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Precision Nutrition for Prevention of Skeletal Muscle Atrophy and Bone Loss during Long-Duration Human Spaceflight: A Review

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Abstract

Long-duration human spaceflight produces profound physiological adaptations because of microgravity, radiation exposure, confinement, altered circadian rhythms, restricted food systems and psychological stress. Among the major health concerns are skeletal muscle atrophy and accelerated bone loss, which may compromise physical performance, mobility and long-term health during extended missions to the Moon and Mars. Nutrition is an important component of countermeasure strategies because inadequate energy intake, insufficient protein and altered calcium and vitamin D metabolism can intensify musculoskeletal deterioration. Conventional nutritional recommendations, however, may not fully account for the considerable inter-individual variation in metabolic responses to spaceflight. Precision nutrition offers an emerging approach in which dietary strategies may be adapted according to individual characteristics including body composition, energy expenditure, nutrient status, metabolic responses, genetic variation, microbiome composition and exercise response. This review examines the physiological basis of muscle and bone deterioration during spaceflight and evaluates the roles of energy, protein, amino acids, calcium, vitamin D, vitamin K, omega-3 fatty acids, antioxidants, fibre, probiotics and functional foods. Evidence relating to nutrient stability, food acceptability and food-system limitations is also considered. The review further discusses the potential application of genomics, transcriptomics, proteomics and metabolomics to individualise nutritional interventions. Current evidence supports an integrated approach combining adequate energy and protein intake, resistance exercise, micronutrient adequacy, food acceptability and continuous physiological monitoring. Nevertheless, direct evidence for precision nutrition interventions in astronauts remains limited and several proposed strategies are based on terrestrial, analogue or experimental models. Future research should therefore focus on validated biomarkers, longitudinal astronaut datasets and practical personalised nutritional protocols suitable for long-duration exploration missions.

Keyword: Precision Nutrition, Spaceflight Nutrition, Skeletal Muscle Atrophy, Bone Loss, Microgravity, Astronauts

1. Introduction

Human spaceflight represents an extreme physiological environment in which the human body is exposed to microgravity, radiation, confinement, isolation, altered circadian rhythms and restricted food systems. These factors can influence energy expenditure, appetite, food intake, body composition, muscle protein metabolism, bone turnover, fluid balance, gastrointestinal function, immunity and

psychological well-being. As space missions become progressively longer, particularly with planned exploration of the Moon and Mars, maintaining nutritional adequacy and physical function will become increasingly important. One of the most significant physiological consequences of microgravity is the progressive deterioration of skeletal muscle and bone. In the absence of normal gravitational loading, the musculoskeletal system receives substantially

less mechanical stimulation. Weight-bearing muscles, particularly the lower-limb musculature, undergo reductions in muscle volume and strength while skeletal unloading increases bone resorption and contributes to reductions in bone mineral density. The magnitude of these changes is influenced by mission duration, exercise participation, individual characteristics and nutritional status. Energy balance is particularly important. Astronauts may consume less energy than their physiological requirements during spaceflight, potentially creating an energy deficit that can contribute to loss of body mass and lean tissue. Studies have reported substantial reductions in energy intake during some missions and have highlighted the importance of adequate energy availability for maintaining muscle protein synthesis and supporting exercise-induced adaptation (Bergouignan *et al.*, 2016; Pittia *et al.*, 2023) ^[3, 15]. Protein is another critical nutritional determinant of muscle preservation. Adequate total protein together with sufficient essential amino acids, particularly leucine, can support muscle protein synthesis. However, protein intake cannot be considered independently of energy intake and physical activity. Resistance exercise remains a major countermeasure against muscle atrophy and appears to work synergistically with appropriate nutrition. Evidence from spaceflight demonstrates that exercise can substantially reduce muscle loss, although it may not completely prevent it (Rittweger *et al.*, 2018) ^[16].

