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Effects of abdominal stabilization maneuvers on the control of spine motion and stability against sudden trunk perturbations

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Abstract

Much discussion exists about which is the most effective technique to improve spine stability. The purpose of this study was to evaluate the effectiveness of abdominal bracing and abdominal hollowing maneuvers to control spine motion and stability against rapid perturbations. Eleven healthy males were posteriorly loaded in different experimental conditions: resting with no knowledge of the perturbation timing; performing each of the stabilization maneuvers at 10%, 15% and 20% of internal oblique maximum voluntary contraction with no knowledge of the perturbation timing; and naturally coactivating the trunk muscles when perturbation timing was known. An EMG biofeedback system was used to control the pattern and intensity of abdominal coactivation. The muscular preactivation of seven trunk muscles (bilaterally registered), the applied force, and the torso muscular and kinematic responses to loading were measured; and the spine stability and compression were modeled. The hollowing maneuver was not effective for reducing the kinematic response to sudden perturbation. On the contrary, the bracing maneuver fostered torso cocontraction, reduced lumbar displacement, and increased trunk stability, but at the cost of increasing spinal compression. When the timing of the perturbation was known, the participants were able to stabilize the trunk while imposing smaller spine compressive loads.

Keywords: Stabilization maneuver; Sudden loading; Biomechanical model; Spine stability; Spine compression

1. Introduction

It is well known that mechanical factors, such as sudden trunk loading and unloading that may occur when falling, hitting, or slipping, have an important role in the development of low back disorders. Passive and active trunk structures under the control of the neural system participate in spine stabilization when the trunk is perturbed (Panjabi, 1992). A variety of experimental and modeling research has shown that the coactivation of the musculature surrounding the spine provides a stiffening mechanism to the vertebral joints and enhances stability (Andersen et al., 2004; Cholewicki and McGill, 1996; Cholewicki et al., 1999; Essendrop et al., 2002; Gardner-Morse and Stokes, 1998, 2001; van Dieën et al., 2003). As a consequence, a variety of trunk coactivation maneuvers and exercises are frequently used in the prevention and the treatment of spine instability (Kavcic et al., 2004b; McGill, 2002).

Although many variables need to be considered to understand the effects of coactivation maneuvers on spine stability and compression, the intensity level of muscular activation is a very influential factor (McGill et al., 2003). Sudden loading investigations while sitting or standing have shown that increasing torso muscle activation before

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perturbation increases trunk stiffness (Andersen et al., 2004; Cresswell et al., 1994; Essendrop et al., 2002; Gardner-Morse and Stokes, 2001; Vera-Garcia et al., 2006), and consequently reduces the torso displacement (Essendrop et al., 2002; Krajcarski et al., 1999; Stokes et al., 2000; Vera-Garcia et al., 2006) and the muscular response to loading (Andersen et al., 2004; Krajcarski et al., 1999; Stokes et al., 2000; Vera-Garcia et al., 2006), but at the cost of increasing spinal compression (Vera-Garcia et al., 2006). The optimal level of coactivation to achieve sufficient spine stability with the minimum compressive penalty depends on the task (Kavcic et al., 2004b; McGill et al., 2003); however, evidence obtained from the current literature suggests that for most of the daily activities, modest levels of torso coactivation (for example, 10–15% of abdominal maximum capability) can be sufficient for ensuring spinal stability with low to moderate lumbar compressive penalty (Cholewicki and McGill, 1996; Vera-Garcia et al., 2006).

An effective stabilization maneuver depends not only on a sufficient level of torso coactivation but also on proper muscular recruitment and timing patterns (McGill et al., 2003). For example, Brown et al. (2006) have recently shown that muscular coordination is of great importance to stabilize the spine against sudden trunk perturbations. Although the optimal coactivation pattern for actively stabilizing the spine has been a topic of much debate and research, there is no consensus between researchers. A few have advocated that isolated coactivation of deep abdominal muscles (transverse abdominis and internal oblique) and multifidus is crucial for spine stabilization (Jull and Richardson, 2000; Marshall and Murphy, 2005; Richardson et al., 1992). The abdominal hollowing maneuver, which coactivates transverse abdominis and internal oblique, has been effective to retrain perturbed motor patterns in abdominal muscles (O'Sullivan et al., 1998), and consequently theorized to increase spine stability and reduce pain and disability (O'Sullivan et al., 1997). However, whether this maneuver is effective to control the spine displacement and stability against sudden perturbation is unclear. Findings from biomechanical analyses in which spine stability was quantified suggest that all muscles play an important stabilizing role and must work harmoniously to fulfill this purpose (Cholewicki and VanVliet, 2002; Kavcic et al., 2004a; McGill et al., 2003). This would suggest that stabilization maneuvers should not focus on isolating the coactivation of a few muscles, but should produce a more global coactivation such as that generated during the bracing stabilization maneuver. Vera-Garcia et al. (2006) have recently shown that abdominal bracing while positioned with the spine in a neutral lumbar position, produced patterns of antagonist trunk cocontraction that significantly increased spine stability and reduced the movement of the lumbar spine after rapid loading.

Our interest in the current paper is to obtain more insight into the relationship between the way the abdominal muscles are coactivated, and the corresponding development of spine stability and spine loads, in order to help clinicians in recommending and teaching the most appropriate rehabilitation and training techniques. Despite many electromyography (EMG) based studies which have tried to evaluate diverse stabilization maneuvers and exercises on the basis of muscular activation profiles (Allison et al., 1998; Richardson et al., 1992; Souza et al., 2001; Vezina and Hubley-Kozey, 2000), very little research has used sudden load paradigms to analyse the effects of these tasks on stabilizing the spine under rapid perturbations.

