Development of a Training Method for Weightless Environment Using Both Electrical Stimulation and Voluntary Muscle Contraction

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Bone and muscle atrophy are severe and undesirable consequences of spaceflight that result from exposure to a low gravity environment (Kozlovskaya et al. 1981; Nicogossian et al. 1994; Trappe et al. 2009). These effects can be reduced by placing stress on the musculoskeletal system and a number of approaches have been tried, ranging from those in which the subject is strapped to a resistance-generating device to neuromuscular electrical stimulation (NMES) have been tried (Convertino 1990; Nicogossian et al. 1994; Thornton and Rummel 1997; Schneider et al. 2003). Most provide some benefits, however, many may produce strong external torques and all have some weaknesses. It may be that a new approach will be more beneficial.

One such technique that utilizes the strength of an electrically stimulated muscle to resist the volitional contraction of its antagonist may be particularly effective as the forces of these contractions are balanced within the body and thereby lessen the need for external stabilization. This approach, often referred to as “Hybrid training” (HYB) due to its combination of electrical and volitional muscle contractions, has already been shown to be both technically sound and clinically effective in ground-based experiments (Shiba 2002; Yanagi et al. 2003; Iwasaki et al. 2006; Matsuse et al. 2006). More specifically, the method is capable of increasing torque production and muscle mass in the upper (Matsuse et al. 2006) and lower extremities by amounts that are comparable to that of conventional weight training (Ito et al. 2004; Iwasaki et al. 2006; Takeuchi et al. 2006). However, this technique has yet to be evaluated in the low-gravity conditions associated with space travel.

This study was designed to address this issue as well as the ability of a new virtual reality (VR) interface to improve exercise performance under the microgravity (μG) environment.
conditions of parabolic flight (PF) after confirming if the training protocol was proper on the ground.

**Methods**

*On the ground experiment*

The experiment in this protocol was approved by the Ethics Committee of Kurume University. The goal of this experiment was to examine the muscle strengthening effect of HYB under the training conditions to be used during PF conditions. Eight healthy sedentary men (age, 22.2 ± 3.4 yr; height, 172.3 ± 4.8 cm; and weight, 70.0 ± 14.4 kg (mean ± S.D.)) participated in this study. Both lower limbs were examined.

**HYB.** Training occurred 3 times a week (Monday, Wednesday, and Friday) for 6 weeks. It was performed with the subject sitting erect in a chair as he performed HYB reciprocal knee flexion and extension training exercises with the hamstrings electrically stimulated as he volitionally extended his knee, and his quadriceps stimulated as he volitionally flexed his knee. Joint ROM was restricted from 0° to 90° and automatically monitored with joint motion sensors. Each session consisted of 10 sets of 10 reciprocal 3-second knee flexion and 3-second extension contractions. Sets were separated by 1-minute rest intervals, and an exercise session involving both lower extremities required 19 minutes to complete.

**Electrical stimulation.** Electrical stimulation parameters were based on a standard Russian waveform (Ward and Shkuratova 2002) in which a 5,000 Hz carrier frequency was modulated at 40 Hz (2.4 ms on, 22.6 ms off) to deliver a rectangular voltage biphasic pulse (Yanagi et al. 2003; Iwasaki et al. 2006; Matsuse et al. 2006). Maximum comfortable stimulation intensities were determined before the training period began in a manner that has been previously described (Yanagi et al. 2003; Iwasaki et al. 2006, Matsuse et al. 2006). The stimulation intensities were set at 80% and 90% of determined maximum comfortable stimulation intensities for the quadriceps femoris and hamstring muscles respectively and adjusted to permit the subjects to perform 25-30 consecutive knee flexion and extension contractions. The mean stimulating voltages were 36.00 ± 7.99 V and 38.15 ± 7.18 V for the quadriceps femoris and hamstring muscles, respectively.

**Equipment.** HYB apparatus consisted of the electrical stimulator surface electrodes, and a joint motion sensor (Mutoh Engineering Inc., Tokyo, Japan) that triggered stimulation of the antagonist once it sensed the initiation of an agonist’s volitional contraction. Low impedance gel-coated electrodes (Sekisui Plastics Co., Tokyo, Japan) were placed over the motor points of the quadriceps and hamstrings in a manner that has been previously described (Iwasaki et al. 2006).

