and resistance exercise in space, resulting in marked reduction in exercise activity thermogenesis (EAT)-related energy expenditure, as well as oxygen consumption and CO₂ production.

Given the incompressibility of water, transportation in space vehicles from the ground has obvious implications for launch mass and volume, and subsequently storage. Thus, for exploration missions, the greater the number of crew and the longer the mission, the greater the challenge, unless water can be 100% recycled or acquired from a planetary body. This study estimates that, for missions lasting 30- to 1,080-d, daily water requirements for

![Graph showing total metabolic heat production (MJ) without (left panel) and with (right panel) countermeasure exercise during exploration missions of 30-, 90-, 180-, 360-, 720- and 1,080-d for a four-person crew based on theoretical male astronaut populations with statures of 1.50-m (broken grey line, filled circles), 1.60-m (solid grey line, open circles), 1.70-m (broken black line, filled circles), 1.80-m (solid black line, open circles) and 1.90-m (solid black line, filled circles).](image-url)
hydration are increased by both body size (+19% independent of mission length) and CM exercise (30-d: +23%; 1,080-d: +33%). In the complete absence of in-flight water recycling and/or in-situ extraction/creation, together, increased body size (resulting from an increase in stature from 1.50- to 1.90-m) and ISS-like CM exercise would require an additional 183.6-kg (0.1836-m³) of water to be stored and launched for each month of a mission for a four-person all-male crew.

Without recycling, water represents over 90% of the required life-support consumables for space missions, with a similar proportion of wastewater being classified as moderately, or slightly contaminated. However, in-flight water recycling and generation as a by-product of other processes (e.g. fuel cell electricity production) can significantly reduce the need for water provision from the ground. The current ISS closed-loop system has an efficacy of approximately 93%, reducing the net mass of water launched from Earth to support six crewmembers by 6,800-kg/year. Additional (2,500-L/year) water is provided on ISS by a Sabitier process-based system integrated into the ISS system.

The primary source of O₂ on ISS is provided via the electrolysis of water yielding O₂ and hydrogen (vented overboard). Additional O₂ is provided by the CO₂ removal system, although only around 50% of the O₂ is recovered. To provide a closed-loop air revitalization system for future exploration missions, 75 to 90% of O₂ must be recovered from CO₂ and efforts are underway to develop technologies that meet this requirement. As O₂ recovery is key to reducing (or even eliminating) reliance on ground supply, but is currently substantially less than 100% efficient, an increased rate of oxygen consumption resulting from increased body size and CM exercise would increase the rate at which a fixed quantity of generated oxygen is depleted and no longer able to support optimal crew cognitive function and subsequently respiration.

Atmospheric CO₂ management is also a critical element of life-support. The ISS CO₂ management system requires crew maintenance every 3–6 months using replacement parts from Earth and is thus incompatible with long-duration exploration missions, which require a closed-loop air revitalization system that recovers 75–90% of O₂ from CO₂. Such technologies are in development, but to what extent the maintenance schedule of such technologies depends on the total amount of CO₂ generated/removed and, therefore, the importance of factors such as body size and CM exercise, is currently unknown. Although the number of crew during exploration missions will likely be fewer than on ISS (four vs. six), the smaller pressurized volume of exploration vehicles/

**Figure 5.** Total water requirements (L) without (left panel) and with (right panel) countermeasure exercise during exploration missions of 30-, 90-, 180-, 360-, 720- and 1,080-d for a four-person crew based on theoretical male astronaut populations with statures of 1.50-m (broken grey line, filled circles), 1.60-m (solid grey line, open circles), 1.70-m (broken black line, filled circles), 1.80-m (solid black line, open circles) and 1.90-m (solid black line, filled circles).
habitats could potentially increase the volatility of CO₂ levels depending upon metabolic CO₂ production and/or CO₂ removal efficiency. The ISS system generally maintains CO₂ partial pressures below 3-mmHg (depending on crew size/activity). Nevertheless, crew frequently report CO₂-related symptoms such as headache and chronic CO₂ elevation has been implicated in the spaceflight-associated neuro-ocular syndrome.

Both the space vehicle/habitat, and its systems/payloads and the crew within, produce ‘waste’ heat, which must be circulated and removed to maintain thermal comfort, which is critical for human performance and wellbeing. In a habitat the size and complexity of ISS (338-m³), the relative contribution to internal heat load of the crew (even including CM exercise) compared with the station systems is minor. However, this contribution may increase (relatively) as vehicle size decreases. Lefeng et al. modelled that, in a 100-m³ volume, increasing crewpopulation and metabolic activity from 80-W during sleep up to 240-W during moderate activity may have a marked effect on temperature. Thus, crew adhering to an intensive CM exercise programme in substantially smaller vehicles/habitats may result in a significant contribution of metabolic heat to the total internal heat load. ISS exercise sessions are typically brief (30–45-min), although some crew prefer to perform their two daily exercise sessions consecutively. As such, a ‘worse case’ scenario, would be all four exploration mission crew performing their twice daily exercise sessions consecutively, equivalent to a person performing CM exercise for in excess of four hours. The present study estimates that, with a ‘large-sized’ (1.90-m) theoretical male astronaut their twice daily exercise sessions consecutively, their ing crew metabolic activity from 80-W during sleep up to 240-W during moderate activity may have a marked effect on temperature. Thus, crew adhering to an intensive CM exercise programme in substantially smaller vehicles/habitats may result in a significant contribution of metabolic heat to the total internal heat load. ISS exercise sessions are typically brief (30–45-min), although some crew prefer to perform their two daily exercise sessions consecutively. As such, a ‘worse case’ scenario, would be all four exploration mission crew performing their twice daily exercise sessions consecutively, equivalent to a person performing CM exercise for in excess of four hours. The present study estimates that, with a ‘large-sized’ (1.90-m) theoretical male astronaut.