The aim of this study was to evaluate the effectiveness of abdominal bracing and abdominal hollowing maneuvers (global abdominal coactivation versus deep abdominal coactivation), to control the spine motion and stability against rapid trunk perturbations of unknown timing. Specifically the muscular preactivation and corresponding spine stability and compression levels were quantified, the applied force was recorded, and the torso muscular and kinematic responses to rapid loading were measured. Moreover, in order to enable a discussion around the objective of better understanding the motor control strategies and subsequent affect on spine stability, these stabilization maneuvers were compared to each participant's ability to naturally stabilize the spine when the exact timing of the trunk perturbation was known.

2. Methods

2.1. Participants

Twelve recreationally trained male volunteers, who had not experienced back pain in the previous year, were recruited from the university population and participated in the study. Data from one of the participants were excluded from this study because it was marred with many artifacts and other technical problems. The eleven subjects with clean data had a mean (SD) age of 27.67 (7.19) years, height of 180.38 (5.63) cm, and mass of 78.58 (9.88) kg. Participants completed an informed consent form approved by the University Office for Research Ethics.

2.2. Instrumentation and data collection

2.2.1. EMG biofeedback and abdominal maneuvers

While maintaining the lumbar spine in a neutral position, the participants were instructed to isometrically tighten their abdominals with two different techniques: bringing their navel up and in toward the spine, so as to draw in the lower abdomen (abdominal hollowing) (O'Sullivan et al., 1998); and without any change in the position of the muscles (abdominal bracing) (Kavcic et al., 2004b). A MyoTrac™ EMG Biofeedback System (Thought Technology Ltd., Montreal, Canada) was used to control the pattern and intensity of coactivation maneuvers (Brown et al., 2006; Vera-Garcia et al., 2006). The MyoTrac has two EMG sensors (MyoScan™). The first sensor was placed over the right internal oblique muscle (halfway between the anterior superior iliac spine of the pelvis and the midline, just superior to the inguinal ligament) and the second over the right rectus abdominis (approximately 3 cm lateral and 10 cm superior to the umbilicus). When bracing or hollowing, the participants used the information from the internal oblique sensor to achieve three different preactivation levels (targets): 10%, 15% and 20% of internal oblique maximal voluntary isometric contraction (MVC) amplitude. Participants were instructed "to try to attain the EMG activation target and to maintain it while holding the lumbar spine in a neutral position". Participants practiced the stabilization maneuvers at the diverse target levels until both they, and the experimenter, were satisfied with their ability. The sensor sited over the rectus abdominis helped to better differentiate between hollow and brace techniques. Unlike abdominal bracing, the aim of the abdominal hollowing technique was to coactivate the deep abdominals with minimal rectus abdominis activation.

2.2.2. Sudden loading

Participants were placed in a semi-seated position in a wooden apparatus that restricted hip motion while leaving the trunk free to move in all directions (Fig. 1). This has been shown to foster a neutral spine posture and elastic equilibrium for the hips and spine (Sutarno and McGill, 1995). Participants were rapidly and posteriorly loaded in different loading conditions: resting (no preactivation); performing bracing and hollow maneuvers at 10%, 15% or 20% of internal oblique MVC; and naturally coactivating the trunk muscles when perturbation timing was known (expectation condition). A steel cable attached to a harness was used to load the trunk (Fig. 1). The cable was aligned approximately with the T7 level, and directed horizontally through a pulley and attached to a 6.8 kg weight, which was dropped from a height of 5 cm to load the cable.

For the expectation condition, a set of 10 loading trials were performed at the beginning of the experiment (prior to the stabilization maneuver trials) to avoid the influencing the participants' natural technique through the teaching process for the stabilization maneuvers. Therefore, during the expectation trials participants were not given any instructions on how to stabilize the spine; participants could choose their own way to stabilize the spinal joints against rapid loading. An experimenter counted down using a metronome programmed at 1 beat/s: "three, two, one, load". The three trials in which the best stability scores were obtained were used to represent the participant's ability to naturally stabilize the spine under expected loading, and subsequently compared with the stabilization maneuvers instructed by the investigators.

For the rest of the conditions (no preactivation, bracing and hollowing; administered in random order), each participant performed three trials where the load was applied by the experimenters without warning, within a 12 s window. Altogether, this study resulted in a total of 31 trials per subject. Approximately, 1 min rest was given between trials to avoid the influence of fatigue on trunk responses to loading.

2.2.3. External force measures

The magnitude and timing of the force perturbation produced by dropping the load was measured using a load-cell force transducer (Transducer Techniques Inc., Temecula, CA, USA) located in-series between the cable and the harness. The force signals were amplified, and A/D converted (12 bit resolution over ±10 V) at 2048 Hz.

2.2.4. Trunk kinematics

Lumbar spine kinematics were measured about three orthogonal axes (flexion-extension, lateral bend, and twist) using an electromagnetic tracking instrument (3Space ISOTRAK, Polhemus Inc., Colchester, VT, USA), sampled at a frequency of 64 Hz. The source was strapped to the pelvis over the sacrum and the receiver on the ribcage, over the T12 spinous process. Thus, the three-dimensional

