Occupational-Specific Strength Predicts Astronaut-Related Task Performance in a Weighted Suit

Andrew Taylor; Christopher J. Kotarsky; Colin W. Bond; Kyle J. Hackney

BACKGROUND: Future space missions beyond low Earth orbit will require deconditioned astronauts to perform occupationally relevant tasks within a planetary spacesuit. The prediction of time-to-completion (TTC) of astronaut tasks will be critical for crew safety, autonomous operations, and mission success. This exploratory study determined if the addition of task-specific strength testing to current standard lower body testing would enhance the prediction of TTC in a 1-G test battery.

METHODS: Eight healthy participants completed NASA lower body strength tests, occupationally specific strength tests, and performed six task simulations (hand drilling, construction wrenching, incline walking, collecting weighted samples, and dragging an unresponsive crewmember to safety) in a 48-kg weighted suit. The TTC for each task was recorded and summed to obtain a total TTC for the test battery. Linear regression was used to predict total TTC with two models: 1) NASA lower body strength tests; and 2) NASA lower body strength tests + occupationally specific strength tests.

RESULTS: Total TTC of the test battery ranged from 20.2–44.5 min. The lower body strength test alone accounted for 61% of the variability in total TTC. The addition of hand drilling and wrenching strength tests accounted for 99% of the variability in total TTC.

DISCUSSION: Adding occupationally specific strength tests (hand drilling and wrenching) to standard lower body strength tests successfully predicted total TTC in a performance test battery within a weighted suit. Future research should couple these strength tests with higher fidelity task simulations to determine the utility and efficacy of task performance prediction.

KEYWORDS: astronaut task performance, strength to body weight ratio, exercise countermeasures.

Taylor A, Kotarsky CJ, Bond CW, Hackney KJ. *Occupational-specific strength predicts astronaut-related task performance in a weighted suit*. Aerosp Med Hum Perform. 2018; 89(1):58–62.

Exposure to microgravity results in musculoskeletal unloading, which leads to a loss of fitness through reduced muscle size, strength, and endurance.[7] Exercise countermeasures (aerobic and resistance) are mandated and effective to mitigate the loss of fitness,[6,14] but despite these efforts weightlessness can still result in a 30% decrease in leg strength after 9 mo[4] and reduce performance for hand grip and pinch force testing after 180–191 d missions.[10] This deconditioning may compromise astronauts' ability to perform jobs that may have been facile at the beginning of their mission. Thus, the maintenance of a baseline level of fitness is vitally important to both the health of the crewmembers and their ability to perform critical tasks such as extravehicular activity.[7] Furthermore, future space missions to the terrestrial environments of the Moon and Mars will require astronauts to not only have to overcome their deconditioning, but build the infrastructure necessary for the long-term support of life, all the while enclosed in a cumbersome and relatively heavy spacesuit. This raises the question of how fit an astronaut must be at the commencement of their mission so that they can complete these tasks even after experiencing deconditioning; and, more importantly, whether there is an acceptable amount of strength and endurance that can be lost without interfering with the mission.

The methodology used to determine the level of pre-mission fitness is still debated and few studies have explored what the value may be and how it can be tested.[11] Measures used at the

From North Dakota State University, Fargo, ND.

This manuscript was received for review in July 2017. It was accepted for publication in October 2017.

Address correspondence to: Kyle J. Hackney, Ph.D., Assistant Professor, Department of Health, Nutrition, and Exercise Sciences, North Dakota State University, 24 Bentson Bunker Fieldhouse, HNES, PO Box 6050, Dept. #2620, Fargo, ND 58108-6050; kyle.hackney@nsdu.edu.

DOI: https://doi.org/10.3357/AMHP.4961.2018

NASA Johnson Space Center include pre- and postflight isokinetic strength testing of large muscle groups such as the knee extensors and flexors.[5] However, these tests may not be well-suited for predicting the performance of smaller muscle groups of the upper extremities that are most often used in construction or detail-oriented work. Therefore, the purpose of this study was to determine if astronaut related task performance could be predicted by adding specificity to the strength testing. We hypothesized the combination of NASA's standard lower body strength testing with occupationally specific upper body strength testing would improve the ability to predict performance.

