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DYNAMIC INTER-LIMB RESISTANCE EXERCISE DEVICE FOR LONG-DURATION SPACE FLIGHT

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ABSTRACT

Essential for fitness on Earth, resistive exercise is even more important for astronauts, who must maintain muscle and bone strength in the absence of gravity. To meet this need, designers and scientists at NASA Ames Research Center, Life Science Division, have worked to develop more effective exercise devices for long-duration exposure to microgravity [1]. One of these concepts is the Inter-Limb Resistance Device which allows the subject to exercise one limb directly against another, strengthening muscle groups in the arms, legs and back. It features a modular harness with an inelastic cable and instrumented pulley. Forces similar to other high resistance exercise equipment are generated. Sensors in the pulley measure force and velocity for performance feedback display and data acquisition. This free-floating apparatus avoids vibration of sensitive experiments on board spacecraft. Compact with low mass, this hardware is also well suited for a 'safe haven' from radiation on board Space Station Freedom, and may prove useful in confined environments on Earth, such as Antarctic stations, submarines, and other underwater habitats. Potential spin-offs of this technology include products for personal strengthening and cardiovascular conditioning, rehabilitation of hospital patients, fitness exercise for the disabled, and retraining after sports injuries.

INTRODUCTION

This paper describes the concept, features, and preliminary trials of a simple, low mass resistive exercise device. The concept of working one limb against another limb is common to many activities in our daily lives. For instance, when we put on shoes, we pull with our hands while pushing with our foot. In the early part of this century, Charles Atlas first systematized this activity as a simple way to exercise a variety of muscle groups without any equipment, and this technique was popularly termed "dynamic tensioning". For example, in one dynamic tensioning exercise, the subject presses one hand against the other hand with arms parallel to the ground, elbows pointing laterally, while moving the hands and arms as a unit from side to side. More recently, inventors have patented mechanisms to facilitate inter-limb resistance. One mechanism transfers forces and motion through levers and chains [2], and another through racks and gearing [3]. The Inter-Limb Resistance device builds upon these mechanisms providing a simple, light-weight system to help transfer forces from one part of the body to another part, and to measure and display the forces and limb velocities.

DESCRIPTION OF DEVICE

Modular Harness, Rope and Instrumented Pulley

Instead of the heavy, rigid steel frames associated with traditional weight stack machines found in fitness clubs, the Inter-Limb Resistance device weighs less than 10 pounds (not including the computer and display) and uses a soft conforming seat harness with shoulder straps, shoulder straps, ergonomic handles, and footplates to interface with a flexible cable and instrumented pulley. The footplates are secured to the feet with quick release straps. As the subject exercises, energy is delivered directly through the inelastic cable and pulley(s) from one limb to another. For instance, during biceps curls, each arm generates an almost identical upward force against each end of the cable, while one arm moves down and the other arm moves up (Fig. 1a). The instrumented pulley is connected to the footplates; thus, the legs resist the forces from both arms. The arm velocity, the combined force from the two arms, and the instantaneous power (force x velocity) are all displayed to the subject as motivational feedback. Data is also digitally stored for further analysis.

At all times during the exercise, the subject has full control of the speed and direction of limb motion and magnitude of muscle force. For instance, the subject may choose to exercise with low force at the extremes limb position to increase flexibility, while generating very high force at the high leverage portion of the stroke to increase muscle strength. Forces similar to other high resistance exercise equipment may be generated as the subject is only limited by his or her volition. The subject's direct control of the forces and velocity, combined with the lack of stored energy, provide for a safe exercise that can be stopped at anytime if the subject feels pain from over exertion.

Concentric, Eccentric and Isometric Exercise

In everyday activities, our muscles contract concentrically, eccentrically and isometrically, depending upon whether the muscle fibers are shortening, lengthening or not changing length, respectively, during muscle activation. For example, when we jump, our leg muscles contract concentrically. When we land, the same muscles need to contract eccentrically to decelerate the body. While stooped to work on something near the floor, those muscles are contracting isometrically to hold the position. During space flight, astronauts experience very little eccentric muscle contraction, especially with their legs, as they do not need to resist gravity. Therefore, it is important to exercise muscles eccentrically during extended space travel [4, 5] to prepare astronauts for return to Earth, or for landing on Mars, when they will need to resist gravity again.

Concentric, eccentric and isometric muscle exercise is possible with the Inter-Limb Resistance device. For example, during biceps curls, the biceps in the arm moving up is contracting concentrically (muscle fiber shortening during activation) as it progresses against the downward force of the cable. The biceps in the arm moving down is contracting eccentrically (muscle fiber lengthening during activation) as it is pulled down by the same downward force of the cable. Essentially, the biceps in the arm moving up is performing work on the biceps in the arm moving down. Contractions with no motion are isometric and may be performed at any position in the range of motion.