**Torque measurement.** Maximum isometric knee extension torques were measured with a Biodex System3-PRO (Biodex Medical Systems Inc., New York, NY, USA) as the subjects sat strapped in a chair and fixed their knee at 60° joint flexion angle. Measurements were made at the beginning and end of the 6-week training program. The mean of three measurements was used for all calculations.

*Parabolic flight experiment*

This study involved a single 36 year-old male subject (mass 61.5 kg, height 1.72 m) and, was approved by the IRB of Japanese Aerospace Exploration Agency (JAXA). Experiments were carried out in a Mitsubishi MU-300 (Diamond Air Service Inc., Aichi Japan) and involved PF cycles each of was composed of 30 seconds at 1 G; 40 seconds at 0.5 - 1.2 G; 20 seconds at 2 G; 20 seconds at µG; and 20 seconds at 1.5 G respectively (Fig. 1). 14 cycles of PF were performed during a one hour flight.

**HYB.** An identical protocol was used as in the ground experiment. In the PF, however, 20 3-second knee extensions and 3-second knee flexions HYB were performed in a continuous manner over a 120 second period with knee position monitored by motion sensors and stimulation altered as he came to the extremes of a 0 to 90° range of motion (ROM).

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Fig. 1. A. Parabolic flight pattern, B. Changes of G during flight

Each PF cycle was composed of 30 seconds at 1G; 40 seconds at 0.5 - 1.2G; 20 seconds at 2G; 20 seconds at µG; and 20 seconds at 1.5G respectively. Fourteen occurrences of PF were performed within the one-hour mission duration. HYB training was performed 20 times consecutively for 120 seconds without rest intervals including all G conditions.
Micro-Gravity Muscle Strengthening

Equipment. The basic construction of equipment was the same as in the ground experiment. The same electrodes and joint motion sensor were used. A wearable device, which consisted of a form-fitting suit, stimulator, battery, electric wires, electrodes, and joint motion sensors, was developed for the subject (Fig. 2A). The suit was designed to position openings covered with electrically non-conductive meshes over the appropriate motor points thereby facilitate optimal electrode placement (Fig. 2B) (Goldwin Inc., Tokyo, Japan). A similar electrical stimulator (mass 1.030 g, dimensions 220 × 140 × 55 mm) was newly developed which is capable of stimulating and controlling multiple muscles simultaneously with a 20 output stimulation capability and 8 motion sensor input channels (Logical Product Inc., Fukuoka, Japan). The device was placed in a small bag with a battery and strapped to the subject’s chest (Fig. 2A). A virtual reality system (VR) system was developed to control the device and to provide visual feedback for the subject. An avatar on the system’s monitor provided real time guidance and helped the subject monitor his performance via a display of his joint motion sensor data stream.

Fig. 2. HYB system
A. The electric stimulator, battery, electric wires and joint motion sensors were attached to the suits. The 20 ch stimulator was set into a small bag with a battery and was fixed to the chest of the subject.
B. The suits were made with meshes at the motor points, which were designed to have the electrodes attached onto them and stimulate the muscles adequately.
C. A VR system was developed to control the HYB training. An animated instructor was shown on the personal computer (PC) monitor to show the correct instructed joint motion to the subject. The joint motion was acquired by the joint motion sensor to show it on the PC monitor, and the adequate stimulation was generated. The training history also was recorded.
Table 1. Experiment condition in each parabolic flight (PF). 14 occurrences of PF were performed during a one hour flight.

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The number of times in each experiment condition is 3 in FIX+VR+, 3 in FIX+VR−, 4 in FIX−VR+, and 4 in FIX−VR− respectively. FIX+: body rigidly fixed to seat, FIX−: body loosely fixed to seat, VR+: with virtual reality system (VR), VR−: without VR

Performance data was recorded and stored for future analysis by the system’s internal computer (Fig. 2C).

Evaluation conditions. The effects of body fixation (FIX) and virtual reality (VR) feedback on training performance were assessed under four conditions: 1) the body firmly strapped to the seat and VR utilized ((FIX+VR+); 2) the body firmly strapped and VR not utilized (FIX+VR−); 3) the body loosely attached to the seat with VR (FIX−VR+); and 4) the body loosely attached without VR (FIX−VR−). In the FIX+ condition, seat belts were used to fix the trunk and pelvis to the seat, and so the subject would not float during the µG portion of the flight. In FIX−, the seat belts were loosely attached, and the subject’s body could float free under µG conditions. In VR+, the subject performed HYB with the ability to compare his joint motion with that specified by the system. In VR−, the subject performed HYB with the assistance of a timing LED only. The relationship between the number of PF and the evaluation conditions are shown in Table 1.