Bone health presents an additional nutritional challenge. Reduced mechanical loading increases bone resorption and urinary calcium loss, while vitamin D status may be compromised by the absence of ultraviolet light exposure. Calcium, vitamin D and vitamin K are therefore important components of skeletal nutritional management. Other nutrients, including magnesium, potassium, omega-3 fatty acids and antioxidant compounds, may also influence bone metabolism and oxidative stress (Orwoll *et al.*, 2013; Smith and Zwart, 2021) ^[14, 17].

Traditional dietary recommendations generally provide population-level targets. However, astronauts demonstrate considerable variation in body composition, metabolism, exercise response, nutrient requirements and physiological adaptation. Precision nutrition may therefore offer a more individualised approach to space nutrition. By integrating physiological monitoring with nutritional, genomic, metabolomic and microbiome information, nutritional interventions could potentially be adapted to individual requirements and changing physiological conditions throughout a mission. This review examines the current evidence concerning nutrition and musculoskeletal health during long-duration human spaceflight, with particular emphasis on the potential role of precision nutrition in preventing skeletal muscle atrophy and bone loss.

2. Methodology

A structured narrative review approach was used to examine literature addressing nutrition, metabolism, skeletal muscle, bone health, food systems and personalised nutritional strategies relevant to human spaceflight. The literature considered in the review included studies addressing astronauts as well as relevant terrestrial, analogue and experimental models where these provided mechanistic information applicable to spaceflight physiology.

The literature was organised according to major themes including spaceflight-associated physiological adaptation, muscle atrophy, protein metabolism, bone loss, micronutrient requirements, oxidative stress, gastrointestinal and microbiome changes, food acceptability, nutrient stability,

functional foods and precision nutrition. Studies published across different periods were considered because several earlier investigations provide foundational evidence concerning musculoskeletal adaptation to microgravity.

The selected literature was critically synthesised according to physiological relevance, nutritional implications and potential application to long-duration missions. Particular attention was given to evidence concerning energy balance, protein intake, calcium and vitamin D status, exercise-nutrition interactions and emerging precision-nutrition approaches. Because the evidence base includes human spaceflight studies, analogue studies and experimental investigations, findings were interpreted according to their level of translational relevance. Experimental mechanisms were not considered equivalent to established nutritional countermeasures in astronauts.

2.1 Spaceflight Environment and Nutritional Challenges

Spaceflight creates a unique nutritional environment in which food must satisfy physiological, operational and psychological requirements simultaneously. Unlike terrestrial diets, space foods must be lightweight, compact, safe, stable for extended periods and easy to consume. Limited storage capacity, water availability, resupply constraints and the need for prolonged shelf stability restrict the range of foods that can be provided. Food acceptability is also important. Sensory changes during spaceflight can influence appetite and food preferences. Taste, smell, texture and appearance can influence food consumption and consequently energy and nutrient intake. Food also serves psychological and social functions, particularly during prolonged confinement. Studies have shown that food acceptability includes functional, sensory, emotional, social and environmental dimensions (Obrist *et al.*, 2019) ^[12].

The nutritional quality of stored food is another important concern. Long-duration storage can result in degradation of selected nutrients. Cooper *et al.* (2017) ^[6] reported substantial losses of vitamin C in some space food products during prolonged storage, together with reductions in selected B vitamins. These observations highlight the importance of considering nutrient stability throughout the complete mission rather than relying only on the nutrient composition of food at the time of production. Food safety, microbiological stability and ease of preparation are also critical. Space food must remain safe and acceptable despite prolonged storage and restricted preparation facilities. Douglas *et al.* (2020) ^[7] emphasised that space foods should be safe, nutritionally adequate, convenient and acceptable to astronauts. Consequently, an effective space nutrition programme must consider not only nutrient requirements but also food technology, sensory characteristics, psychological factors, storage stability and individual preference.