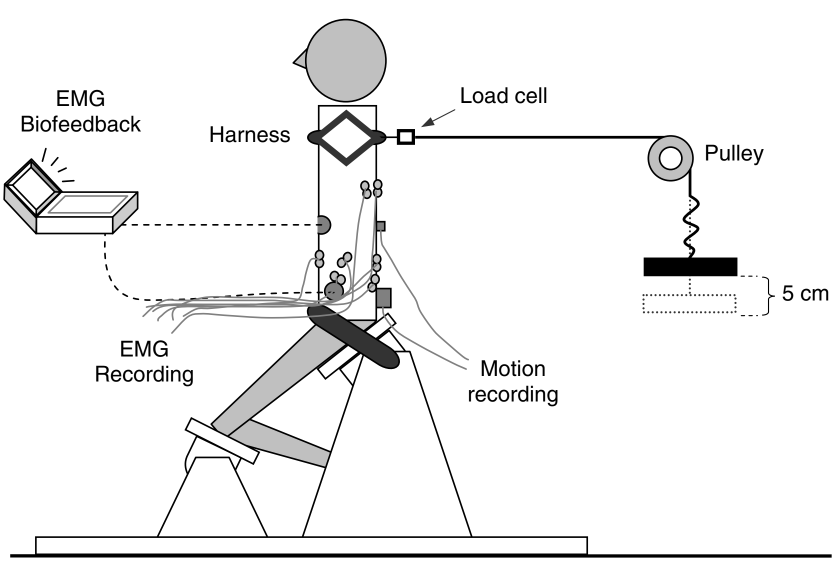

Fig. 1. Experimental set-up for generating sudden posterior loading.

angular displacements of the ribcage relative to the sacrum were measured.

2.2.5. EMG recording

Surface electromyographic signals were collected bilaterally (R = right; L = left) from the following trunk muscles and locations: rectus abdominis (RA), approximately 3 cm lateral to the umbilicus; external oblique (EO), approximately 15 cm lateral to the umbilicus; internal oblique (IO), 3 cm cephalad and medial to the anterior superior iliac spine and just superior to the first EMG biofeedback sensor site; latissimus dorsi (LD), lateral to T9 over the muscle belly; and erector spinae at T9, L3 and L5 [considered thoracic (ET9), lumbar (EL3), and multifidus (EL5) levels, respectively], located approximately 5, 3 and 1 cm lateral to each spinous process. Disposable bipolar Ag–AgCl disc surface electrodes (Blue Sensor, Ambu A/S, Denmark) were positioned parallel to the muscle fibers with a centre-to-centre spacing of 3 cm. The electromyographic recording was synchronized to the ISOTRAK and load cell data with a common trigger.

The EMG signals were amplified (±2.5 V), A/D converted (12 bit resolution) at 2048 Hz, full wave rectified and low pass filtered (second order single pass Butterworth) at 2.5 Hz. Then, the filtered EMG was normalized to MVC amplitudes. The MVCs were obtained in two sets of isometric maximal exertion tasks against manual resistance carried out prior to the sudden load trials. For the abdominal muscles, the participant produced maximal isometric efforts in trunk flexion, right lateral bend, left lateral bend, right twist and left twist. For the extensor muscles, isometric trunk extensions were performed in the Biering–Sorensen position. The participant was verbally encouraged during the maximal performance.

2.3. Data reduction

2.3.1. Force, kinematics and electromyography

A computer algorithm was used to facilitate the detection of the force perturbation from the load-cell signal. According to the algorithm, the perturbation was considered to occur when, for at least a 50 ms period, load-cell signal exceeded the sum of the mean plus one standard deviation of the force signal calculated over the previous 100 ms. Each trial was visually checked against the computer-derived timing to ensure that the onset of force perturbation was meaningful. Time windows of 200 ms before and 250 ms after perturbation were selected for subsequent analyses.

EMG, force and kinematic signals were visually inspected and data with artifacts were excluded from further analyses. The peak angular lumbar extension in the 250 ms after sudden loading was recorded in every trial. For each muscle site, the average normalized EMG of the 50 ms before the perturbation was used to evaluate the amplitude of the muscle preactivation in each trial. The ratios of activation of internal oblique relative to rectus abdominis and external oblique (IO/RA and IO/EO, respectively) were calculated with the purpose of verifying that the stabilization maneuvers were correctly executed. Further, the peak EMG level achieved in the 50–250 ms post loading window was recorded. Both the absolute difference as well as the ratio between the peak EMG response and the average EMG preactivation were calculated in order to evaluate the absolute and the relative magnitude of the muscle responses, respectively.

2.3.2. Stability and compression

First, static whole-body postures were hand digitized from a single digital video image and entered into a full-body linked segment model to determine the 3-D reaction forces and moments at the L4–L5 joint. Next, 14 channels of EMG and three-dimensional lumbar spine angles acquired from the 3-Space were entered into an anatomically detailed spine model representing 118 muscle elements as well as lumped passive tissues, spanning the six lumbar joints (T12-L1 through L5-S1). This model has been comprehensively reported previously (Cholewicki and McGill, 1996). Muscle stiffness and force were calculated as the 1st and 2nd moments respectively of a Distribution Moment Model (Ma and Zahalak, 1991) representing the instantaneous number of attached cross-bridges in a given muscle, dependent on muscle cross-sectional area, activation, length and velocity.

To quantify spine stability, an 18×18 (six joints by three anatomical axes) Hessian matrix of the 2nd partial derivatives of the potential energy of the entire lumbar spine system was calculated, and diagonalized to obtain its eigenvalues. The potential energy theory states that each eigenvalue of the matrix must be positive definite in order for the system to be stable. Both the lowest eigenvalue and the stability index (an average of the 18 eigenvalues (Howarth et al., 2004)) were therefore utilized as measures of spine stability. Specifically, the lowest eigenvalue indicates the absolute stability of the system (“weakest link”) while the index provides a solution more sensitive to all joints and potential modes of buckling. L4–L5 compressive force and the two measures of spine stability were analysed as the average over the 50 ms prior to the sudden load.

