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Occupational Physical Requirements for Astronauts

Philippe St-Martin; François Lalonde; Félix Bouchard-Lévesque; Isabelle J. Dionne

INTRODUCTION: Through the Artemis program, space agencies and astronauts are preparing for extended durations in space and on planetary surfaces, expanding their occupational tasks. Although standardized laboratory tests are effective in assessing health and mitigating deconditioning, their reliability in forecasting occupational performance is uncertain. Consequently, a recent shift in exercise testing has emerged, shifting focus from health-oriented criteria to operational performance. This involves identifying the physical demands associated with components of an astronaut's tasks and determining a minimum level of performance, referred to as Physical Employment Standards. The aim of this systematic review is to provide an updated overview of the scientific literature on astronaut occupational tasks and physiological requirements.

METHODS: A search was conducted spanning from 1970 to October 2023. Articles meeting the inclusion criteria underwent screening using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses for an evidence-based systematic review.

RESULTS: There were 10 studies selected for inclusion in the current review and pertinent information was extracted. There were 14 tasks physiologically assessed: ambulation on various terrains, physical abilities field, device operations/activity board, re-entry and landing, hatch opening, capsule egress, recovery from fall, jump down, ladder climb, material transfer, emergency crewmember drag, hand drilling, construction wrenching, and upper-limb weighted tasks.

DISCUSSION: Physical Employment Standards for astronauts have yet to be established; however, certain tasks have been identified, enabling tailored occupational assessments for astronauts, increasingly recognized as tactical athletes. The results of this literature review lay the foundations for scientific task analysis and the development of operational physical tests for astronauts.

KEYWORDS: systematic review, occupational fitness, physical testing, tactical athletes, spaceflight.

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Human space exploration is at a turning point between long-duration flight on the International Space Station (ISS) and deep-space exploration. Future astronauts will need to extend their time in space from weeks (like in the early days of exploration from the Gemini, Apollo, space shuttle era, and early Artemis missions) to many years, for missions on the Moon or Mars.[1] Microgravity exposure results in musculoskeletal unloading, leading to fitness loss and health impairments through reduced muscle size, strength, and endurance.[2]

Currently, astronaut medical and fitness assessments are mainly performed for health purpose pre-, during, and postflight. Each space agency has its own assessment methods, with most of those tests being standardized laboratory assessments used in exercise sciences. As an example, the European Space Agency developed a new test battery which includes assessment of aerobic capacity, muscular strength and power, core stability, balance, and flexibility.[3]

While these tests are highly valuable for evaluating health and deconditioning, they may not precisely predict occupational performance. This aligns with the recent shift of paradigm in exercise testing, moving from health requirements to

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operational performance, recognizing the occupational physiological demands within the framework of a job.[4,5] This approach has been applied to tactical athletes such as military personnel, firefighters, law enforcement officers, and emergency responders, but it has yet to be implemented for astronauts.[6,7]

The Canadian Armed Forces recently moved from traditional fitness tests to the Fitness for Operational Requirements of Canadian Armed Forces Employment test, an occupational fitness test assessment.[8,9] Briefly, six fundamental and physically challenging military duties that personnel must be able to perform regardless of age, gender, rank, or military occupation have been evaluated and Physical Employment Standards (PES) have been established. Each task of the Fitness for Operational Requirements of Canadian Armed Forces Employment test targets different aspects of physical fitness, but altogether they are a proxy of agility, lower- and upper-body power, anaerobic capacity, strength, and aerobic capacity and endurance. Some Canadian Space Agency astronauts, who are also members of the Canadian Armed Forces, must pass this new evaluation; however, military duties differ from space-related responsibilities.[10]

Based on the PES model, developing an occupational fitness test for astronauts, incorporating eventual health-related fitness standards, could ensure they meet the minimum requirements (yet to be defined) for performing physically demanding spaceflight tasks, while promoting optimal occupational performance. Additionally, integrating these assessments during microgravity analogs, such as head-down bed rest (HDBR) campaigns, could help understand deconditioning effects on astronauts' performance levels. Identifying occupational tasks on which to establish a standard is the first step in PES development.[11] This review aims to provide updated information on physical assessment and the occupational tasks performed by astronauts.

METHODS

Potential studies were identified using Scopus, SPORTDiscus with Full Text, and PubMed. The full search strategy is available in **Table I**. For each database, the date range was 1970 to the 25th of October 2023. The language options included both English and French. Reference lists of articles retrieved were manually checked for additional articles, and duplicates were excluded.

Table I. Search Strategy for Database Literature Search.

SEARCH NO.	TERM	KEYWORDS IN BOOLEAN LOGIC FORMAT
1	Astronaut	"astronaut*" OR "cosmonaut*" OR "parabonaut*"
2	Occupationnal	"occupation*" OR "task*" OR "functional*"
3	Requirement	"evaluation*" OR "test*" OR "simulation*" OR "performance*" OR "prediction*" OR "requirement*"
4	Physical	"exercise countermeasure*" OR "physical" OR "exercise test"

Inclusion criteria for study selection are available in **Table II**. Primary research studies, including pilot experiments and clinical trials, not limited to randomized control trials, had to be published in a peer-reviewed journal to be eligible for this review. Animal studies, case reports, case studies, conference papers, government reports, study proposals, master theses, doctoral theses, and review articles were excluded. The primary outcome related to different physical tasks of astronauts must be measured either by oxygen consumption [$\dot{V}O_2$, $\dot{V}CO_2$, respiratory exchange ratio (RER), VE], strength, power, endurance, heart rate, blood pressure, perceived effort, time to complete a task, minimum standard of a task scale, and any other physiological measurements or performance measurements.

All studies that met the eligibility criteria and investigated astronauts' fitness and/or physical demand of a task, or in relation to tasks, were selected. Studies underwent initial screening based on titles and abstracts, with subsequent full manuscript review for relevance to the study's scope. This process was conducted independently by two reviewers using Rayyan software[12] and following Preferred Reporting Items for Systematic Reviews and Meta-Analyses guidelines and framework.[13] A third reviewer made the final decision in case of disagreement. The review is divided into three sections: cardiovascular and metabolic requirements, neuromuscular requirements, and sensorimotor requirements.

Table II. Inclusion Criteria.

SUBJECTS/ POPULATIONS	INTERVENTION/ INTEREST	CONTROL/ COMPARISON	OUTCOME MEASURES	STUDY TYPES
No restrictions are placed on astronauts and subjects for fitness levels. Subjects must be at least 18 yr old.	Physical assessment tests on different occupational tasks of astronauts. All studies investigating astronaut's fitness and/or physical demand of an occupational and operational tasks.	No control/comparison as this is not an intervention review.	The primary outcome related to different physical tasks of astronauts must be measured either by oxygen consumption ($\dot{V}O_2$, $\dot{V}CO_2$, RER, VE), strength, power, endurance, heart rate (HR), blood pressure (BP), rate of perceived effort (RPE), time to complete a task, minimum standard of a task scale and any other physiological measurement.	Primary research studies must be published in a peer reviewed journal to be eligible for this review (not only limited to randomized control trials; RCT). RCTs, pilot studies and observational cohort studies on humans investigating astronaut's fitness and/or physical demand of a task and met the eligibility criteria will be selected.

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RESULTS

After an initial database search, 479 records were retrieved, and following the selection process, 10 studies were incorporated into this systematic review. A total of 380 articles did not meet the inclusion criteria and were excluded from the analysis (see **Fig. 1**). The characteristics of the 10 studies included are presented in **Table III**.

Comprehensive Effect of Deconditioning

A comprehensive study by Mulavara et al. aimed to determine how spaceflight influences the performance of representative functional tests of critical exploration mission tasks, as well as to identify physiological factors related to the cardiovascular, neuromuscular, and sensorimotor systems that could limit performances.[19] For this purpose, a battery of tests representing the critical occupational tasks of astronauts and various physiological tests were conducted on long-duration mission astronauts and subjects undergoing a 70-d HDBR, before and after exposure to actual or simulated microgravity. The specific tests are detailed in Table III.

