Introduction

An exercise device has recently been developed to activate deep spinal muscles [1, 2]. The device, called the Functional Re-adaptive Exercise Device (FRED, Figure 1), is similar in its kinematics to an elliptical trainer, but it offers little resistance to lower limb movement [3]. Using surface and intramuscular electromyography (EMG) as well as B-mode ultrasound imaging, previous studies revealed tonic activation of lumbo-pelvic muscles during FRED exercise as compared to walking [1-3]. As tonic activation of postural muscles is an aspect of function that is modified in LBP, this suggests a potential role for this device as a rehabilitation tool to reinforce this function. Compared with walking, FRED exercise was associated with less activity of superficial trunk muscles (e.g. obliquus externus abdominis (OE) – a muscle that is often found to have additional activation in LBP [4, 5] whereas the mean activity of the Transversus Abdominis (TrA) and Multifidus (MF) muscles was similar between tasks [3].

It was therefore proposed that FRED exercise could be beneficial if integrated into rehabilitation interventions following long term micro-gravity exposure or LBP [6]. In particular, tonic activation of trunk muscles induced by FRED exercise [3] has been suggested as a potentially useful training stimulus to train these muscles [7]. However, whether such activation leads to sustained improvements in motor control and/or an increased activation (in the following this is referred to as background activation) of the activated deep spinal muscles during upright standing after completion of the task has not been investigated.

One method to assess the coordination of trunk muscles involved in spinal control is to investigate anticipatory postural adjustments to predictable perturbations to the trunk during rapid arm movements [8-10]. This method provides insight into the preplanning by the nervous system *in advance of* any perturbation, i.e. feed-forward control. Previous studies have shown early activation of the TrA and MF muscles as a component of these anticipatory postural adjustments [11, 12], and that early activation is needed to prepare the spine in a manner that is somewhat independent of the direction of force applied to the spine (e.g. forward or backward perturbation) [11, 13]. Notably, activation of the TrA and LM muscles is delayed in individuals with LBP [8, 9]. Further, training of voluntary activation of the TrA muscle induces earlier activation of this muscle in an arm movement task both immediately after training [14] and during a six months follow-up if training is repeated [15]. Conversely, activation of the TrA muscle without conscious attention during sit-ups [14], walking training [16] or higher intensity generalised abdominal bracing tasks [17] induced no change in timing. FRED exercise encourages conscious attention to trunk alignment and lower limb movement but does not require conscious activation of the spinal muscles. However, whether training using the FRED induces changes in muscle activation during trunk perturbations requires investigation.

This study investigated whether a single bout of exercise on the FRED device induces changes in feedforward activation of spinal muscles in association with rapid arm movements. It was hypothesized that in pain free individuals a single exercise session on the FRED would lead to earlier onsets of spinal muscles in association with rapid arm movements. Further, it was hypothesized that ongoing background activation of the LM and TrA muscles in standing would be greater after one exercise session with the FRED.

Methods

Participants

Nine healthy male volunteers (mean(SD) age: 27(5) years; height: 1.74(0.05) m; body mass: 73(10) kg; body mass index: 24(3) kg/m^2) who had no history of joint or muscle disease or any current muscle, ligament or tendon pain or injury were recruited for the present study. Participants provided written informed consent prior to study inclusion. The study was approved by the Institutional Medical Research Ethics Committee of the University of Queensland and all procedures were in accordance with the Declaration of Helsinki.

Electromyography

Intramuscular Electromyography: Pairs of fine-wire electrodes (two Teflon-coated 75µm 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 x 70 or 0.50 x 32 mm-needle) were inserted unilaterally into muscles on the right side of the trunk with guidance using B-mode ultrasound imaging (Aixplorer, Supersonic Imagine, Aix-en-Provence, France). Electrodes were sterilized in a vacuum steam autoclave (Sterilclave 18, Cominox, Carate Brianza, Italy). Skin was cleaned with sterilization swabs (Persist Plus, BD, Franklin Lakes, USA). Electrodes were inserted into the following trunk muscles: deep fibres of LM – over the L4-5 facet joint 30 mm laterally to spinous processes; the longissimus part of the lumbar erector spinae muscle (LES) 40 mm lateral to the L2 spinous process; OE, obliquus internus abdominis (OI) and TrA – separated by 5 mm midway along a line from the anterior superior iliac spine and the distal edge of the rib cage.