2.4. Statistical analysis

For each of the experimental conditions, each dependent variable was averaged over three trials. Two-Way (4×3) repeated measures analyses of variance (ANOVA) were performed to evaluate the influence of internal oblique preactivation level (no preactivation, and 10%, 15% and 20% of MVC) and maneuver (expectation, hollow, brace) on each of the dependent variables (muscular preactivation level, response/preactivation ratios, and absolute responses for each muscle, IO/RA and IO/EO EMG ratios, the peak of lumbar extension after loading, and the modeled estimates of lumbar stability (lowest eigenvalue and stability index) and compression at L4–L5). Where applicable, post-hoc analyses were performed using the Tukey HSD test. Significance levels were set to $\alpha = 0.05$ for all tests.

3. Results

3.1. Muscular preactivation

For internal oblique, the experimental preactivation levels monitored by EMG biofeedback were statistically different from one another ($P < 0.0001$ both LIO and RIO) (Fig. 2); in contrast, differences in internal oblique activation between stabilization maneuvers were not found. Similar results were reported for erector spinae at L5 (multifidus site). For the rest of the muscles, abdominal bracing resulted in higher levels of preactivation than abdominal hollowing. Interestingly, when the timing of the loading was known (expectation), the participants preactivated the trunk muscles with similar averaged magnitudes to those observed during bracing and hollowing at 10% of internal oblique MVC (Fig. 2).

As shown in Fig. 3, the IO/RA and IO/EO EMG ratios were statistically higher for the hollowing maneuvers. The IO/RA ratio has been previously used for controlling the correct performance of the draw-in or hollowing technique, which is supposed to isolate the coactivation of the deep abdominal muscles and reduce the participation of rectus abdominis (O'Sullivan et al., 1998). As a result, using EMG biofeedback the participants were able to differentiate two abdominal stabilization maneuvers (brace and hollow) at three levels of internal oblique activation (10%, 15% and 20% of MVC). However, no subject accomplished hollowing by activating deep abdominals alone, as has been

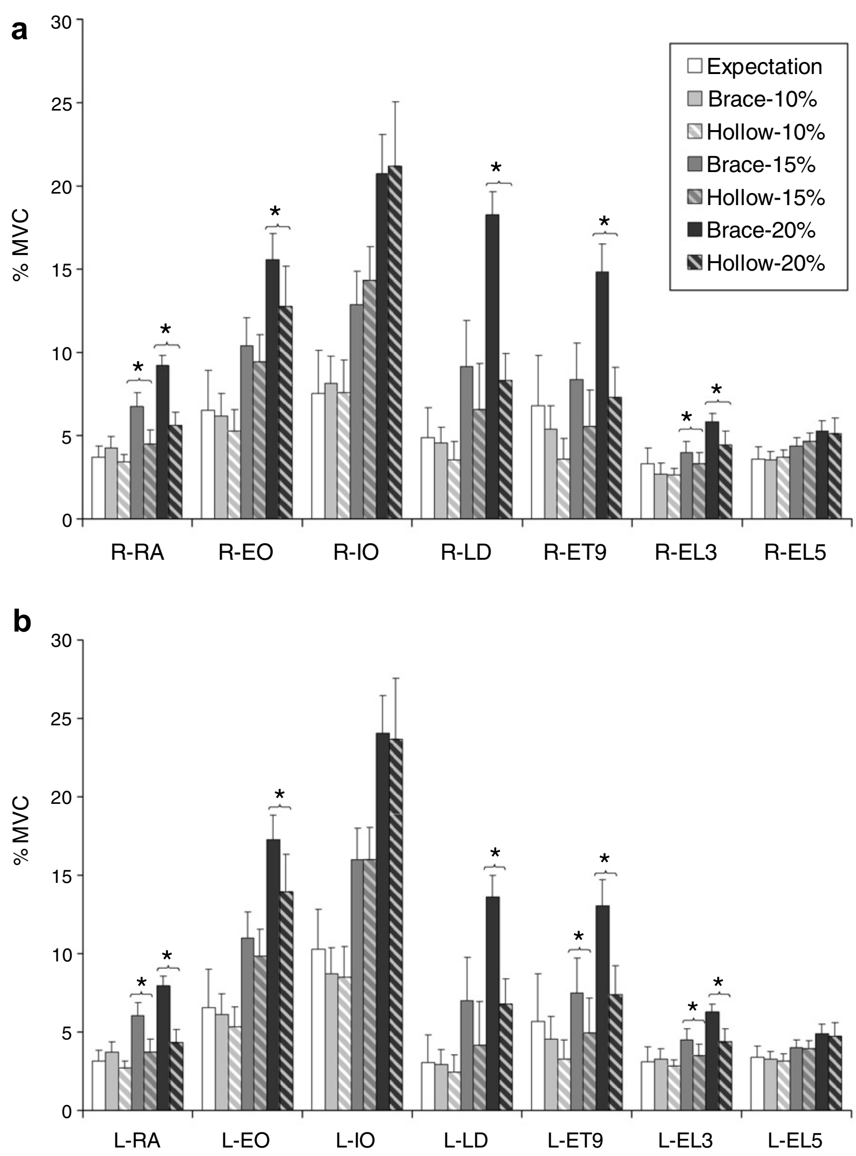

Fig. 2. Averages and standard deviations of the normalized EMG amplitudes during the 50 ms before loading for the right (a) and left (b) trunk muscles. Muscle abbreviations are explained in the text. It should be noted that for internal oblique (muscle monitored by EMG biofeedback), there were no differences between brace and hollow maneuvers at any of the preactivation levels. For clarity, only the results of the multiple comparisons between brace and hollow maneuvers are shown: $^{*}P < 0.05$.