Briefly, a significant decrease in performance was observed following microgravity exposition in the recovery from fall to stand test and in the seat egress and walk test in astronauts (11 men and 2 women, aged 47 ± 5 yr; +66% and +31%, respectively), in HDBR control subjects (10 men, aged 38 ± 7 yr; +54% and +38%, respectively) and HDBR exercisers (9 men, aged 34 ± 6 yr; +42% and +23%, respectively). There was a noteworthy increase in completion time in both bed-rest groups during the ladder climb test ($P < 0.008$). In contrast, ISS crewmembers demonstrated a modest rise in completion time ($P = 0.009$). Object translation and jump down test performances were affected by both HDBR (+26% for both tests) and spaceflight (+58% for both test); however, exercising

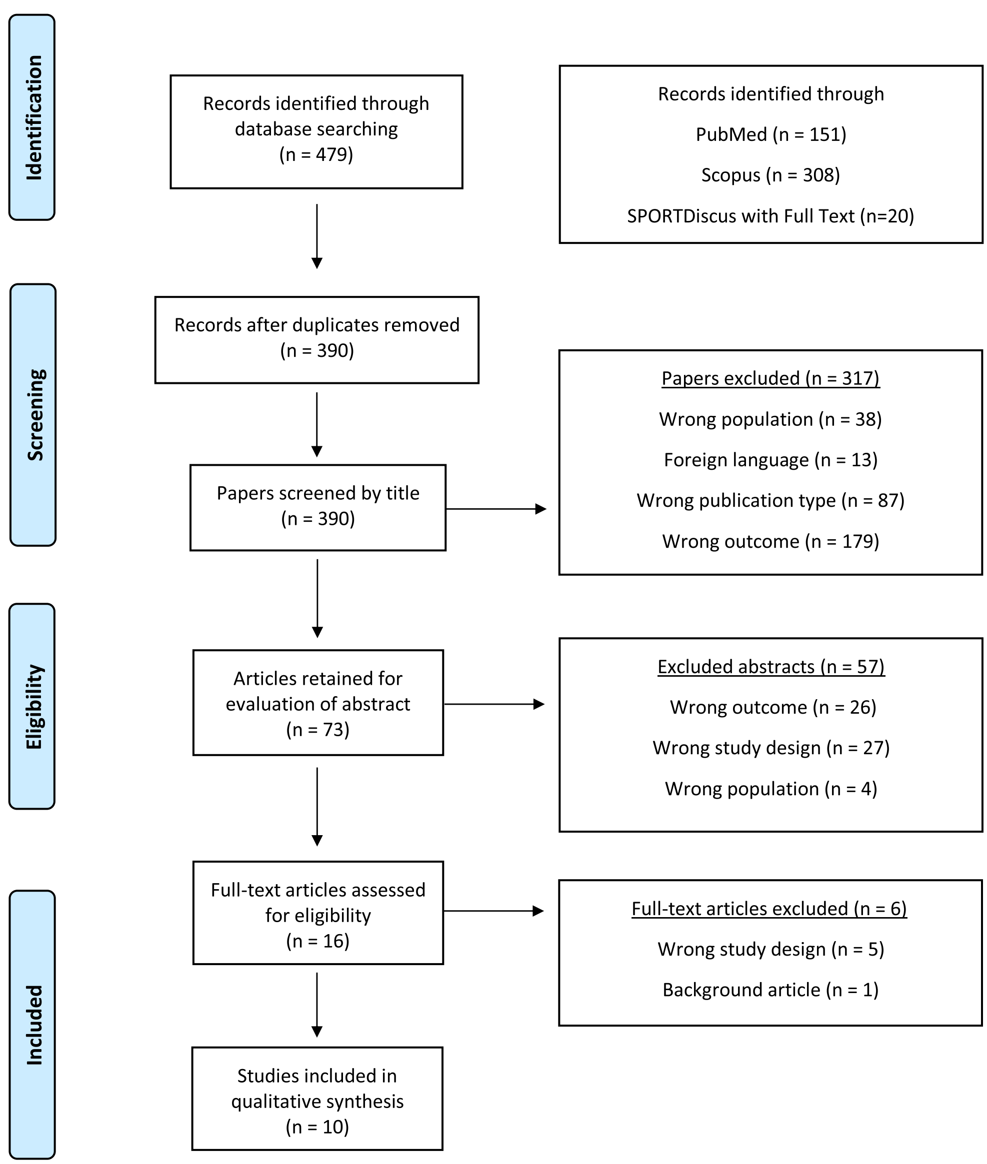

Fig. 1. PRISMA flow diagram of inclusion/exclusion process.

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Table III. Characteristics of the Included Studies.

AUTHORS	SUBJECTS	TASKS/ OCCUPATIONAL FITNESS TEST	OUTCOME MEASURES
Ade et al.[14]	71 subjects • 40 men, 31 women • Age 23 ± 5 yrs • Height 174 ± 9.8 cm • Body mass 73.8 ± 15.7 kg	10 km walk-back: simulate a walk-back from a rover failure • Indoor track • Casual athletic apparel Physical abilities field test 1) Climb and descent of a 12-ft ladder 2) Agility cones course 3) Ascent and descent 4.5-m set of stairs 4) Lateral wall climb 5) 4.5-kg and 9-kg box lifts 6) 40-cm step-over task and duck-under chest level poles • 10 m between each task • 15 rounds as quickly as possible	Field tests 10 km walk-back test 1) Time-to-completion Physical abilities field test 1) Time-to-completion Laboratory tests 1) Lower limb $\dot{V}O_2$ max 2) Upper limb $\dot{V}O_2$ peak 3) Gas exchange threshold (GET) 4) Heart rate (HR) 5) Running speed at $\dot{V}O_2$ max (S-$\dot{V}O_2$ max) 6) Running speed at GET (S-GET) 7) Peak power output (PPO) 8) Running critical speed (CS) 9) Upper-body critical power (CP) 10) Total distance covered above CS 11) Total work performed above CP 12) Time-to-exhaustion 13) Lower-body muscular endurance with a 2-min maximum body squat
Ade et al.[15]	70 subjects • 39 men, 31 women • Age 23 ± 5 yr	Material transport • 10 rounds as quickly as possible 1) Material loading (10 sample of 10 kg) from a table to cart 2) Pushing the loaded cart over a 54-m level-track 3) Material unloading from cart to table Device operations • 5 rounds as quickly as possible 1) Valve and bolt manipulations 2) Hose couplings 3) Balance beam walk 4) Equipment drag (weighted sled over 18 m)	Field tests 1) Time-to-completion Laboratory tests 1) Running $\dot{V}O_2$ max 2) Running and arm crank gas exchange threshold (GET) 3) Running speed at $\dot{V}O_2$ max (S-$\dot{V}O_2$ max) 4) Running critical speed (CS) 5) Finite distance covered above CS (D’) 6) Arm cranking $\dot{V}O_2$ peak 7) Arm cranking critical power (CP) 8) Arm cranking peak power output (PPO) 9) Finite work performed above CP (W’) 10) Max body-weight squat in 2 min 11) Maximal isometric handgrip contraction strength (MVC) 12) Standard push-up test
Alexander et al.[16]	15 subjects • 5 men, 10 women • Age 47 ± 4 yr • Height 169 ± 10 cm • Body mass 90 ± 23 kg	Emergency NASA’s Orion space capsule egress • Custom-build mock-up of the NASA Orion space capsule • Minimum or two familiarization trial prior to data collection • As quickly as possible 1) Seated supine position: rolling from the seat 2) Manipulation of two 5-kg bags over 1 m 3) Securing a rope ladder to the capsule floor 4) Bags carry through the top hatch 5) Capsule egress	Field tests Emergency NASA’s Orion space capsule egress 1) Time-to-completion 2) Metabolic data 3) Heart rate Laboratory tests 1) Cycling $\dot{V}O_2$ peak / $\dot{V}CO_2$ peak / peak ventilation 2) Rowing $\dot{V}O_2$ peak / $\dot{V}CO_2$ peak / peak ventilation 3) Cycling peak power output (PPO) 4) Rowing peak power output (PPO) 5) Rowing critical power (CP)
Cowings et al.[17]	20 subjects • 14 men, 6 women • Age (men) 35.5 ± 2.3 yr, (women) 35.5 ± 6.22 yr	Re-entry and landing of the Orion crew vehicle • Rotating chair to simulate angular acceleration • Manual dexterity and mental arithmetic task 1) Pretest resting baseline (no rotation) 2) Manual dexterity task (no rotation) 3) Rotation and task 4) Deceleration 5) Rotation stops	Laboratory tests Motion sickness tolerance test 1) Rotating chair test duration 2) Symptom diagnostic scale Field tests Orion Spacecraft re-entry simulation 1) Heart rate 2) Respiration rate and volume 3) Finger pulse blood volume 4) Forearm extensor and gastrocnemius muscle activity 5) Skin temperature 6) Skin conductance level 7) Cardiac output 8) Stroke volume 9) Blood pressure

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Table III. (*Continued*).