Electromyogram and Knee joint motion. A surface electromyographic (EMG) and telemetry system (Niho Koden, Tokyo, Japan) was used to monitor vastus lateralis and medial hamstring stimulation adequacy. The transmitter was placed in the subject’s waist pouch and EMG data was saved on a data logger (GL500A Graphite Corporation, Yokohama, Japan) 200 Hz sampling rate. Knee joint motion was measured using a joint motion sensor and recorded by VR system. The maximum flexion and extension angles and joint motion velocity were examined from the recorded data. The subject was instructed to perform 3 second flexions and 3 second extensions alternately. The stable and linear joint speed was acquired from 15° to 75° of ROM, and its velocity was 43°/sec. ROM was divided into two parts: the first half, ROM (15° - 45°) and latter half, ROM (45° - 75°) in flexion, and the first half; ROM (75° - 45°) and latter half; ROM (45° - 15°) in extension to evaluate the influence of gravity on joint velocity.

Congruity of joint motion. Root-mean-squares (RMS) analysis of the differences between the subject’s actual joint motions and instructed joint motions were calculated as follows:

\[
\text{RMS} = \sqrt{\frac{\sum_{i=1}^{n} (x_i - y_i)^2}{n}}
\]

(Where \(x_i\) and \(y_i\) represent the desired angle and the subject’s actual knee joint angles respectively at time \(t\).)

The sampling rate of joint motion was 100 Hz. RMS values were calculated for the four experimental conditions during the 1 G, 2 G, and µG exposure periods. Maximum flexion and extension angles were calculated for the FIX+VR+ condition under the 1 G and µG environments to examine the influence of gravity on joint motion during HYB.

| Table 2. Number of knee extensions and flexion motions during a total of 14 occurrences of parabolic flight with different conditions in variable Gs. |
|------------------|---|---|---|
|                  | µG| 1G| 2G|
| VR+              | 9 | 15| 9 |
| VR−              | 9 | 15| 9 |
| VIR              | 12| 20| 12|
| FIX+             | 12| 20| 12|

Evaluation data. The data of the knee joint motion and EMG were acquired at 1 G (30 seconds), 2 G (20 seconds), and µG (20 seconds) sequentially for evaluation in each PF (Fig. 1). The number of times of knee joint extension and flexion was 5 at 1 G, 3 at 2 G, 3 at µG respectively during a PF, and a total of 14 PFS was showed in each condition for evaluation in Table 2.

Statistics

In the ground experiment, torque production measures were taken for subjects at baseline and again after 6 weeks just after completing the training and these measures were analyzed using a paired t-test. In the parabolic flight experiment, statistical analysis was also performed using one-way analysis of variance (one way ANOVA). RMS with the four conditions, and maximum flexion and extension angle during the 1 G, 2 G and µG exposures were compared respectively. Both analyses were performed by using R version 2.7.2 (R Development Core Team 2008), and statistical significance was accepted for a level of < 0.05.

Results

On the ground experiment

Isometric knee extension torque

All the subjects completed the 6 weeks on the ground training successfully. Maximum isometric knee extension torque increased in a statistically significantly manner from 209.5 ± 52.7 Nm at baseline to 250.8 ± 61.2 Nm at the end of the training (19.7%, \(p < 0.0001\)) (Fig. 3).

Parabolic flight experiment

The PF subject also completed the ground experiment before PF as mentioned above. No adverse events or interruptions occurred during PF. The wearable HYB device as
well as the VR and EMG recording systems functioned normally and collected data throughout the 14 PF cycles. The EMG recordings confirmed that adequate and appropriate electrical stimulation was provided to the antagonist muscles during HYB (Fig. 4).

