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Intra-abdominal pressure and abdominal wall muscular function: Spinal unloading mechanism

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ABSTRACT

Background: The roles of antagonistic activation of abdominal muscles and of intra-abdominal pressurization remain enigmatic, but are thought to be associated with both spinal unloading and spinal stabilization in activities such as lifting. Biomechanical analyses are needed to understand the function of intra-abdominal pressurization because of the anatomical and physiological complexity, but prior analyses have been over-simplified.
Methods: To test whether increased intra-abdominal pressure was associated with reduced spinal compression forces for efforts that generated moments about each of the principal axis directions, a previously published biomechanical model of the spine and its musculature was modified by the addition of anatomically realistic three-layers of curved abdominal musculature connected by fascia to the spine. Published values of muscle cross-sectional areas and the active and passive stiffness properties were assigned. The muscle activations were calculated assuming minimized muscle stress and stretch for the model loaded with flexion, extension, lateral bending and axial rotation moments of up to 60 Nm, along with intra-abdominal pressurization of 5 or 10 kPa (37.5 or 75 mm Hg) and partial bodyweight (340 N).
Findings: The analysis predicted a reduction in spinal compressive force with increase in intra-abdominal pressurization from 5 to 10 kPa. This reduction at 60 Nm external effort was 21% for extension effort, 18% for flexion effort, 29% for lateral bending and 31% for axial rotation.
Interpretation: This analysis predicts that intra-abdominal pressure produces spinal unloading, and shows likely muscle activation patterns that achieve this.

1. Introduction

The roles of abdominal muscles and of intra-abdominal pressure (IAP) remain enigmatic, especially the apparently antagonistic activation of abdominal muscles during extension efforts. This uncertainty has led to controversy about appropriate lifting techniques and rehabilitation exercises for people with back pain, and whether use of corsets has prophylactic value. Abdominal pressurization associated with abdominal muscle activation has been thought to be beneficial by producing spinal unloading during extension efforts (Morris et al., 1961; Arjmand and Shirazi-Adl, 2006; Daggfeldt and Thorstensson, 1997; Hemborg et al, 1985; Hodges et al., 2001). Furthermore, it has been proposed that the added muscular stiffness associated with muscle co-activation provides increased stability of the trunk (Cholewicki et al., 1999a; Essendrop et al., 2002; Gardner-Morse and Stokes, 1989; Hodges et al., 2003; Tesh et al., 1987). Training of these muscles is included in exercise regimens for people with low back pain, based on these presumed beneficial effects. The supposed spinal unloading effect of IAP in lifting (extension) efforts results from the pressure acting on the diaphragm and pelvic floor (producing an extension moment) but must be offset against the flexion moment generated by the activation of abdominal musculature. However, it is thought that the resultant is a net extension moment (Morris et al., 1961), although the biomechanical basis for this has been questioned (McGill and Norman, 1987). The supposed stabilizing effect of activation of the abdominal wall muscles is a consequence of the stiffness of activated muscle (Bergmark, 1989). Experimental studies have supported this idea (Cresswell and Thorstensson, 1994; Cholewicki et al., 1999b; Stokes et al., 2000). Simplified biomechanical analyses of spinal buckling have also quantified the added stability (Cholewicki et al., 1999a; Gardner-Morse and Stokes, 1989).

Experimentally, little or no decrease in dorsal muscle activation (where reduced muscle activation implies spinal unloading) has been reported in studies of live humans with voluntary augmentation or inhibition of abdominal muscle activation (Krag et al., 1986; Nachemson et al., 1986). However, these contrived experiments are not necessarily a realistic representation of normal physiological

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recruitment of abdominal muscles. Increased spinal extension moment (implying spinal unloading) was recorded when intra-abdominal pressure was increased in experimental subjects by stimulating the phrenic nerve to induce diaphragm contraction (Hodges et al., 2001). Therapeutically, one supposed effect of wearing a lumbar corset or belt is to facilitate abdominal pressurization, and hence produce spinal unloading and also increased stability (Ivancic et al., 2002; McGorry and Hsiang, 1999; Miyamoto et al., 1999; Woodhouse et al., 1995; Cholewicki et al., 1999b).

Because live human subjects find it difficult to control abdominal pressurization in contrived experimental conditions, biomechanical analyses provide a way to explore the function of IAP. However, most prior analyses have represented the abdominal wall as an elastic membranous pressure vessel (Daggfeldt and Thorstensson, 1997) or by straight line muscle paths that do not contain intra-abdominal pressure and therefore biomechanically over-simplify the anatomical and physiological complexity of the abdominal wall (Arjmand and Shirazi-Adl, 2006; Stokes and Gardner-Morse, 1999; Grenier and McGill, 2007).

This paper reports on use of a new analysis of trunk biomechanics that includes an abdominal wall with all three muscle layers having realistic curved muscle paths added to a previously developed model (Stokes and Gardner-Morse, 2001). Relative to prior analyses of the biomechanics of intra-abdominal pressurization, this model includes a substantially more detailed representation of the lumbar spine and the dorsal musculature. In the present analyses, the abdominal muscles are curved (hence there is a relationship between their tension and the intra-abdominal pressure determined by force equilibrium) and have transverse stiffness properties and longitudinal stiffness that is dependent on the degree of activation. The model analyses were used to estimate the effects of raised intra-abdominal pressure on the compression loading of the spine in response to varying external loads applied in the cardinal planes, and to predict the associated trunk muscular activity needed to maintain spinal equilibrium. These analyses were used to test whether increased intra-abdominal pressure was associated with reduced spinal compression forces for efforts that generated moments about each of the principal axis directions.