In this study, estimated sweat rates during exercise ranged from 10.1- to 17.1·mL/min. Sweat rates in excess of 8·mL/min have been considered undesirable in space because of the potential formation of a sheeting layer over the skin. However, the maximum evaporated power of the environment modelled in this paper is twice the value that was previously (for the Space Shuttle: 27 °C, 21·Torr [80 F/70% relative humidity]) resulting in lower skin wettedness estimates and risk of sheeting. However, smaller habitable volumes and/or lower maximal evaporative potentials may increase humidity. Vehicular environmental control challenges may also be partially offset by personal cooling technologies. A variety of microclimate cooling garments have been used to reduce body heat storage during work performed while wearing protective clothing. Modern conventional liquid cooling and ventilation garments worn for extra-vehicular activities (space walks) can remove between 200- and 200-W of metabolic heat, which is 20–30% of what has been modelled during exercise in this study. The use of a personal cooling garment with 100- to 200-W of cooling power during exercise would reduce body heat storage by increasing dry (sensible) heat exchange. As a result, a sweat rate of 15·g/min could be reduced to between 6- and 10·g/min. This would reduce the ‘worse case’ scenario for heat load management without the need for a change in the maximal evaporative capacity of the vehicle environment or reduction in exercise intensity.

The most obvious limitation of this study is the necessity to make a number of assumptions about the components of TEE in microgravity as a result of the absence of spaceflight data, although in-flight studies are underway. The typical thermic effect of food (TEM) profile, for example, may be delayed due to a reduction in gastrointestinal transit rate in microgravity, although this is unlikely to have a significant impact on TEE. Non-exercise activity thermogenesis (NEAT) was assumed to be minimal, but not negligible, resulting in a Physical Activity Level (PAL) estimate of 1.4. Exactly how physically active (excluding CM exercise) crew will be during future exploration missions is unknown, and likely depends of the size of the vehicle/habitat, the demands of operating it and any other operational activity requirements. As a result, a PAL of 1.4 might be an under- or overestimate of NEAT. Surface operations will, of course, increase NEAT, but to what extent is unknown, but will depend on a range of factors such as the activity, protective environment (i.e. habitat or space suit), and the surface and gravitational environment, hence surface operations were not included in the calculations.

Secondly, although it was assumed that the elevated atmospheric level of CO₂ would have no effect on metabolism at rest or during exercise, an effect of a CO₂ concentration of ~ 0.5% CO₂ on the ventilatory response to exercise cannot be ruled out. An additional limitation is the modelling of resistance exercise as a second bout of aerobic exercise in the absence of appropriate validated equations for calculation of energy expenditure and water requirements. In fact, single bout resistance exercise energy expenditure estimates range from 2.7- to 11-kcal/min, presumably reflecting factors such as number of sets and repetitions, and types of exercise. Such variation will of course influence VO₂, VCO₂, water needs and heat production estimates. A fourth limitation is that the equation used to predict exercise sweat losses in this study, which also requires estimates of the biophysical properties of clothing, was not explicitly designed with microgravity in mind. However, it is based upon biophysical principles that have been applied previously to estimate the exercise sweating response to exercise in space yielding sweat rates in this study consistent with those estimated using a pure heat balance approach.

This paper focused only on male astronauts and, as a result, used available data and equations (e.g. VO₂max resting metabolic rate [RMR]) specific to males. However, although historically a high percentage of astronaut populations have been male, five of the 11 astronauts selected by NASA in 2019 were female. As such, given that there are physiological differences between males and females in terms of body composition and metabolism, and responses to the spaceflight environment, but the effects of these differences on resource requirements have not been evaluated, future studies should repeat these calculations with a specific focus (assumptions and equations) on females and compare the results of those with males across an identical height range. Finally, in order to provide an estimate of VO₂max in L/min for subsequent calculations, in the absence of the availability of individual astronaut data, it was necessary to make an assumption about relative (in mL/kg/min) VO₂max from mean values published from an astronaut population. This assumes geometric similarity between the different body sizes, but such similarity is not evident for muscle mass in both athletic and non-athletic populations, which has implications for metabolism, energy expenditure and VO₂max. As such, the assumption of geometric similarity in this paper may mask potential variability between individuals and is likely to result in
an underestimate of metabolism and energy expenditure in the larger theoretical populations. With access to individual body masses and direct measures of VO$_{2\text{max}}$ from a large group of astronauts of varying body sizes, future investigations should evaluate the use of multi-parameter allometric scaling techniques. This should also include separate analysis of male and female astronauts to account for the possible influence of differences in body somatotype/composition and metabolism.