Surface Electromyography: The skin was prepared using abrasive paste (Nuprep, Weaver and Company, Aurora, USA) and cleansed using alcohol swabs. Pairs of Ag/Ag-Cl surface EMG electrodes (Blue Sensor N, Ambu, Ballerup, Denmark) were placed on the skin adjacent to the insertion point of the fine-wires for LM (LM_S), and over the anterior (AD) and posterior (PD) deltoid muscles. LM_S signals have to be interpreted with caution as they most likely represent a mix of different muscles underneath the surface electrodes and do not solely reflect actual activity of LM (see also discrepancy between LM and LM_S signals in [3]).

A reference surface electrode was placed over the iliac crest. EMG signals were pre-amplified 2000 times, band-pass filtered between 20 and 1000 Hz (Neurolog, Digitimer, Welwyn Garden, UK) and recorded at a sampling rate of 2000 Hz using a Power1401 data acquisition system and Spike2 software (Cambridge Electronic Design, Cambridge, UK).

Study protocol

Data were collected in a single session. Following attachment of the EMG electrodes participants completed 10 repetitions of the rapid arm movement manoeuvre. Participants stood in a relaxed position with their feet shoulder-width apart and their arms by their sides. Participants were instructed to react as quickly as possible to flex or extend their shoulder to approximately 15 deg as sharply as possible upon the appearance of a visual cue, displayed approximately 1 m in front (a green light indicated shoulder flexion, and red indicated shoulder extension).

After baseline data collection participants were familiarized with FRED exercise for 10 minutes, during which they completed three different amplitude settings (data from these tasks are published elsewhere [3], beginning with the smallest amplitude [18]. The three different amplitude settings were 0.2 m (small) 0.36 m (middle) and 0.5 m (large). Increasing amplitudes result in longer foot trajectories and increased instability [3]. Participants were instructed to keep their feet on the footplates and to maintain the upper body as “still” as possible while moving their lower limbs with as little movement variability as possible. Visual feedback of exercise cycle frequency and variability of foot movement was provided on a screen in front at eye level. Throughout the duration of FRED exercise, participants were asked to maintain cycle frequency at 0.42 cycles per second. After familiarization, participants completed a 30 min test battery of three FRED amplitude settings in random order [3] followed by a ten minute continuous sequence in the middle amplitude setting. Outcome measures (EMG at rest while standing and during rapid arm movements) were recorded immediately after completion (*post*) of the exercise and after a 10-minute wash-out during which they remained standing (*10-min WO*).

Data analysis

Electromyography signals were processed using Matlab (Version 2014a, Mathworks, Natick, MA, USA). Signals were digitally band-pass filtered using a fourth order Butterworth filter (fine-wire EMG: 50-1,000 Hz; surface EMG: 20-500 Hz) and an adaptive ARMA whitening second order filter. For each arm movement, the times of EMG onset were detected using the approximated generalized likelihood ratio method [19]. This algorithm uses statistically optimal decision with a predefined threshold to detect changes in EMG amplitude. The automatically detected times of change in amplitude were then visually inspected and onsets were rejected if they were related to bursts of EMG not related to the arm movement (e.g. ECG bursts or other movement artifacts). The relative latency between the EMG onset of the deltoid (arm flexion - AD; extension - PD) and each of the trunk muscles was calculated and used for analysis.

Statistics

Preliminary analysis of EMG data identified large between-subject variability in background EMG for some of the trunk muscles. Ongoing background EMG activity may modify the necessity for an anticipatory adjustment and may change the sensitivity of the EMG onset detection method (i.e. it is more difficult to identify EMG onset if the muscle is already active). To assess the potential influence of background EMG on the detected onsets, the Pearson's correlation coefficient was calculated between the time of EMG onset and the root mean square (RMS) EMG amplitude in the time window from 150-50 ms preceding deltoid muscle EMG onset.