2. Methods

A biomechanical model of the spine and its musculature (Stokes and Gardner-Morse, 2001) was modified by the addition of anatomically realistic curved abdominal wall musculature connected by fascia to the spine, and with transverse elastic (spring) elements connecting the contractile elements in a three-layer lattice. Curved abdominal muscles are required to contain intra-abdominal pressure. Important characteristics of the analysis included 111 symmetrical pairs of muscle 'slips' (77 pairs of dorsal muscle slips including psoas, 11 pairs each of internal oblique, external oblique and transversus abdominis, and one pair representing rectus abdominis), and 5 lumbar vertebra (between the fixed pelvis, and rigid thorax) linked by flexible intervertebral joints.

The geometry of the abdominal wall was simplified as three concentric elliptical barrel-shaped layers, with 10 mm spacing between them, representing the three muscle layers of the external obliques, internal obliques and transversus abdominis (Fig. 1). The 10 mm spacing between muscle layers represented the estimated thickness of the muscle layers, as identified in Visible Human (http://www.nlm.nih.gov/research/visible/visible_human.html, accessed June 2010) cross sectional anatomy. Rectus abdominis was represented as a symmetrical pair of slips, each consisting of 12 elements to provide its curvature, and it was set into the middle layer of abdominal muscles (Fig. 1). The concentric ellipses had major axes of 230, 250, and 270 mm and minor axes of 160, 180, and 200 mm, and a bulge of 10 mm, similar to dimensions given by Gatton et al. (2001). The height of the abdominal wall was equal to the height of the spine from T12 to S1, which was 196 mm.

Each concentric elliptical 'barrel' section (layer) was divided into 13 elliptical strata of nodes separated vertically, and each stratum was specified by 24 'nodes' around the circumference. Interconnections (elements) within strata and between nodes in each stratum formed a triangular mesh. Although each element was straight, the nodes described a curved path for each muscle slip (Fig. 1). The muscle layers were represented by 11 slips, and each slip consisted of between 2 and 12 straight-line elements between adjacent nodes. The number of slips and elements were chosen to represent adequately the complex volume and curved geometry of these muscles. The contractile elements were either circumferential (to represent transversus abdominis muscle), or longitudinal (to represent rectus abdominis muscle), or helical (to represent the internal and external oblique muscles). Non-contractile elements were considered to be passive elastic elements representing connective tissue (fascia, etc.). Additional radial elements having high stiffness joined the concentric barrel sections. The radial elements were needed to maintain the 10 mm separation between the midlines of the three muscle layers, while transmitting the contact forces between them. For each abdominal wall muscle, each of the eleven slips was assigned one eleventh of the total physiological cross sectional area (PCSA) consistent with muscle volumes given by Stokes and Gardner-Morse (1999). PCSA is the muscle volume divided by its length, and provides a measure of the average cross-sectional area and hence the force generating potential of a non-pennated muscle. The active muscle force in each muscle was constrained to have a value between zero and its PCSA multiplied by maximum stress equal to 0.46 MPa (Stokes and Gardner-Morse, 2001).

Each muscle element was represented as a force generator, in parallel with a spring. The spring had an activation-dependent and constant component. The activation-dependent stiffness of each muscle was equal to a modulus multiplied by the degree of activation (between zero and one) and the muscle's cross-sectional area, and divided by its length (Bergmark, 1989). The modulus was equal to the maximum muscle stress (0.46 MPa), as derived from the form of the Hill's model length-tension relationship (Winters, 1990). The constant (passive) modulus was set to one tenth of the maximum muscle stress (hence passive stiffness was one tenth of the active stiffness at maximum activation, as an approximation of the length tension relationship of muscle, partitioned into active and passive components). The transverse connections between muscle slips, and the passive elastic elements representing fascia were assigned the same modulus as the passive muscle stiffness when in compression, and 100 times this value when in tension. The cross-sectional areas of these transverse muscle elements and the fascia corresponded to that of the muscle slips of internal oblique (the intermediate muscle layer). The sensitivity of the spinal compression forces to different values of muscular stiffness was evaluated empirically.

In the analyses, a value of intra-abdominal pressure was pre-specified as either 5 kPA or 10 kPa. The forces generated by the IAP acted on each node of the innermost abdominal layer. First, the forces were calculated for each triangular section of the abdominal wall, (pressure multiplied by triangle area) and then distributed between the three nodes forming that triangle. In addition to acting radially on the nodes of the inner-most muscle layer, the intra-abdominal pressure also produced upwards force on the diaphragm, and a downwards force on the pelvis. This force was calculated as the pressure multiplied by the area of the polygon formed by the nodes on the upper and lower elliptical surfaces (27,600 mm^2). The diaphragm was considered to be rigid (isometric) and attached to a rigid thorax, hence details of its structure and deformations were not included in the analyses.

The analysis was run with geometrical and other variables set to the presumed correct values (the 'Baseline' model), and then sensitivity analyses were made to evaluate the effects of changing key parameter values. These analyses included variations in the angles