Using a stature range of 1.50- to 1.90-m and based on assumptions about the crew (all male; age: 40 years old; body mass index (BMI): 26.5-kg/m$^2$; resting VO$_{2}$, and VO$_{2\text{max}}$: 3.3- and 43.4-mL/kg/min, and geometric similarity across the stature range) and their energy expenditure, several of which should be refined as, and when, appropriate spaceflight data become available, this theoretical study provides the first insight into the potential implications of body size and the performance of ISS-like CM exercise upon the provision of life-support required to sustain humans during exploration missions. Novel technological approaches are required and should be evaluated considering crew composition (body size) and predicted exercise CM regimes. Although such technologies will reduce the absolute magnitude of some effects of body size and CM exercise, relative differences will remain. Whilst closed-loop regenerative O$_2$, water and CO$_2$ management systems may be possible, consideration of strategies to minimize and meet crew metabolic energy needs (and dissipation), estimated in this study to increase with body size and CM exercise by 966-MJ per month and requiring an additional 5,688-kg of food occupying 7.7-m$^3$ during a 1.080-d mission, is required.

Methods

Assumptions and rationales. For the purpose of all calculations in this paper, and to provide upper and lower limits for the examining the effects of body size, the following has been assumed.

Assumptions about the missions and vehicle/habitat.

1. Mission durations will range from 30-d (transit-out, Lunar orbit, transit-back) up to 1,080-d (transit-out, prolonged Martian orbit, transit-back), all without human surface exploration (i.e. crew will remain inside vehicles/habitats for the entire mission);
2. Missions will be crewed by four male astronauts.
3. The environment inside the vehicle is comparable to that currently on ISS: 760-mmHg barometric pressure, 20.9% oxygen, ~ 0.5% CO$_2$, balance nitrogen at 101.3-kPa (14.7-psi), mean temperature 22°C, 55% relative humidity
4. The elevated CO$_2$ concentration inside the space vehicle has no effect on metabolism, either at rest, or during exercise. The respiratory response to 1.0% CO$_2$-induced acidosis is a 3.5-mL/min increase in minute ventilation and thus VO$_{2}$, although to our knowledge, the effect of 0.5% CO$_2$ is unknown. However, given that resting minute ventilation tends to return to baseline values by the second to third week of exposure to 1.0% CO$_2$, it is assumed that there is no significant chronic ventilatory response to 0.5% CO$_2$.
5. Airflow experienced by the crew member (provided by the vehicle/habitat ventilation system) during CM exercise is 0.5 m/s.

Assumptions about the crew and their physiology at rest.

1. Crew stature ranges from 1.50- (“small”) to 1.90-m (“large”) (59.1–74.8"), which is representative of historical and current stature requirements (for both males and females) for NASA, and the European (ESA) and Canadian (CSA) Space Agencies.
2. Crew are geometrically similar across this stature range.
3. Independent of stature, all crew have, and maintain, a BMI of 26.5-kg/m$^2$, calculated from the mean height (1.755-m) and body mass (81.6-kg) of a group of 30 male astronauts.
4. Crew are all 40 years old. Neither NASA or CSA include age restrictions in their selection requirements, and ESA only state a ‘preferred age range’ of 27–37 years old. NASA astronaut candidates selected in the past have ranged from 26 to 46 years old, with the current average being 34 years old. As such, when accounting for the prolonged training required for an exploration mission, it is assumed that all crew will be at least 40 years old;
5. As no 24-h TEE, or its components (RMR, and non-resting energy expenditure, composed of NEAT, EAT and TEM) are currently available from spaceflight, the following are assumed:

   a. RMR is equivalent to that on Earth, and does not change during the mission;
   b. NEAT is minimal but not negligible, resulting in a PAL of 1.4 (equivalent to a very sedentary lifestyle on Earth) excluding CM exercise (see below for assumptions/calculations related to EAT for astronauts performing CM exercise). PAL estimates in space range from 1.2 (Vostok missions) to as much as 1.7–1.75 (Skylab missions). Values of 1.2 are associated with low levels of activity (in fact no formal exercise was prescribed during Vostok missions) and, therefore, presumably reflects microgravity-induced hypokinesia, whereas values of 1.7–1.75 reflect intensive performance of CM exercise by Skylab crew. Thus, whilst exploration vehicles/habitats have yet to be fully defined, they will likely possess sufficient internal volume to allow free movement with crew being required to perform light operational activities (e.g. scientific experiments) each day, resulting in a moderate energy cost. Therefore, whilst formal CM exercise is considered separately (see below), calculated RMR, and resting VO$_{2}$ and CO$_2$ values were multiplied by 1.4;


6. VO₂ at rest (RMR) is 3.3-mL/kg/min. Resting VO₂ is generally accepted to be approximately 3.5-mL/kg/min\(^{68,69}\), however, Kozey et al.\(^{69}\) reported figures of 3.3- and 3.2-mL/kg/min in groups aged 33- and 45-years old. Kozey et al.\(^{69}\) also showed that resting VO₂ is influenced by estimated (via a prediction equation based on age, height, sex, body mass, and physical activity) fitness level\(^{70}\), with resting VO₂ being 2.7, 3.2, 3.3, 3.5 and 3.3-mL/kg/min per ascending quintile. Pre-flight astronaut aerobic fitness varies considerably between individuals, however, mean ± standard deviation values of 43.4 ± 7.8 and 40.5 ± 7.0 mL/kg/ min have been reported for men and women, respectively\(^{56}\). Such values place male and female crew aged 30- to 50-years, within Kozey et al.’s fifth quintile (3.3-mL/kg/min);

7. Respiratory exchange ratio (RER) at rest is 0.788. Human RER ranges considerably at rest but, based on these data of McNeil et al.\(^{71}\) and Weyer et al.\(^{72}\), has an average of 0.788.

