An Upper Limb Exoskeleton Design for Reduced Gravity Training of Astronauts

Jiang Yifan, *Qiao Bing* *

College of Astronautics, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, P. R. China

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Abstract: A wearable passive exoskeleton is proposed for reduced gravity astronauts training. The main component unit of the proposed robotic exoskeleton is the spring-based parallelogram mechanism which can passively balance any proportion of the gravity load acting on it through designing an appropriate stiffness of the spring or adjusting the install position of the spring. A conceptual exoskeleton model capable of gravity compensation for upper limbs applying to such technology is designed and the corresponding simulation is presented, in which the muscle activations are collected to show the effectiveness of the design.

Key words: gravity compensation; passive exoskeleton; reduced gravity simulation; spring parallelogram

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0 Introduction

Exoskeleton can be classified as active style and passive style according to their energy source. Benefited from sufficient energy supply from motors, powered exoskeletons are usually designed to offer assistance to soldiers and industry workers in carrying heavy equipment[1]. A robotic exoskeleton named X1 can also serve as an exercise countermeasure to muscle strength degradation and bone density loss in space for the crew member of international space station (ISS), beyond its original function of increasing mobility[2]. Rehabilitation is another domain for the application of exoskeletons, especially the passive exoskeleton[3-7]. The passive exoskeleton employed gravity compensation technology recovers from the cumbersome structure and heavy weight of these powered ones and achieves better motion coordination with human.

Spring-based passive exoskeleton technology is newly grafted in reduced gravity simulation for astronaut training[8,9]. Ma et al.[10] proposed a design concept of passive reduced gravity simulator system consisting of spring-based parallelogram mechanism. The weight of the torso is compensated by the spring-balanced parallelogram mechanism and the weight of lower limb is compensated by the leg exoskeleton.

Parallel efforts to duplicate the reduced gravity environment for astronaut training have been practised since the manned space activity comes into being. Generally, parabolic flight, natural buoyancy facility and the body weight suspension system are main accesses to simulate reduced gravity environment for astronauts training[11, 12]. Each approach owns advantages and disadvantages. Parabolic flight is effective at replicating high-fidelity reduced gravity conditions. Unfortunately, the period of time of reduced gravity environment it produced is quite limited, no more than 20 seconds[13]. Natural buoyancy method succeeds in simulating the zero-gravity environment. Natural buoyancy poorly provides sufficient room for full-scale space vehicle mockup operation and multi-crew member corporation in mission training[14]. However, the major constraint that limits the simulation realism is the in-

* Corresponding author, E-mail address: bqiao@nuaa.edu.cn.

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herent hydrodynamic viscosity as well as the need to add ballast mass to the subjects[15]. Body weight suspension system counterbalances certain proportion of the subject's body weight by means of adjusting the tension force of the cordage attached on the subject[13]. ARGOS[16] and EZLS[17], developed by NASA, is representative of such technology. However, the complicated active body weight compensation technology and limited degrees of freedom of body motion constraint its function.

As an alternative to those existing approaches, spring-based passive exoskeleton can compensate any proportion of the subject's body weight to adapt to the training of different mission, thus avoiding the complicated active gravity compensation control system and the harness device. It also supports full-scale mockup operation and multi-crew member corporation, without time limitation and the interference of extra body load. Statistically speaking, most tasks are related to upper limb during the manned space mission[18]. Hence, a design concept of reduced gravity astronaut training oriented upper arm exoskeleton is prompted in this paper, upon which the spring-balanced parallelogram mechanism is employed.

1 Gravity Compensation Principle

The gravity compensation of the upper limb is achieved using a spring-balanced parallelogram mechanism, a typical passive gravity compensation mechanism widely is applied to passive exoskeleton, e. g. Wilmington robotic exoskeleton (WREX)[19-21]. To describe its working theory of gravity compensation, the upper limb can be simplified as a two-link rigid body model, as shown in Fig. 1.