METHODS

Subjects

Eight healthy participants (five men, three women; mean ± SD: age = 34.88 ± 3.69 yr, height = 176.06 ± 5.91 cm, body mass = 72.90 ± 8.34 kg) completed six tasks relevant to astronauts performing construction while wearing a 48-kg weighted suit designed to emulate the weight distribution of the NDX-2 space suit. In order of completion, the six tasks were hatch opening, hand drilling, construction wrenching, incline walking, collecting samples, and dragging a crewmember to safety. These tasks were coupled with a knee extensor-flexor strength and endurance testing identical to that used at NASA Johnson Space Center for pre-post flight strength assessment[5] and three occupational-specific strength tests (hatch opening, hand drilling, construction wrenching) that were novel to the study. To be eligible for the study, participants had to be of typical astronaut age (between 30 and 54 yr), generally healthy, and a nonsmoker with no history of muscle, skeletal, heart or lung impairment or disease. Health status was determined from a physical activity readiness questionnaire[2] and a health history questionnaire.[3] The study protocol was approved in advance by North Dakota State University Institutional Review Board. Each subject provided written informed consent before participating.

Equipment

Height and body mass were measured using a digital scale (Denver Instruments, DA series, Denver, CO) and stadiometer (Seca 213, Chino, CA) prior to a 5-min, pretrial warm-up on a cycle ergometer (Monark 828E Ergometer Testing Bike, Monark Exercise AB, Vansbro, Sweden). Following the warm-up, knee extensor-flexor strength and endurance were measured using the NASA standard strength and endurance protocol, which included 3 repetitions of extension and flexion at an angular velocity a of $60° \cdot s^{-1}$ followed by a 30-s rest period, then 21 repetitions of extension and flexion at $180° \cdot s^{-1}$ angular velocity.[5] Participants were instructed to complete these measurements with maximal effort as quickly and safely as possible. Measurements of peak torque and total work for hatch opening, hand drilling, and construction wrenching as well as the NASA standard strength tests were performed using a Biodex System 4 Pro (Biodex Medical Systems, Shirley, NY). Measurements for heart rate were extracted using a heart rate monitor and watch (Polar N2965, Accurex IIa, Kempele, Finland). Oxygen utilization ($\dot{V}O_2$), respiratory exchange ratio, and time-to-completion (TTC) data during hatch opening, hand drilling, construction wrenching, and inclined walk were taken using a metabolic cart (Ultima Series Medgraphics, St. Paul, MN), which was calibrated in accordance with manufacturer recommendations prior to each data collection session. TTC data for sample collection and emergency crewmember drag were recorded using a stopwatch (Pro survivor, 601×-3v, Accusplit, Pleasanton, CA).

Procedures

Participants visited and completed all measurements and trials during a single visit, with one exception. One subject had to return on a second day to complete the incline walking task due to an equipment malfunction. Following the NASA standard measure of knee extensor-flexor strength-endurance, participants were equipped with a weighted backpack and a series of weights across their body totaling 48 kg to simulate the NDX-2 space suit (de Leon P. Personal communication; March 2014). The distribution of weights in the suit were: ankle = 9.07 kg, chest = 11.34 kg, waist = 9.07 kg, wrist = 2.29 kg, and backpack = 15.88 kg, for a total = 47.63 kg. After donning the weighted suit, the participants completed the six tasks outlined below that were modified based on the work of Ryder et al.[11] Prior to the timed trial for each task, each participant was provided with three to five practice repetitions to assure the tasks could be safely completed and provide the subject with some insight into the difficulty of the tasks. Following each task, each subject was provided 5 min between each task to recover, obtain water, and adjust the weighted suit. The total time of the testing session was approximately 1 h 30 min, but varied slightly depending on how quickly the participant completed each task.