Comparison to Other Types of Resistance Exercise Devices

By transferring forces from one limb to another, there is no need for energy storage such as lifting a weight stack to store potential energy or compressing a spring to store strain energy. Such storage of energy on other devices makes it possible to have an eccentric phase on the return stroke, such as letting the weight stack down after a leg press. However, the eccentric phase is always present in one of the limbs with the Inter-Limb Resistance device, when the contralateral muscles are contracting concentrically. Other devices use a friction drum to absorb energy from concentric muscle contractions. Such energy is unavailable for eccentric muscle contractions and is essentially wasted. In addition, some types of exercise equipment require external power, such as an active treadmill. The Inter-Limb Resistance device requires only a small amount of power for the instrumentation.

Modular Components Accommodate Multiple Exercises

With modular components it is possible to reconfigure the system easily to accommodate a variety of arm and leg exercises. For instance, in one configuration, the subject performs a reciprocating leg press (Fig. 1b). Simple adjustment of cable length accommodates various individual sizes, or permits adjustment for varying initial joint angles. For example, by releasing cable, both legs have a more extended initial position. With legs nearly equally extended, hip and knee joints can be held in one position while the foot dorsiflexes and plantarflexes, isolating the soleus and gastrocnemius muscle groups. This is particularly important to astronauts as they often experience atrophy in these muscle groups.

A quick conversion of the harness configuration and repositioning of the instrumented pulley allows arm exercises. A force spreader bar can be attached to the footplate pulley blocks connecting the feet and forming a bridge from above each forefoot. The instrumented pulley is then attached to the spreader bar as a base for arm exercises. To change to another arm exercise, such as military press, the subject quickly adjusts the initial cable length by repositioning the line gripping handles commonly used in sailboat rigging.

Because the arm exercises are resisted at the feet, the forces and moments generated during the several arm exercises must be supported by the back, strengthening important back muscle groups as well. Another conversion facilitates leg abduction (moving the legs apart against force), where one end of the cable is held in the subject's hand resisting the abduction.

Force and Motion Sensors in the Instrumented Pulley

Sensors in the instrumented pulley (Fig. 2) measure force and motion for performance feedback display and data acquisition. Force is measured with a 750 pound load cell (Sealed Super-Mini Load Cell, Interface Inc., Scottsdale, AZ). The velocity of the flexible cable is continually determined with an incremental optical encoder (Model 815, Litton, Chatsworth, CA). The encoder detects the angular motion of the pulley shiv, thereby proportionally measuring the linear motion of the cable as it passes through the pulley. An IBM 386 computer acquires and displays the pulley force and cable velocity data in conjunction with the data from an accelerometer. The computer interface was designed using a commercial software development package for data acquisition, control and display (LabWindows, National Instruments, Austin TX). The display is presented on an IBM VGA color monitor and includes graphs, numbers and bar meters of the instantaneous force, velocity and power (the product of force times velocity) for each bout of exercise. The G-level from the accelerometer, useful during zero-G testing on board NASA's KC-135, is presented as a digital number from zero to two Earth gravitational equivalents.

The motion and forces sensed at the instrumented pulley can be related to limb motion through the geometry of the flexible cable and harness for each exercise. For instance, during reciprocating leg presses, a single cable is connected at one side of the seat harness, runs down the outside of the leg, through the foot pulleys, back up between the legs, through the instrumented pulley which is connected to the lower back of the seat harness, and then symmetrically interfaces with the other leg. During exercise, the force developed by each leg is resisted approximately equally by the cable on the outside of the leg which attaches to the seat harness, and by the cable on the inside of the leg which runs through the instrumented pulley. Therefore, the instrumented pulley senses only half of the force developed by each leg. A swivel allows the instrumented pulley to align with changes in force direction.

During arm exercise, the instrumented pulley resists the total force from each arm, because the cable ends at each handle. Therefore, it is currently necessary to distinguish exercises when reading the measured load cell forces to know how the force data relate to the contribution of a particular limb during exercise. We plan to incorporate configuration information into the human-computer interface, so the subject can simply indicate the name of the exercise and then receive meaningful feedback during the exertion.

In tension, the cable is the most efficient way to transfer forces, as the stresses are distributed evenly across the cable cross-section. In other words, very little mass is required to do the same function that may be performed alternatively by a linkage or geared drive train. Another advantage of the cable is its flexibility, making it convenient to fold and store with the flexible harness as a lightweight, compact multi-exercise device. The modularity encourages experimentation with other configurations, and the design is expected to continue to evolve with use.

