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Research article

The effect of movement and load on the dynamic coupling of abdominal electromyography

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ABSTRACT

This study investigated the degree of neural coupling in abdominal muscle activity and whether the task constraints of movement and load altered the coupling within three muscle pairings. Nineteen young, physically-active individuals performed sit-up and reverse crunch movements in bodyweight (BW) and loaded (+4.54 kg) conditions. Surface electromyography (sEMG) was recorded from the rectus abdominus (RA), external oblique (EO), and transverse abdominus (TA) muscles. Linear (correlation coefficient) and non-linear (Cross-Approximate Entropy) measurements evaluated the degree of couplings across three muscle pairings. Compared to a resting coupling state, most conditions showed evidence of coupling. The linear coupling showed greater coupling compared to the resting state. Dynamic coupling showed lower degrees of coupling for the RA-EO and RA-TA pairings but stronger coupling for the EO-TA pairing with the sit-up movement exhibiting lower Cross-ApEn (higher dynamic coupling) than the reverse crunch. The results provide preliminary evidence of coupling in abdominal muscle activity that was influenced by movement, but not load. The functional roles of the RA (prime mover), EO and TA (stabilizers) muscles may have influenced the degree of coupling and future investigations are needed to better understand the coupling of abdominal muscle activity.

1. Introduction

Abdominal exercises are used for a variety of purposes including enhancing athletic performance, improving general components of fitness, and restoring core stability in clinical conditions such as low back pain [1]. The key musculature in the abdominal region provides numerous functions to movement and simultaneously affords a multitude of exercises that can be used to target specific muscular performance deficits. However, these muscles also represent a control issue with redundant degrees of freedom (DOF) available to execute any one particular movement pattern [2–4]. Understanding the neuromuscular control properties within the abdominal region has important implications when developing muscular strength and endurance programs. Also, the identification of healthy-state control strategies can be used to guide rehabilitation protocols.

In the abdominal muscle literature there lacks a general consensus on what exercises effectively stimulate the activity of abdominal muscles. Most studies have shown that full versus partial sit-up motion produces greater muscle activations levels [5]; however, factors like movement speed, traditional versus non-traditional movements, and use of free weights compared to machines have been shown to elicit different activation patterns within the abdominal muscles [1,6]. It is important to note that the evaluation of posterior muscle (lumbar multifidus and erector spinae, etc.) activation patterns also plays an important role in the notion of core stability [6]. Overall, there has been a strong reliance on magnitude-based indices of muscle activation (i.e., root mean square) to determine effort level and motor control properties; however, such approaches fail to account for shared activation patterns between muscles that can reflect a coupling control strategy.

The human body consists of redundant biomechanical and neuromuscular DOF and a central question relates to how the neuromuscular system channels one specific coordination pattern in the face of redundant solutions [2–4]. This issue is present with abdominal muscles in that variable muscle activity can achieve the same movement as well as with the shared functional roles across multiple muscles. From a motor control perspective, correlated activity of biomechanical (joint angle motion, muscle activity, etc.) variables has been used to determine whether a neural strategy includes control of each DOF independently or coupling occurs across multiple DOF. Previous evidence of coupling has primarily been derived from finger force production tasks, postural control, and gait [7–10]; however, if such coupling is a general property then it should be present throughout the neuromuscular system. The focus of the current investigation was to identify the presence (or lack) of coupling in abdominal muscles activity and

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whether coupling varied by certain task constraints (movement and load).

Previous evidence suggests that coupling or the formation of motor modules is used as a neural control strategy, although several theoretical and experimental factors remain unresolved [11]. In particular, neural and biomechanical constraints may contribute to correlated muscle activity not reflective of a specific neural control strategy. Here, we used three abdominal muscles with common neural innervations (i.e., intercostal nerves in the lower thoracic vertebrae region) but different functional roles to examine whether the same muscle coupling strategy was used under different task constraints. Additionally, the spatio-temporal properties of the surface electromyography (sEMG) signal revealed through cross approximate entropy (Cross-ApEn) analysis provided insight on coupled muscle activity and the dynamic control strategies. Cross-ApEn, examines the similarity of spatial patterns between two signals based on time-dependent properties. For paired muscle activity, Cross-ApEn provides an index to which the sEMG signals are controlled as independent DOF (e.g., high Cross-ApEn) or as a single DOF (e.g., low Cross-ApEn)t o reveal the collective organization of a neural control strategy.

The aims of the current investigation were to examine: (i) the degree of coupling between three abdominal muscles and (ii) whether coupling varied with the manipulation of movement and load. Provided the limited study of muscle activity coupling and the inherent variability of EMG, a resting condition without movement was recorded to provide baseline measurement of abdominal muscle coupling strength and represented a potential boundary condition in which compared to the experimental trials.