**Maximum knee extension angle.** The mean value of maximum knee extension angles for all four measurement modes at both 2G (−6.43 ± 4.24°) and 1G (−5.89 ± 3.38°) was less than at μG (−1.75 ± 3.60°) (p < 0.05) (Table 3, Fig. 5). In FIX+VR+, the maximum extension angle at μG (1.00 ± 2.17°) was larger than at 2G (−6.88 ± 3.79°) (p < 0.05), and the value at 1G was −5.83 ± 3.88 (n.s.). In FIX+VR−, the value at μG (0.67 ± 0.58°) was larger than at 2G (−5.83 ± 2.57°) and 1G (−5.83 ± 2.75°) (p < 0.05). Compared with different conditions of μG, it was larger for FIX+VR− (1.00 ± 2.17°) than for FIX−VR− (−4.88 ± 3.09°) (p < 0.05). The maximum extension angle at μG was larger than at 1G and 2G, however it decreased and the subject could not extend his knee joint without body fixation if the VR was not used at μG. A significant difference was not observed, however, between the conditions of FIX+VR+ (1.00 ± 2.17°) and FIX-VR+ (−2.50 ± 4.02°) in both maximum extension angles at μG, and it showed that the maximum extension angle did not change with or without the body fixation if VR was used during μG.

**Maximum knee flexion angle.** The mean maximum
knee flexion angle in all four measurement modes was 92.71 ± 3.88° at 1G, 92.82 ± 3.46° at 2G and 90.61 ± 2.72° at μG respectively, and no difference was observed among them (Table 3). In FIX+VR+, the maximum knee flexion angle was 92.33 ± 1.15° at 1G, 93.67 ± 1.26° at 2G and 92.00 ± 3.50° at μG respectively, and no difference was observed among them also. Comparing within the μG conditions, it was larger in FIX+VR− (92.00 ± 3.50°) than that in FIX−VR− (89.38 ± 1.65°) (p < 0.05) (Table 3). The subject was not able to flex his knee joint enough without body fixation if the VR was not used at μG. However significant difference was not observed between the conditions of FIX+VR+ (92.00 ± 3.50°) and FIX−VR+ (88.50 ± 1.35°) in both maximum flexion angles at μG, the subject was able to flex his knee joint as the instruction nevertheless the body fixation if the VR was used.

Knee extension velocity. Mean knee extension velocity of all four conditions was 40.83 ± 4.44° at 2G, 42.1 ± 5.39° at 1G, and 43.55 ± 10.10° at μG respectively and no differences were observed among them (Table 4, Fig. 5). When the ROM was divided into two parts, Flexion velocity of 2G in first half ROM (15° - 45°) (64.69 ± 11.65°/sec) was faster than that in latter half (45° - 75°) (35.54 ± 7.16°/sec) (p < 0.05). Similar tendency was observed at 1G (52.96 ± 15.51°/sec) and that of 2G in first half ROM (15° - 45°) (64.69 ± 11.65°/sec) was faster than that of 2G in first half ROM (15° - 45°) (52.18 ± 12.33°/sec) in first half ROM (15° - 45°) (n.s.), and that of μG was 39.06 ± 2.61°/sec in latter half ROM (45° - 75°) and 52.85 ± 9.63°/sec in first half ROM (75° - 45°) (n.s.). Other extension velocity data in each condition was showed in Table 4.

Knee flexion velocity. Mean flexion velocity of all four conditions was 45.68 ± 7.10°/sec at 2G, 41.35 ± 7.03°/sec at 1G, and 45.21 ± 6.48°/sec at μG respectively and no differences were seen among them (Table 4, Fig. 5). When the ROM was divided into two parts, Flexion velocity of 2G in first half ROM (15° - 45°) (64.69 ± 11.65°/sec) was faster than that in latter half (45° - 75°) (35.54 ± 7.16°/sec) (p < 0.05). Similar tendency was observed at 1G (52.96 ± 15.51°/sec) and that of 2G in first half ROM (15° - 45°) (64.69 ± 11.65°/sec) was faster than that of 2G in first half ROM (15° - 45°) (52.18 ± 12.33°/sec) in first half ROM (15° - 45°) (n.s.), and that of μG was 39.06 ± 2.61°/sec in latter half ROM (45° - 75°) and 52.85 ± 9.63°/sec in first half ROM (75° - 45°) (n.s.). Other extension velocity data in each condition was showed in Table 4.
Micro-Gravity Muscle Strengthening

Fig. 5. Instructed joint motion and actual motion of subject with and without virtual reality (VR) system and body fixation at μG, 1G and 2G.