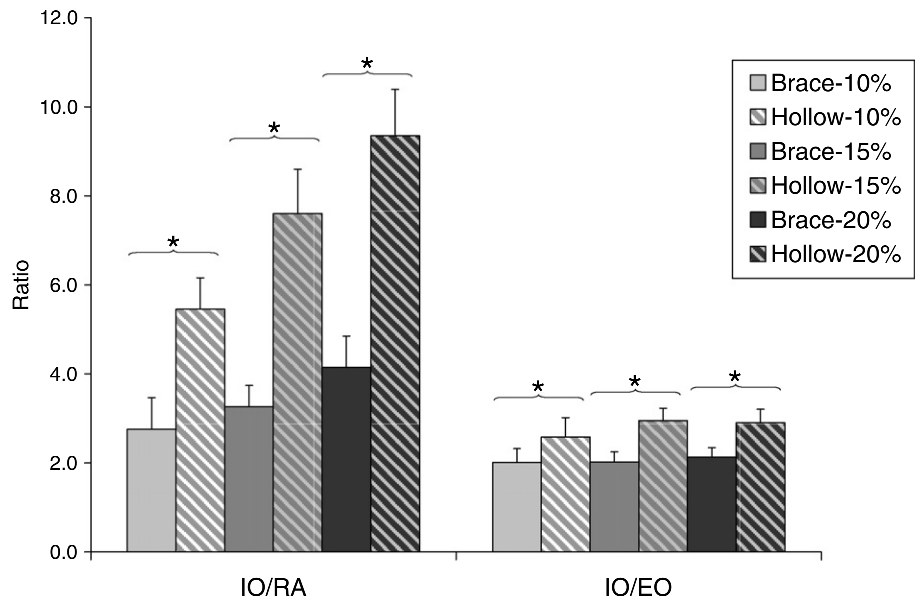

Fig. 3. Averages and standard deviations of the ratios "internal oblique/rectus abdominis" (IO/RA) and "internal oblique/external oblique" (IO/EO) in brace and hollow maneuvers for each preactivation level (10%, 15% and 20% of IO MVC). The hollowing maneuvers always show higher ratios, especially in the IO/RA ratio, which has been previously used to control the correct performance of hollowing techniques (O'Sullivan et al., 1998). Results of the multiple comparisons: $^{*}P < 0.05$.

claimed, since substantial activation was always noted in both the internal and external oblique.

3.2. Stability and compression

Preactivation of the trunk muscles significantly increased the stability index and spine compression before loading ($P < 0.0001$). At each preactivation level, compression and the stability index were statistically higher for the abdominal brace than for the abdominal hollow (Fig. 4). A similar trend was observed in the lowest eigenvalue, however differences failed to reach statistical significance, possibly because of the variability between subjects. As was observed in the muscular preactivation (Fig. 2), the expectation condition resulted in similar levels of spine stability and compression to the 10% MVC hollow and brace conditions (Fig. 4).

3.3. Trunk displacement

When the load was suddenly and posteriorly applied to the trunk, lumbar extension was observed. For the abdominal brace conditions, increasing the preactivation level reduced trunk motion ($P < 0.020$) (Fig. 5). Abdominal bracing at 20% of internal oblique MVC as well as knowing the perturbation timing (expectation condition) resulted in a significant (~43%) reduction in lumbar extension compared with the no preactivation condition. On the other hand, no statistical differences were found between the hollowing preactivation levels and the no preactivation condition. Moreover, the lumbar displacement when hollowing at 10% or 15% of internal oblique MVC was significantly higher than the lumbar extension when bracing at 10%, 15% or 20% of internal oblique MVC. Hollowing at 20% MVC was similar to bracing at 10% MVC.

3.4. Amplitude of the muscular response

Rapid posterior loading while semi-seated mainly activated the abdominal muscles. During the no preactivation condition, the responses of latissimus dorsi and erector spinae at T9 also were considerable. As shown in Figs. 6 and 7, preactivation reduced the relative and absolute response of the abdominal muscles. The reduction was significant when comparing no preactivation with the bracing and hollowing conditions. It should be noted that as a general trend the relative response amplitudes (response/preactivation ratios) of rectus abdominis, external oblique, latissimus dorsi and erector spinae at T9 and L3 were higher for the hollowing conditions than for the bracing conditions at each level of internal oblique preactivation (Fig. 6). The differences between maneuvers almost reached statistical significance for left rectus abdominis ($P = 0.071$) and right external oblique ($P = 0.064$). On the contrary, the absolute response amplitude of rectus abdominis (calculated as the magnitude of response minus the preactivation) was significantly higher for the bracing conditions than for the hollowing conditions, and did not change for the rest of the muscles (Fig. 7).

In the expectation condition, relative and absolute muscular responses were higher than when bracing or hollowing at 15% and 20% of internal oblique MVC (Figs. 6 and 7).