8. Resting VCO₂ is 2.6-mL/kg/min. Resting VCO₂ is commonly assumed to be 200-mL/min. However, resting VCO₂ is dependent upon energy substrate utilization reflected in the RER (VCO₂/VO₂). Thus, assuming a resting VO₂ of 3.3-mL/kg/min and a resting RER of 0.788, yields a resting VCO₂ of 2.6-mL/kg/min.

9. Respiratory water losses are balanced by metabolic water production, and thus can be discounted, whereas transcutaneous water loss is only considered for total body water balance\(^{73}\).

10. Protein (95-g/d), sodium (4,320-mg/d) and potassium (3,062-mg/d) intake data are as reported in ISS Expeditions 26–37\(^{74}\).

11. Core temperature is 37 °C.

Assumptions about the crew and their physiology during exercise. Countermeasure exercise on ISS currently consists of two sessions per day (1 × 30–45-min of aerobic and 1 × 45-min of resistance), 6-d/week, with target workloads for steady-state and interval-type aerobic protocols of 75–80% and 60–90% VO₂\(_{\text{max}}\). However, due to the challenge of modelling non-steady state exercise\(^{75,76}\) such as intermittent, high intensity resistance exercise as used on ISS, for the purpose of this paper, CM exercise will be modelled as 30-min of steady-state aerobic exercise at 75% VO₂\(_{\text{max}}\), twice per day, 6-d/week. The assumptions used are as follows:

12. Crew have a relative VO₂\(_{\text{max}}\) of 43.4-mL/kg/min, as reported for a group of 30 male astronauts\(^{56}\);

13. During aerobic exercise crew wear light sports clothing (shorts, t-shirt and socks), with thermal and evaporative resistances equal to 0.06 m\(^2\) × °C/W and 0.01 m\(^2\) × kPa/W, respectively\(^{55}\).

14. VO₂ during exercise is 32.6-mL/kg/min (i.e. 75% of 43.4-mL/kg/min). For the purpose of calculation simplification, any warm-up or cool-down periods have been excluded;

15. RER during exercise at 75% VO₂\(_{\text{max}}\) is 0.898. In the study of Scott et al.\(^{77}\), subjects exercising at 75 ± 3% VO₂\(_{\text{max}}\) in a fasted state had a mean RER of 0.898. Pre-exercise food consumption may alter substrate utilization, and thus RER during exercise. However, Bergman and Brooks\(^{78}\) showed that, whilst food intake significantly increased RER at exercise intensities up to 59% VO₂\(_{\text{peak}}\), RER was unaffected at 75% VO₂\(_{\text{peak}}\).

16. Based on a VO₂ of 32.6-mL/kg/min and an RER of 0.898, VCO₂ during exercise is 29.2-mL/kg/min.

17. Excess post-exercise oxygen consumption, energy expenditure and VCO₂ will be 6% of that consumed during exercise itself. No data (% of energy expended during exercise) for 30-min at 75% VO₂\(_{\text{max}}\) is available, but Bahr et al.\(^{79}\) report figures of 5.1% and 6.8% for 20- and 40-min of exercise at 70% VO₂\(_{\text{max}}\) and the mean of those two values has been used;

18. RER is equivalent to that at rest during recovery from exercise. Immediately following exercise at 70% VO₂\(_{\text{max}}\), there is a brief increase in RER followed by a rapid decline, lasting around 10-min in total\(^{80}\). Initially, the decline in VO₂ exceeds the rate of ventilation reduction (resulting in more CO₂ release from the lungs), after which ventilation rates falls in line with VO₂ albeit limited by the drive to restore acid–base balance thereby promoting CO₂ retention. As such, RER during this brief period may not be an accurate index of energy substrate utilization, after which, RER is at, or very close to, that measured pre-exercise\(^{80}\).

