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A novel approach to activate deep spinal muscles in space—Results of a biomechanical model

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ABSTRACT

Introduction: Exposure to microgravity has various effects on the human musculoskeletal system. During spaceflight many astronauts experience low back pain and the risk of spine injuries is significantly greater post-flight. Nonetheless, the increased lumbo-pelvic injury risk is not specifically addressed by current countermeasures. Considering this, a novel exercise device has been developed to specifically counteract atrophy of deep spinal and postural muscles. The aim of the present study was to test the possibility of transferring this exercise concept from earth to space using a biomechanical simulation.
Methods: A biomechanical model of the exercise device was developed and validated using intramuscular electromyographic (EMG) data as previously acquired on a terrestrial prototype of the exercise device. The model was then modified to the needs of a 0-g environment, creating gravity-like conditions using shoulder straps.
Results: Modelled activation patterns of the investigated muscles were in line with the experimental data, showing a constant activation during exercise. The microgravity modifications of the model lead to increased muscle activation of deep spinal muscles and to decreased activation of superficial moment creating trunk muscles.
Discussion: The results of the biomechanical model suggest that the exercise concept can be transferred from 1-g to space conditions. The present study is a first step in the investigation process of a novel exercise concept and human studies should be conducted to confirm the present theoretical investigation.

1. Introduction

The evolutionary process, as proposed by Charles Darwin [20] allowed the human body to successfully adapt to the 1-*g* environment of our planet Earth. When exposed to the microgravity environment in space, the human body experiences various immediate and long term adaptations that have, amongst other things, a significant impact on the structure and function of the musculoskeletal system [18].

Upright activities on earth cause the human body to be vertically loaded (Gz loading) and it has been found that the direction of loading is of particular importance for the integrity of the spine and its adjacent structures [3,5,21]. It has been well documented that, in the absence of Gz loading

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during space flight, or bed rest, the spine experiences structural and functional changes that make it more susceptible to injury when the Gz vector is restored [2,4,5,19].

Interestingly, it has been observed that in a bed rest environment, some muscle groups of the lumbo-pelvic region adapt differently to others [3]. Under bed rest conditions the cross sectional area of deep spinal muscles and spinal extensor muscles decreases in size, however, the cross section of spinal flexor muscles increases [5]. Importantly, dysfunctional or atrophied muscles in the lumbo-pelvic region are directly linked to the prevalence of low back pain (LBP) [13]. Given the evidence suggesting that the functional and structural integrity of the transversus abdominis (TrA) and lumbar multifidus (LM) muscles are required to maintain spinal health [13,14,17], current rehabilitation regimens aim at specifically exercising these muscles [15,23].

Current state of the art in-flight exercise interventions aim to counteract the physiological effects of microgravity by temporarily generating mechanical and metabolic stimuli to the human body. On average 1.75 h of exercise (of a 2.5 h daily allocation) is conducted each day, comprising typically of 1 h of aerobic and 45 mins of resistive exercise [25]. Resistive exercise is done using the Advanced Resistive Exercise Device (ARED), a machine that allows performance of a various different exercises of the global movement muscles [25].

Aerobic on-board exercise is performed on either a treadmill or on a cycle ergometer [25]. Despite the fact that upright activities such as walking are associated with an activation of deep spinal muscles [6], evidence suggests that the currently applied treadmill exposure is not sufficient to preserve spinal health, given the four-fold increased risk of astronauts experiencing a herniated disc postflight [19].

Recently, a novel exercise device (the Functional Re-adaptive Exercise Device, or the FRED, Fig. 1) has been developed [8] that showed promising results to immediately increase lumbo-pelvic stability during movement in healthy terrestrial individuals, as indicated by a decreased range of hip rotation in the transverse plane [11]. The device is similar in action to an elliptical trainer but requires the user to work against almost no resistance in order to move the feet. This feature constitutes a postural challenge to the user because of the need to actively control the movement of the legs while maintaining a stable trunk. It has been shown that the combination of weight bearing in an upright posture and functional leg movement while exercising on the FRED immediately increases the activation of TrA and LM compared to standing on an unstable base or leg movement without weight bearing [8]. Exercise on the FRED also appears to promote an immediate phasic-to-tonic shift in lumbo-pelvic muscle activation as well as an increase in spinal extensor and reduction in spinal flexor muscle activation [6]. These findings suggest that the FRED could provide a useful tool in the rehabilitation of astronauts [9].

Fig. 1. The current prototype (Mark II) of the FRED with an exercising subject.

Whilst previous findings support the use of the FRED on Earth, the aim of the present work was to evaluate the potential to use the FRED as a direct in-flight countermeasure to counteract atrophy of deep spinal muscles and to prevent the unloading-induced tonic-to-phasic shift of lumbo-pelvic muscle activation as it has been reported in a previous study after prolonged bed rest [5]. A biomechanical model of the FRED was developed and modified for a potential use in microgravity. It was hypothesized that both the modelled application of the modified device and the terrestrial model would lead to similar muscle recruitment patterns of lumbo-pelvic muscles.

2. Methods

In the following section, the acquisition of the experimental data for model validation, the model definition as well as its output are described. Furthermore the premises under which the model is validated and compared to its microgravity adaptation.

2.1. Experimental data

Intramuscular electromyographic data for the validation of the model were acquired in a previous study with the exercise device testing nine healthy male participants. This study was conducted at the Centre of Clinical Research Excellence in Spinal Pain, Injury and Health of the University of Queensland in Brisbane, Australia (manuscript submitted). The setup comprised intramuscular bipolar fine-wire electrodes (two Teflon-coated 75 μm stainless-steel wires with 1 mm insulation removed from the ends, bent back to form hooks at 2 and 3 mm length, threaded into a hypodermic 0.50×70 or 0.50×32 ⌀xlength [mm]-needle) which were inserted into the right side of the trunk under ultrasound guidance (Aixplorer, Supersonic Imagine, Aix-en-Provence, France).

The intramuscular EMG electrodes were placed in the following positions.

– Transversus abdominis (TrA): between the anterior superior iliac crest and the lowest rib;