2.2 Microgravity and Skeletal Muscle Atrophy

Skeletal muscle is highly responsive to mechanical loading. Under terrestrial conditions, gravitational loading and physical activity provide continuous mechanical stimuli that contribute to maintenance of muscle mass and function. Microgravity substantially reduces these stimuli and consequently produces rapid alterations in muscle protein metabolism. Weight-bearing muscles are particularly vulnerable. Reductions in muscle volume, fibre size and strength have been reported during spaceflight. Rittweger *et al.* (2018) ^[16] demonstrated substantial differences in muscle volume and strength between astronauts with different levels of exercise exposure. In one astronaut, medial gastrocnemius volume decreased by approximately 18.1% and soleus volume

by 21.1%, while plantar-flexor strength decreased by approximately 30.6%. Single-fibre size reductions were also observed. These findings demonstrate both the severity of spaceflight-associated muscle deterioration and the importance of exercise intensity.

At the cellular level, unloading can influence several pathways associated with muscle protein turnover. Alterations in AKT/mTOR signalling, the ubiquitin-proteasome system, endoplasmic reticulum stress, calcium homeostasis, myostatin signalling and apoptosis have been implicated in muscle deterioration associated with unloading (Liu *et al.*, 2024) ^[10]. These mechanisms have similarities to pathways involved in age-associated sarcopenia and other conditions characterised by muscle disuse. Consequently, spaceflight provides a valuable model for understanding muscle wasting and developing countermeasures. Nutrition plays an important role in maintaining muscle protein synthesis during unloading. However, protein supplementation alone is unlikely to completely overcome the effects of reduced mechanical loading. The strongest approach is likely to involve sufficient energy intake, adequate high-quality protein, appropriate essential amino acid availability and structured resistance exercise.

2.3 Energy Balance and Protein Requirements

Energy availability is fundamental to the maintenance of lean tissue. A sustained energy deficit can increase the risk of loss of body mass and skeletal muscle. Astronauts have been reported to consume less energy than estimated requirements during some missions, with reductions of approximately 20-30% described in selected studies (Bergouignan *et al.*, 2016; Pittia *et al.*, 2023) ^[3, 15]. The causes of reduced energy intake are multifactorial. Appetite alterations, food fatigue, sensory changes, gastrointestinal effects, operational workload and psychological factors may all contribute. Therefore, increasing food availability alone may not necessarily correct an energy deficit. Protein is particularly important because skeletal muscle protein turnover is strongly influenced by protein quantity, quality, amino acid composition and timing. Essential amino acids are required to stimulate muscle protein synthesis and leucine is particularly important because of its role in activating anabolic signalling pathways.

The nutritional response to protein may vary among individuals. Body size, age, habitual activity, metabolic status and exercise exposure may influence requirements. Precision nutrition could therefore move beyond a single protein recommendation towards individualised protein targets based on lean mass, energy expenditure and physiological response. Carter *et al.* (2022) ^[4] reported that spaceflight-associated changes in body and muscle mass may occur relatively rapidly and highlighted the potential contribution of metabolomics and nutrigenomics to monitoring astronaut health. Nutritional strategies should therefore consider the interaction between macronutrient intake and exercise rather than treating protein as an isolated intervention. A practical strategy for long-duration missions may involve regular assessment of body composition, energy intake, exercise performance and biochemical markers. Nutritional prescriptions could then be adjusted according to individual response.

2.4 Bone Loss during Spaceflight

Bone loss is one of the most important long-term consequences of microgravity. Weight-bearing bones normally receive mechanical loading generated by gravity and physical activity. In microgravity, this stimulus is greatly

reduced, resulting in increased bone resorption and reduced bone formation. Orwoll *et al.* (2013) ^[14] reported reductions in bone mineral density in weight-bearing regions of approximately 1.0-1.5% per month in some astronauts. Earlier observations have also reported substantial monthly losses in skeletal mineral during prolonged spaceflight (Lane and Feiback, 2002) ^[9].