Statistical analyses were performed using STATA statistics software (Version 13, StataCorp LP, College Station, Texas, USA). EMG onsets for each muscle were compared between trials performed *pre-* and *post*-exercise and after *10-min WO* using one-way repeated measures ANOVA, with a Bonferroni *post hoc*. The significance level alpha was set to 0.05. Data are expressed as mean ± standard deviation throughout the text and figures unless stated otherwise.

Results

EMG onsets

Figure 2 shows overlaid individual and averaged rectified EMG signals for each muscle (left panels) as well as the mean, SD and individual participant data points of EMG onsets of the trunk muscles (right panels) at each time point (*pre, post, 10 min wash-out*). Pre-training trials show TrA was the first muscle active prior to AD in shoulder flexion, with the onset of LM at a similar time to AD. The EMG onsets of TrA EMG did not precede that of PD in shoulder extension, and an early onset of OE and a late onset of LES EMG was observed.

EMG onsets of LM, TrA, OI and OE did not significantly change after the exercise bout with the FRED or after *10-min WO*, for either shoulder flexion or extension movements (main effect of time: $P \geq 0.07$). For LES, during shoulder flexion, EMG onsets became earlier after training, from -1 ms (SD: 32 ms) at baseline to -11 ms (SD: 27 ms) *post-exercise* and -16 ms (SD: 22 ms) at *10-min WO* after the FRED exercise bout (main effect of time: $P = 0.03$; *post* hoc $P < 0.05$ for pairwise comparisons with baseline). LES EMG onset in association with shoulder extension was unchanged between time points ($P = 0.22$).

Correlation between background EMG and EMG onsets

Figure 3 depicts the correlation between background EMG amplitude and EMG onsets of the investigated trunk muscles. During shoulder extension, significant correlations were found between background EMG and onset times for TrA (r = 0.6; $P < 0.001$), OI (r = 0.59; $P < 0.001$), LES (r = 0.32; $P = 0.046$) and LM_S (r = 0.77; $P < 0.001$). There were no other significant correlations (all $P \geq 0.09$). The background EMG amplitude of the investigated muscles did not change between time points (all $P \geq 0.28$).

Discussion

The main outcomes of this study were that in healthy individuals with no history of pain (and presumably "normal" control of the trunk muscles): 1) EMG onsets of most of the investigated trunk muscles were not modified by FRED exercise, with the exception of LES which had earlier EMG onset both immediately after FRED exercise and after a ten minute wash-out period; 2) EMG onsets of TrA, OI, LM_s and LES depended on the amplitude of background activity prior to the postural disturbance; and 3) background (tonic) activity of trunk muscles in relaxed standing position prior to a postural disturbance was not affected by FRED exercise.

EMG onsets

Changes in timing of activation of spinal muscles in response to or in anticipation of postural disturbances have been identified in association with LBP [8, 9, 11]. In healthy individuals, spinal muscles such as LM and TrA are usually activated in anticipation of the postural perturbation in order to protect the spine from imposed forces [9]. On the other hand, it has been observed that people with LBP have delayed EMG onsets when the trunk is challenged by a postural perturbation, and this has been suggested to make the spine more vulnerable [8, 9].