Calculations

1. RMR was calculated using the Revised Harris–Benedict equation\(^{81}\) for males, where:

   \[
   RMR = 88.362 + (13.397 \times \text{weight in kg}) + (4.799 \times \text{height in cm}) - (5.677 \times \text{age in years}).
   \]

2. BMI\(^{82}\) was calculated as:

   \[
   BMI (\text{kg/m}) = \text{body mass (kg)} \div \text{height (m)}^2
   \]

3. Energy expenditure (EE) during exercise (kcal/min) was estimated using the Weir equation\(^{83}\), where:

   \[
   EE = 3.94 \text{VO}_2 (\text{mL/min}) + 1.11 \text{VCO}_2 (\text{mL/min})
   \]

4. Body surface area (BSA) was calculated using the formula of Du bois and Du bois\(^{84}\):
BSA = 0.007184 · height (in metres)0.725 · weight (in kg)0.425

5. Insensible water needs (IWN), dietary solute load (DSL) and urine volume to maintain a 24-h urine volume at a concentration of 600-mmol/kg (UV600) was calculated as:

\[ IWN = \left( 0.4 \cdot \text{Energy Needs (in kcal)} \right) / 1000 \]
\[ DSL = \left( \text{Protein intake [g/d]} / 0.175 \right) + \left( 2 \times \left( \text{Na intake [mg/d]} / 23 \right) + \text{K intake [mg/d]} / 39 \right) \]
\[ UV600 = DSL / 600 \]

6. The rate of metabolic heat production \( (M_{\text{prod}}) \) at rest was calculated as:

\[ M_{\text{prod}}(J/s) = \left( VO_2 [\text{mL/min}] \times \text{Thermal Equivalent of O}_2 \right) / 0.01433 \]

where the thermal equivalent of O\(_2\) at resting RER (0.788) is 4.788-kcal/ml/L.

7. \( M_{\text{prod}} \) during exercise was calculated using the above formula, where the thermal equivalent of O\(_2\) at exercising RER (0.898) is 4.924-kcal/ml/L.

8. Using an \( M_{\text{prod}} \) adjusted for the rate of external work during cycling \( (M_{\text{prod}} \sim \text{Rate of External Work} [W]) \), where W was assumed to be 20% of \( M_{\text{prod}} \) for non-cyclists\(^86\), sweat rate during exercise was calculated by first, using partitional calorimetry formulae for body heat balance to derive the requirement for evaporative cooling \( (E_{\text{req}}) \) and the maximal evaporative capacity of the environment \( (E_{\text{max}}) \). The equation of Gonzalez et al.\(^89\) was then applied to estimate steady-state exercise sweating rate. No allowance was made for the thermal inertial lag in sweating onset as it is generally balanced by the reciprocal thermal decay post-exercise\(^88\).

Received: 16 April 2020; Accepted: 30 June 2020
Published online: 14 August 2020

References

1. National Aeronautics and Space Administration. Recycling Water is not Just for Earth Anymore. https://www.nasa.gov/mission_pages/station/behindscenes/waterrecycler.html (2010a).
2. Junaudi, C. et al. Compact and Lightweight Sabatier Reactor for Carbon Dioxide Reduction. National Aeronautics and Space Administration. https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20120016419.pdf (2011).
3. The International Space Exploration Coordination Group. ISEC Global Exploration Roadmap (3rd edn). https://www.globalsexploration.org/wordpress/wp-content/isecg/GER_2018_small_mobile.pdf (2018).
4. National Aeronautics and Space Administration. International Space Station Facts and Figures ISS. https://www.nasa.gov/feature/facts-and-figures (2019a).
5. National Aeronautics and Space Administration. Orion Quick Facts. https://www.nasa.gov/sites/default/files/fs-2014-08-004-jsc-orion_quickfacts-web.pdf (2014).
6. Gerstenmaier, W. & Crusan, A.A. Cislunar and Gateway Overview. National Aeronautics and Space Administration. https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20180015586.pdf (2018).
7. Canadian Space Agency. Canadian Space Agency Requirements and conditions of employment for astronauts. https://www.asc-csa.gc.ca/eng/astonauts/how-to-become-an-astonaut/requirements-and-conditions.asp (2016).
8. European Space Agency. European Space Agency Astronaut training requirements. https://www.esa.int/Our_Activities/Human_and_Robotic_Exploration/Astronaut/Astronaut_training_requirements (No Date Given).
9. National Aeronautics and Space Administration. Astronaut Requirements. https://www.nasa.gov/audience/forstudents/posts/economy/features/F_Astronaut_Requirements.html (2017a).
10. James, J.T. Carbon dioxide. in Encyclopedia of Life Support Systems, Vol. 315, R496–R499 (2018).
11. Law, J. et al. Relationship between carbon dioxide levels and reported headaches on the international space station. J. Occup. Environ. Med. 56, 477–483 (2014).
12. Hughson, R. L., Yee, N. J. & Greaves, D. K. Elevated end-tidal P\(_{\text{CO}}\) during long-duration spaceflight. Aerosp. Med. Hum. Perform. 87, 894–897 (2016).
13. Buckey, J. C. et al. Microgravity-induced ocular changes are related to body weight. Am. J. Physiol. Regul. Integr. Comp. Physiol. 315, R496–R499 (2018).
14. White, C. R. & Seymour, R. S. Mammalian basal metabolic rate is proportional to body mass2/3. Proc Natl. Acad. Sci. USA. 100, 4046–4049 (2003).
15. Cramer, M. N. & Jay, O. Selecting the correct exercise intensity for unbiased comparisons of thermoregulatory responses between groups of different mass and surface area. J. Appl. Physiol. 1985(116), 1123–1132 (2014).
16. Loehr, J. A. et al. Physical training for long-duration spaceflight. Aerosp. Med. Hum. Perform. 86, A14–A23 (2015).
17. Wu, B. N. & O’Sullivan, A. J. Sex differences in energy metabolism need to be considered with lifestyle modifications in humans. I. Nutr. Metab. https://doi.org/10.1155/2015/391809 (2011).
18. Mark, S. et al. The impact of sex and gender on adaptation to space: executive summary. J. Womens Health 2002(23), 941–947 (2014).
19. Cooper, M., Douglas, G. & Perchonok, M. Developing the NASA food system for long-duration missions. J. Food. Sci. 76, R40–R48 (2011).
20. Argote. Brown rice with chicken and vegetables. https://www.readytolunch.com/en/single-course/13-whole-rice-with-chicken-turmeric-and-vegetables.html (2014).
21. National Aeronautics and Space Administration. How Does Your Space Garden Grow? https://www.nasa.gov/feature/how-does-your-space-garden-grow (2017b).
22. Ewert, M.K. & Broyan Jr, J.L. Mission Benefits Analysis of Logistics Reduction Technologies. National Aeronautics and Space Administration. https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20130013292.pdf (2013).
23. Linne, D.L., Palastewski, B.A., Gokoglu, S. & Gallo, C.A. Waste Management Options for Long-Duration Space Missions: When to Reject, Reuse, or Recycle. National Aeronautics and Space Administration. https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20140010284.pdf (2014).
24. Huber, C. S., Heidelbaugh, N. D., Smith, M. C. & Klicka, M. Space foods. In Health and foods (eds Birch, G. G. et al.) 130–151 (Wiley, New York, 1972).