FIX+: body rigidly fixed to seat, FIX−: body loosely fixed to seat, VR+: with virtual reality system (VR), VR−: without VR
A: FIX+VR+ at μG, B: FIX−VR+ at μG, C: FIX+VR− at μG, D: FIX-VR− at μG,
Dashed line: instructed joint motion, Solid line: subject’s actual joint motion.
Knee extension was insufficient at 1G (E, F, G, H) and 2G (I, J, K, L), and was less than at μG (A, B, C, D). The extension velocity of the latter half of range of motion was slower than that of the first half at 1G (E, F, G, H) and 2G (I, J, K, L), however there was no difference between the two at μG (A, B, C, D). The actual and instructed joint motions were matched well when using VR at μG (A, B), 1G (E, F) and 2G (I, J).
There was no difference among them. When the ROM was divided into two parts, at 2G the result was 44.47 ± 5.69°/sec in the first half of ROM (15° - 45°) and 43.49 ± 5.19°/sec in latter half (45° - 75°) (n.s.). At 1 G it was 48.11 ± 3.27°/sec in the first half of ROM (15° - 45°) and 36.32 ± 2.55°/sec in latter half of ROM (45° - 75°) (n.s.), and the results were 50.42 ± 3.27°/sec in the first half of ROM (15° - 45°) and 36.32 ± 2.55°/sec in latter half of ROM (45° - 75°) (n.s.). At 1 G it was 44.47 ± 3.27°/sec in the first half of ROM (15° - 45°) and 36.32 ± 2.55°/sec in latter half of ROM (45° - 75°) (n.s.).
and firm fixation (FIX−VR−) were large, they decreased when VR was employed with \( p < 0.0001 \) or without firm fixation \( p < 0.0005 \). The presence of statistically significant differences between the RMS values during training performed with and without VR observed at 1G and \( \mu G \) indicates that VR improved performance at these levels.

**Discussion**

This study consisted of two parts. The first was the evaluation of a proposed microgravity hybrid electrical stimulation-volitional muscle contraction strengthening system (HYB) in a ground based setting and the second was the evaluation of this approach under the conditions of parabolic flight. Our results were encouraging in that we obtained an almost 20% increase in strength with the system in the ground based setting and the trials with our prototype under PF were successful. These results will benefit from further discussion. One issue of obvious importance is the choice of the appropriate electrical stimulation intensity and joint speed.

It is also important to realize that two devices were involved in the PF evaluations. One was a wearable combined electrical stimulation-volitional contraction muscle strengthening apparatus and the other was a VR control system. Assessment of each in a 36 year-old man in the \( \mu G \) environment of parabolic flight revealed that each functioned well. The combination of the HYB muscle training and VR performed effectively during brief periods of \( \mu G \) exposure.

Knee joint ROM was set at 0°- 90°, and alternate 3-second knee extensions and 3 second flexions HYB were performed in this study. To change the motion direction from extension to flexion or from flexion to extension, deceleration and acceleration before and after switching the direction of motion were required. Therefore linear joint velocity was maintained from 15° - 75° of ROM and the velocity was 43°/sec.

We hypothesized that there is significant gravitational influence on knee joint motion when the knee is in an extension position, and the maximum knee extension angle at \( \mu G \) was greater than at 1G and 2G \( p < 0.05 \) as the subject was able to extend his knee joint easily at \( \mu G \) because of the lack of gravity. ROM was divided into two parts, the first half (15° - 45°) and latter half (45° - 75°) of flexion, and the first half (75° - 45°) and latter half (45° - 15°) of extension, to evaluate the influence of gravity on knee joint velocity. Extension velocity in latter half of ROM (45° - 15°) was slower than in the first half (75° - 45°) at 1G and 2G \( p < 0.05 \), however no difference was observed between them at \( \mu G \) because the leg was essentially weightless at \( \mu G \). The flexion velocity at 2 G was faster than at 1 G and \( \mu G \) in the first half (15° - 45°) because of the influence of hyper gravity \( p < 0.05 \). Those results showed the influence of the changing gravity in PF on the knee joint motion during HYB.