Task 1: hatch opening. To simulate the motions of opening or closing a hatch, the Biodex upper extremity wheel attachment was affixed to the Biodex dynamometer head. The dynamometer head was raised to position 10 and oriented such that the wheel's arc of motion was perpendicular to the floor. Participants first completed an isometric strength trial consisting of one set of three repetitions, applying force for 3 s in both clockwise and counterclockwise directions during each repetition. Following the strength test, participants completed an endurance trial that required them to turn the wheel clockwise and counterclockwise against an isotonic resistance of $10 \text{ N} \cdot \text{m}^{-1}$ until 15 kJ of work had been performed by the wheel.

Task 2: hand drilling. To simulate the motions of using a hand drill during a construction task, the Biodex lateral rotating pinch attachment was installed into the multiple tool adapter that was then itself affixed to the Biodex dynamometer head. The head was raised to position 10 and set such that the armature's arc of motion was perpendicular to the floor. Participants first completed an isometric strength trial consisting of one set of three repetitions, applying force for 3 s in both clockwise and counterclockwise directions during each repetition. Following the strength test, participants completed an endurance trial that required them to move the armature through the dynamometer's entire arc of motion both clockwise and a counterclockwise against an isotonic resistance of $2\ N \cdot m^{-1}$ until a total of 100 repetitions had been performed.

Task 3: construction wrenching. To simulate the motions of using a wrench or lever during a construction task, the Biodex upper extremity wrench attachment was affixed to the Biodex dynamometer head. The head was raised to position 4 and rotated upwards at 90° such that the wrench's arc of motion was parallel to the floor. Participants first completed an isometric strength trial consisting of one set of three repetitions, applying force for 3 s in both clockwise and counterclockwise directions during each repetition. Following the strength test, participants completed an endurance trial that required them to move the wrench both clockwise and counterclockwise against an isotonic resistance of $40\ N \cdot m^{-1}$ until 20 kJ of work had been performed. Additionally, participants were also instructed to use their entire body while keeping a consistent stance, but were allowed to self-select a comfortable range of motion.

Task 4: inclined walk. In this task, participants walked for 0.8 km (0.5 mile) on a treadmill (Full Vision, Inc, Newton, KS) programmed to increment its angle of inclination by 1° every 2 min until it reached 5°, at which point it began to decline at an identical rate down to 0°. Note that this program was maintained regardless of the subject's pace, and some participants finished before the incline returned to 0°.

Task 5: sample collection. The sample collection task required participants to collect nine medicine balls arranged in two successive rows at 3 and 6 m from a designated starting position. Participants were instructed to retrieve the samples from the first row and then the second using safe lifting practices (e.g., flexing at the knee and hip) and return them to a storage rack. The mass of the samples were 5.4 kg, 5.4 kg, 5.0 kg, 4.0 kg, 3 kg, 2.7 kg, 2.7 kg, 2.0 kg, and 1.0 kg.

Task 6: emergency crewmember drag. The final task required the participant to drag a 54-kg dummy across 13.5 m. The participant was instructed to drag the dummy 8.5 m until they reached an orange cone, at which point the participant would turn 90° and drag the dummy an additional 5 m to a second cone.

Statistical Analysis

This study's dependent variables included total TTC, which was calculated by summing the TTC of each of the six individual tasks performed in the weighted suit. Basic descriptive statistics including means, standard deviations, and confidence intervals were used to explore the dependent variables. Linear regression using an enter method was used to predict total TTC using two independent variable models, which included NASA standard measures alone and NASA standard measures with the addition of hatch opening, hand drilling, and construction wrenching isometric strength. Hatch opening isometric strength was excluded from the second model due to collinearity. The authors recognize that the sample size is marginal for this type of analysis, hence we consider this analysis exploratory. Analysis of variance was used to determine differences in task performance for duration, peak $\dot{V}O_2$, respiratory exchange ratio, heart rate, and ratings of perceived exertion. Significance was set at $P < 0.05$, but when significance was obtained Bonferroni corrections were applied to reduce type II error.