AUTHORS	SUBJECTS	TASKS/ OCCUPATIONAL FITNESS TEST	OUTCOME MEASURES
Miller et al.[18]	Astronauts Short-duration missions: 12.9 ± 1.8 d 4 men, 2 women • Age 43.0 ± 5.7 yr • Height 178 ± 4 cm • Body mass 77.2 ± 8.4 kg Long-duration missions: 158.9 ± 17.1 d 11 men, 2 women • Age 46.6 ± 4.5 yr • Height 178 ± 6 cm • Body mass 83.5 ± 13.6 kg Bedrest subjects (70-d HDBR) Controls subjects: 10 men, 0 women • Age 37.7 ± 7.2 yr • Height 175 ± 6 cm • Body mass 81.4 ± 8.9 kg Exercisers: 9 men, 0 women • Age 33.8 ± 5.5 yr • Height 178 ± 4 cm • Body mass 78.2 ± 6.5 kg	Seat egress and walk 1) 5-point harness release 2) Rising/rolling from seated position (trial 1/trial 2) 3) Portal: step-over and ducking hurdles 4) Slalom 5) Inclined ramp walk climb 6) Palm-button push 7) Ramp descend • As quickly and as safely as possible (without running) Object translation: transferring three weights (2.7, 4.5, and 9 kg) between racks while in a standing position. • Two rounds • From least heavy to most heavy • As quickly and as safely as possible Recovery from fall/stand: standing for 3.5 min from a prone position, feet shoulder-width apart • As quickly as possible • Without spacesuit Jump down test Two-footed jump down a 30-cm height	Field tests Seat egress and walk 1) Time-to-completion 2) Split times Object translation 1) Time-to-completion Recovery from fall/stand 1) Postural Settling Time 2) Mean sway speed 3) Center of pressure Jump down 1) Postural Settling time Laboratory tests 1) Continuous equilibrium score (computerized dynamic posturography) 2) Tandem Walk Parameter (tandem walk test)
Mulavara et al.[19]	Astronauts Long-duration missions: 159 ± 17 d 11 men, 2 women • Age 47 ± 5 yr • Height 178 ± 6 cm • Body mass 84 ± 14 kg Bedrest subjects (70-d HDBR) Controls subjects: 10 men, 0 women • Age 38 ± 7 yr • Height 175 ± 6 cm • Body mass 80 ± 9 kg Exercisers: 9 men, 0 women • Age 34 ± 6 yr • Height 178 ± 4 cm • Body mass 77 ± 7 kg	Seat egress and walk See above Miller et al.[18] Recovery from fall/stand See above Miller et al.[18] Object translation See above Miller et al.[18] Jump down See above Miller et al.[18] Ladder climb: 40 rungs, self-selected pace • As quickly and as safely as possible Activity board 1) Relocating two hose connectors from their original attachments 2) Shifting three electrical connectors from a vertical to a horizontal position 3) Handle attachment by screws into C-channels Hatch opening test • Handle wheel turn counterclockwise, increasing effort until maximum	Field tests Seat egress and walk 1) Time-to-completion Recovery from fall/stand 1) Mean sway speed Object translation 1) Time-to-completion Jump down test 1) Postural Settling time Ladder climb test 1) Time-to-completion Activity board test 1) Time-to-completion Hatch opening test 1) Peak force produced Laboratory tests 1) Plasma volume 2) Heart rate (recovery from fall/stand test) 3) Blood pressure (recovery from fall/stand test) 4) Maximal central muscle activation capacity (neuromuscular drive test) 5) Upper-body maximal isometric force 6) Lower-body maximal isometric force 7) Upper-body total work (isotonic power endurance test) 8) Lower-body total work (isotonic power endurance test) 9) Continuous equilibrium score (dynamic posturography test) 10) Percentage of correct steps (tandem walk test) 11) Time to complete task (fine motor control test) 12) Lower-body lowest coefficient of variation (Force control test) 13) Upper-body lowest coefficient of variation (Force control test)

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Table III. (*Continued*).

AUTHORS	SUBJECTS	TASKS/ OCCUPATIONAL FITNESS TEST	OUTCOME MEASURES
Ryder et al.[20]	20 subjects • 10 men, 10 women • Age 36 ± 10 yr • Height 172 ± 12 cm • Body mass 68.8 ± 14.7 kg	Seat egress and walk Supine or upright 1) 5-point harness release (upright only) See above Miller et al.[18] for details and additional steps Rise from fall • In a prone position • As quickly as possible Hatch opening Upright posture Isometric condition: maximal torque for 3–4 s Isotonic conditions: 50% maximal torque, as many turns as possible for 20 s. Ladder climb See above Mulavara et al.[19] Objects carry See above Miller et al.[18] Construction board activity See above Mulavara et al.[19]	Field tests All (except hatch opening) 1) Time-to-completion Hatch opening 1) Maximal isometric strength (torque) 2) Total work Laboratory tests 1) Knee extension peak isokinetic torque 2) Knee extension maximal isometric force 3) Leg press maximal isometric force 4) Leg press isotonic power 5) Leg press total work 6) Bench press maximal isometric force 7) Bench press isotonic power 8) Bench press total work
	Astronauts Space shuttle (11–15 d) 4 men, 2 women	Upright seat egress and walk See above for details	Field test 1) Time-to-completion Laboratory tests 1) Muscle performance tests (leg press and knee extension). See above.
Ryder et al.[21]	60 subjects • 32 men, 28 women • Age 37 ± 7 yr • Height 173 ± 10 cm • Body mass 75.0 ± 13.3 kg	Capsule egress: unaided top-hatch in a space capsule mock-up 1) 5-point harness release 2) Handling of undeployed life raft mock-up (13.6 kg) and 2 survival packs (6.4 kg) 3) Egress ladder deployment 4) Manipulation of life raft and survival packs over the top hatch 5) Capsule exit • As quickly as possible Ambulation and supply transfer: simulate moving between landers on planetary surface, handling supplies with crew transfer bags to a rover. 1) 1.5-km walk on regolith-like surface 2) Handling of 30 crew transfer bags one at a time over 5 m (10.9 kg each) • As quickly as possible, without running Emergency crewmember drag: simulate securing and dragging an incapacitated crewmember on a rescue sled to safety. 1) Roll the mannequin (75 kg) over onto the sled and secure it 2) Drag the mannequin 50 m around the track Hill climb and descent: simulate a roundtrip to set up a line-of-sight communications antenna. 1) Walk "uphill" carrying mock-up antenna (4.1 kg) over 1010 m on a treadmill (variable rise 2–8%, 4% average grade) 2) Handling of the antenna 3) Walk "downhill" • Self-paced	Field test 1) Time-to-completion Laboratory tests 1) Isokinetic peak torque (concentric/eccentric; knee, calf and trunk) 2) Maximal isometric force (leg press, knee extension, bench press, midthigh pull) 3) Isotonic power (leg press and bench press) 4) Isotonic work (leg press and bench press) 5) Countermovement vertical jump over 6) Peak aerobic capacity ($\dot{V}O_2$ peak) 7) Wingate anaerobic cycle power

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Table III. (*Continued*).