25. Bourlard, C. T. The development of food systems for space. Trends. Food. Sci. Technol. 4, 271–276 (1993).

26. Stoklosa, A. Packaged food mass reduction trade study. National Aeronautics and Space Administration. https://taskbook.nasa.gov/Publication/index.cfm?action=public_query_taskbook_content&TASKID=7369 (2009).

27. Scott, J. P. R., Weber, T. & Green, D. A. Introduction to the Frontiers research topic: optimization of exercise countermeasures for human space flight—lessons from terrestrial physiology and operational considerations. Front. Physiol. 10, 173. https://doi.org/10.3389/fphys.2019.00173 (2019).

28. Hurst, C., Scott, J. P. R., Weston, K. L. & Weston, M. High-intensity interval training: a potential exercise countermeasure during human spaceflight. Front. Physiol. 10, 581. https://doi.org/10.3389/fphys.2019.00581 (2019).

29. Matsuo, T. et al. An exercise protocol designed to control energy expenditure for long-term space missions. Aviat. Space. Environ. Med. 83, 783–789 (2012).

30. Ralston, G. W. et al. Re-examination of 1- vs. 3-set resistance exercise for pre-spaceflight muscle conditioning: a systematic review and meta-analysis. Front. Physiol. 10, 864. https://doi.org/10.3389/fphys.2019.00864 (2019).

31. Kramer, A. et al. High-intensity jump training is tolerated during 60 days of bed rest and is very effective in preserving leg power and lean body mass: an overview of the Cologne RSI Study. PLoS ONE 12, e016979. https://doi.org/10.1371/journal.pone.016979 (2017).

32. Kramer, A., Gollhofer, A., Armbrrecht, G., Felsenberg, D. & Gruber, M. How to prevent the detrimental effects of two months of bed-rest on muscle, bone and cardiovascular system: an RCT. Sci. Rep. 7, 13177. https://doi.org/10.1038/s41598-017-13659-8 (2017).

33. Kramer, A., Poppendieker, T. & Gruber, M. Suitability of jumps as a form of high-intensity interval training: effect of rest duration on oxygen uptake, heart rate and blood lactate. Eur. J. Appl. Physiol. 119, 1149–1156 (2019).

34. Tamponnet, C. et al. Water recovery in space. ESA Bull. 97, 56–60 (1999).

35. National Aeronautics and Space and Administration. International Space Station Environmental Control and Life Support System. https://www.nasa.gov/centers/marshall/pdf/104840main_eclss.pdf (2008).

36. Fechete, I. Paul Sabatier—The father of the chemical theory of catalysis. C. R. Chim. 19, 1374–2138 (2016).

37. National Aeronautics and Space and Administration. International Space Station Water System Successfully Activated. https://www.nasa.gov/home/press/2010/oct/10-HQ_10-275_Sabatier.html (2010b).

38. National Aeronautics and Space and Administration. The Sabatier System: Producing Water on the Space Station. https://www.nasa.gov/sites/default/files/2015_nasa_technology_roadmaps_ta_6_human_health_life_support_habitation.pdf (2015).

39. National Aeronautics and Space and Administration. Space Technology: Game Changing Development SpaceCraft Oxygen Recovery (SCOR). https://gameon.nasa.gov/gcd/files/2019/03/SCOR_FS_FINAL_3-08-19.pdf (2018).

40. National Aeronautics and Space and Administration. NASA Technology Roadmaps TA 6: Human Health, Life Support, and Habitation Systems. https://www.nasa.gov/sites/default/files/atoms/files/2015_nasa_technology_roadmaps_ta_6_human_health_life_support_habitation.pdf (2015).