RESULTS

Total TTC of the test battery ranged from 20.2–44.5 min. NASA upper leg standard measures alone (KE peak torque, KF peak torque, KE total work, KF total work) accounted for 61.5% of the variability in TTC [$F(4,7) = 3.799$, $P = 0.15$]. The addition of hand drilling (average torque toward and away) and wrenching (average torque toward and away) to NASA upper leg standard measures

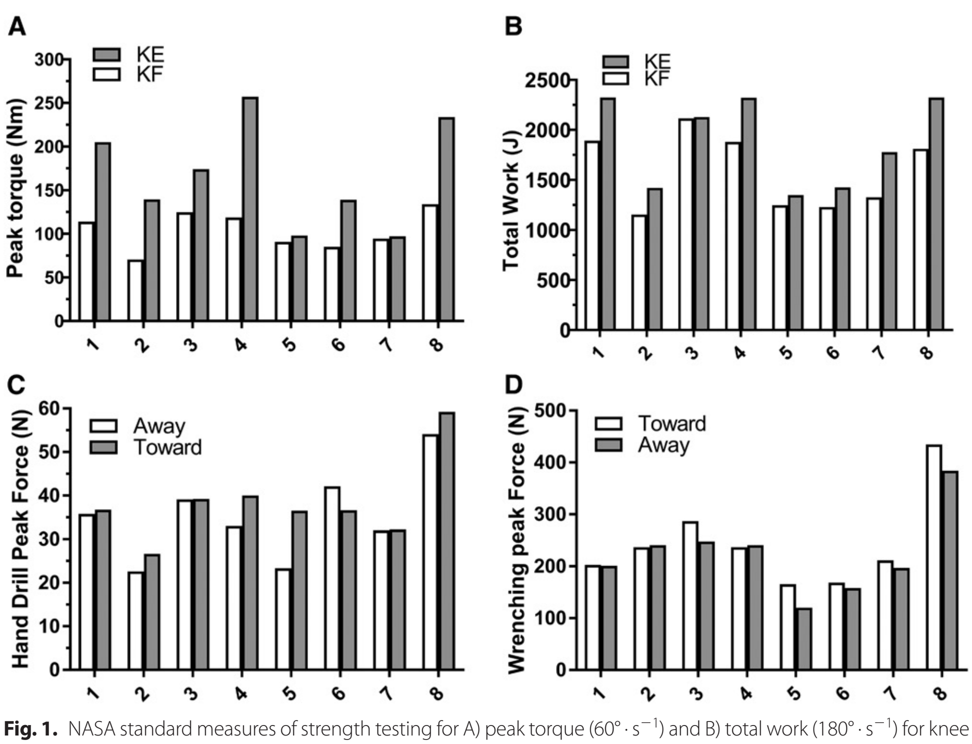

Fig. 1. NASA standard measures of strength testing for A) peak torque ($60° \cdot s^{-1}$) and B) total work ($180° \cdot s^{-1}$) for knee extension (KE) and flexion (KF). Occupational specific strength testing ($0° \cdot s^{-1}$) both toward and away for C) hand drilling and D) construction wrenching.

Table I. Gender Comparisons for Various Strength Assessments ($N = 8$).