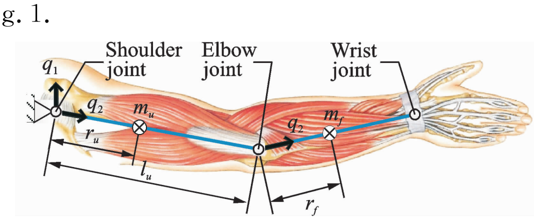

Fig. 1 Two-link upper limb model

The wrist joint and hand are in charge of local accurate operation, however, out of the interest of the design works. Hence, the wrist and hand are not investigated here. m_u and m_f stand for the mass of the upper arm and forearm, respectively, and r_u and r_f the locations of the center of mass (COM) of the upper arm and forearm, respectively. l_u is the distance from the center of shoulder joint to that of the elbow joint. $\boldsymbol{q}_1$, $\boldsymbol{q}_2$ and $\boldsymbol{q}_3$ are unit vectors of the vertical direction, upper arm and forearm, respectively. The configuration of the exoskeleton can be modeled in a vertical plane, composed with a pair of spring-balanced parallelogram links and a spring-balanced single-link connected with a rotation joint in the elbow position, as shown in Fig. 2. Here $m_1, m_2, \cdots, m_4$ stand for the mass of Link 1, Link 2, $\cdots$, Link 4, respectively, $r_1, r_2, \cdots, r_4$ the locations of the COM of each link, respectively, a_1, b_1 and a_2, b_2 the locations of the attachment points of the spring k_1 and k_2, respectively, and k_1 and k_2 the stiffness of each spring. l_1 stands for the length of Link 1.

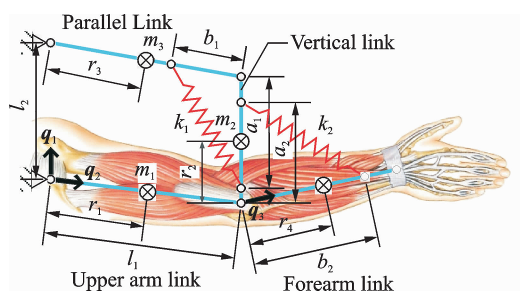

Fig. 2 Exoskeleton configuration

The nature of the static balance of the spring-based gravity compensation is the energy equal exchange between the gravitational potential energy and the elastic potential energy[22]. The gravitational potential energy and the elastic potential energy can be expressed in the form of "stiffness matrix"[23]. Hence, the stiffness matrix of the gravitational potential energy of the upper limb and the exoskeleton is

$$\boldsymbol{K}_{\mathrm{Gu}}=\begin{bmatrix}0 & \dfrac{m_{\mathrm{u}}r_{\mathrm{u}}+m_{\mathrm{f}}l_{\mathrm{u}}}{2}g & \dfrac{m_{\mathrm{f}}r_{\mathrm{f}}}{2}g \\ & 0 & 0 \\ \mathrm{sym} & & 0\end{bmatrix} \tag{1}$$

and

$$\boldsymbol{K}_{\mathrm{Ge}}=\begin{bmatrix}(m_2r_2+m_3l_2)g & \dfrac{m_1r_1+m_2l_1+m_3r_3+m_4l_1}{2}g & \dfrac{m_4r_4}{2}g\\ & 0 & 0\\ \text{sym} & & 0\end{bmatrix} \tag{2}$$

where "sym" represents the symmetric part of the matrix. The stiffness matrix of the elastic potential energy of springs k_1, k_2 are

$$\boldsymbol{K}_{\mathrm{E1}}=\begin{bmatrix}\frac{1}{2}a_1^2k_1 & -\frac{1}{2}a_1b_1k_1 & 0\\ & \frac{1}{2}b_1^2k_1 & 0\\ \text{sym} & & 0\end{bmatrix} \tag{3}$$

and

$$\boldsymbol{K}_{\mathrm{E2}}=\begin{bmatrix}\frac{1}{2}a_2^2k_2 & 0 & -\frac{1}{2}a_2b_2k_2\\ & 0 & 0\\ \text{sym} & & \frac{1}{2}b_2^2k_2\end{bmatrix} \tag{4}$$

Eqs. (3) and (4) are founded on the assumption of "ideal spring"[24], which is defined with zero free-length.

If the off-diagonal component to the stiffness matrixes becomes zero, the total potential energy of the system will be a constant no matter what the rotational angle of each joint is[22]. The gravity of exoskeleton should be totally compensated while the gravity of upper limb should be compensated partially according to the mission. To satisfy the requirement, there are

$$k_1a_1b_1/g=\rho(m_ur_u+m_fl_u)+(m_1r_1+m_2l_1+m_3r_3+m_4l_1) \tag{5}$$

and

$$k_2a_2b_2/g=\rho m_fr_f+m_4r_4 \tag{6}$$

where ρ is the percentage of the gravity to be compensated. For instance, ρ should be set as 5/6 for the lunar gravity simulation since the lunar gravity almost equals to 1/6 of the Earth's.