The physiological consequences extend beyond changes in bone mineral density. Increased bone resorption can increase urinary calcium excretion and may contribute to an elevated risk of renal stone formation. More importantly, prolonged skeletal deterioration may increase fracture risk after return to a gravitational environment. Exercise remains a central countermeasure. However, nutrition is required to provide the substrates necessary for bone remodelling. Calcium and vitamin D are particularly important, while vitamin K contributes to bone protein metabolism. Magnesium and potassium may also contribute to skeletal health. The interaction between diet and bone metabolism is complex. High sodium intake may increase urinary calcium excretion, while dietary patterns rich in fruits and vegetables may provide potassium and other compounds associated with favourable skeletal outcomes (Smith and Zwart, 2021) ^[17].

2.5 Calcium, Vitamin D and Vitamin K

Calcium is essential for bone mineralisation and normal neuromuscular function. During spaceflight, increased bone resorption may increase calcium release from the skeleton and urinary calcium excretion. Maintaining adequate dietary calcium is therefore important, although supplementation should be considered in the context of overall dietary intake and individual requirements. Vitamin D presents a particular challenge because astronauts are protected from direct ultraviolet radiation. Consequently, endogenous cutaneous vitamin D synthesis is greatly reduced. Cooper *et al.* (2017) ^[6] highlighted concerns regarding vitamin D and other micronutrients in space food systems.

Vitamin K is also relevant to bone health because of its involvement in the activation of vitamin K-dependent proteins associated with bone mineralisation. Calcium, vitamin D and vitamin K should therefore be considered as components of a broader skeletal nutrition strategy rather than independent supplements. Precision nutrition could potentially identify individuals with lower vitamin D status, altered bone turnover or increased skeletal risk and provide targeted nutritional intervention. Such an approach would be particularly relevant during prolonged missions where individual differences may become increasingly important.

2.6 Omega-3 Fatty Acids and Bone Metabolism

Omega-3 fatty acids may have potential relevance to skeletal health through their effects on inflammatory and osteoclast-related pathways. Zwart *et al.* (2010) investigated the effects of eicosapentaenoic acid on RANKL-mediated osteoclast differentiation and reported inhibition of pathways involved in osteoclast activity. The potential value of omega-3 fatty acids extends beyond bone metabolism. They may also influence inflammatory processes and cardiovascular health. However, the evidence for omega-3 supplementation as a definitive spaceflight bone countermeasure remains limited. Baba *et al.* (2020) ^[2] considered nutritional strategies involving omega-3 fatty acids together with other nutritional components during spaceflight. These findings support further investigation but should not be interpreted as evidence that omega-3 supplementation alone prevents spaceflight-associated bone loss. The precision-nutrition approach would

involve determining which individuals are most likely to benefit from increased omega-3 intake based on dietary intake, biochemical status and physiological response.

2.7 Oxidative Stress and Antioxidant Nutrition

Spaceflight exposes astronauts to environmental stressors that can influence oxidative balance. Radiation exposure is of particular concern during long-duration missions beyond low Earth orbit. Oxidative stress can influence cellular signalling, inflammation and tissue integrity. Antioxidant-rich foods containing polyphenols, flavonoids and other bioactive compounds have therefore received increasing attention. Zhao (2024) ^[19] discussed the potential biological relevance of polyphenol-rich foods, including berries, tea and resveratrol-related compounds. However, an important distinction must be made between biological plausibility and demonstrated efficacy in astronauts. Much of the evidence concerning antioxidant compounds originates from experimental models rather than controlled human spaceflight trials. Consequently, antioxidant-rich foods may be considered promising components of a healthy dietary pattern, but supplementation cannot currently be regarded as an established radiation countermeasure. A food-based approach may be preferable because foods can provide combinations of antioxidants, fibre, vitamins, minerals and other bioactive compounds. Precision nutrition could potentially determine individual antioxidant requirements by integrating dietary intake with oxidative stress biomarkers.