41. National Aeronautics and Space and Administration. Life Support Systems Sustaining Humans Beyond Earth. https://www.nasa.gov/content/life-support-systems (2017d).

42. Winton, D. et al. Carbon dioxide removal technologies for space vehicles: past, present, and future. in 46th International Conference on Environmental Systems ICES-2016-425 10–14 July, Vienna, Austria. (2016).

43. Papale, W., Nalette, T. & Sweertelitsch, J. Development status of the carbon dioxide and moisture removal amine swing-bed system (CAMRAS). SAE Int. https://doi.org/10.4271/2009-01-2441 (2009).

44. Zhang, L. F. & Hargens, A. R. Spaceflight-induced intracranial hypertension and visual impairment: pathophysiology and countermeasures. Physiol. Rev. 98, 59–87 (2018).

45. Lefeng, S. et al. Modeling and Simulation on Environmental and Thermal Control System of Manned Spacecraft. in Proceedings of the 12th International Modellica Conference, May 15–17, Prague, Czech Republic. https://doi.org/10.3384/ecp17132397 (2017).

46. Gonzalez, R.R. Modeling heat exchange characteristics of long-term space operations: role of skin wettedness. National Aeronautics and Space Administration. https://apps.dtic.mil/dtic/tr/fulltext/u2/a294005.pdf (1995).

47. Pandolf, K.B. Tri-Service Perspectives on Microclimate Cooling of Protective Clothing in the Heat. Army Medical Research and Material Command (Provisional). https://apps.dtic.mil/dtic/tr/fulltext/u2/a294005.pdf (1995).

48. Izenson, M. et al. Multifunctional Cooling Garment for Space Suit Environmental Control. 45th International Conference on Environmental Systems, 12–16 July, Bellevue, Washington (2015).

49. National Aeronautics and Space and Administration. Astronaut's Energy Requirements for Long-Term Space Flight. https://apps.dtic.mil/dtic/tr/fulltext/u2/a294005.pdf (2015).

50. Amidon, G. L., DeBrincat, G. A. & Najib, N. Effects of gravity on gastric emptying, intestinal transit, and drug absorption. J. Clin. Pharmacol. 31, 968–973 (1991).

51. Richter, C., Braunstein, B., Winnard, A., Nasser, M. & Weber, T. Human biomechanical and cardiopulmonary responses to partial gravity—a systematic review. Front. Physiol. 8, 583. https://doi.org/10.3389/fphys.2017.00583 (2017).

52. Poon, C. S. & Greens, J. G. Control of exercise hyperpnea during hypercapnia in humans. J. Appl. Physiol. 1985(59), 792–797 (1985).

53. Reis, V. M., Júnior, R. S., Zajac, A. & Oliveira, D. R. Energy cost of resistance exercises: an update. J. ASTM Int. 33–39 (2011).

54. Gonzalez, R. R. et al. Expanded prediction equations of human sweat loss and water needs. J. Appl. Physiol. 1985(107), 379–388 (2009).

55. Zuo, J. & McCullough, E. A. Heat transfer characteristics of sports apparel. J. ASTM Int. 1, 1–10 (2004).

56. Moore, A. D., Lynn, P. A. & Feiveson, A. H. The first 10 years of aerobic exercise responses to long-duration ISS flights. Aviat. Space. Environ. Med. 86, A78–A86 (2015).

57. Nevill, A. M., Stewart, A. D., Olds, T. & Holder, R. Are adult physiques geometrically similar? The dangers of allometric scaling using body mass power laws. Am. J. Phys. Anthropol. 124, 77–182 (2004).

58. Nevill, A. M., Debrincat, G. A. & Najib, N. Effects of gravity on gastric emptying, intestinal transit, and drug absorption. J. Clin. Pharmacol. 31, 968–973 (1991).

59. Pingree, B. J. Acid-base and respiratory changes after prolonged exposure to 1% carbon dioxide. Clin. Sci. Mol. Med. 52, 67–74 (1977).

60. Schaefer, K. E., Hastings, B. J., Carey, C. R. & Nichols, G. Jr. Respiratory acclimatization to carbon dioxide. Eur. J. Appl. Physiol. 56–60 (1999).

61. National Aeronautics and Space and Administration. NASA Facts: Astronaut Selection and Training. https://www.nasa.gov/people/johnson/pdf/606877main_JSC-astro_trng.pdf (2019b)

62. Chirkov, B. A. Energy expenditures of the “Soiuz-9” space crew during an 18-days flight. Kosm. Biol. Aviakosm. Med. 9, 48–51 (1975).

63. Rambaut, P. C., Heidelberg, N. D., Reid, J. M. & Smith, M. C. Jr. Caloric balance during simulated and actual space flight. Aerosp. Med. 44, 1264–1266 (1973).