AUTHORS	SUBJECTS	TASKS/ OCCUPATIONAL FITNESS TEST	OUTCOME MEASURES
Taylor et al.[22]	8 subjects • 5 men, 3 women • Age 34.88 ± 3.69 yr • Height 176.06 ± 5.91 cm • Body mass 72.9 ± 8.34 kg	*With a 48-kg weighted suit designed to emulate the NDX-2 spacesuit weight distribution. Hatch opening 1) Isometric strength trial: 1 set × 3 repetitions; clockwise and counterclockwise; 3 s 2) Isotonic endurance trial: 10 N · m−1 – 15 kJ work performed; clockwise and counterclockwise Hand drilling 1) Isometric strength trial: 1 set × 3 repetitions; clockwise and counterclockwise; 3 s 2) Isotonic endurance trial: 2 N · m−1 – 100 repetitions; clockwise and counterclockwise Construction wrenching Isometric strength trial: 1 set × 3 repetitions; clockwise and counterclockwise; 3 s Isotonic endurance trial: 40 N · m−1 – 20 kJ work performed; clockwise and counterclockwise Incline walking 1) Walk "uphill" over 800 m on a treadmill (+1° every 2 min, until 5°) 2) Walk "downhill" over 800 m on a treadmill (–1 ° every 2 min, until 0°) • Self-paced Samples collection: collect 9 samples positioned in two consecutive rows, located at 3 and 6 m from starting point (5.4, 5.4, 5.0, 4.0, 3.0, 2.7, 2.7, 2.0 and 1.0 kg) • Safe lifting practices Emergency crewmember drag 1) Drag a 54-kg mannequin over 8.5 m 2) Turn 90° 3) Drag the 54-kg mannequin over 5 m	Field tests 1) Tasks time-to-completion 2) Total time-to-completion 3) Peak torque (hatch opening, hand drilling and construction wrenching) 4) Total work (hatch opening, hand drilling and construction wrenching) 5) Heart rate (hatch opening, hand drilling, construction wrenching and inclined walk) 6) Oxygen utilization ($\dot{V}O_2$, hatch opening, hand drilling, construction wrenching and inclined walk) 7) Respiratory exchange ratio (RER; hatch opening, hand drilling, construction wrenching and inclined walk) 8) Ratings of perceived exertion Laboratory tests 1) Knee extensor strength (peak torque) 2) Knee flexor strength (peak torque) 3) Knee extensor endurance (total work) 4) Knee flexor endurance (total work)
Volkova et al.[23]	32 subjects • 18 men, 14 women • Age 34.88 ± 3.69 yr • Height 175 ± 11.0 cm • Body mass 71.22 ± 17.21 kg	*Tasks conducted in 1 G and underwater (Moon and Mars gravity) Holding weights with outstretched arm Holding weights in an arm bent at the elbow Dynamic task 1) Lifting hand motion with weight (3 s range of motion) 2) Lowering hand motion with weight (3 s range of motion) Repetitive task 1) Lifting 2) Horizontal transfer 3) Lowering 4) Pause without load	Field tests 1) Endurance time 2) Mental workload 3) Muscle voluntary contraction Laboratory tests 1) Grip strength 2) Back-leg-chest strength

during HDBR mitigated the detrimental alterations, with HDBR exercisers showing no significant change in performance for either test. Performance in the activity board and hatch-opening tests did not exhibit significant alterations following spaceflight or HDBR. Astronauts experienced an approximate 8% reduction in the maximum power output of their lower body, while HDBR control subjects had a 14% reduction; similarly, total lower body work decreased by 10% for astronauts and 19% for HDBR control subjects only.

The following sections will discuss outcome variables from other studies related to cardiovascular and metabolic, neuromuscular, and sensorimotor systems that may restrict performance.

Cardiovascular and Metabolic Requirements

Ade et al. suggested that running critical speed and upper limb $\dot{V}O_2$ peak would be better parameters than running $\dot{V}O_2$ max and upper limb $\dot{V}O_2$ peak for predicting physical performance during planetary abilities field test and extravehicular activity (EVA) walkback.[14] Ade et al. recruited 71 subjects (40 men and 31 women, aged 23 ± 5 yr) and administered two tests associated with the physical demands of astronaut tasks; a continuous circuit consisting of 6 tests (12-ft ladder climb, cone agility test, 4.5-m stair climb, lateral wall climb, box lifts, and 40-cm step-over task) and a 10-km walk-back test. Subjects were unaware of the distance and number of completed laps to prevent pacing. The relationship between the two occupational

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tests and laboratory-based physical performance measures were evaluated. Running at critical speed ($11.9 \pm 2.2\,km \cdot h^{-1}$) was the best single predictor of 10-km walk-back time in men (59.2 ± 12.3 min, r = −0.88, $P < 0.001$) and women (63.3 ± 13.6 min, r = −0.82, $P < 0.001$).

For the physical abilities field test, the best predictors of time completion were running at critical speed (12.4 ± 2.3 and $11.2 \pm 2.0\,km \cdot h^{-1}$, r = −0.82 and r = −0.78, men and women, respectively, $P < 0.001$) and arm-cranking $\dot{V}O_2$ peak ($28.7 \pm 6.0\,ml \cdot kg \cdot min^{-1}$ and $24.4 \pm 5.0\,ml \cdot kg \cdot min^{-1}$, r = −0.69 and −0.52, $P < 0.001$ and $P < 0.05$, men and women, respectively). In this context, critical speed serves as a proxy for the maximum sustainable aerobic metabolic rate, representing 58.1 ± 7.3 and $61.4 \pm 8.7\%$ of $\dot{V}O_2$ max in men and women, respectively.

Ade et al. recruited 70 subjects and administered 2 tests derived from tasks identified by the NASA Human Research Program in 2009; a material transport field test involving loading, transporting, and unloading geological samples; and a device operations field test comprising tasks related to equipment setup and the manipulation of controls and valves.[15] This study aimed to assess how standard aerobic fitness and muscular strength tests relate to performance in these mission-critical upper-body activities. Only 24 subjects underwent the second test. The average duration of the material transport field test was 36.0 ± 9.2 min, ranging from 25.8–79.7 min. Arm cranking critical power (62.3 ± 22.9 W, r = −0.66, $P < 0.001$), running critical speed ($11.8 \pm 2.2\,km \cdot h^{-1}$, r = −0.56, $P < 0.001$) and arm-cranking $\dot{V}O_2$ peak ($26.9 \pm 5.9\,ml \cdot kg \cdot min^{-1}$, r = −0.54, $P < 0.001$) were the parameters with the strongest relationship to predicted performance during the material transport test. A critical power of ≤39.8 Watts during the arm cranking test indicates a high risk for falling into the 4th quartile of material transport field test times. The average duration of the device operations field test was 32.2 ± 6.4 min, with a range of 19.5–47.9 min. Arm cranking critical power (r = −0.70, $P < 0.001$), running critical speed (r = −0.62, $P < 0.001$), number of completed push-ups (r = −0.59, $P < 0.001$) and arm cranking peak power output (PPO) (r = −0.56, $P < 0.05$) exhibited the strongest correlation with the device operations field test time.

Astronauts must perform an unaided emergency exit through the space capsule's top hatch as quickly as possible upon re-entry to Earth.[24] Alexander et al. enlisted 15 individuals (5 men and 10 women, aged 47 ± 4 yr), and conducted an egress test in an Orion capsule mock-up.[16] Additionally, subjects were mandated to undergo two incremental exercise tests until exhaustion, one on a cycle ergometer and one on a rowing ergometer. Egress completion time was 54.9 ± 19.4 s, ranging from 34–114 s, and was not correlated to age, body mass, or height. There was a negative correlation (r = −0.60, $P = 0.03$) between egress time and rowing PPO normalized to body mass. Subjects' peak $\dot{V}O_2$ (mean cycling $24.0 \pm 4.8\,ml \cdot kg \cdot min^{-1}$ and mean rowing $25.0 \pm 4.4\,ml \cdot kg \cdot min^{-1}$) during the egress test reached $72 \pm 25\%$ of relative $\dot{V}O_2$ peak. Handling the 5-kg bags elicited the larger increase in ventilation, from $19.31 \pm 9.88\,l \cdot min^{-1}$ at baseline to $31.68 \pm 9.30\,l \cdot min^{-1}$.

Taylor et al. recruited eight subjects (five men and three women; average age 34.88 ± 3.69 yr) and subjected them to six simulated astronaut tasks: hatch opening, hand drilling, construction wrenching, incline walking, samples collection, and emergency crewmember drag.[22] Tasks are detailed in Table III. As for the cardiovascular and metabolic requirements, notable variations in aerobic metabolism and fuel utilization were observed, but there were no significant differences in heart rate or perceived intensity. For instance, the highest respiratory exchange ratio (RER or $\dot{V}CO_2/\dot{V}O2$) was observed during the task of hatch opening, reaching 1.44 ± 0.21. The task with the highest oxygen uptake demands was walking 800 m on an inclined treadmill with a 48-kg weighted suit, replicating the NDX-2 spacesuit weight distribution, with values of $32.28 \pm 6.57\,ml \cdot kg \cdot min^{-1}$.