METHODS

To evaluate its performance in actual, short-duration microgravity, a first fully-functional prototype of the Inter-Limb Resistance device was tested on board NASA's KC-135 parabolic flight in March, 1991. To achieve near zero-G free fall, the KC-135 climbs to approximately 38,000 feet elevation and then dives to approximately 22,000 feet creating a parabolic trajectory that repeats typically forty times (4 sets of 10). Over the top of each parabola, subjects are essentially falling in a parabolic curve experiencing a period of approximately 25 seconds of actual microgravity. As the plane pulls out at the bottom of the dive, approximately 1.8-G is felt before the next zero-G period.

With four subjects each exercising during one of the four sets of 10 parabolas, a variety of arm and leg exercises were performed during the simulated microgravity on board the KC-135 flight. They included leg press, running in place, calf press (ankle extension), leg abduction, biceps curl, arm rowing, and military press. Arm exercises and leg exercises resisted through the shoulder harness recruited back muscle groups for spinal loading, as well. All exercises were performed at sub-maximal effort.

RESULTS

The Inter-Limb Resistance exercise device performed very well during its first "shake-down" test in the short duration microgravity on board the KC-135. Three subjects generated peak forces ranging from 640 to 1156 N (144 to 260 lbs) during the leg press (sum of force from both legs). Two subjects performed the calf press and generated peak forces of 702 to 782 N (158 to 176 lbs). The biceps curl exercise produced up to 623 N (140 lbs) for one subject. Forces approaching peak values were sustained throughout the range of motion for all exercises. Subjects successfully donned, reconfigured, and removed the Inter-Limb Resistance device during microgravity tests.

DISCUSSION

Ground-based studies are planned to validate the efficacy of the Inter-Limb Resistance device as a countermeasure against muscle atrophy due to long-term inactivity or exposure to microgravity. Such studies will investigate basic muscle physiology. For example, the device may be used to isolate muscle groups in the lower leg, employing measurements of intramuscular pressure and electromyography to compare the training effects of eccentric and concentric muscle contractions.

Future generations of this device will be more self-contained, incorporating a miniature full screen display (Private Eye, Reflection Technology, Waltham, MA) for performance feedback, replacing the current dependence on full-sized CRT displays. Ultimately, the system hardware will feature its own dedicated microprocessor as well, requiring no umbilical connection to a separate computer system during exercise. With such a microprocessor, special features may be programmed. For example, protocols may be presented to the subject through a compact display permitting isokinetic, isotonic, and isometric contractions for a variety of arm, leg and back exercises. To accomplish this, the subject will follow a prescribed target value for force and/or velocity throughout the range of motion.

Potential markets for the Inter-Limb Resistance device include those for personal training at home and for sport fitness centers. Also, its application in rehabilitation is being explored in collaboration with the Palo Alto VA Rehabilitation R&D Center.

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REFERENCES

1. SCHWANDT, D.F., R.T. WHALEN, D.E. WATENPAUGH, S.E. PARAZYNSKI, AND A.R. HARGENS. Development of exercise devices to minimize musculoskeletal and cardiovascular deconditioning in microgravity. *The Physiologist*, Vol. 34, No. 1, Suppl., pp. S189-S190, 1991.
2. JONES, A.A. Exercising apparatus and method. US Patent #4,493,485, 1985.
3. PITKANEN, A.R. Computer directed exercising apparatus. US Patent #4,556,216, 1985.
4. DUDLEY, G.A., P.A. TESCH, B.J. MILLER, AND P. BUCHANAN. Importance of eccentric actions in performance adaptations to resistance training. Aviat. Space Environ. Med., 62:543-50, 1991.
5. HARGENS, A.R., S. PARAZYNSKI, M. ARATOW, AND J. FRIDEN. Muscle changes with eccentric exercise: implications on Earth and in space. *Advances in Myochemistry*, 2:299-312, 1989.