Although it was hypothesized that onsets of spinal muscles would be earlier after FRED exercise, only minor changes were observed in healthy individuals with presumably "normal" control prior to training in most trunk muscles observed. However, immediately after a single exercise bout with the FRED and after a ten-minute washout period, participants showed earlier onsets of LES EMG associated with shoulder flexion. During shoulder flexion movements, the reactive angular moment from arm movement causes the spine to flex, and requires early LES activation [20]. Contraction of the LES (upper lumbar spine) generates posterior shear forces on the lumbar spine which might be required to counter anterior shear forces associated with trunk flexion [21].The present data show that this activation of the LES was “tuned” and became earlier after the FRED training. This finding might have implications for rehabilitation of people with LBP and astronauts post mission. With respect to LBP, a recent large cross-sectional study has shown that there was a significant association between fatty infiltration of the LES (upper lumbar spine) and LBP [22]. As many LBP patients report problems with activities in the sagittal plane, control of the anterior shear forces associated with activities such as lifting [23] afforded by the LES during this and other activities may be of benefit for these patients. In addition, Claus et al. [24] identified that LES is more active during a “short lordosis” posture (i.e. lumbar lordosis with smooth transition to thoracic kyphosis at the thoracolumbar junction) than in flat, “long lordosis” and slump postures. As recent work has highlighted a greater (short) lordosis in the FRED task than walking [18], this could explain greater bias to activation of LES after a period of FRED exercise. However, this might also be expected to impact activity of LM, which was also reported to be most active in the short lordosis posture by Claus et al. [24], yet this was not observed in the present study.

In astronauts and individuals following prolonged bedrest, the spinal extensor muscles – predominantly the LES and LM - atrophy while the flexor muscles (e.g. psoas major) hypertrophy [6, 25-27]. The early recruitment of the LES muscle in anticipation of shoulder flexion following a single 10-minute bout of FRED exercise may indicate that FRED exercise could be a useful adjunct to current astronaut rehabilitation regimes, as has previously been suggested [1, 6].

There was no change in EMG onset of the TrA or LM muscles with training. The timing of EMG onset of these muscles was in most respects similar to what has been shown previously for people without a history of LBP [9], with the exception that the onset of the TrA muscle occurred after PD onset in shoulder extension (Figure 2). Of note, in previous studies that have tested the impact of training tasks on onset of the TrA muscle, participants have been individuals with LBP, who showed delayed activation at baseline [15]. Whether FRED exercise can impart a change in timing on people with LBP and abnormal timing remains to be tested.

Relationship between background activity and onset of EMG

Despite the pain-free status of the participants, some individuals did not show an anticipatory activation of TrA during the shoulder extension task. This contrasts with a previous study of healthy individuals that demonstrated a consistent onset of TrA in advance of perturbation during both shoulder flexion and extension [11]. Investigation of the relationship between background activity while standing and onset of TrA activation (Figure 3) showed that the amplitude of background TrA EMG was a determinant of EMG onset: onsets were later when background activation was higher (in the shoulder extension trials). The same correlation was found for the LES, OI and LM_s muscles. There are two likely explanations for this finding. First, a higher background muscle activity (tonic activation) results in an increased level of spinal control rendering ‘additional’ muscle activity unnecessary until later. Second, because of the higher background activity, the EMG onset detection method was less sensitive than with lower background activity. This may explain the difference between the present data and previous studies [11] – If background activity was lower, then earlier onsets of TrA EMG would have been expected in the extension task. The data of LM_s should be interpreted with caution as surface EMG recordings of the LM at the level of L5 may be insufficiently selective and most likely represent a mix of both LES and LM muscle EMG [3].

The fact that the relationship between background activity and onset of activation was not significant for shoulder flexion would explain why, regardless of the amount of background activation, we were still able to detect early EMG onsets in that task, consistent with previous studies [9, 15, 20].

Limitations of the study

Our interest in this study was to investigate healthy individuals with no previous experience with FRED exercise and a standardised period of familiarisation (10 min) before data collection. It is unknown whether FRED exercise would have a different effect for people with greater familiarity with FRED or for people with compromised trunk muscle function.

Summary & Conclusions

The presented data suggest that a single exercise bout on the device has a small but significant effect on timing of one trunk muscle but no effect on background muscle activation in healthy individuals while standing still. The only significant change was earlier activation of LES, which might have positive implications for the rehabilitation of people with LBP and astronauts post mission.

Acknowledgements

This investigation was funded by the Space Medicine Office (HRE-OM) of the European Space Agency (ESA). The study was supported by the National Health and Medical Research Council of Australia.

Conflict of Interests

Nothing to report.