2 Design of the Exoskeleton

To combine spring-balanced gravity compensation technology with an exoskeleton, attentions should be paid on several points including safety, mobility, wearability, etc[1]. Safety requirement, above all, should be guaranteed. The design of the exoskeleton should offer an apposite range of motion (ROM) to follow that of human's upper limb. Besides the ROM obstruction, the design of exoskeleton should also prohibit the collision with the human body. The attachment between human body and exoskeleton should prevent it from obstructing the ROM of human body and increasing fatigue.

The upper limb exoskeleton is designed to install on a back holder which is the interface of a series spring-balanced parallelogram mechanism, as shown in Fig. 3.

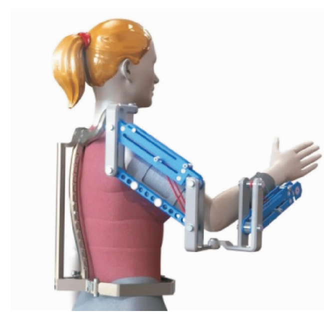

Fig. 3 The back holder and upper limb exoskeleton

The weights of the upper limb exoskeleton and human body can both obtain gravity compensation by the series spring-balanced parallelogram mechanism[9], so no extra burden will exert on the user's self. As the interface between the subject and reduced-gravity training system, the back holder is designed closer to the lineament of spine curve for ergonomics. The forearm and upper arm are ligatured by elastic bandages on the arm guards to wear the exoskeleton.

The functionality of human upper limbs is mainly determined by the shoulder joint, elbow joint, radioulnar joint, wrist joint and hand. The shoulder joint is one of the most complicated structures among human body, the degree of freedom (DOF) it allows are much more than what simple mechanical joints can offer[25, 26]. In the engineering design, however, the shoulder joint is simplified as a spherical joint while the elbow joint is modelled to be a hinge joint; what's more, the radioulnar structure is modelled as a pivot joint[27]. The spherical joint can be implemented by three serial revolute joints[28]. Here the definition of the flexion-abduction-rotation axis is used. Therefore, there are 5 DOFs upon the upper limb mechanical model: flex./extension, abd./adduction and in./external rotation for the shoulder joint[29], flex./extension for the elbow joint and pro./supination for the radius-ulna joint. The physical ROM, human's activities of daily living (ADL) ROM[30-32] are listed in Table 1. Sf/e refers to the shoulder flex./extension, Sab/d the shoulder abd./adduction, Hf/e the horizontal flex./extension, Ef/e the elbow flex./extension and Rp/s the radioulnar pro./supination.

Table 1 ROM comparison

Motion	Physical ROM	ADL ROM	Exoskeleton ROM
Sf/e	−50°—180°	51°—108°	18°—120°
Sab/d	0°—180°	20°—145°	18°—120°
Hf/e	−50°—135°	−46°—105°	0°—180°
Ef/e	−10°—150°	12°—50°	−45°—45°
Rp/s	−90°—90°	−53°—13°	−90°—90°

As shown, there are seven joints in the exoskeleton. Due to the nature of parallelogram mechanism, however, it can be analysed as a 5 DOF upper limb exoskeleton. Joints 2, 3 and 5 are parallel to the horizontal while Joints 1 and 4 keep perpendicular to it. Two arm-guards with elastic bandages are utilized to attach the exoskeleton to the upper arm and forearm, allowing the relative rotation between arm segments and the exoskeleton. DH parameters of the proposed exoskeleton model are shown in Table 2 with the coordinate frame definition in Fig. 4.

Table 2 DH parameters of the exoskeleton

Joint	θ/(°)	d	a/mm	α/(°)
1	$-180\leqslant\theta_1\leqslant 90$	0	0	−90
2	$-72\leqslant\theta_2\leqslant 30$	0	l_1	0
3	$\theta_3=-\theta_2$	0	15	90
4	$0\leqslant\theta_4\leqslant 90$	0	15	−90
5	$-45\leqslant\theta_5\leqslant 45$	0	l_2	0

As listed in the last column of Table 2, ROM of designed exoskeleton joint basically occupies that of human ADL. Due to the nature of parallelogram mechanism, the ROM of Joints 1,3 is restrained by the mechanical collision between

