Ergonomics Evaluation of Three Operation Postures for Astronauts

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Abstract. Push/pull is very common and frequent activity for astronauts in the space operation. For the sake of researching on the strength change of astronauts' upper limbs during different operation postures, this paper major on performed the simulation aviation operation experiment. The paper quantitatively evaluates the absolute peak force, relative peak force of human single left/right hand and strain energy of grip made by operating force in comfortable, horizontal widest, and longitudinal widest span. The result here demonstrates that absolute peak force, relative peak force, strain energy are effective factors to estimate upper limbs strength, and the individual upper limbs power is significantly effected by different postures.

Keywords: astronaut, upper limb, absolute peak force, relative peak force, strain energy.

1 Introduction

Astronauts play a very important role in manned spacecraft system. In microgravity environment, however, they must go through decreases in muscle tone mass, alterations in the neuromuscular functions, etc. As the results, these changes of skeletal muscle will induce the remodeling of muscle, and then decrements occur in skeletal muscle strength, fatigue resistance, motor performance and connective tissue integrity[1].Within the investigation of spaceflight experience and previous studies: the maximal force of several muscle groups showed a substantial decrease (6-25% of pre-flight values), the maximal power during very short "explosive" efforts of 0.25-0.30s showed an even greater fall, being reduced to 65% after 1 month and to 45% (of pre-flight values) after 6 months[2]. Therefore, astronauts must expose to different degrees of altered performance in strength, endurance, balance, coordination, and the ability to ambulate in different muscle groups in the various mission specific periods. The structural degradation of muscle functions could increase the risk of health and interfere with the safe completion of critical tasks during spaceflight or during emergency procedures or EVA (Extravehicular Activity).

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The evaluation for the skeletal muscle characteristics has become global research hot spot in the field of Manned Space Flight, with significant theoretical meaning. A large number of studies have been performed to obtain quantitative criteria of muscle function not only in ground-based experiments but also in on-orbit tasks: with humans currently occupying the International Space Station (ISS) for six months and space exploration missions of one to three years on the earth. NASA had designed the Effect of Prolonged Space Flight on Human Skeletal Muscle Program to assess muscle volume [3,4]. The other study-Evaluation of Skeletal Muscle Performance and Characteristics [5] has similar purpose of understanding muscle de-conditioning and evaluating the effects of the in flight countermeasures on muscle performance. Within this experiment, a survey of hand endurance was carried out at current and relative strength levels with a hand dynamometer. When monitored the current strength, the subjects will be asked to hold a 50% as long as possible, the absolute endurance was assessed with a series of contractions(3s contraction, 2s relaxation) at 75% of preflight strength, but relative endurance was (relative to 50% current level of strength) increased or was maintained after long duration flight. Muscle Atrophy Research and Exercise System (MARES) sponsored by ESA, is capable of supporting measurements and exercises on seven different human joints, encompassing nine different angular movements, as well as two additional linear movements(arms/legs)[6,7]. It's considerably more advanced than current ground based medical dynamometers (measure force or torque). MARES could gather the datum for parameters, such as position control, velocity control, torque/force control and quick release that is generally associated with any desired external devices. The Enhanced Dynamic Load Sensor (EDLS) experiment was established in the Mir habitat module to respond to the crew-induced forces and torques imparted on interior surfaces. Analysis of collected datum indicated that the crew loads induced on module internal structures were no greater than 70N at a frequency of range from 0 to 10 Hz [8,9,10,11,12].

From above mentioned research experiences, it is directed that a successful measurement and evaluation for skeletal muscle activity is important to understand the operators' physiological capabilities and limitations. The capabilities and limitations of operators as critical factors will affect safety, performance, and productivity for spaceflight tasks. In order to evaluate the local load of astronauts arm muscles, the ground based experiment was conducted in this study. So two especial circumstances were simulated: ① when subjects participate in this experiment, they must put on the spacesuit which inner excessive pressure is 40Kpa and inner temperature fluctuates from 18 to 26℃; ② the body of subject who wore spacesuit was supported by a metal ring frame near the centre of waist, the feet of subject were hung in the air and slightly attached the ground. Three issues that relate to the muscles activity were concerned: ① the type of manual handling, push and pull behaviors were paid attention in this study; ② the mechanical properties of skeletal muscle, focus was paid on the isometric (static) contraction; ③ the position of upper limb, three positions which two arms of operators relative to their chest was considered.

