ELSEVIER

Journal of Electromyography and Kinesiology 13 (2003) 353–359

JOURNAL OF ELECTROMYOGRAPHY AND KINESIOLOGY

www.elsevier.com/locate/jelekin

Coordination of muscle activity to assure stability of the lumbar spine

Stuart M. McGill [a,*], Sylvain Grenier [a], Natasa Kavcic [a], Jacek Cholewicki [b]

[a] *Faculty of Applied Health Sciences, University of Waterloo, Waterloo, ON N2L 3G1, Canada*
[b] *Yale University School of Medicine, New Haven, CT, USA*

Abstract

The intention of this paper is to introduce some of the issues surrounding the role of muscles to ensure spine stability for discussion—it is not intended to provide an exhaustive review and integration of the relevant literature. The collection of works synthesized here point to the notion that stability results from highly coordinated muscle activation patterns involving many muscles, and that the recruitment patterns must continually change, depending on the task. This has implications on both the prevention of instability and clinical interventions with patients susceptible to sustaining unstable events.

Keywords: Stability; Lumbar; Muscle; Motor control

1. Introduction

The spine is inherently unstable since, in vitro, the osteo-ligamentous lumbar spine buckles under compressive loading of only 90 N [8]. A critical role of the musculature is to stiffen the spine in all potential modes (and at each node) of instability (three rotational and three translational nodes at each intervertebral joint). But given the wide range of individuals and physical demands, questions remain as to what is the optimal balance between stability, motion facilitation (mobility) and moment generation—if stability is achieved through muscular cocontraction, how much is necessary and how is it best achieved? The intention of this paper is to introduce some of the issues for discussion purposes surrounding the role of muscles to ensure spine stability. The collection of works synthesized here point to the notion that stability results from highly coordinated muscle activation patterns involving many muscles, and that the recruitment patterns must continually change, depending on the task. This has implications on both the prevention of instability and clinical interventions with patients susceptible to sustaining unstable events.

* Corresponding author. Tel.: +1-519-888-4567x6761; fax: +1-519-746-6776.

E-mail address: mcgill@healthy.uwaterloo.ca (S.M. McGill).

‘Stability’ is a very popular term when discussing the low back—but it may be widely misunderstood, and inappropriately used. First, all sorts of tissue damage result in joint laxity which in turn can lead to instability. For example, strained or failed ligaments cause joint laxity and unstable motion under load. Endplate fractures with loss of disc height are another example of tissue damage allowing unstable joint behaviour. Clearly, joint instability is a consequence of tissue damage (this is nicely summarized by Oxland et al. [28]). A fundamental tenet is that lost mechanical integrity in any load bearing tissue will result in stiffness losses and an increased risk of unstable behaviour. Second, we have seen in a competitive lifting task where instability was observed in vivo, that injury resulted. Specifically, as a national class power lifter lifted the barbell from the floor, a single motion segment in his lumbar spine experienced excessive rotation as seen on videoflouroscopy [3]. The rotation at the single joint was beyond the normal range of motion while all other joints remained still, and stable. So, instability can both cause, and be the result of, injury. Finally, overlaying the tissue-based aspects of stability are the motor control aspects since coordinated contraction stiffens the joints ultimately determining joint stability. Both normal and abnormal motor patterns have been documented in a wide variety of tasks and are linked with back disorders (reviewed in [26,32,34,16a]). The terms ‘motor patterns’ and ‘motion patterns’ are

1050-6411/03/$ - see front matter © 2003 Elsevier Science Ltd. All rights reserved.
doi:10.1016/S1050-6411(03)00043-9

used throughout this manuscript. Motor patterns refer to the way in which muscles are activated, usually in a specific pattern to accomplish a controlled task—for example sequences of muscle onset are characteristic as is the amplitude of various muscles during a task. Motion patterns refer to the kinematic description of the body segments. For example, when rising from a chair a similar motion pattern can be achieved with different motor patterns, one characterized by dominant knee extensor torque and another characterized by dominant hip extensor torque. Two motor patterns achieved a similar motion pattern but with quite different consequences in terms of joint loading and joint stability.

In the clinical world, stability is often discussed—however the meaning of the words 'spine stability', 'core stability' and 'stabilization exercise' depends on the background of the individual: to the biomechanist they pertain to a mechanical structure that can become unstable when a 'critical point' is reached; a surgeon may view abnormal joint motion patterns as unstable but correctable by changing the anatomy; the manual medicine practitioner may interpret patterns of muscle coordination and posture as indicative of instability (or perhaps 'imbalance) and attempt to alter one, or a few, muscle activation profiles. In reality, anatomical or geometric anomalies (or 'imperfections') are indicative of the potential for instability but stability itself is an instantaneous phenomenon. Several groups have made contributions to the stability issue but only a very few have attempted to actually quantify stability. Attempts to enhance stability and prevent instability are compromised without an understanding of the influencing factors (a more detailed discussion is found in McGill [26]).