Neuromuscular Requirements

Ryder et al. studied task performance by adjusting strength, power, and endurance to body weight (BW) ratio using a weighted suit.[20] The goal was to determine the muscle performance thresholds required for tasks that replicate astronaut work. Subjects (10 men and 10 women, aged 36 ± 10 yr) engaged in 6 astronaut tasks (seat egress and walk, rise from fall, hatch opening, ladder climb, object carry, and construction board activity) as well as traditional laboratory tests, including leg press, bench press, and knee extension performance assessments. The astronaut data supported the resulting models. For lower body performance, the best predictor for the upright and supine seat egress and walk test, object carry, ladder treadmill, and rise from fall tasks was determined to be leg press maximal isometric force per BW (LPMIF/BW), with corresponding R^2 values of 0.6, 0.68, 0.52, 0.6, and 0.54, respectively. The highest threshold for LPMIF/BW performance was observed during upright seat egress task at $17.8\,N \cdot kg^{-1}$. Consequently, any increase in load from the astronaut's body weight gain or the inclusion of equipment like the spacesuit, without a concomitant increase in strength, would impact this ratio, potentially prolonging the time required to complete these tasks. Overall, the upright seat egress and walk task showed the highest thresholds for lower body measures: isokinetic knee extension per BW ($1.9\,Nm \cdot kg^{-1}$; $R^2 = 0.44$), knee extension maximal isometric force per BW ($5.9\,N \cdot kg^{-1}$; $R^2 = 0.43$), LPMIF/BW ($17.8\,N \cdot kg^{-1}$; $R^2 = 0.6$), leg press power per BW ($17.6\,W \cdot kg^{-1}$; $R^2 = 0.41$), and leg press work per BW ($78.8\,J \cdot kg^{-1}$; $R^2 = 0.41$).

Regarding upper body performance, the most significant predictor for hatch opening was the bench press work per BW (BPW/BW), yielding an R^2 of 0.74, with a threshold estimated at $18.3\,J \cdot kg^{-1}$. For object carry and construction activity board tasks, the bench press maximal isometric force per BW (BPMIF/BW) was the top predictor, with R^2 values of 0.34 and 0.07, respectively. Relative strength thresholds for upper body performance were also investigated.[20] The highest threshold for upper body measures was hatch opening: BPMIF/BW ($13\,N \cdot kg^{-1}$; $R^2 = 0.62$), bench press power per BW ($10.8\,W \cdot kg^{-1}$; $R^2 = 0.63$), and BPW/BW ($46\,J \cdot kg^{-1}$; $R^2 = 0.74$).

Similarly, Ryder et al. enlisted 60 subjects (32 men and 28 women; average age 37 ± 7 yr) to investigate whether indicators of muscle strength and physical capacity could predict subjects' ability to complete various astronaut tasks within an acceptable

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timeframe.[21] Alongside traditional laboratory tests evaluating aerobic, anaerobic, and neuromuscular capacity, subjects performed simulations of four astronaut planetary EVA tasks: capsule egress, ambulation and supply transfer, rescue drag, and hill climb and descent. For all tasks, the threshold values remained consistent across predictor variables. Isometric midthigh pull, isokinetic knee extension work, bench press work, and aerobic capacity emerged as the most reliable indicators for predicting performance in capsule egress, ambulation and supply transfer, rescue drag, and hill climb and descent [receiver operator characteristics (ROC) area under the curve = 0.88, 0.89, 0.9, and 0.92, respectively]. For example, concentric isokinetic knee extension ranged from 1.83–1.86 $Nm \cdot kg^{-1}$, with isokinetic knee extension work from 22.84–23.34 $J \cdot kg^{-1}$. Bench press work varied from 25.08–26.50 $J \cdot kg^{-1}$, isometric midthigh pull from 18.3–18.53 $N \cdot kg^{-1}$, and aerobic capacity from 27.4–27.57 $ml \cdot kg \cdot min^{-1}$ across all tasks.

Building upon the Ryder et al. research, Taylor et al. investigated whether NASA's lower body strength testing could predict astronaut occupational task performance and if occupational upper body strength test could improve predictions.[22] They enlisted eight healthy individuals (five men and three women; aged 34.88 ± 3.69 yr) and conducted six occupational tasks (hatch opening, hand drilling, construction wrenching, incline walking, sample collection, and emergency crewmember drag), alongside NASA's standard upper leg strength measures (knee extension-flexion strength). The total time to complete all tasks varied from 20.2–44.5 min. NASA's standard strength measurements contributed 61.5% of the variability. Adding hand-drilling and wrenching performance to NASA standard measurements explained 99.6% of the variability in time-to-completion ($P = 0.15$). In men, the exertion of wrenching away and toward produced forces of 262 ± 71 N and 301 ± 111 N, respectively. Hand drilling away and toward yielded forces of 36 ± 12 N and 39 ± 12 N, respectively. In women, wrenching forces were 160 ± 40 N and 198 ± 17 N and hand drilling generated strengths of 34 ± 10 N and 37 ± 1 N for away and toward actions, respectively. Gender comparisons revealed differences in knee flexion peak torque ($P = 0.006$), overall work ($P = 0.016$), and knee extension total work ($P = 0.002$).

Partial gravity, as on the Moon and Mars, may help astronauts with some occupational tasks. In a study by Volkova et al., a positive correlation ($P = 0.02$) was found between endurance time in upper extremity tasks and gravity level, with negative coefficients for both men and women in static tasks.[23] The study involved 32 subjects (18 men and 14 women; aged 34.88 ± 3.69 yr) who performed 4 upper extremity tasks in 1 G and underwater (1/3 G and 1/6 G) to simulate Martian and lunar gravity. The tasks varied in intensity, with weights from 0.5–9 kg, adjusted to match the respective gravitational levels. Endurance task time increased 3.54-fold for women and 3.14-fold for men under lunar gravity compared to Earth's gravity.

Sensorimotor Requirements

Sensorimotor alterations, highlighted by Miller et al. using data from spaceflight and simulated microgravity, may impact astronauts' performance on operational tasks upon landing on a planetary surface.[18] Balance control system evaluations challenging mission-critical tasks were conducted on astronauts before and after missions of varying durations. Assessments were also performed on subjects undergoing 70 d of continuous HDBR. Subjects completed a seated egress and walking test to simulate emergency evacuation tasks, an object translation test for manipulating an item on a planetary surface, a recovery from fall/stand test, and a jump down test. Control group subjects confined to bed (10 men, with an average age of 37.7 ± 7.2 yr) exhibited decreased performance immediately after the bed rest period. Bedridden individuals who exercised (nine men, aged 33.8 ± 5.5 yr) displayed comparable changes to those who did not exercise, with no significant difference between the two groups following bed rest. Similarly, individuals returning from extended space missions (11 men and 2 women, with an average age of 46.6 ± 4.5 yr) demonstrated reduced performance across all parameters. Specific performance changes are shown graphically in the article, limiting their applicability in future research. Notable findings include an increase in egress portal time (seated and reclined: P = 4.5e-06 and 1.1e-09, respectively), a decrease in continuous equilibrium score (P = 7.6e-13), and increases in fall recovery parameters such as postural settling time and mean sway speed (P = 5.1e-09 and 1.7e-29, respectively). Significant alterations were also noted in jump down settling time (P = 7.2e-09), object translation time (P = 1.1e-10), and tandem walk parameter (P = 2.3e-21). The decreases were more pronounced and required longer recovery compared to astronauts on short-duration missions (four men and two women, aged 43.0 ± 5.7 yr).

Mulavara et al. highlighted that occupational tasks requiring enhanced body coordination and postural stability, such as seat egress and walk, recovery from fall/stand, object translation, jump down, and ladder climb tests, are particularly affected by prolonged spaceflight and long-duration HDBR.[19] In contrast, tasks demanding less postural stability, like the hatch opening and activity board test, displayed no performance impairment following real or simulated microgravity.

Astronauts' performance may be restricted by spatial disorientation and motion sickness during spacecraft re-entry. Cowings et al. evaluated whether Autogenic-Feedback Training Exercise (AFTE), a physiological training method, could alleviate these issues for the Orion spacecraft.[17] A group of 20 subjects (14 men with an average age of 35.5 ± 2.3 yr and 6 women with an average age of 35.5 ± 6.22 yr) underwent a simulated re-entry, occurring after the deployment of the drogue parachute. The simulation involved Coriolis acceleration in a rotating chair. Severe discomfort occurred in 60% of the subjects when the chair speed mimicked the parachute deployment phase. Subjects who completed 2 h of AFTE displayed reduced adverse symptoms, while those with 4 and 6 h of training had fewer symptoms and more consistent performance compared to the control group. This suggests that longer AFTE durations are more effective for subjects responding to this form of treatment.