2 Method

2.1 Subjects

11 healthy male volunteers took part in the laboratory study. According to the normal criterion of Body Mass Index (BMI) for adults in China is between 19 and 25, subjects whose BMI is coincident with the criterion were selected. All subjects were in good health and must not be suffering from physical complaints at the time of study.

2.2 Simulation of the Operation Task

The handle which is mainly made of alloy steel with implanted six-dimensional (3D forces/moments) strain transducer was designed for this test. The handle's holding rod is 20cm long. Two handles are both fixed on the Lucite plate with measuring scale which has scale mark on its surface, accurately indicating the installation location of handles.

Based on the experience from human spaceflight push/pull is very common activities in the space operation, for instance, hatch opening, traversing in the space capsule, and climbing the ladder on the outside surface of vehicles. The simulation mainly consisted of push/pull activities. The three positions that two arms of operators relative to the body themselves were considered: ① *P1*, left/right handles located at comfortable height and width over the subjects' chest; ② *P2*, the widest span between left and right handle that at comfortable height over the subjects' chest; ③ *P3*, put the left handle above chest and right handle under chest, the furthest span between left and right handle that at comfortable width over subjects' chest (see Fig.1).

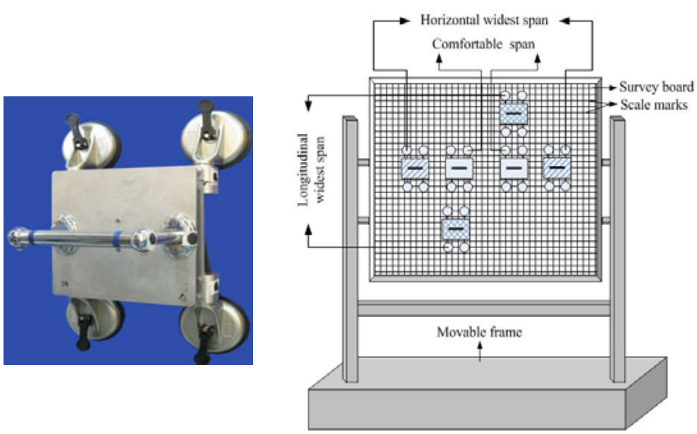


Fig. 1. Real handle object and its installation location

2.3 Procedures

The participants operated handles at P1, P2, P3 positions when they wore the spacesuit. There are two measurement statues that included single left-hand and right-hand operation. In addition, there are six-way measurement directions that included left/right, forward/back, up/down (Table1). Thereby, the overall experiment was carried out in six sub-tests. Taking the density of carbon dioxide inner the spacesuit into account, each sub-test lasted about 5±1min, between these sub-tests, the subjects were allowed to rest for about 2min (5±1min contraction, 2min relaxation). An additional emergency break was also allowed in the experiment for the health of subjects. Each measuring directions consisted of three successive push/pull isometric contractions short intervals (12s). Participants finish the push/pull tasks by their most strongly force according with their feelings.

Table 1. Operating force measurement list

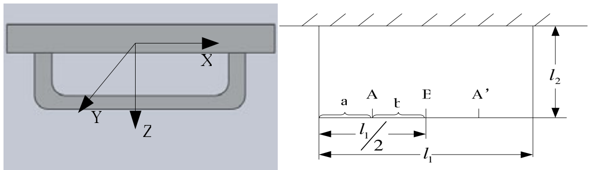
Positions	Status	Directions
$P1$ $P2$ $P3$	Single left-hand / Single right-hand	left right up down front back

2.4 Data Analysis

In order to verify the effect of different positions in the evaluation of push and pull isometric contractions for participants, the different forces of sub-tests in simulated situations were measured by the strain transducers of handles. Results from transducer recordings were analyzed for the absolute peak forces, the relative peak forces, and the strain energy of handles. Choosing the peak forces in measurement results of the three successive push/pull isometric contractions as the push-pull effort was called the absolute peak forces, $F_{abs-peak}$ (N). The quotient that the absolute peak forces divided by the weight of operators themselves is the relative peak forces, $F_{rel-peak}$ (N/kg):

$$F_{rel-peak} = \frac{F_{abs-peak}}{W} \tag{1}$$

There is no velocity and displacement when muscles complete isometric contractions. In order to give a description of the energy for operations a method applied strain energy to estimate operators' energy is proposed in this paper. V_{ε} is used to represent strain energy. Fig. 2a shows the coordinate of the handle, Fig. 2b provides the parameters of the handle.