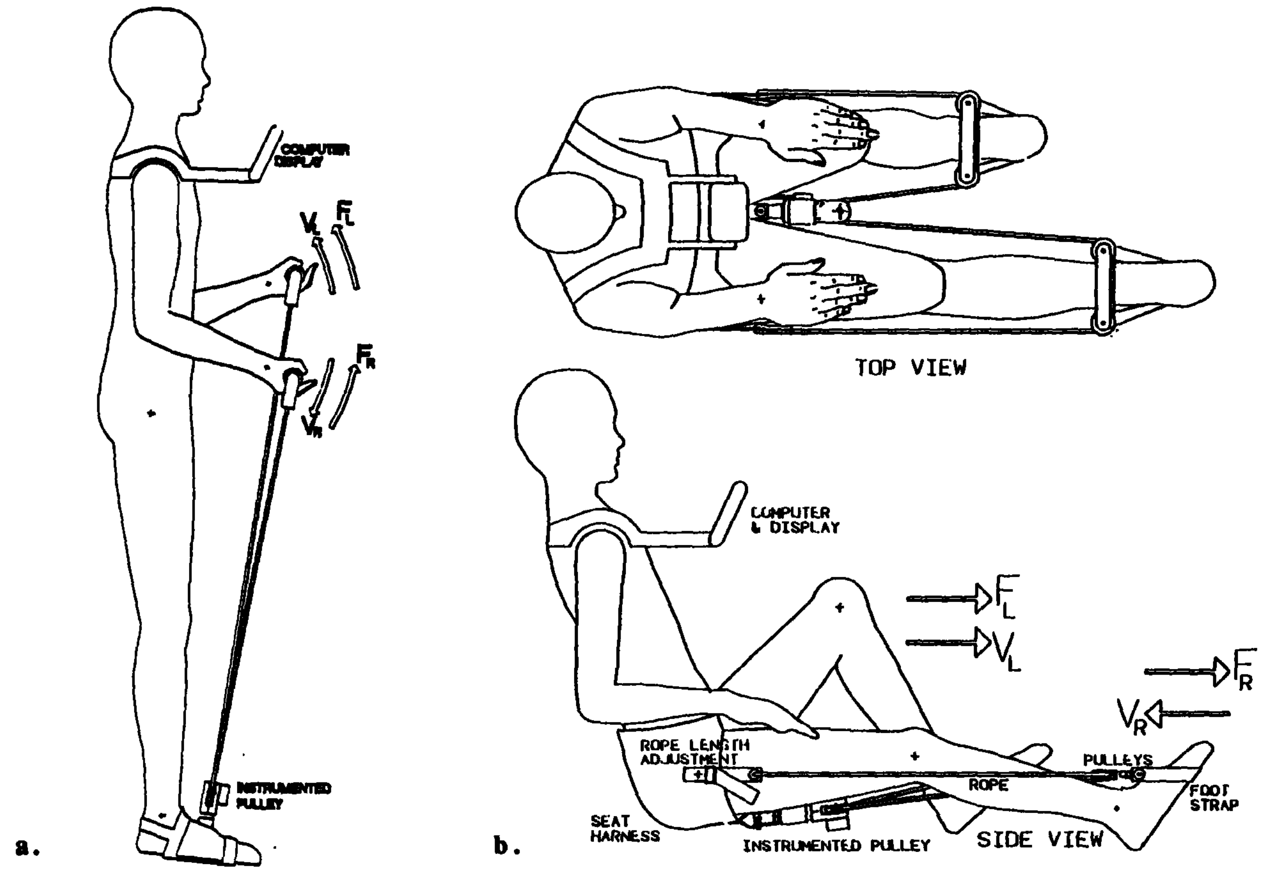

Figure 1. a) During Inter-Limb Resistance to strengthen biceps, the force generated by one arm is resisted by the other. The sum of the force from each arm is resisted at the feet with an instrumented pulley. b) During leg press exercise, the force (F_L) generated during lower body exercise by the subject's left leg as it extends concentrically (velocity, V_L) is delivered through a cable and instrumented pulley to the right leg, which develops an equal resistive force (F_R) during eccentric contraction (V_R). Although not shown, a shoulder harness is used to help resist leg forces and load the spine.

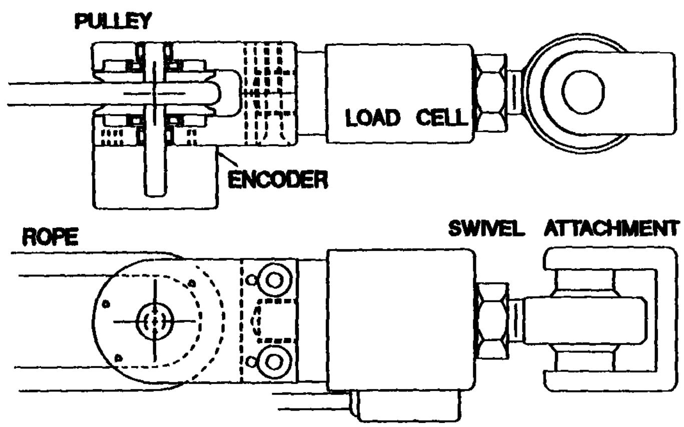

Figure 2. Schematic drawing of the instrumented pulley showing the load cell and the optical encoder. For all exercises, the magnitude and direction of arm or leg velocities and forces are controlled by the subject through the range of motion. Performance data are displayed to the subject.

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