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DISCUSSION

The aim of this review is to provide updated information on physical assessment tests that identify the occupational tasks of astronauts, which is essential for developing future PES standards. This review examines 14 occupational tasks, detailing their specific requirements and thresholds.

Current understanding of EVA, critical mission tasks, and astronaut occupational duties for a deep-space mission remains largely conceptual, as shown by the notable variations in tasks and contexts in **Table IV**. With the Artemis program progressing, defining astronaut tasks and PES for upcoming Moon missions is becoming more necessary. Given the ambitious lunar base objective, it becomes crucial to assess astronauts' tasks on

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Table IV. Astronaut Occupational Tasks Analysis.[11]

TASKS/ OCCUPATIONAL FITNESS TEST	PARAMETERS OF TASK ANALYSIS		
	EQUIPMENT	LOAD MOVEMENT	ENVIRONMENT
Ambulation on various terrains	Minimum No equipment Maximum Weighted suit 80% of the subject's body weight distributed anthropometrically	Distance Distance covered between 0.8 km and 10 km, with varying inclinations Velocity Controlled by subject's speed Average pace between the studies = 6:06 min · km^{-1} to 18:11 min · km^{-1}	Location and terrain All studies were conducted indoors, on a treadmill or a track (predictive surface) Posture All studies in an upright posture Urgency of the task Usually mentioned as quickly and safely as possible, sometimes restricted to walking speed, and sometimes not specified Protective clothing All studies were conducted in casual athletic apparel or not specified, with or without the weighted suit to simulate the spacesuit. Temperature/humidity Not specified
Capsule egress	Minimum No equipment Maximum Weighted suit 120% of the subject's body weight distributed anthropometrically + manipulation of external weight (such as undeployed life raft (13.6 kg) and crew survival packs (6.4 kg)	Range of movement No manipulation to external load manipulation from ground level to 1.5 high. No restriction on load velocity or stability Distance Highly variable: from mock-up of NASA's Orion space capsule to obstacle course without specified distance	Dimensions and accessibility of the work space Not specified for obstacle course studies (designed as low-fidelity simulation) Mock-up of NASA's Orion space capsule (floor, 3.6 m diameter; ceiling, 2.5 m diameter; ceiling, 1.5 m height from floor; top hatch tunnel, 83 cm length, 81 cm diameter at narrowest point) Posture Starting position: seated upright or supine Protective clothing Most studies were conducted in casual athletic apparel or not specified, with or without the weighted suit to simulate the spacesuit. Location and terrain All studies were conducted indoors, in laboratory environment (predictive and stable surface) Urgency of the task As quickly and safely as possible, with obstacle course studies limited to self-selected walking speed Temperature/humidity Not specified
Construction wrenching	48-kg weighted suit anthropometrically distributed	Load movement relative to operator's body Upright posture Wrench's arc of motion parallel to the floor Range of movement associated with the task None (isometric contraction) to self-select range of motion to complete 20 kJ work against 40 N · m^{-1} resistance	Location and terrain Laboratory environment (indoor) Urgency of the task With maximal effort as quickly and safely as possible Temperature/humidity Not specified Protective clothing Weighted suit to simulate the spacesuit

(*Continued*)

Table IV. (*Continued*).

TASKS/ OCCUPATIONAL FITNESS TEST	PARAMETERS OF TASK ANALYSIS		
	EQUIPMENT	LOAD MOVEMENT	ENVIRONMENT
Device operations/ activity board	Minimum No equipment Maximum Weighted suit 120% of the subject's body weight distributed anthropometrically	Velocity Controlled by subject's speed Load movement relative to operator's body Some manipulations are individualized to the subject's height (shoulder and waist height) Distance No-movement task to manipulation coupling with carrying a weighted sled (weight not specified) over 18m with a rope using a hand-over-hand motion Task descriptions are highly variable and frequently lack detail.	Location and terrain Laboratory environment (indoor) Posture All studies conducted in standing position Urgency of the task As quickly and safely as possible Temperature/humidity Not specified Protective clothing Casual athletic apparel or not specified, with or without weighted suit to simulate the spacesuit
Emergency crewmember drag	Minimum Weighted suit 20% of the subject's body weight Maximum Weighted suit 80% of the subject's body weight Dummy 54 kg - 75 kg	Distance 13.5–50 m Velocity Controlled by subject's speed	Location and terrain Laboratory environment (indoor) Flat surface to regolith-like surface (undulations up to 15 cm) Temperature/humidity Not specified Urgency of the task With maximal effort as quickly and safely as possible Posture All studies conducted in standing position Protective clothing Studies conducted in casual athletic apparel or not specified, with weighted suit to simulate the spacesuit.
Hand drilling	48-kg weighted suit anthropometrically distributed	Range of movement associated with the task None (isometric contraction) to dynamometer's entire arc of motion against $2\,N \cdot m^{-1}$ resistance until 100 reps is completed, Load movement relative to operator's body Arc of motion perpendicular to the floor Velocity Controlled by subject's speed	Location and terrain Laboratory environment (indoor) Posture Standing position Urgency of the task With maximal effort as quickly and safely as possible Temperature/humidity Not specified Protective clothing Casual athletic apparel, with weighted suit to simulate the spacesuit
Hatch opening	Minimum No equipment Maximum Weighted suit 120% of the subject's body weight	Load movement relative to operator's body Arc of motion perpendicular to the floor Range of movement associated with the task None (isometric contraction) to endurance trials Task descriptions are highly variable ~22.86 cm radius handle wheel Load movement relative to the operator's body Sometimes at a fixed position, sometimes individualized (e.g., midsternum level)	Location and terrain Laboratory environment (indoor) Posture Standing position Temperature/humidity Not specified Protective clothing Casual athletic apparel or not specified, with or without weighted suit to simulate the spacesuit Urgency of the task With maximal effort, as quickly as possible and safely as possible Dimensions and accessibility of the work space Not specified

(*Continued*)

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Table IV. (*Continued*).

TASKS/ OCCUPATIONAL FITNESS TEST	PARAMETERS OF TASK ANALYSIS		
	EQUIPMENT	LOAD MOVEMENT	ENVIRONMENT
Jump down	No equipment	Range of movement associated with the critical task Two-footed hop from a 30 cm high platform	Location and terrain Laboratory environment (indoor) Posture Standing position, arms on the sides Temperature/humidity Not specified Protective clothing None, casual athletic apparel
Ladder climb	Minimum No equipment Maximum Weighted suit 120% of the subject's body weight (limited to maximum 150 kg - treadmill ladder manufacturer's recommendation)	Distance 40 rungs to complete Velocity Controlled by subject's speed	Location and terrain Laboratory environment (indoor), on a passive treadmill ladder Temperature/humidity Not specified Urgency of the task As quickly and as safely as possible Protective clothing None, casual athletic apparel
Material transfer	Minimum No equipment Maximum Weighted suit 120% of the subject's body weight Mass Highly variable across studies, but always <11 kg Order not always specified in studies with various weights Dimension From weights with grip handles to crew transfer bags (60 × 36 × 20 cm) Position Highly variable across studies, from the ground to 40 cm from the ground Modifications that could improve the economy of the task Usually not specified, but in some studies, any transfer strategy could be used, but no transfer from one hand to another during transit One study limited the material transfer to safe lifting practices only (bending at the knee and hip)	Distance 0.38–54 m Range of movement associated with the critical task Not specified, controlled by subject Load movement relative to operator's body Position and transfer strategy are variables across studies and not always specified, usually one weight at a time Velocity Controlled by subject's speed Stability of the load during movement Not specified Height of the load movement Not specified	Location and terrain Laboratory environment (indoor) Flat surface to regolith-like surface (undulations up to 15 cm) Temperature/humidity Not specified Urgency of the task With maximal effort, as quickly and as safely as possible, sometimes running is prohibited Protective clothing Studies conducted in casual athletic apparel or not specified, with weighted suit to simulate the spacesuit

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Table IV. (*Continued*).