a. The coordinate of handle b. The parameters of handle

Fig. 2. The handle illustration

Strain energy for the grip (SEG) of handles was calculated using the following formula (2-7):

$$V_{\varepsilon-axes1} = \frac{(\frac{1}{2}F_x)^2 \cdot (\frac{1}{2}l_1)}{2E_1A_1} \tag{2}$$

Where: $V_{\varepsilon-axes1}$ = SEG along grip axes (J), F_x =the operating force in direction X, E_1 = Young’s modulus of the grip (N/m^2), A_1 = cross sectional area of the grip (m$^{2)}$;

$$V_{\varepsilon-twist1} = \frac{(\frac{1}{2}M_x)^2 \cdot a}{2G_1I_{p1}} + \int_0^b (\frac{1}{2}M_x \cdot \frac{b-x}{x}) \cdot \frac{1}{G_1I_{p1}}dx \tag{3}$$

Where: $V_{\varepsilon-twist1}$ = SEG along grip twist (J), M_x =the operation moment in direction X, G_1 =shear modulus of the grip, I_{p1} = polar moment of inertia of the grip(m^4), I_1 = cross sectional moment of inertia of the grip (m^4).

The grip of handle consists of hollow cylinder, so:

$$I_p = \frac{\pi D^4}{32}(1-\alpha^4) \quad , \quad I = \frac{\pi D^4}{64}(1-\alpha^4) \tag{4}$$

Where: D =external diameter(m), d =interior diameter (m).

Otherwise, the mathematical formula considering strain energy along grip bend in indirection Z and Y are as following, respectively:

$$V_{\varepsilon z-bend1} = \int_0^a \frac{(\frac{1}{2}M_z - \frac{1}{2}F_y \cdot x)^2}{E_1I_1}dx + \int_0^b \frac{(\frac{1}{2}M_z - \frac{1}{2}F_y \cdot a - \frac{1}{2}F_y \cdot \frac{bx-x^2}{2b} - \frac{1}{2}F_y \cdot \frac{x}{2})^2}{E_1I_1}dx \tag{5}$$

Where: $V_{\varepsilon z-bend1}$ = SEG along grip bend in direction Z (J), F_y the operating force in direction Y (N), M_z the operation moment in direction Z (N • m).

$$V_{\varepsilon y-bend1} = \int_0^a \frac{(\frac{1}{2}M_y + \frac{1}{2}F_z x)^2}{E_1I_1}dx + \int_0^b \frac{(\frac{1}{2}M_y + \frac{1}{2}F_z \cdot a + \frac{1}{2}F_z \cdot \frac{bx-x^2}{2b} + \frac{1}{2}F_z \cdot \frac{x}{2})^2}{E_1I_1}dx \tag{6}$$

Where: $V_{\varepsilon y-bend1}$ = SEG along grip bend in direction Y (J), F_y the operating force in direction Z (N), M_z the operation moment in direction Y (N • m).

The overall SEG when subjects applied power on the grip was define as:

$$V_{\varepsilon-grip} = \frac{V_{\varepsilon-axes1} + V_{\varepsilon-twist1} + V_{\varepsilon z-bend1} + V_{\varepsilon y-bend1}}{2} \quad (7)$$

3 Results

3.1 Anthropometric Data of Subjects

The collective of subjects has specific characteristics with respect to BMI19~25. All subjects were on an average 168.66±3.83cm tall, 65.97±4.59Kg weight and 30±5 years old. The distributions of weight and height for 11 subjects are presented in Fig. 3.

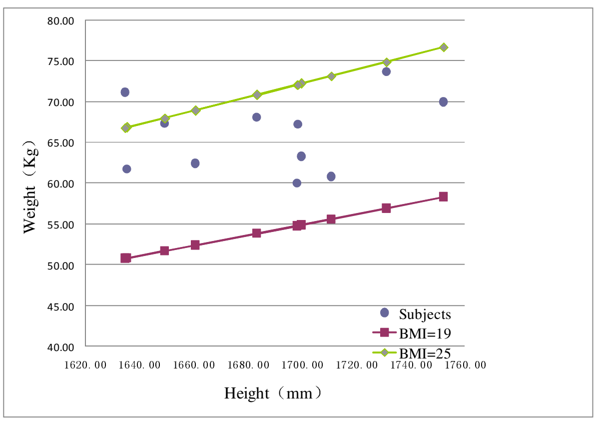


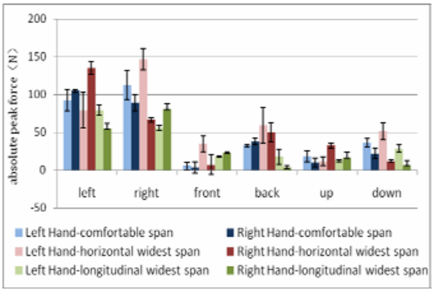
Fig. 3. Distributions of weight and height for subjects