ASSESSMENT	MEN	WOMEN	T-SCORE	DF	*P*-VALUE
KE peak torque $60° \cdot s^{-1}$ (Nm)	194 ± 62	126 ± 24	−1.778	6	0.126
KF peak torque $60° \cdot s^{-1}$ (Nm)	113 ± 14	76 ± 7*	−4.199	6	0.006
KE Total Work $180° \cdot s^{-1}$ (J)	2175 ± 237	1431 ± 87*	−5.096	6	0.002
KF Total Work $180° \cdot s^{-1}$ (J)	1806 ± 291	1227 ± 63*	−3.301	6	0.016
Hatch Opening Away $0° \cdot s^{-1}$ (N)	104 ± 36	87 ± 33	−0.681	6	0.521
Hatch Opening Toward $0° \cdot s^{-1}$ (N)	111 ± 41	77 ± 19	−1.351	6	0.226
Wrenching Away $0° \cdot s^{-1}$ (N)	262 ± 71	160 ± 40	−2.230	6	0.067
Wrenching Toward $0° \cdot s^{-1}$ (N)	301 ± 111	198 ± 17	−1.539	6	0.175
Hand Drilling Away $0° \cdot s^{-1}$ (N)	36 ± 12	34 ± 10	−0.302	6	0.773
Hand Drilling Toward $0° \cdot s^{-1}$ (N)	39 ± 12	37 ± 1	−0.382	6	0.716

(KE peak torque, KF peak torque, KE total work, KF total work) accounted for 99.6% of the variability in time-to-completion [$F(6,7) = 264.205$, $P = 0.047$]. Lower leg standard measures, hand drilling, and construction wrenching data for each participant are shown in **Fig. 1** and **Table I**. **Table II** shows the hatch opening strength assessments data for right and left sides. There were significant differences in the task time [$F(5,42) = 35.928$, $P < 0.001$], aerobic metabolism [$F(3,28) = 8.599$, $P < 0.001$], and fuel utilization [$F(3,28) = 4.253$, $P = 0.014$] of astronaut related tasks, but no significant differences in heart rate [$F(3,28) = 2.704$, $P = 0.064$] or perceptual intensity [$F(5,41) = 2.123$, $P = 0.082$]. Pairwise comparisons with Bonferroni corrections are shown in **Table III**.

DISCUSSION

Current pre-mission fitness assessments employed by NASA are limited to lower body strength and endurance tests, which may fail to account for upper extremity occupational specific fitness. Thus, our purpose was to assess the predictive capacity of an occupationally specific upper extremity strength test in conjunction with NASA's standard lower extremity strength and endurance assessment on total TTC of six occupationally specific tasks. The main finding of this study was that the inclusion of astronaut-related upper body strength testing—hand drilling and construction wrenching—significantly predicted task performance time when combined with NASA's lower body standard measures testing. These data suggest that more occupationally specific strength assessments could be useful for predicting the TTC of tasks that astronauts may perform compared to strength testing that has been historically performed for Shuttle Transport System and International Space Station missions.[5] The results of this study also expand on the importance of identifying potential limiting factors for astronaut-related task performance.[11]

Correctly identifying these limiting factors will be crucial to future space missions, given NASA's current goals are to limit strength loss to no more than 20%.[9] However, this flat percentage does not take into consideration the variability in starting strength levels, which may be influenced by gender or age, and is typically related to larger muscle groups such as the knee extensors-flexors, plantar-dorsi flexors, or trunk. Thus, while a 20% loss of muscle strength for one crewmember may not impair them during the course of their duties because of their high starting level of fitness or dexterity, even a 10% loss of muscle strength for a less fit crewmember may restrict them from survival-critical tasks such as overcoming the resistance of an airlock door.[7] In particular, the force capability of smaller hand, wrist, and forearm muscles are highly variable and may be critical for specialized tasks related to construction, especially within a pressurized spacesuit with gloves. Interest in the strength of these muscles beyond microgravity-induced deconditioning decrements may be further warranted given the hand is the most common location for injury during spaceflight missions.[13] Future research with larger samples sizes for both men and women is needed to characterize if the occupational tasks differ by gender or age. Our preliminary data show some differences in the lower body tasks, but not in the newly developed occupational tasks.