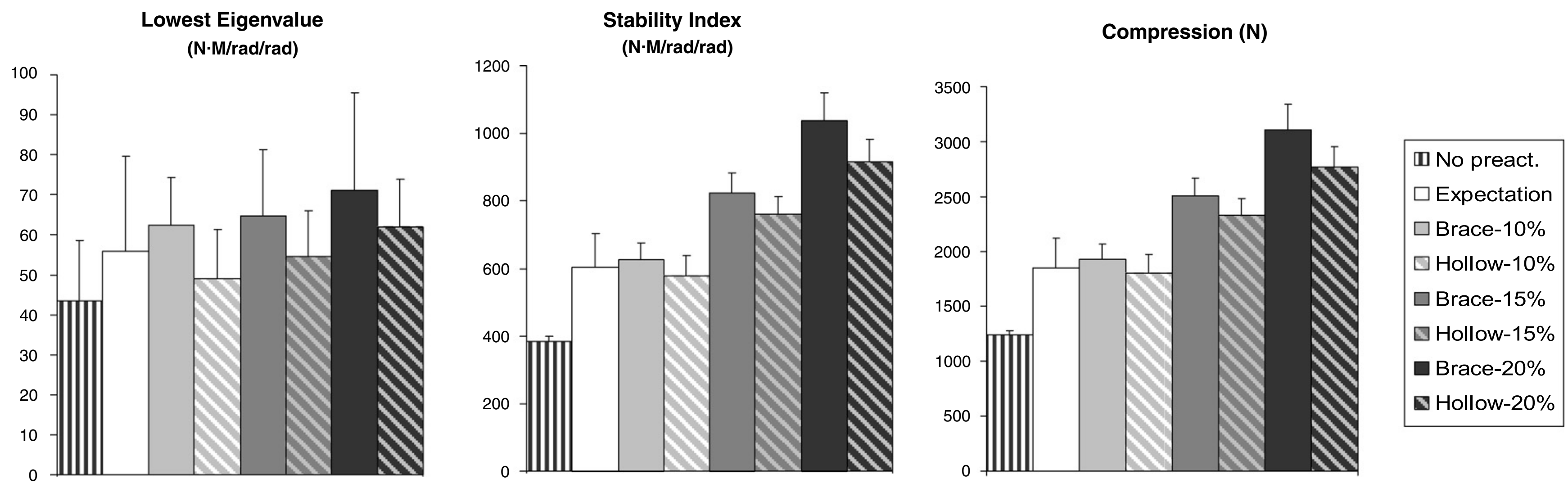

Fig. 4. Averages and standard deviations of lowest eigenvalue, stability index and compressive force for no preactivation, expectation, brace and hollow conditions (10%, 15% and 20% of IO MVC). This was examined as the average over the 50 ms pre-load. More preactivation stiffens and stabilizes the spine at the cost of higher spine compressive force. Notice that for abdominal brace, stability (lowest eigenvalue and stability index) and compression were higher than for abdominal hollow at each preactivation level.

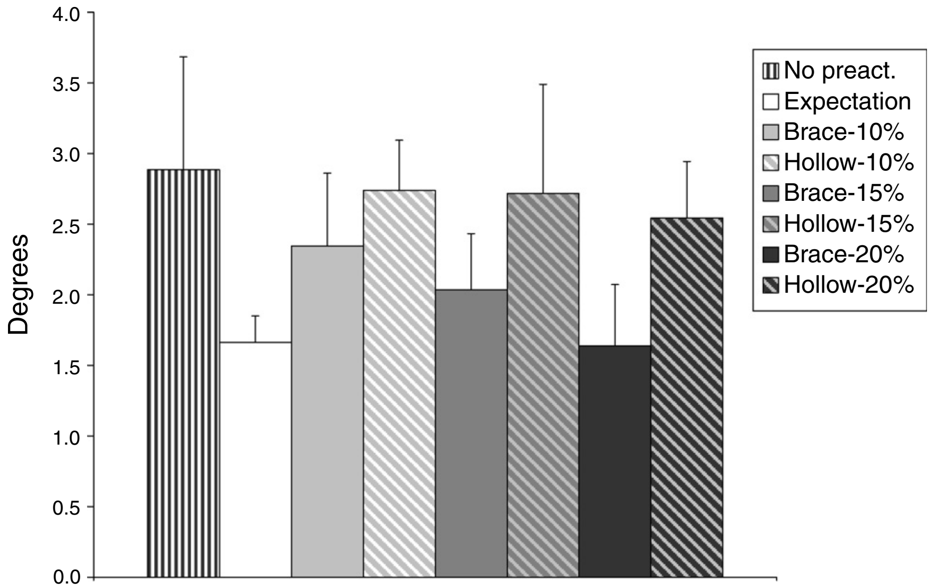

Fig. 5. Averages and standard deviations of the lumbar spine extension resulting from rapid posterior loading. While bracing, spine displacement decreased when preactivation level increased. In the hollowing maneuvers the movement remains quite similar to that in the no preactivation condition. The displacement in the expectation condition was similar to the displacement during bracing at 20% of IO MVC.

4. Discussion

Abdominal bracing and abdominal hollowing are popular stabilization maneuvers used in rehabilitation and training programs. In this study, the effects of these maneuvers on spine stability, trunk displacement and muscular responses to posteriorly applied sudden loads have been investigated. The major finding was that abdominal bracing performed better than abdominal hollowing for stabilizing the spine against rapid perturbations. Specifically, bracing actively stabilized the trunk and reduced the lumbar spine displacement after loading; however, hollowing was ineffective for buttressing the spine under perturbation.

Abdominal hollowing is a popular instructional tool for people performing tasks needing spine stability, thought to promote the isolated coactivation of the deep abdominal muscles (Richardson and Jull, 1995). As shown in this study (Figs. 2 and 3), the activity of rectus abdominis and external oblique when hollowing is significantly smaller than when bracing. O'Sullivan et al. (1997, 1998) found that this technique is effective as a way to retrain perturbed motor patterns in deep abdominal muscles, which some have suggested a link to spine stability. This suspected link has motivated some to suggest hollowing or drawing-in exercises for use in rehabilitation program for patients with segmental spinal instability. Unfortunately, others have misinterpreted this data to mean that hollowing maneuvers or minimizing rectus abdominis activity during core stability exercises directly enhances stability. As our results show, even though the stability index (calculated by the mathematical model) was higher for abdominal hollowing than for the no preactivation condition (Fig. 4), this maneuver was not an effective technique for reducing the kinematic response to posterior and rapid perturbations (Fig. 5). Thus, abdominal hollowing does not directly enhance stability and does not seem a good technique for stabilizing the trunk when performing lifting, jumping, pressing or pushing actions in sport or daily activities. Moreover, Vezina and Hubley-Kozey (2000) have suggested that the hollowing technique probably does not recruit the abdominal muscles to adequate levels for strengthening in healthy populations. It should be noted that we did not test the ability of the stabilization maneuvers to train or retrain motor patterns to allow for improved stability under natural circumstances.