3.2 Absolute/ Relative Peak Forces

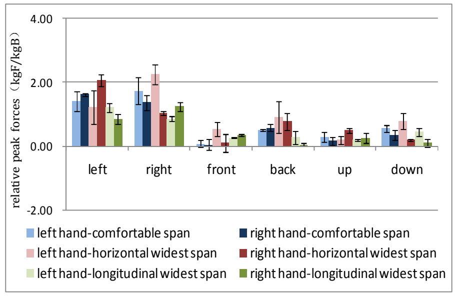
The absolute/relative peak operation strength of single left/right hand at 3 postures in 6-dimensional direction was presented in Fig.4.

3.3 Strain Energy for Grip

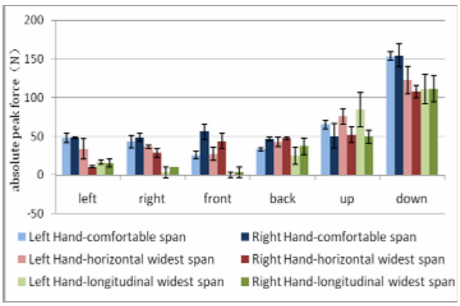
The grip is alloy steel which will result the slightly energy from subjects operation. Due to the difference of grip's transformation, corresponding energy level is very low. In y-axis of Fig.5, the strain energy of grip is expressed in units of 10^{-6} joules (J).



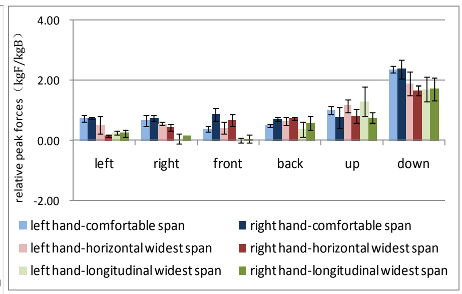
a1) X- direction absolute peak forces



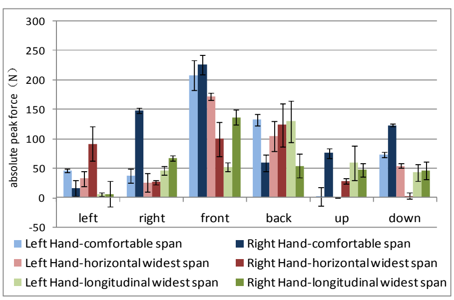
a2) X- direction relative peak forces



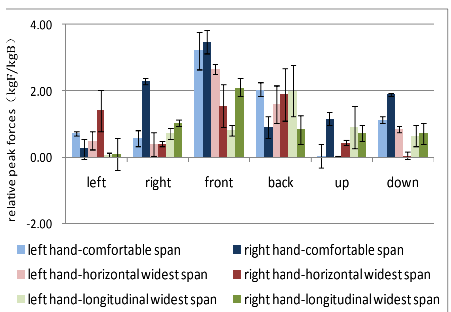
b1) Y-direction absolute peak forces



b2) Y-direction relative peak forces



c1) Z-direction absolute peak forces



c2) Z-direction relative peak forces

Fig. 4. Absolute/ relative peak forces at 3 postures 6-D directions of single left/right hand

4 Discussions

(1)Based on the description of 11 subjects about manipulation idioms, all of them are used to prefer to right/dominant side, but the movements were not higher for the right/dominant side than for left/non-dominate when they wore spacesuit in all three postures (Fig. 6). This is caused by a multifaceted aspect, one of the most important reasons is that both of arms motion were restricted by the flexibility and the range of spacesuit’s joint, for example, wrist, elbow and shoulder joint. Simultaneously, the motion of arms must overcome the obstacles of excessive pressure 40Kpa inner spacesuit when subjects completed extending and bending actions. In extreme circumstances, the predominance of right hand, such as strength, balance stability, and alternant perception between brain and limbs, will go down. As non-dominant hand, left side is even more skillfully than right/dominant side.

