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Development of an integrated countermeasure device for use in long-duration spaceflight

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ABSTRACT

Prolonged weightlessness is associated with declines in musculoskeletal, cardiovascular, and sensorimotor health. Consequently, in-flight countermeasures are required to preserve astronaut health. We developed and tested a novel exercise countermeasure device (CCD) for use in spaceflight with the aim of preserving musculoskeletal and cardiovascular health along with an incorporated balance training component. Additionally, the CCD features a compact footprint, and a low power requirement. *Methods:* After design and development of the CCD, we carried out a training study to test its ability to improve cardiovascular and muscular fitness in healthy volunteers. Fourteen male and female subjects (41.4 ± 9.0 years, 69.5 ± 15.4 kg) completed 12 weeks (3 sessions per week) of concurrent strength and endurance training on the CCD. All training was conducted with the subject in orthostasis. When configured for spaceflight, subjects will be fixed to the device via a vest with loop attachments secured to subject load devices. Subjects were tested at baseline and after 12 weeks for 1-repetition max leg press strength (1RM), peak oxygen consumption (VO_{2peak}), and isokinetic joint torque (ISO) at the hip, knee, and ankle. Additionally, we evaluated subjects after 6 weeks of training for changes in VO_{2peak} and 1RM. *Results:* VO_{2peak} and 1RM improved after 6 weeks, with additional improvements after 12 weeks (1.95 ± 0.5, 2.28 ± 0.5, 2.47 ± 0.6 L min^{-1}, and 131.2 ± 63.9,182.8 ± 75.0, 207.0 ± 75.0 kg) for baseline, 6 weeks, and 12 weeks, respectively. ISO for hip adduction, adduction, and ankle plantar flexion improved after 12

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weeks of training (70.3 ± 39.5, 76.8 ± 39.2, and 55.7 ± 21.7 N m vs. 86.1 ± 37.3, 85.1 ± 34.3, and 62.1 ± 26.4 N m, respectively). No changes were observed for ISO during hip flexion, knee extension, or knee flexion. *Conclusions:* The CCD is effective at improving cardiovascular fitness and isotonic leg strength in healthy adults. Further, the improvement in hip adductor and abductor torque provides support that the CCD may provide additional protection for the preservation of bone health at the hip.

1. Introduction

The degree to which the musculoskeletal system will maintain its integrity during prolonged sojourns in microgravity has yet to be fully elucidated. In-flight countermeasures are required to prevent losses in muscle strength and volume [1,2], cardiovascular fitness [3,4], bone mineral density (BMD) [5], and bone geometry [6]. Additionally, there is increasing evidence that impairments in sensorimotor function that lead to post-flight disturbances in balance and gait control occur following long term exposure to reduced gravity environments [7]. Currently, there are several countermeasures used by crewmembers aboard the International Space Station (ISS) that strive to mitigate the deleterious impacts on the musculoskeletal and cardiovascular systems occurring as a result of prolonged weightlessness. Crewmembers perform cardiovascular exercise using a cycle ergometer and/or a treadmill to preserve cardiovascular fitness [4]. To preserve muscular strength and contribute to the preservation of bone geometry and bone mineral density, crewmembers perform resistance training using the Advanced Resistive Exercise Device (ARED). Currently, no countermeasure mitigates the sensorimotor adaptive changes leading to balance and gait dysfunction during long-duration spaceflight.

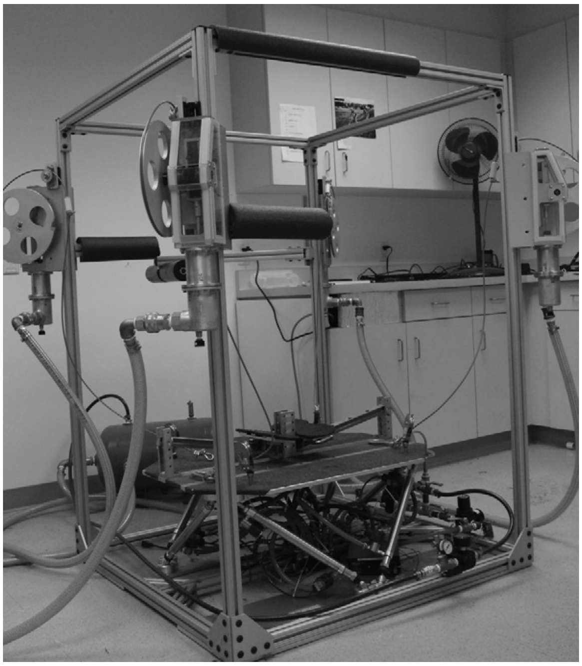

Fig. 1. The Combined Countermeasure Device (CCD).

Each piece of equipment on the ISS has a distinctly different footprint with unique set-up requirements that create some logistical challenges related to available physical space and the amount of time crewmembers must spend configuring each exercise apparatus for use. A recent investigation by Cavanagh et al. (2010) found that despite allocating approximately 2.5 h per day for exercise, crewmembers averaged only 43 min (approximately 30% allocated time) actually engaged in loaded physical activity [8]. An as yet undetermined amount of this "down time" can be attributed to the time and effort required to reposition and set-up exercise equipment.

We have developed the Combined Countermeasure Device (CCD) (Fig. 1) to integrate resistance training and cardiovascular conditioning with a balance training component. Our aims were to develop a low power, small footprint device, and to demonstrate its efficacy as a complete exercise countermeasure. As a first step toward achieving this aim, we carried out a single-arm training study using healthy, untrained, volunteers to determine whether exercise training using the CCD produced a similar training effect when compared to previously published studies using traditional exercise equipment [9–12].

2. Methods and subjects

2.1. CCD description

Design and development of the CCD was a collaborative effort between the research team and Zin Technologies (Cleveland, OH). The CCD has a footprint of $110 \times 110\ cm^2$ and features 4 pneumatically operated Subject Load Devices (SLDs) that generate resistance using cylinders of compressed air via a cable pulley system. The supplied resistance serves as a stimulus for muscle strength training and would provide crewmember restraint in a spaceflight application. When configured for spaceflight, subjects will be fixed to the device via a training vest with loop attachment points (Fig. 2). Since the current study was carried out in a 1 G environment, for the purposes of the training study, the vest was only used when necessary to enable the completion of squat and heel-raise exercises. The device is built upon a Stewart Platform that operates in either a "lockdown" or a "balance" mode. In lockdown mode, the exercise platform is fixed and stable. All exercises in this study were conducted with the CCD platform in lockdown mode. In balance mode, the platform is pressurized via an increase in air pressure to the bottom portion of the pneumatically controlled cylinders separating the platform from the CCD's base, providing an unstable, floating