2.8 Gastrointestinal Health and the Gut Microbiome

The gastrointestinal system is another physiological system potentially affected by spaceflight. Changes in diet, stress, circadian rhythms, environmental conditions and microbial exposure may influence the intestinal microbiome. Dietary fibre, prebiotics and probiotics may support microbial diversity and gastrointestinal health. Functional foods containing fermented components may therefore have particular relevance to long-duration missions. Douglas *et al.* (2020) ^[7] reported that an enhanced spaceflight diet incorporating fruits, vegetables, fish, fibre, calcium, potassium and omega-3 fatty acids was associated with favourable changes in selected physiological and microbiome-related outcomes. However, not all immune and microbial outcomes changed significantly, highlighting the complexity of the gut ecosystem.

Precision nutrition provides an opportunity to integrate microbiome characteristics into dietary recommendations. Individuals with different microbial profiles may respond differently to the same dietary intervention. Future space nutrition systems could therefore potentially incorporate microbiome monitoring together with nutritional and metabolic assessment.

2.9 Functional Foods for Long-Duration Missions

Functional foods may offer practical advantages in space because a single food product can potentially provide energy, protein, micronutrients and bioactive compounds. Potentially relevant functional components include high-quality proteins, calcium, vitamin D, vitamin K, omega-3 fatty acids, antioxidants, fibre, probiotics and prebiotics. Fermented foods may also contribute to gastrointestinal health and dietary variety. Clemente-Villalba and Cerdá-Bernad (2025) ^[5] discussed functional foods and emerging food technologies for space missions, including nutraceutical products, algae-based foods and advanced food production technologies. Mahalakshmi *et al.* (2025) ^[11] investigated a strawberry and finger millet freeze-dried yoghurt mix containing protein, fat,

calcium and antioxidant activity. Such products illustrate the potential of combining traditional food ingredients with space-compatible processing technologies. Future food systems may also incorporate microgreens and controlled-environment agriculture. Hydroponic and aeroponic production could provide opportunities for fresh food production during long missions, thereby improving dietary variety and potentially supplying nutrients that may degrade during long-term storage (Oluwafemi *et al.*, 2018) ^[13]. However, functional foods should not be regarded as replacements for a balanced dietary pattern. Their value will depend on nutritional composition, stability, sensory acceptance, production feasibility and individual requirements.

2.10 Food Acceptability and Psychological Well-Being

Nutrition in space is not solely a physiological issue. Food contributes to psychological well-being, comfort, social interaction and the maintenance of normal routines. Prolonged confinement and isolation may affect mood, appetite and eating behaviour. Arone *et al.* (2021) ^[1] discussed psychological consequences relevant to spaceflight environments. Food variety and personal preference may therefore be important for maintaining adequate intake. Douglas *et al.* (2022) ^[8] evaluated food acceptability among astronauts during 6-12-month International Space Station missions and reported generally high acceptability, while also identifying individual preferences, limited variety and the value of supplementary and international foods and condiments. These findings have important implications for precision nutrition. Personalisation should not be limited to biochemical requirements. It should also consider sensory preference, cultural dietary habits and food familiarity. A nutritionally ideal food that an astronaut does not want to eat may have limited practical value.

2.11 Genetic Variation and Precision Nutrition

Individuals can respond differently to the same nutritional exposure because of genetic variation. Nutrient metabolism, oxidative stress responses, inflammation and bone metabolism may be influenced by genetic polymorphisms. Genetic variation involving pathways including CYP450, MTHFR, MTR, CBS and HFE in relation to physiological effects relevant to spaceflight. This supports the concept that nutritional requirements may not be identical across astronauts. Genetic information could potentially contribute to the identification of individuals at greater risk of specific nutritional or physiological complications. However, genomic information should not be interpreted in isolation. Precision nutrition is more appropriately understood as a multi-dimensional approach incorporating genetics together with phenotype, dietary intake, metabolic biomarkers, body composition, exercise and environmental exposure.