For the same levels of internal oblique activity, abdominal bracing produced more torso coactivation than abdominal hollowing. As Vera-Garcia et al. (2006) previously found, abdominal bracing, in a semi-seated position with a neutral spine, principally activated the internal oblique muscle, but also generated great levels of antagonist cocontraction, which stiffens the trunk and increases spinal stability (Cholewicki et al., 1999; Gardner-Morse and Stokes, 1998, 2001). In this study, muscular trunk coactivation when bracing at low levels of internal oblique MVC increased stability, and consequently reduced the trunk displacement after sudden loading. In fact, abdominal bracing at 20% of internal oblique MVC resulted in a significant (~43%) reduction in lumbar extension compared with the no preactivation condition.

In spite of these potential benefits of bracing, increasing stability through the modulation of muscle cocontraction significantly increased the compressive loads acting on the lumbar spine (Fig. 4), a mechanical factor which has been linked to low-back pain and disorders (NIOSH, 1981; Norman et al., 1998). The effect of cocontraction on compressive spine forces has been well documented

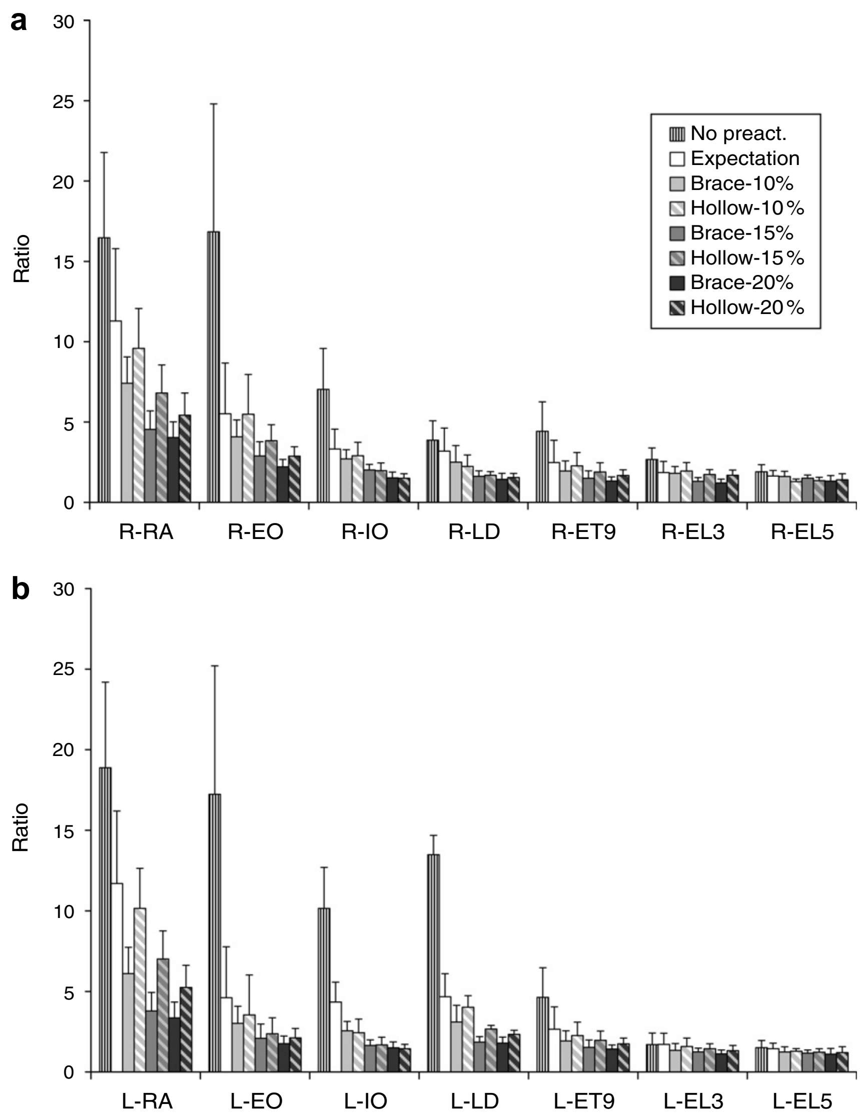

Fig. 6. Averages and standard deviations of the EMG response/preactivation ratios (relative response amplitude) for the right (a) and left (b) trunk muscles. Muscle abbreviations are explained in the text. Preactivation reduced the response/preactivation ratio of the muscles. Notice that the relative response magnitude of rectus abdominis, external oblique, latissimus dorsi and erector spinae at T9 and L3 was higher for the hollowing conditions than for the bracing conditions.

(Gardner-Morse and Stokes, 1998; Granata and Marras, 2000; Vera-Garcia et al., 2006). For low extensor moments in the trunk (lifting), Granata and Marras (2000) found that the margin between spine stability (benefit) and compression (penalty) increases significantly with cocontraction. In the current study, abdominal hollowing showed the worst cost–benefit relationship in protecting against spinal instability, since it increased the spinal compressive loads without successfully reducing trunk displacement after perturbation. It must be noted that the expectation condition, which represents the natural maneuver chosen by the participants to stabilize the trunk when the timing of the loading is known, resulted in the best cost–benefit relationship; that is, the participants effectively reduced the extension movement while generating low compressive forces. On the basis of these results, even though abdominal bracing (cocontraction) is an effective technique for stabilizing the spine in preparation for sudden loading, knowing the timing of the perturbation seems the most important factor in protecting against potential injury. Therefore, the combination of perception and attention tasks as well as stabilization exercises may be a useful method for reducing the loading consequences in patients with spinal instability.