TASKS/ OCCUPATIONAL FITNESS TEST	PARAMETERS OF TASK ANALYSIS		
	EQUIPMENT	**LOAD MOVEMENT**	**ENVIRONMENT**
Physical abilities field	No equipment + two 4.5-kg boxes + two 9-kg boxes from waist level to eye level + two 9 kg boxes from the floor to waist level (individualized)	Distance 10 m between each task, ~900 m traveled in total between tasks + 180 ft of ladder climb in total + 67.5-m ascend and descend stair climb in total Load movement relative to operator's body 4.5-kg movements from waist level to eye level and 9-kg from floor level to waist level (individualized) + Step over (40-cm high hurdles) + Duck under chest-level poles (individualized) Velocity Controlled by subject's speed (box lifts—one at a time, using both hands)	Location and terrain Laboratory environment (indoor) Temperature/humidity Not specified Urgency of the task As quickly as possible Protective clothing None, casual athletic apparel
Recovery from fall	Minimum No equipment Maximum Weighted suit 120% of the subject's body weight	N/A	Location and terrain Laboratory environment (indoor) From a stable force plate to a 10-cm thick memory foam Position Lying prone position, then standing up (feet shoulder-width apart, looking forward, arms on the sides) Temperature/humidity Not specified Urgency of the task As quickly as possible Protective clothing None, casual athletic apparel
Re-entry and landing	No equipment + (2.094 rad $\cdot$ s^{-1})	N/A	Location and terrain Laboratory environment (indoor) Rotating chair to simulate angular acceleration profile crew will experience during re-entry of the Orion space vehicle (2.094 rad $\cdot$ s^{-1}) Temperature/humidity Not specified Urgency of the task N/A Protective clothing None, casual athletic apparel
Upper-limb weighted tasks	No equipment + Ballasts (0.5, 1, 3, 5, 7, and 9 kg) on different body parts for partial gravity intensities (individualized) "The choice of maximum load was dependent on the physical capabilities of the subject and the gender"	Load movement relative to operator's body Outstretched arm and arm bent at the elbow Velocity Slow dynamic motion and repetitive motion Stability of the load during movement Not specified Range of movement associated with the critical task Not specified, controlled by subject	Location and terrain Indoor pool (buoyancy equivalent to gravity on the Moon (G = 1.626 m $\cdot$ s^{-2}) and Mars (G = 3.72076 m $\cdot$ s^{-2}) Temperature/humidity Water temperature constant at 29° Urgency of the task N/A

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the cardiometabolic and metabolic, neuromuscular, and sensorimotor systems to predict performance accurately and establish performance thresholds to ensure their safety and mission success.

Cardiovascular and Metabolic Requirements

According to NASA Constellation Program's EVA Systems Project Office and the Health and Human Performance Directorates' EVA Physiology, Systems, and Performance Project, rovers will not travel more than 10 km from base.[25] Consequently, astronauts should be prepared to walk up to 10 km in a spacesuit if the rover fails, matching the distances recorded in the identified studies (Table IV).

Although $\dot{V}O_2$ max is significantly linked to astronauts' occupational tasks, Ade et al. suggest that arm-cranking critical power and running critical speed—representing the highest sustainable aerobic workload—might be better performance predictors than $\dot{V}O_2$ max or $\dot{V}O_2$ peak for metabolically demanding tasks, such as the 10-km walk-back.[14,15] This could be attributed to the combined influence of the aerobic energy systems' capacity and the subject's functional metabolic efficiency, meaning the amount of energy spent per unit of velocity.[26] This last parameter is more sensitive between subjects with the same $\dot{V}O_2$ max since the metabolic cost for a task is highly variable. Thus, the relationship between performance and $\dot{V}O_2$ max tends to weaken with increasing duration of effort compared to critical speed or critical power. Critical speed and critical power might be more accurate for predicting astronaut performance during EVAs, which often span several hours, than $\dot{V}O_2$ max, which remains the standard for ISS missions. These findings suggest developing PES with relevant measurements for the astronaut environment. Ventilatory threshold, calculated from $\dot{V}O_2$ max performed on the CEVIS, could serve as an alternative to critical power.[27,28] Despite the lack of direct applicability to predicting astronaut performance thresholds due to a lack of contextualization, Ade et al. support shifting the assessment focus to better evaluate astronauts' physical capabilities for long-duration missions.[14,15]

Nevertheless, caution is warranted as studies on astronauts' occupational tasks often overlook the distinct gravitational conditions, challenging environments (terrain and temperature), and altered metabolic costs associated with suited ambulation (Table IV). Norcross et al. showed that in lunar analog conditions, walking in suited conditions had a submaximal metabolic cost but was still higher than on Earth.[29] In contrast, brisk walking on Mars in a suit requires near-maximal physiological effort, emphasizing the importance of these factors in evaluating astronauts' fitness tasks. The metabolic impact of the spacesuit, regardless of its weight, can be evaluated by comparing suited trials to unsuited weight-matched controls. This difference is about $8.0\,ml \cdot kg \cdot min^{-1}$, representing roughly 18% of the subjects' average $\dot{V}O_2$ peak. For example, Ade et al. found that individuals completed the 10-km walk-back on an indoor track in 61.0 ± 12.9 min without spacesuit,[14] compared to 95.8 ± 13.0 min recorded by Norcross et al. while suited and on simulated lunar gravity.[29]

Exploring key performance thresholds for astronauts is essential. This involves examining factors like space deconditioning,[19] challenging terrain, the metabolic demands of the spacesuit, and variations in gravitational forces. Ryder et al. studied the impact of various weights, simulating the spacesuit, on astronaut EVA tasks.[21] Aerobic capacity was the main predictor for performance in hill climb and descent. Among the studies, the task with the highest oxygen uptake was inclined walking while wearing a 48-kg weighted suit mimicking the NDX-2 spacesuit weight distribution, registering values of $32.28 \pm 6.57\,ml \cdot kg \cdot min^{-1}$.[22] This aligns with NASA's preliminary fitness criteria, which aim to mitigate the physical performance decline due to reduced fitness.[1] The $\dot{V}O_2$ max, as determined by either direct or indirect measures, should be maintained at levels no lower than $32.9\,ml \cdot kg \cdot min^{-1}$ for missions involving microgravity EVAs and $36.5\,ml \cdot kg \cdot min^{-1}$ for missions with EVAs on celestial surfaces. Given the historical declines of 15–25% decrease in $\dot{V}O_2$ max during spaceflight, pre-mission $\dot{V}O_2$ max guidelines are set at 38.7 and $43.8\,ml \cdot kg \cdot min^{-1}$, respectively. In-mission aerobic capacity must be sustained at or above 80% of the pre-mission capacity, achieved through either countermeasures or work performance. NASA guidelines rely on either flight data or analog study findings and would adequately accommodate the average peak EVA $\dot{V}O_2$ of $19.4\,ml \cdot kg \cdot min^{-1}$ and even the average of the top 10 EVA peak $\dot{V}O_2$ values, which stood at $32.3\,ml \cdot kg \cdot min^{-1}$. However, factors such as challenging terrains,[30,31] spacesuit movement restrictions, and their metabolic consequences may affect performance.

Assessing maximum oxygen consumption during spaceflight necessitates an onboard pulmonary gas exchange system, ideally a breath-by-breath metabolic cart. Historically, the ISS has supported such health-monitoring, but upcoming flight systems (e.g., Orion space capsule) may face challenges due to constraints such as limited space, weight, and technical restrictions.[32] Besides maximal oxygen uptake, future exercise physiologists may take a closer look at what happens to oxygen uptake kinetics and ventilatory threshold in space.[27] Ventilatory threshold may be a stronger predictor of human performance in orbit than maximal oxygen uptake itself.

Unaided top hatch emergency exit, as exemplified by Alexander et al., represents a unique task.[16] This is especially crucial because, in the event of an emergency, it must be performed quickly under Earth's gravity following a mission that may cause deconditioning and a considerable decline in physical capabilities. As individuals with relatively low PPO and $\dot{V}O_2$ peak below $20\,ml \cdot kg \cdot min^{-1}$ were still able to complete the egress mock-up test in under 2 min, $\dot{V}O_2$ peak and PPO may not serve as reliable discriminators of astronauts' conditions for emergency egress performance. Nevertheless, considerations such as the motion sickness or vestibular impairment induced by a quick return to gravity should be noted. Since NASA anticipates ocean landings, the completion time for this test may increase compared to the same egress test conducted on a flat surface with controlled conditions. Therefore, it is essential to assess these tests and performance

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benchmarks under conditions similar to those astronauts might encounter, potentially deconditioned, upon returning to Earth.