The second aim further examined the presence of muscle coupling by varying the movement pattern (standard sit-up and reverse crunch) and load. The movements used here represent different task constraints imposed on the muscles due to upper and lower body movement during execution, respectively, and it was expected that coupling would differ between these task constraints [13]. Previous investigations in finger force production tasks have shown changes in coupling with different levels of forces [14,15]; therefore, it was predicted that an increased load would result in greater abdominal muscle coupling, in part due to the increased neural drive from common innervations, to accommodate the higher resistance level. Coupling between muscle pairs was evaluated through sEMG activity from the rectus abdominus (RA), external oblique (EO), and transverse abdominus (TA) muscles during the execution of a standard sit-up and a reverse crunch under bodyweight and loaded conditions.

2. Methods

Twenty healthy participants (9 male, 11 female; mean ± SD; age 20.4 ± 1.0 years; height: 173 ± 9.8 cm; weight: 69.1 ± 11.1 kg) provided written informed consent to participate in the study and were provided compensation for involvement. The study conformed with the practices and policies of the university's institutional review board. After consenting procedures, stature and body mass were recorded followed by a short survey that quantified the level of abdominal work performed during a typical week. Inclusion criteria included self-reported levels of physical activity that included a minimum frequency (e.g., at least 3 times per week and at least 50 repetitions per workout) of performing abdominal exercises as part of their normal exercise routine.

The sEMG signals of the RA, EO, and TA muscles were recorded using wireless surface electrodes (Trigno Lab, Delsys) with an inter-electrode distance of 10 mm. The signals were bandpass filtered (4–500 Hz), differentially amplified with a common mode rejection (< −80 dB), a baseline noise ratio < 2.5 uV), and were sampled at 1926 Hz. Prior to electrode attachment the skin was shaved, abraded, and then cleaned with an alcohol pad, to reduce impedance. Positioning of the electrodes followed previous investigations [1,5,16] and were placed in a direction parallel to the alignment of the muscle fibers over the muscle belly. All muscle bellies were readily identified on the participants through active contraction to ensure proper electrode placement [17]. One subject's data were removed from further analysis due to poor sEMG recordings during data collection.

Prior to the abdominal movements, EMG recordings were collected with participants laying in a supine position and the measured EMG activity was used to determine a baseline coupling state for each muscle pairing. The resting state was recorded for one second and analyzed through the same coupling approaches (described below) to determine whether the results of the experimental trials differed from that of the resting condition.

Brief instructions were provided for each exercise with emphasis on proper pacing (see below) and executing full range of motion for each movement. Participants performed 10 repetitions of the sit-up and reverse crunch movements under bodyweight and loaded conditions with the exercise order randomized across participants. The loaded conditions included weighted straps (4.54 kg) attached to the wrist or feet for the sit-up and reverse crunch movements, respectively. Movement duration was standardized to a pacing of 30 complete (concentric and eccentric phases) cycles per minute with a metronome set to a cadence of 60 beats per minute. Practice cycles were provided to ensure proper pacing. Rest was provided between each exercise condition as determined by the participant and primary researcher with most participants showing little signs of fatigue through the protocol.

In the sit-up movements, participants started in a supine position with arms held across the chest, hips and knees flexed, and feet supported by a researcher. The movement required hip and lumbar flexion and participants made elbow contact to the thigh proximal to the knee, then return to starting position. In the reverse crunch, participants started in a similar supine position except with feet elevated off the ground and flexed hips and knees. Instructions focused on moving the knees toward the participant's chin and returning the hips to the mat through lumbar and hip flexion motion to complete a full movement cycle.

The raw data were analyzed using custom-written code in MATLAB 2016b (The Mathworks, Natick, MA) and focused on the analysis of EMG magnitude, linear coupling and dynamic coupling of the EMG signals. The magnitude of each EMG signal was quantified by root mean square (RMS) to index the level of muscle activity. A correlation coefficient was calculated for the three muscle pairings [rectus abdominus-external oblique (RA-EO), rectus abdominus-transverse abdominus (RA-TA), and external oblique-transverse abdominus (EO-TA)] for each condition. The Cross-ApEn statistic assesses the conditional irregularity and dynamic coupling strength between two signals based on the recurrence of similar patterns with m length and within a defined variance range (r). Following previous recommendations [12,14], the input parameters for Cross-ApEn were $m = 2$ and $r = 0.2$ (the r value is multiplied by the standard deviation of the signal). A lower Cross-ApEn value indicates greater time-dependent covariation between the two signals and a stronger degree of dynamic coupling. Conversely, higher values of Cross-ApEn indicate greater degrees of independent control and lower coupling strength for the two signals.

Paired *t-tests* were conducted for each of the three muscle pairings between the resting state and each of the four conditions for linear correlation and Cross-ApEn values to establish whether coupling was present. The magnitude (RMS) of the EMG signals and the coupling measures were analyzed in separate two-way (movement × load) repeated measures ANOVAs with results deemed statistically significant when $p < 0.05$ and all analyses were performed using SPSS software (version 23.0).

3. Results

The mean (SD) RMS for each muscle and condition are shown in Fig. 1. Non-significant differences were found between the sit-up and