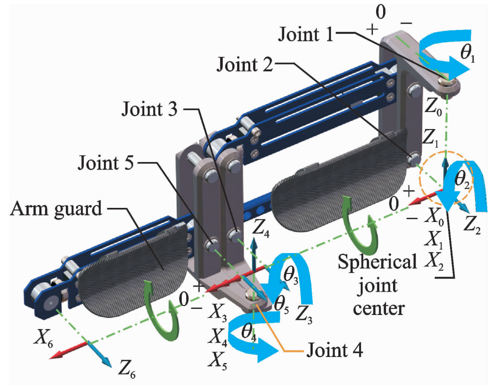

Fig. 4 Coordinate frame definition

the upper arm link and the vertical link, as well as the parallel link. Considering the most frequent activities of the astronaut in extra vehicular activity (EVA) mission focusing on the limited region forward the body, the ROM of the exoskeleton design can satisfy the training-oriented requirement.

To achieve the gravity compensation functionality, the stiffness of springs and the install position of springs should satisfy both Eqs.(5),(6). It's hard to find springs off-the-shelf with accurate stiffness as required, so the install position of the springs should be adjustable. Here a lead screw is utilized to convert the rotation of the hand wheel to the linear motion of the spring attachment point for the purpose of adjusting the "b" value. As mentioned above, the spring-based parallelogram mechanism works on the condition of the "ideal spring". Actually, there is no spring off the shelf for the concept. Here normal helical spring is combined with cable and pulley to impart it the zero-free-length characteristic, as shown in Fig. 5.

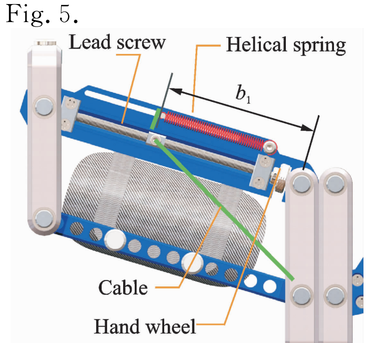

Fig. 5 Spring for the zero-free-length condition

3 Simulation Verification

A biomechanical simulation has been designed to the assistance of AnyBody™. As the actuators of living bodies, muscles are controlled by the central nervous system. AnyBody™ mimics the workings of the central nervous system by computing backwards from the movement and load specified by the user to the necessary muscle forces in an inverse dynamics process[33]. The upper limb physical parameters, listed in Table 3, are preset according to the statistical data[32]. The parameters of the exoskeleton configuration are listed in Table 4.

Table 3 Upper limb physical parameters

l_u /mm	r_u /mm	l_f /mm	r_f /mm	m_u /kg	m_f /kg
311.6	160.36	221.8	132	1.474	0.755

Table 4 Exoskeleton configuration parameters

$m_1,\cdots,m_4$ /kg	l_1 /mm	r_1, r_3 /mm	r_4 /mm	a_1, a_2 /mm	b_1 /mm	b_2 /mm	ρ
0.5	311.6	155.8	110.9	100	311.6	221.8	5/6

As a typical upper limb movement, elbow flexion with a dumbbell handled[34] was simulated. An elbow flexion was set in the lunar gravity (1/6 of the Earth gravity) without the exoskeleton as the baseline condition. The same motion was also simulated in the Earth gravity under the effect of the exoskeleton as the control condition. Under the lunar gravity simulation condition, the mass of dumbbell was set to be 60 kg which was set to be 10 kg under the Earth gravity condition, so the external force was the same.

The inverse dynamic approach (IDA) is used by AnyBody software to compute muscle forces of the human muscle-skeleton module. The muscle recruitment problem was transferred as an optimization problem to circumvent the "statically indeterminacy" in IDA. Several attempts have been made to compute muscle forces with various forms of equation[34]. The most popular form of the objective function G is the polynomial criteria[34] as follows

$$G(f^{(M)}) = \sum_{i=1}^{n^{(M)}} \left(\frac{f_i^{(M)}}{N_i} \right)^p \tag{7}$$

where $i \in \{1,\cdots,n^{(M)}\}$, $f^{(M)}$ is the muscle force, $n^{(M)}$ the number of muscles in the muscle-skeleton module, p the polynomial power, and N_i the normalization factor, which takes the form of muscle strength in this simulation. The ratio $f_i^{(M)}/N_i$ refers to the muscle activity[33, 35].