The deconditioning effects of spaceflight can significantly impact certain astronaut tasks. According to Mulavara et al., the decline in plasma volume observed after microgravity was linked to decreased performance in the seat egress and walk test, as well as the ladder climb.[19] Simultaneously, alterations in heart rate were positively correlated with performance declines in functional tasks that strain the cardiovascular system, particularly those involving prolonged upright posture like seat egress and walk, recovery from fall to stand, object translation, ladder climb, and hatch opening.[19] This indicates that accounting for plasma volume and heart rate adaptations to spaceflight is crucial in shaping countermeasures and establishing performance thresholds for Moon or Mars missions, especially for tasks requiring extended periods of whole-body upright physical activity. Furthermore, Taylor et al. found that performing tasks in a weighted suit made the hatch opening task particularly challenging, as evidenced by the peak RER.[22]

A factor scarcely addressed in the studies is neurovestibular deconditioning resulting from extended exposure to microgravity.[19] This issue could potentially impair performance during tasks and pose safety risks to astronauts. Research from NASA's Human Physiology, Performance, Protection & Operations Laboratory has highlighted a notable increase in post-mission time required for unassisted capsule egress.[33] Hence, establishing a minimum requirement for this task also necessitates considering the landing terrain type and accounting for expected deconditioning based on the mission duration and implemented countermeasures. On Earth, using a virtual reality set-up to mimic neurovestibular impairment might be a viable option for preparation before performing a physically challenging task.[34]

Neuromuscular Requirements

Research on the relationship between neuromuscular capacities assessed through traditional laboratory tests and performance in occupational tasks has yielded inconsistent findings. The strength of associations varies, with the most robust correlation reported by Ryder et al., indicating a high R^2 value of 0.9 for bench press work and crewmember rescue drag performance.[21] Building on this, Taylor et al. demonstrated that incorporating occupational task performance, in addition to NASA standard measurements, accounted for 99.6% of the variability in the overall time-to-completion for a test battery.[22] This was a major improvement compared to the 61.5% variability explained by NASA standard measurements alone.

As stated earlier, the deconditioning effects of spaceflight can pose important risks. Mulavara et al. demonstrated that certain tasks, such as seat egress and walk, recovery from fall to stand, and object translation, were notably associated with declines in lower-body neuromuscular performance metrics.[19] Conversely, upper-body neuromuscular performance seems to remain relatively preserved during HDBR and spaceflight, as there was no clear association between changes in upper-body neuromuscular function and task performance.

Ryder et al. highlighted that defined muscle performance thresholds are critical for executing occupational tasks, with performance diminishing when these thresholds are not met.[20,21] In establishing muscle function thresholds for astronauts, it is essential to account for individual body weight, suit weight, and the effects of partial gravity.[20,21] The added weight of the suit can significantly affect performance. For example, a 20% and 40% decrease in power relative to body weight below $17.6\,W \cdot kg^{-1}$ in the upright seat egress tasks results in an additional 2.8 s and 6.7 s in task duration, respectively, which could pose safety risks.[20] In line with the aforementioned lack of association with maximum oxygen consumption, relative leg press maximal isometric force, with a threshold of $17.8\,N \cdot kg^{-1}$, emerges as a reliable predictor for short-duration tasks (<50 s) involving an ambulatory component. For longer-duration tasks, the threshold falls within the range of $17.3–17.65\,N \cdot kg^{-1}$.[21] Due to the task-specific nature of thresholds, bench press performance metrics, such as relative bench press work at 46 and $25.08\,J \cdot kg^{-1}$, are effective predictors for the hatch opening task[20] and crewmember rescue, respectively.[21] Overall, these studies suggest that strength requirements for unaided egress are greater upon returning to Earth than for planetary surface, and the microgravity environment can ease the execution of certain tasks.[23]

When predicting astronaut performance based on ground-based tests, it is crucial to address the lack of an astronaut-specific context. The microgravity environment and the pressurized spacesuit increase physical demands, leading to higher metabolic cost and reduced performance.[25] NASA's current pre-mission neuromuscular fitness evaluations primarily focus on traditional lower-body strength and endurance laboratory tests, which may overlook the specific fitness requirements of the upper extremities in occupational tasks.[22]

NASA's preliminary fitness criteria specify that astronauts should meet pre-mission muscle strength requirements (deadlift and bench press) and maintain at least 80% of these baseline strength values during the mission.[24] The minimum standards are set at 1.0 times body weight for deadlift and 0.7 times body weight for bench press. For EVAs on celestial surfaces, higher thresholds are suggested: 1.6 times body weight for deadlift and 1.0 times bodyweight for bench press. Currently, there are no explicit recommendations for missions to the Moon or Martian surfaces, and the rationale behind these benchmarks remains unknown. NASA notes that "EVA suit design (i.e., how the suit design affects human performance) must be taken into account and may necessitate adjustments to these values."[1]

Sensorimotor Requirements

Maintained cardiorespiratory capacity, muscular strength, and endurance do not guarantee optimal execution of functional tasks after spaceflight. Cowings et al. provides evidence supporting that spatial disorientation and motion sickness may impact the performance during and after spacecraft re-entry.[17]

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Thus, these factors must be considered when establishing acceptable performance thresholds. However, Cowings et al. used a simulation that does not fully replicate real-life conditions. Further research is needed to involve subjects in tasks that closely align with astronauts' responsibilities during re-entry and account for deconditioning factors.

Astronauts performance during occupational tasks might be limited by sensorimotor impairment, as spaceflight can affect postural equilibrium.[35,36] This finding is corroborated by Miller et al., who indicates that deconditioning during bed rest markedly influences functional performance and balance control during simulated activities, such as seated egress in emergencies, object manipulation, recovery from fall/stand, and jumping down.[18] Additionally, the extent of functional performance deficits was directly related to mission duration, and countermeasures were insufficient to counteract these effects, even though bed-rest exercise regimen enabled faster recovery.

Changes in fine motor control constrained tasks involving reaching, grasping, and object manipulation, such as the object translation and activity board tests.[19] Most exercises, including those performed on the ISS, are performed on machines[5] that may restrict the neuromuscular coordination required for tasks. For extended missions such as a journey to Mars, a countermeasure must address sensorimotor changes to efficiently reduce postflight postural impairments. Nevertheless, specific occupational tests need to be designed to capture these aspects.

Stress during spaceflight is well documented[37] and must be considered when establishing performance thresholds for occupational and critical tasks. During extended space missions, sleep deprivation, disruptions to circadian rhythms, and work overload are prevalent, contributing to diminished performance, concentration, and alertness.[38] As a result, the likelihood of errors and accidents increases, and the execution of critical tasks may be impaired.

In the studies reviewed, participants underwent varying degrees of familiarization, from none to four practice sessions. However, details about these practice trials and familiarization periods are seldom thoroughly reported in the methods sections. Given that astronauts undergo extensive training to prepare for various scenarios during space missions, it is crucial for simulation protocols to incorporate adequate familiarization. Since some tasks involved the use of weighted suits and unfamiliar equipment, additional practice sessions should be considered to ensure that participants are tested under conditions more closely resembling those faced by astronauts.

The limited number of studies meeting this review's criteria, combined with significant variability in tasks and contexts, impedes the current establishment of definitive standards. Nevertheless, this review identifies the occupational tasks that should serve as the foundation for developing standards in future astronaut PES research. A limitation of this review is the exclusion of conference papers or organization reports from the synthesis, though these may be addressed in the discussion. Such documents often lack the detailed information necessary to evaluate the quality and relevance of occupational assessments effectively. The review is also restricted to French and English due to the authors' language proficiency. However, we believe this does not hinder the identification of articles pertinent to this review on astronaut occupational tasks.

In summary, this review highlights the variety of muscle performance metrics available for predicting success in astronaut mission tasks and explores the physical demands of astronaut tasks, offering new insights into this area of research. Relying solely on standard laboratory tests to establish performance thresholds may overlook critical factors. It is recommended to base thresholds on the actual physical demands of astronaut tasks, irrespective of age or gender. Currently, to the best of the authors' knowledge, no task-specific standards for astronauts have been officially set by NASA or other space agencies. While training to mitigate microgravity effects is well-documented, understanding operational performance in microgravity, especially in deconditioned astronauts, remains limited. This review advocates a shift in fitness assessment to develop tailored PES for astronauts, viewed as tactical athletes.

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