2.12 Integrated Nutrition and Exercise Countermeasures

Nutrition should not be considered independently from exercise. The most effective strategy for maintaining muscle and bone is likely to involve an integrated countermeasure programme. Resistance exercise provides mechanical stimulation required to maintain muscle mass and skeletal loading. Protein and essential amino acids provide substrates for muscle protein synthesis. Calcium and vitamin D support bone mineral metabolism while adequate energy availability provides the metabolic foundation for tissue maintenance. Rittweger *et al.* (2018) ^[16] demonstrated that exercise can substantially reduce but does not necessarily eliminate muscle

deterioration. This finding emphasises the need for complementary nutritional strategies. Baba *et al.* (2020) ^[2] reported nutritional and exercise-related characteristics in astronauts and highlighted the complexity of maintaining body composition during spaceflight. Briguglio (2021) similarly described the interaction between reduced food intake, protein metabolism, calcium loss, oxidative stress and immune effects in the spaceflight environment.

2.13 Nutrient Stability and Long-Term Food Storage

Long-duration missions create unique challenges for nutrient preservation. Food products may remain in storage for months or years before consumption. Temperature, oxygen, light and processing conditions can influence nutrient stability. Cooper *et al.* (2017) ^[6] reported significant degradation of selected nutrients during prolonged storage of space foods. Vitamin C losses were particularly notable in some fruit products, while reductions in B vitamins were also observed. This creates an important distinction between the nutrient content of a food at production and the nutrient content actually consumed during a mission. Nutritional planning must therefore incorporate degradation over time. Potential solutions include improved packaging, stabilisation technologies, periodic nutrient monitoring and formulation adjustments. Nutrient-dense functional foods may also help compensate for storage-related losses. Precision nutrition could further assist by identifying nutrients that are most critical for each astronaut and prioritising their preservation or supplementation.

2.14 Emerging Technologies and Future Food Systems

Future missions will require food systems that are substantially more sustainable than those used during short-duration missions. Resupply from Earth will become increasingly difficult as mission distance and duration increase. Controlled-environment agriculture using hydroponic and aeroponic systems may provide fresh vegetables and other crops during long missions. Oluwafemi *et al.* (2018) ^[13] highlighted the potential of sustainable food-production systems for space environments. Advanced food technologies, including 3D food printing, algae-based foods and nutraceutical formulations, have also been proposed (Clemente-Villalba and Cerdá-Bernad, 2025) ^[5]. The future food system may therefore combine stored shelf-stable foods with fresh crops and personalised functional foods. Digital monitoring could determine individual requirements and recommend food combinations according to nutritional needs and physiological response.

2.15 Challenges in Implementing Precision Nutrition in Space

Despite its potential, precision nutrition in space remains an emerging field. First, the number of astronauts available for research is inherently small. This limits statistical power and makes it difficult to distinguish individual effects from environmental effects. Second, many studies are based on analogue environments, animal models or laboratory experiments rather than actual long-duration spaceflight. Experimental evidence can provide valuable mechanistic insight but should not automatically be interpreted as evidence of efficacy in astronauts. Third, nutritional monitoring during missions is challenging. Accurate food intake measurement, biological sampling and continuous metabolic assessment require equipment, crew time and operational resources. Fourth, food systems have strict constraints regarding mass, volume, storage stability, safety and preparation. Personalised diets must therefore remain

operationally feasible. Fifth, omics-based precision nutrition generates large quantities of complex information. Translating these data into practical nutritional recommendations requires validated biomarkers and decision-support systems. Finally, individual preferences and psychological responses must be incorporated. Personalisation should therefore include not only biological characteristics but also food acceptability and behavioural factors.

3. Research Gaps and Future Directions

Several research priorities should be addressed before precision nutrition can become a routine component of long-duration mission planning. Longitudinal studies should examine the relationship between dietary intake, exercise, body composition, bone turnover and muscle metabolism throughout complete missions. Standardised biomarkers should be developed to identify astronauts at greatest risk of muscle and bone deterioration. Further research is required to determine whether individualised protein intake provides greater benefits than standard protein recommendations when combined with resistance exercise. The role of omega-3 fatty acids, antioxidants, vitamin K, probiotics and functional foods requires controlled human investigation. Microbiome research should determine whether specific dietary interventions can produce clinically meaningful improvements in gastrointestinal and systemic health. Nutrient stability studies should examine foods under realistic long-duration storage conditions. Finally, precision nutrition should be integrated with digital health technologies capable of providing real-time recommendations based on food intake, exercise, body composition and physiological biomarkers. The transition from population-level recommendations towards dynamic nutritional prescriptions may be particularly important for Mars missions where medical evacuation and rapid resupply will not be possible.