The muscle activation of three kinds of muscles: Biceps brachii, brachialis and brachioradialis are compared in both conditions as shown in Fig. 8.

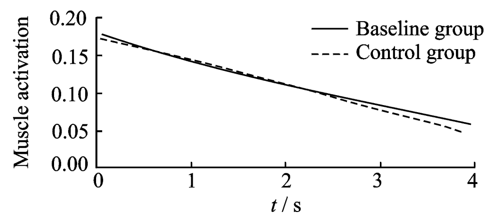

Fig. 6 Biceps brachii muscle activation

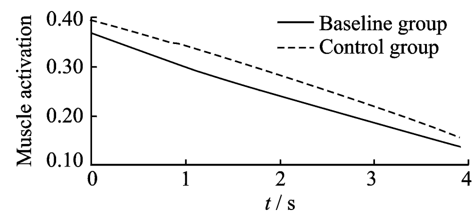

Fig. 7 Brachialis muscle activation

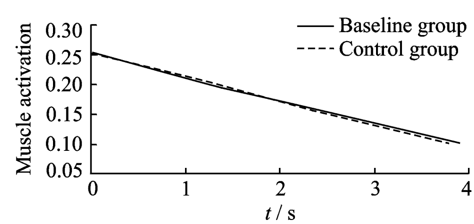

Fig. 8 Brachioradialis muscle activation

To assess the quality of the control trial, the control condition muscle activations were compared with the baseline condition data. The Pearson correlation coefficient r, as well as the Spraque and Geers magnitude difference (S &G M) and phase difference (S &G P)[36], was calculated (in absolute value) to evaluate the proximity between the corresponding data pair quantitatively, as listed in Table 5. Pearson r was categorized as $r \leqslant 0.35$, $0.35 < r \leqslant 0.67$, $0.67 < r \leqslant 0.9$, $0.9 < r$ to be weak, moderate, strong and excellent correlations, respectively[37]. While the metrics of S &G M and S &G P were designed to be zero if the data curves are identical[36].

Table 5 Pearson r, S&G M and P of muscle activations

Item	Biceps brachii	Brachialis	Brachioradialis
Pearson r	0.995	0.996	0.999
S & G M	0.99%	1.39%	0.09%
S & G P	1.50%	0.84%	0.60%

For all the pairs of muscle activations, excellent correlations ($0.9<r$) were observed (r ranges from 0.995 to 0.999). The S &G M of muscle activations ranges from 0.09% to 1.39%, while the S &G P of them ranges from 0.6% to 1.50%. Muscle activation of the brachioradialis shows the minimums in both the magnitude difference and the phase difference among all the three pairs. The magnitude difference of brachioradialis is almost 0.56% above the mean value (0.82%) while the pace difference of biceps brachii is 0.52% above the mean value (0.98%).

Therefore, the effectiveness of the exoskeleton design obtains the preliminary verification.

4 Conclusions

Inspired by the pioneer's work, the design of a passive upper limb exoskeleton is presented. The description of the gravity compensation principle of it is also offered. Its ROM meets the requirement of astronaut training. The reduced gravity simulation functionality is verified by the result of a control trial simulation in which excellent correlations between baseline conditions and control conditions were shown as well as relatively minor magnitude difference and the phase difference.

Exoskeletons combined with the spring-balanced gravity compensation technology are possible to become an alternative to existing approaches for the reduced gravity astronaut training. Criterions of muscle work under reduced gravity environment and the relationships between the design parameters and the fidelity of reduced gravity simulation deserve further study in the future. Our final objective is to design and construct a full body reduced gravity simulation system for astronaut training and reduced gravity biomechanical research.

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Mr. **Jiang Yifan** received his B. S. degree in Mechanical Engineering and Automation from Nanjing University of Aeronautics and Astronautics (NUAA) in 2015. As a Master degree candidate, he is guided by associate professor Qiao Bing. He focuses on the research of passive exoskeleton technology during 2015 to 2018 at College of Astronautics, NUAA.

Dr. **Qiao Bing** received the Ph. D. degree in Mechanical and Electrical Engineering from Nanjing University of Aeronautics and Astronautics (NUAA) in 1999. From 2008 to 2009, he was a visiting scholar at Mechanical & Aerospace Engineering Department, New Mexico State University (NMSU). Currently, he researches in space robotic, spacecraft on-orbit service technology and passive gravity offload technology at College of Astronautics, NUAA.

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