64. Schoeller, D. A. & Greetebek, R. J. Energy utilisation and exercise in spaceflight. In Nutrition in Spaceflight and Weightlessness Models (eds Lane, H. W. & Schoeller, D. A.) 97–115 (CRC Press, Boca Raton, 2000).
65. Kinabo, J. L. & Durnin, J. V. Thermic effect of food in man: effect of meal composition, and energy content. Br. J. Nutr. 64, 37–44 (1990).
66. Ainsworth, B. E. et al. Compendium of physical activities: classification of energy costs of human physical activities. Med. Sci. Sports Exerc. 25, 71–80 (1993).
67. Ainsworth, B. E. et al. Compendium of physical activities: an update of activity codes and MET intensities. Med. Sci. Sports Exerc. 32, 5498–5504 (2000).
68. Part, A. Physical Activity Guidelines Advisory Committee Report 2008: Part A. Executive Summary. Nutr. Rev. 67, 114–120 (2009).
69. Kozey, S., Lyden, K., Staudenmayer, J. & Freedson, P. Errors in MET estimates of physical activities using 3.5 ml x kg(-1) x min(-1) as the baseline oxygen consumption. J. Phys. Act. Health. 7, 508–516 (2010).
70. Matthews, C. E., Heil, D. P., Freedson, P. S. & Pastides, H. Classification of cardiorespiratory fitness without exercise testing. Med. Sci. Sports Exerc. 31, 486–493 (1999).
71. McNeill, G., Bruce, A. C., Ralph, A. & James, W. P. T. Interindividual differences in fasting nutrient oxidation and the influence of diet composition. Int. J. Obes. 12, 455–463 (1988).
72. Weyer, C., Snitker, S., Rising, R., Bogardus, C. & Ravussin, E. Determinants of energy expenditure and fuel utilization in man: effects of body composition, age, sex, ethnicity and glucose tolerance in 916 subjects. Int. J. Obes. 23, 715–722 (1999).
73. Cheuvront, S. N. & Montain, S. J. Myths and methodologies: making sense of exercise mass and water balance. Exp. Physiol. 102, 1047–1053 (2017).
74. Smith, S. M., Zwort, S. R. & Heer, M. Human adaptation to spaceflight: the role of nutrition. https://www.nasa.gov/sites/default/files/human-adaptation-to-spaceflight-the-role-of-nutrition.pdf (2014).
75. Scott, C. B. Quantifying the immediate recovery energy expenditure of resistance training. J. Strength. Cond. Res. 25, 1159–1163 (2011).
76. Scott, C. B. & Fountaine, C. Estimating the energy costs of intermittent exercise. J. Hum. Kinet. 38, 107–113 (2013).
77. Scott, J. P. et al. The role of exercise intensity in the bone metabolic response to an acute bout of weight-bearing exercise. J. Appl. Physiol. 1985(110), 423–432 (2011).
78. Bergman, B. C. & Brooks, G. A. Respiratory gas-exchange ratios during graded exercise in fed and fasted trained and untrained men. J. Appl. Physiol. 88(6), 479–487 (1999).
79. Bahrs, R., Ingnes, L., Vaage, O., Szajersted, O. M. & Newsholme, E. A. Effect of duration of exercise on excess postexercise O2 consumption. J. Appl. Physiol. 1985(62), 485–490 (1987).
80. Short, K. R. & Sedlock, D. A. Excess postexercise oxygen consumption and recovery rate in trained and untrained subjects. J. Appl. Physiol. 1985(83), 153–159 (1997).
81. Roza, A. M. & Shizgal, H. M. The Harris Benedict equation reevaluated: resting energy requirements and the body cell mass. J. Am. Coll. Nutr. 40, 168–182 (1984).
82. Queulet, L. A. I. Physiique Sociale. Vol 2 Brussels, Belgium: C. Muquardt; 92 (1869).
83. de Weir, J. B. V. New methods for calculating metabolic rate with special reference to protein metabolism. J. Physiol. 109, 1–9 (1949).
84. Du Bois, D. & Du Bois, E. F. Clinical calorimetry. Tenth paper. A formula to estimate the approximate surface area if height and weight be known. Arch. Intern. Med. XVII, 863–871 (1916).
85. Cheuvront, S. N. & Kenefick, R. W. Am i drinking enough? Yes, no, and maybe. J. Am. Coll. Nutr. 35, 185–192 (2016).
86. Hopker, J. G., Coleman, D. A. & Wiles, J. D. Differences in efficiency between trained and recreational cyclists. Appl. Physiol. Nutr. Metab. 32, 1036–1042 (2007).
87. Cramer, M. N. & Jay, O. Partitional calorimetry. J. Appl. Physiol. 1985(126), 267–277 (2019).
88. Cheuvront, S. N. & Kenefick, R. W. CORP: Improving the status quo for measuring whole body sweat losses. J. Appl. Physiol. 1985(123), 632–636 (2017).

Author contributions
J.S. and G.W. conceived the study. J.S., D.G. and S.C. defined the assumptions. J.S. and S.C. performed the required calculations. The first draft of the manuscript was written by J.S. and S.C. All authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Competing interests
J.S. and D.G. are both employed by KBR, Cologne, Germany; G.W. is employed by the European Space Agency; S.C. owns and operates Sports Science Synergy, LLC. No specific funding was acquired for the article.

Additional information
Correspondence and requests for materials should be addressed to J.P.R.S.

Reprints and permissions information is available at www.nature.com/reprints.

Publisher’s note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The images or other third party material in this article are included in the article’s Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the article’s Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this license, visit http://creativecommons.org/licenses/by/4.0/.

© The Author(s) 2020