4. Discussion

The evidence reviewed indicates that skeletal muscle atrophy and bone loss during spaceflight arise from multiple interacting physiological and environmental factors. Microgravity reduces mechanical loading, while inadequate energy intake, altered metabolism, radiation, confinement and restricted food systems may further influence physiological adaptation. Nutrition therefore represents an essential component of the overall countermeasure strategy. Adequate energy availability is fundamental because persistent energy deficiency can compromise lean tissue maintenance. Protein quality and quantity are particularly important for skeletal muscle, while calcium and vitamin D remain central to skeletal health. Nevertheless, a major limitation of the current evidence is that nutritional countermeasures are often studied individually. In reality, astronauts consume dietary patterns rather than isolated nutrients and simultaneously participate in exercise programmes. Future studies should therefore investigate integrated nutritional patterns rather than focusing exclusively on individual supplements. Another important consideration is the distinction between established evidence and emerging hypotheses. Exercise is an established component of musculoskeletal countermeasure programmes. Adequate protein, calcium and vitamin D are physiologically well justified. In contrast, specific polyphenols, novel nutraceuticals, experimental molecular targets and advanced food technologies require further validation.

Precision nutrition offers a conceptual framework for addressing these limitations. Rather than assuming that all astronauts respond identically, it recognises that individual

variation may influence energy requirements, protein utilisation, bone turnover, micronutrient status and food preference. The future of space nutrition may therefore involve a dynamic cycle of assessment, intervention and reassessment. An astronaut's dietary plan could initially be designed according to body composition, baseline nutritional status and mission demands. Subsequent physiological measurements could then identify changes in energy expenditure, muscle mass, bone turnover or micronutrient status. The nutritional prescription could consequently be adjusted throughout the mission.

This approach is particularly relevant to long-duration exploration because the physiological consequences of nutritional inadequacy may accumulate over time. Prevention is likely to be more practical than attempting to reverse severe muscle and bone deterioration after a mission.

5. Conclusion

Long-duration human spaceflight presents a complex nutritional challenge in which microgravity, radiation, confinement, altered circadian rhythms, restricted food systems and psychological factors interact to influence physiological health. Skeletal muscle atrophy and bone loss are among the most important consequences because they can impair physical performance and increase long-term health risks. Current evidence supports an integrated strategy involving adequate energy intake, high-quality protein, essential amino acids, calcium, vitamin D, vitamin K, appropriate dietary fat, omega-3 fatty acids and a diverse dietary pattern rich in fruits, vegetables, fibre and bioactive compounds. Resistance exercise remains essential and should be combined with nutritional intervention rather than replaced by it. Functional foods, controlled-environment agriculture, microbiome-directed nutrition and advanced food technologies may provide additional opportunities for future missions. However, many emerging interventions remain supported primarily by experimental or terrestrial evidence and require validation in human spaceflight. Precision nutrition represents a promising future direction because it allows nutritional strategies to be adapted according to individual physiology, body composition, dietary intake, metabolic response, genetic characteristics, microbiome profile and exercise response. The ultimate objective should be the development of a dynamic nutritional system capable of identifying individual risk, delivering targeted interventions and continuously adjusting dietary recommendations throughout a mission. As human exploration progresses towards longer missions beyond low Earth orbit, nutrition should be regarded not merely as a means of meeting dietary requirements but as an active component of preventive medicine and physiological countermeasure planning. Integrating nutrition, exercise, food technology, biomarker monitoring and precision approaches may provide the most effective strategy for preserving muscle, maintaining skeletal health and supporting astronaut performance during future long-duration missions.

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