In regard to the muscular reaction to loading, the abdominal muscular response was higher than the extensor muscular response, due to the posterior loading orientation. However, every single muscle reacted to the sudden load, and consequently, all trunk muscles seem have some important function in stabilizing the spine, supporting the findings of Kavcic et al. (2004a) and Cholewicki and VanVliet (2002). Abdominal preactivation, when bracing or hollowing, reduced the absolute and relative trunk muscular responses to perturbation (Figs. 6 and 7). In the same

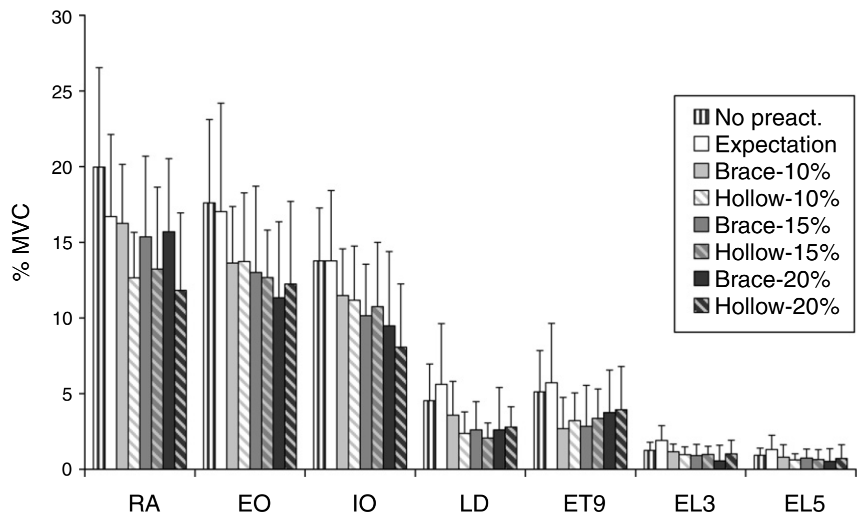

Fig. 7. Averages (across all subjects and both right and left muscles) and standard deviations of the absolute EMG responses (calculated as the magnitude of response minus the preactivation) averaged across the right and left trunk muscles. Muscle abbreviations are explained in the text.

way, previous studies found that trunk muscle activation before loading reduced the amplitude and/or the frequency of the reflex response (Andersen et al., 2004; Krajcarski et al., 1999; Stokes et al., 2000; Vera-Garcia et al., 2006). Interestingly, the relative response amplitudes (response/preactivation ratios) of rectus abdominis, external oblique, latissimus dorsi and erector spinae at T9 and L3 were higher for the hollowing conditions than for the bracing conditions (Fig. 6). On the basis of these ratios, it appears that the smaller trunk displacement observed in the bracing conditions (Fig. 5) could reduce the reflex muscular response to loading. However, the ratios are highly sensitive when preactivation levels are low. As we have showed, abdominal hollowing resulted in smaller levels of preactivation than abdominal bracing. The low levels of preactivation, especially at rectus abdominis sites, could affect the response/preactivation ratios. Using the response-preactivation difference, the rectus abdominis response was significantly smaller for the hollowing conditions (Fig. 7). It is possible that the higher preactivation of this muscle when bracing could increase the activity of the gamma system and the excitability of its muscle spindles, hence increasing the reaction intensity. Moreover, the concave shape of rectus abdominis when hollowing may be less suitable to evoke stretch reflexes under posterior perturbation. Nevertheless, speculating on the reasons for these findings is very complicated since we do not exactly know the neural pathways which drove the muscular responses. In our opinion, surface electromyography is a complex but valuable tool for evaluating muscular function, however, understanding spine stability needs a more rigorous approach (i.e., that includes kinetic, kinematic, and electromyographic signals input to a stability analysis measuring stiffness and potential energy).

During the motor learning process of the abdominal stabilization maneuvers, the participants showed more difficulty in performing the hollowing as compared to the bracing technique. In previous studies, O'Sullivan et al. (1997, 1998) reported that some patients with lumbar segmental instability and perturbed patterns of abdominal coactivation needed 4 or 5 weeks to learn the hollowing maneuver. Healthy individuals also appear to have difficulty performing abdominal hollowing exercises (Vezina and Hubley-Kozey, 2000). However, the healthy and recreationally trained participants in our study rarely required more than 20 min to correctly perform the technique. In this case, the EMG biofeedback system was a great help for teaching, learning and controlling the correct coactivation pattern.

In summary, the current study analysed the effects of abdominal bracing, abdominal hollowing, and expectation on the trunk responses to posteriorly applied sudden trunk loads in a neutral lumbar position. On the basis of our findings, the hollowing maneuver does not directly enhance stability. In contrast, the bracing maneuver fostered torso cocontraction, reduced lumbar displacement, and increased trunk stability, but at the cost of increasing spinal compression. When the timing of the perturbation was known, the participants were able to stabilize the trunk while imposing smaller compressive forces on the lumbar spine. Interpretations of the data of this study are limited to our subjects being healthy and relatively physically fit; it may not be appropriate to generalize the present experimental results to other populations such as patients with low back instability. Further research is needed to evaluate the effectiveness of stabilization techniques and expectation for ensuring spinal stability when the healthy or unstable spine is loaded in different directions, postures and motions.

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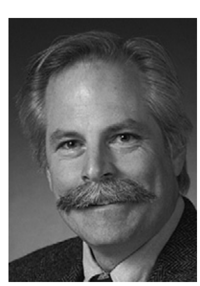

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