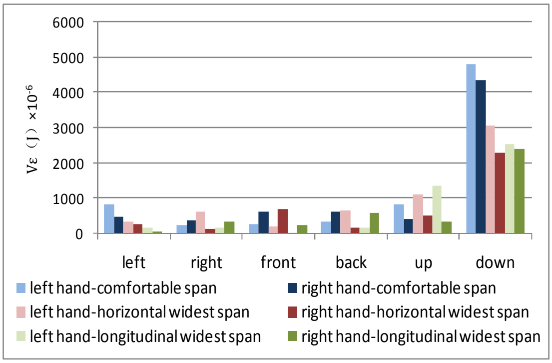


Fig. 5. SEG at 3 postures in 6-D directions of single left/right hand

(2) In Fig. 6, it also revealed that in the direction of applying force, the minimum of peak force appears at longitudinal widest span by right hand up-direction pushing, it is 49.28±8.28N. The maximum of peak force appears at comfortable span by right hand forward-direction pushing. It is 226.18±16.37 N. Meanwhile, for all three postures, the average of peak force in Z-axis is maximum (149.36N), and the average of peak force in Y-axis is minimum (62.83N).

(3) These stability of operating force in Z-axis by left hand was the worst, namely forward and backward push/pull behavior, the standard deviation in Z-axis of three postures is 66.40N. The stability of operating force in Y-axis by left hand was the best, namely up and down push/pull behavior, the standard deviation in Y-axis of three postures is 14.70N.

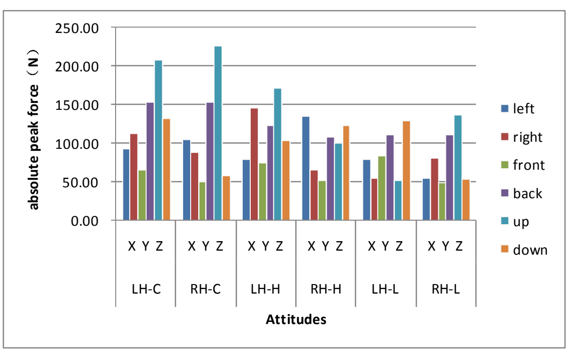


Fig. 6. Comparison with the 3-D forces at three postures of single left/right hand*

*LH-C/RH-C: left/ right hand comfortable span; LH/RH-H: left/ right hand horizontal widest span; LH/RH-L: left/ right hand longitudinal widest span.

(4) Either left or right hand, SEG made by down-direction action greater than other direction in 3 operation postures.

(5) In accordance with the relative force evaluation standard: over 2.49, Excellent "A"; 2.48~2.17, good "B"; 2.16~1.95, favorable "C"; 1.94~1.65, bad "D"; below 1.64, poor "E". The strength of operating force can be divided into five ranks (Table 2).

Table 2. Operating force with relative force evaluation standard

		X-axis relative force	rank	Y-axis relative force	rank	Z-axis relative force	rank
P_1	left hand	1.4	E	1.01	E	3.21	A
		1.73	D	2.36	B	2.05	C
	right hand	1.61	E	0.78	E	3.48	A
		1.37	E	2.38	B	0.91	E
P_2	left hand	1.22	E	1.16	E	2.66	A
		2.26	B	1.89	D	1.61	E
	right hand	2.08	C	0.80	E	1.54	E
		1.02	E	1.66	D	1.90	D
P_3	left hand	1.22	E	1.30	E	0.80	E
		0.86	E	1.71	D	2.00	C
	right hand	0.85	E	0.76	E	2.10	C
		1.25	E	1.72	D	0.83	E

5 Conclusions

This paper deals with the study of simulation aviation operation experiment, three parameters were applied to quantitatively assess the musculoskeletal strength of upper limb when human performed isometric contraction on 6-D pushing and pulling at three postures: absolute peak force, relative peak force, strain energy. The result here demonstrates that above three indexes are specific and effective approaches available to successfully estimate the change of upper limb strength in 3 postures, and the individual upper limb power was significantly affected by different postures Astronauts' operations remain a critical factor in safe and efficient aviation operations. In the future, biomechanics combined with the EMG signal will be important tool that can better address human operation evaluation issues. How to move the study of these issues out of the laboratory and apply it into real world operating environments is still a grand challenge.

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