The metabolic data reported in the current study demonstrate the energy demand of many of the tasks implemented in the performance battery. During long duration space missions, NASA attempts to prevent $\dot{V}O_{2peak}$ losses of greater than 25% and to maintain an aerobic capacity greater than $\sim$32.9 ml · kg · min^{-1}.[9] In this simulation none of the mean $\dot{V}O_{2peak}$ values obtained during the occupational tasks completed for performance time were greater than the NASA defined value ($\sim$32.9 ml · kg · min^{-1}), suggesting this current recommendation remains valid. Similarly, the highest $\dot{V}O_{2peak}$ reported was our longest task simulation ($\sim$15 min), the inclined walk at $\sim$32.3 ml · kg · min^{-1}.

It should of course be noted here that physiological deconditioning, encumbrance of an actual suit, hypogravity, and many other relevant stressors or environmental factors were not present in this study. Few studies have reported actual metabolic data within a planetary space suit during simulated hypogravity using tasks that astronauts may actually have to perform during exploration.[8] More common approaches to define these parameters include 1-G field tests,[1] 1-G weight suit simulations,[11] or simulated hypogravity using harnesses,[12] all of which bear results consistent with those of the present investigation. Further, given the tasks and weighted suit were foreign to the participants, additional practice via a separate familiarization trial

Table II. Hatch Opening Peak Force for Each Participant ($N = 8$).

PARTICIPANT (#)	AWAY (*N*)	TOWARD (*N*)
1	114.5	80.2
2	55.5	66.3
3	145.1	162.5
4	112.2	95.6
5	50.0	56.2
6	95.3	93.4
7	80.1	86.3
8	127.7	145.4

Table III. Metabolic, Cardiovascular, and Perceptual Indicators of Task Intensity.

	DURATION (min)	$\dot{V}O_{2PEAK}$ ($ml \cdot kg \cdot min^{-1}$)	RER PEAK ($\dot{V}CO_2/\dot{V}O_2$)	HR PEAK (bpm)	RPE (ARBITRARY UNITS)
Hatch Opening	4.11 ± 2.28‡≠	24.80 ± 4.36	1.44 ± 0.21†	154.88 ± 23.55	6.87 ± 2.32
Hand Drilling	3.06 ± 0.40‡	18.53 ± 3.01†	1.29 ± 0.15	135.63 ± 25.44	5.50 ± 2.06
Construction Wrenching	4.64 ± 1.80‡≠	28.32 ± 6.30ǂ	1.19 ± 0.08*	158.63 ± 14.75	6.75 ± 1.85
Inclined Walk	14.54 ± 4.59*ǂ†≠	32.28 ± 6.57ǂ†	1.18 ± 0.10*†	164.50 ± 14.10	6.25 ± 1.98
Sample Collection	1.58 ± 0.56‡	ND	ND	158.63 ± 09.81	4.25 ± 1.48
Emergency Drag	0.39 ± 0.11*‡	ND	ND	157.00 + 10.91	4.79 ± 1.73

Data are mean ± SD; ND = no data given metabolic cart mobility limitations.
RER: respiratory exchange ratio; HR: heart rate; RPE: ratings of perceived exertion.
* Significantly different from hatch opening, ǂsignificantly differently from hand drilling, †significantly different from construction wrenching, ‡significantly different from inclined walking, §significantly different from sample collection, ≠significantly different from emergency drag.

may help decrease the TTC of the different tasks. Hence, the question of what boundaries exist on an astronaut's minimum fitness remains difficult to answer; in fact, to our knowledge there are no standards for astronaut related tasks or task durations that have been released by NASA as of yet that could be used to create a baseline level of fitness. Further research will be needed to more adequately determine metabolic cut points for future missions beyond low Earth orbit.

This study shows that occupationally related strength testing combined with current NASA lower body testing can be used to enhance the prediction of astronaut-related task performance. Hand drilling and wrenching strength indices represent smaller, upper body muscle groups that can limit performance in detail oriented or construction work. While further studies with a greater sample size and high-fidelity task simulations will be needed to determine the utility and efficacy of performance prediction, these data can be used to enhance current standard measures strength testing for future space missions.

