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Relationships of EMG to effort in the trunk under isometric conditions: force-increasing and decreasing effects and temporal delays

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Abstract

Background. Electromyograms are used in increasingly sophisticated biomechanical analyses to estimate forces within the trunk to prevent and evaluate painful spinal conditions. However, even under nominally isometric conditions the relationship between EMG and effort is complex. This study quantified influences of pulling direction, increasing versus decreasing effort and electromechanical delay on the EMG/effort relationships for principal lower trunk muscle groups in isometric pulling tasks, to determine whether the observed differences between increasing versus decreasing effort relationships were consistent with electromechanical delay or activation differences.

Methods. Twenty-three healthy subjects (15 male, 8 female; mean age 32 years; mean bodymass 74.5 kg) each stood in an apparatus to stabilize the pelvis and performed ramped isometric efforts with a harness around the thorax connected to each of a series of five anchor points on the wall, for angles of pull at each 45° increment from 0° to 180° to the anterior direction. A load cell recorded the generated force for a 5 s timed increase up to a voluntary maximum, a 1 s 'dwell', and a 5 s relaxation back to zero effort. EMG signals were recorded via electrodes (surface, except indwelling for multifidus) from right and left rectus abdominis, internal and external obliques, longissimus, iliocostalis and L2 and L4 level multifidus. EMG signals were rectified with a 250 ms root-mean-square moving average filter. Effort-increasing and effort-decreasing sections of recordings were analyzed separately.

Findings. The EMG/effort relationship had a statistically significantly greater gradient as the effort was increasing than when decreasing for 28 of 70 muscle-angle permutations. This difference in gradient was found to explain a significant part of the apparent lag between effort generated and EMG signal that averaged between 261 and 658 ms before and between 31 and 196 ms for different muscles after the slope difference was taken into account.

Interpretation. The findings were consistent with the notion that the motor unit recruitment differs in increasing versus decreasing isometric efforts, probably because of a small stretching of the muscle as its tension increases. The residual temporal delay was thought to represent electromechanical delay.

Keywords: Electromyography; Trunk-muscles; Electromechanical delay; Muscle activation; Lumbar spine

1. Introduction

The magnitudes of the forces that act on the lumbar spine depend on the degree of muscle activation. The pattern of muscle activation must be compatible with force equilibrium, but since there is a 'redundant' number of muscles compared to the number of degrees of freedom they control, the muscle forces cannot be calculated uniquely. The individual muscle forces may be estimated by analytical models that optimize a 'cost function' that represents the presumed strategy of the

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central nervous system. To add realism to biomechanical analyses, and to avoid the need to specify the cost function, electromyographic (EMG) measurements are often employed to provide information on the degree of activation of muscles. These models are commonly referred to as being 'EMG-assisted' (Cholewicki and McGill, 1994; Granata and Marras, 1995a,b), or EMG-driven (Sparto et al., 1998).

However, there is a complex relationship between EMG and muscle force (Solomonow et al., 1990; Baratta et al., 1993). In order to estimate muscle force from an EMG signal, the signal may be expressed as a proportion of that recorded at maximum activation (in a maximum voluntary effort). Then the force can be estimated as the product of this normalized value, the muscle cross-sectional area, and the 'specific stress', i.e. the maximum force generated per unit cross section (Cholewicki and McGill, 1994; Sparto et al., 1998; Granata and Marras, 1995a; van Dieën and Visser, 1999). The specific stress varies with the degree of muscle pennation (Kaufman et al., 1989). This represents a linear and time-independent representation of the EMG/force relationship. A more physiological representation of the muscle force includes corrections for the muscle length, shortening velocity, posture (Mouton et al., 1991), and fatigue (Dolan and Adams, 1993; Potvin et al., 1996). It is also known that there is a time lag between the EMG signal and the generated force, often called electromechanical delay (Cavanagh and Komi, 1979; Thelen et al., 1994; Vos et al., 1991; van Dieën et al., 1991). A further practical difficulty in deducing muscle forces from EMG signals is the presence of 'crosstalk' whereby an EMG electrode records a signal from numerous muscles, and is not specific to the activity of the intended muscle over which it is placed.

It has been noted that the EMG/effort relationship differs, depending on whether the effort is increasing or decreasing (Stokes et al., 1987). This has implications for estimating forces from EMG, but the origin of this effect is not clear, but there are at least three plausible explanations:

1. Differing recruitment of motor units as is observed in lengthening and shortening activations (Joyce et al., 1969). Even in nominally isometric efforts, it is likely that there is shortening of the muscle as the effort increases and vice versa, as a result of series elasticity in the muscle, tendon and other structures.
2. Recruitment at the whole muscle level—the CNS might transfer force generation between different parallel muscles when the task changes from increasing to decreasing force generation. (However, if this were the case, one would expect to see some muscles having increased, and others decreased activation after maximum effort were achieved.)
3. Electromechanical delay (Cavanagh and Komi, 1979; Thelen et al., 1994; Vos et al., 1991; van Dieën et al., 1991). The time lag between the EMG signal and the force generated gives the appearance of hysteresis when EMG is plotted graphically against effort.

This study empirically determined the relationship between the effort (external resisted force) and the EMG signal from seven pairs of trunk muscles in nominally isometric conditions. The recordings were examined for nonlinearities, synergies of muscular recruitment for the different pulling directions, differences in EMG–effort relationships during increasing versus decreasing effort, and temporal lags between EMG and effort. The purpose of this study was to quantify influences of pulling direction, increasing versus decreasing effort and electromechanical delay on the EMG/effort relationships for principal lower trunk muscle groups in isometric pulling tasks in which subjects generated an external force (effort) acting horizontally at different angles, and to determine whether the observed differences between increasing versus decreasing effort relationships were consistent with electromechanical delay or activation differences.

2. Methods

Twenty-three subjects (Table 1) who reported no recent (prior year) back pain were tested while each subject stood in an apparatus with the pelvis immobilized (Fig. 1). They were asked to performed 'ramped-effort' tests with a 5 s timed increase up to a voluntary maximum effort, a 1 s 'dwell', and a 5 s relaxation back to zero effort. Resistance was provided by a horizontal cable from a harness around the thorax to one of five anchorage points on a wall track to the subject's right side at angles of 0°, 45°, 90°, 135° and 180° to the forward direction (Fig. 1b). The sequence of angles was randomly selected. The cable was aligned approximately horizontally and at the level of the T-12 vertebra. Three trials were performed at each angle. A computer screen in front of the subject displayed a vertical bar whose height was proportional to the effort generated, and with a mark to indicate the prior maximum effort.

EMG signals from seven right and left pairs of trunk muscles were recorded, using bipolar EMG electrodes (Delsys Inc. Type DE-02.3, Boston, MA USA). These

Table 1
Details of subjects studied

	Age (years)	Height (m)	Body mass (kg)
Female ($n = 8$)	33.5 (13.2)	1.63 (0.1)	60.7 (10.6)
Male ($n = 15$)	30.3 (9.1)	1.68 (0.5)	81.8 (14.2)

Mean values (with standard deviation in parentheses) are presented.