Because the gravitational influence on the body disappeared at \( \mu G \), it was also hypothesized that the subject’s body would float and HYB exercise might become difficult to perform. Conditions of exercise were tested with and without the body fixation (FIX+ and FIX−) to evaluate the effect of body fixation in PF. VR system for HYB was developed to give visual feedback on instructed joint motion in PF, and HYB was performed with and without VR (VR+ and VR−) to evaluate its effect also. Both maximum extension and flexion angles were smaller in FIX−VR− than those in FIX+VR− \( p < 0.05 \) (Table 3), and ROM was insufficient without body fixation in the absence of VR at \( \mu G \). It showed that the body should be fixed to follow the instructed ROM in the absence of VR. However no difference was observed between the conditions of FIX+VR+ and FIX−VR+ in either maximum extension or flexion angles at \( \mu G \), and the subject was able to extend and flex his knee joint appropriately regardless of body fixation if the VR was used. It showed that body fixation was not

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<tr>
<td>VR+ FIX+</td>
<td>9.41 ± 2.41</td>
<td>11.58 ± 1.47</td>
<td>16.82 ± 5.23</td>
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<td>VR+ FIX−</td>
<td>9.62 ± 0.69</td>
<td>11.92 ± 2.16</td>
<td>13.55 ± 0.63</td>
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<tr>
<td>VR− FIX+</td>
<td>20.48 ± 11.03</td>
<td>19.90 ± 8.60</td>
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<td>VR− FIX−</td>
<td>41.87 ± 3.77</td>
<td>17.94 ± 1.85</td>
<td>31.76 ± 13.41</td>
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\*\( p < 0.001 \), **\( p < 0.0005 \), ***\( p < 0.0001 \)

\[ \text{RMS} = \sqrt{\frac{\sum (x_i - y_i)^2}{n}} \]

Where \( x_i \) and \( y_i \) represent the desired angle and the subject’s actual knee joint angles respectively at time \( t_i \).

FIX+: body rigidly fixed to seat, FIX−: body loosely fixed to seat, VR+: with virtual reality system (VR), VR−: without VR
necessary during HYB if the VR was used at \( \mu G \). However it was difficult to discern other tendencies in the joint velocity data for each evaluation condition, and RMS was used to verify the congruity between the subject’s joint motion and the instructions he was given. RMS errors during G in the absence of VR and body fixation \((41.87 \pm 3.77)\) were large, and they decreased when VR was employed in conjunction with \((9.41 \pm 2.41, p < 0.0001)\) or without fixation \((9.62 \pm 0.69, p < 0.0005)\). These results showed that VR was considered useful to improve the exercise performance of HYB at \( \mu G \).

A developed wearable HYB and VR system appears to function well during the brief periods of \( \mu G \). HYB was performed in varied G during PF repeatedly in this study, however it will be in used in a continuous \( \mu G \) environment for a long term space stay. Usually astronauts have to exercise 2 hours/day for 6 days/week to maintain their physical condition (Trappe et al. 2009), and to keep the subject’s motivation for the exercise is important during a long term space stay. A VR system is able to record exercise HYB history and show achievements gained. VR also has some entertainment factor during HYB exercise. These features of the HYB VR system are considered useful to maintain exercise motivation during the long term space flight.

It should also be noted that HYB has a number of distinctive and beneficial physiological features due to the fact that it 1) duplicates the reciprocal motions central to everyday life and 2) provides both electrically stimulated and volitional muscle contractions. There is a significant amount of evidence that an optimal exercise program should not only involve reciprocal limb movements but should also incorporate both eccentric and concentric muscle contractions (Shiba 2002; Yanagi et al. 2003; Iwasaki et al. 2006; Matsuse et al. 2006). HYB, by design does this, while some of the alternatives proposed for spaceflight exercise programs such as isometric strengthening may not. In addition, the fact that electrically stimulated eccentric contractions appear to be about 30-50% greater than those of a concentric nature at similar stimulation intensities (Séger and Thorstensson 2000) suggests that HYB may allow eccentric strengthening to occur at lower stimulation intensities than would otherwise be possible.

Although HYB appears to have advantages over other approaches (Matsuse et al. 2006), it has disadvantages as well. One of these is the complexity of the required equipment and, at least at the beginning of training, the need to don a tight suit and isolate optimal stimulation sites. However, the task becomes rapidly easier with experience and modifications such as the mesh patch openings over the stimulation areas make the process easier.

Our ultimate goal is to develop a ubiquitous device, which provides a load on the body in the course of normal daily activities in space (thereby preventing skeletal and muscle atrophy) without the need for a specific training program.

Conclusions

A developed wearable HYB and VR system functioned well during the brief periods of \( \mu G \) during a PF. The changed Gs affected the maximum extension and flexion angle, joint velocity and the congruity of joint motion of HYB, and the VR system was useful to improve the exercise performance of HYB at \( \mu G \). HYB was considered a useful training method for future human space exploration.

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References