ACKNOWLEDGMENTS

We would like to thank ND NASA EPSCOR for supporting this project.

Kyle Hackney designed the study and wrote drafts of the manuscript, Andrew Taylor and Christopher Kotarsky participated in data collection and edited drafts of the manuscript, and Colin Bond performed statistical analysis and edited drafts of the manuscript. All four authors approved the final version of the manuscript.

Authors and affiliations: Andrew J. D. Taylor, MSEE, BSEE, Kyle J. Hackney, Ph.D., M.Ed., and Christopher J. Kotarsky, M.S., North Dakota State University, Fargo, ND; and Colin W. Bond, M.S., Sanford Sports Science Institute, Sanford Health, Fargo, ND.

REFERENCES

1. Ade CJ, Broxterman RM, Craig JC, Schlup SJ, Wilcox SL, Barstow TJ. Relationship between simulated extravehicular activity tasks and measurements of physical performance. Respir Physiol Neurobiol. 2014; 203:19–27.
2. American College of Sports Medicine. ACSM's Health/Fitness Facility Standards and Guidelines. Champaign (IL): Human Kinetics; 1997.
3. American Council on Exercise. Health History Questionnaire. San Diego (CA): American Council on Exercise; 1996.
4. di Prampero PE, Narici MV. Muscles in microgravity: from fibres to human motion. J Biomech. 2003; 36(3):403–412.
5. English KL, Lee SM, Loehr JA, Ploutz-Snyder RJ, Ploutz-Snyder LL. Isokinetic strength changes following long-duration spaceflight on the ISS. Aerosp Med Hum Perform. 2015; 86(12, Suppl.)A68–A77.
6. Fitts RH, Trappe SW, Costill DL, Gallagher PM, Creer AC, et al. Prolonged space flight-induced alterations in the structure and function of human skeletal muscle fibres. J Physiol. 2010; 588(Pt. 18):3567–3592.
7. Hackney KJ, Scott JM, Hanson AM, English KL, Downs ME, Ploutz-Snyder LL. The astronaut-athlete: optimizing human performance in space. J Strength Cond Res. 2015; 29(12):3531–3545.
8. Norcross JR, Clower KG, Clark T, Harvill L, Morency R, et al. Metabolic costs and biomechanics of inclined ambulation and exploration tasks in a planetary suit. Hanover (MD): NASA Center for AeroSpace Information; 2010.
9. Ploutz-Snyder LL, Ryder JW, English KL, Buxton RE, Bloomberg JJ, Ploutz-Snyder R, editors. Strategies for identification of strength thresholds for exploration tasks. Human Research Program Investigators Workshop: Integrated Pathways to Mars; 2015; Galveston, TX. Cleveland (OH): NASA Glenn Research Center; 2015.
10. Puglia I, Balsamo M, Vukich M, Zolesi V. Long term microgravity effects on isometric hand grip and precision pinch force with visual and proprioceptive feedback. International Journal of Aerospace Engineering. 2017; (in press).
11. Ryder JW, Buxton RE, Goetchius E, Scott-Pandorf M, Hackney KJ, et al. Influence of muscle strength to weight ratio on functional task performance. Eur J Appl Physiol. 2013; 113(4):911–921.
12. Salisbury T, Baptista RR, Fei J, Susin F, Russomano T. Physiological aspects of walking in simulated hypogravity. Journal of Exercise Physiology. 2015; 18(6):13–23.
13. Scheuring RA, Mathers CH, Jones JA, Wear ML. Musculoskeletal injuries and minor trauma in space: incidence and injury mechanisms in U.S. astronauts. Aviat Space Environ Med. 2009; 80(2):117–124.
14. Trappe S, Costill D, Gallagher P, Creer A, Peters JR, et al. Exercise in space: human skeletal muscle after 6 months aboard the International Space Station. J Appl Physiol. 2009; 106(4):1159–1168.