2. On stability: the quantitative foundation

The following demonstration of structural stability illustrates key issues. Suppose a fishing rod is placed upright and vertical, with the butt on the ground. If the rod were to have a small load placed in its tip, perhaps a few newtons, it would soon bend and buckle. Take the same rod, and attach guy wires at different levels along its length and attach their other ends to the ground in a circular pattern. (for example [25]). Now of critical importance—tighten each guy wire to the same tension. Repeat the exercise, loading the tip of the rod and one will observe that the rod can now sustain huge compressive forces successfully. Next, reduce the tension in just one of the wires. The rod will now buckle at a reduced load, and the node or locus of the buckle could have been predicted. Now, we will repeat the exercise on a human lumbar spine. Typically, an osteoligamentous lumbar spine, from a cadaver, will buckle under approximately 90 N (about 20 lb) of compressive load (first noted by Lucas and Bresler [20]). This is all that an unbutressed spine can withstand! The first role of the muscles is to form the guy wires to prevent buckling. This analogy demonstrates the critical role of the muscles to first ensure sufficient stability of the spine so that it is prepared to withstand loading, and sustain postures and movement. Also demonstrated with this example is the role of the motor control system to ensure that the tensions in the cables are proportional so as to not create a nodal point where buckling will occur. Revisiting the buckling injury that we observed flouroscopically in the power lifter, we would hypothesize that it was caused by a motor control error where possibly one muscle reduced its activation, or from the previous analogy—lost its stiffness. The synchrony of balanced stiffness produced by the motor control system is absolutely critical. With this background the issues of how stability is quantified and modulated can be addressed.

During the 1980s, Professor Anders Bergmark of Sweden, very elegantly formalized stability in a spine model with joint stiffness and 40 muscles [1]. In this classic work he was able to formalize mathematically the concepts of the minimum potential energy, stiffness, stability and instability using the elastic potential energy approach. The approach was limited to analysis of 'local stability' since the many anatomical components contribute force and stiffness in synchrony to create a surface of potential energy with many local minima. These minima are found from examination of the second derivative of the energy surface. In this particular approach, spine stability is quantified by forming a matrix where the total 'stiffness energy' for each degree of freedom of joint motion is subtracted from the applied work. A major issue for the future is to unravel the biomechanical implications of how the matrix is solved to render a 'stability index'. The matrix can be solved via triangulation to produce a single number or 'average' impression of lumbar stability, or it can be diagonalized to create 18 eigenvalues each representing a lumbar level (six levels) and degree of rotational freedom (three degrees—flexion/extension, lateral bend and twist) (note that in this example of stability analysis the translational degrees of freedom are ignored). Eigenvalues less than zero indicate potential for instability. The eigenvector associated with the lowest eigenvalue (one is associated with each eigenvalue) predicts the mode or shape of the buckled spine thereby locating the instability. The sensitivity analysis may reveal the possible contributors allowing unstable behaviour, or for clinical relevance—what muscular pattern would have prevented the instability? Much more work is required in the future on post-buckling behaviour to unravel the principles of spine stability.

Several groups have begun the challenging task of investigating critical elements of the motor control needed to maintain stability or survive unstable events. For example, Gardner-Morse et al. [9], and Gardner-

Morse and Stokes [10] have initiated interesting investigations by predicting patterns of spine deformation due to impaired muscular intersegmental control leading to the asking - which muscular pattern would have prevented the instability? They utilized another approach to determine structural stability by searching for the critical muscle stiffness or proportionality constant ‘q’ that would ensure a stable spine. Crisco and Panjabi [8] began investigations into the contributions of the various passive tissues. Our own most recent work has attempted to evaluate the relative contributions of each muscle group to influence stability (Cholewicki and VanVliet [7], where a muscle knockout procedure was used; and Kavcic et al. [18], which employed a convolution of the activity (EMG) of each muscle with a sinusoid oscillating from 0 to 100% amplitude). For example the average response from 10 normal subjects performing a variety of ‘stabilization exercises’ revealed that many muscles are important and that their relative contributions are variable depending upon other constraints such as the dominant moment required to sustain a posture or create a movement (see Fig. 1). Moreover, the relative contributions of each muscle continually changes throughout a task, such that discussion of the ‘most important stabilizing muscle’ is restricted to a transient instant in time.

Activating a group of muscle synergists and antagonists in the optimal way now becomes a critical issue. In clinical terms, the full complement of the stabilizing musculature must work harmoniously to both ensure stability, generation of the required moment, and desired joint movement. But only one muscle with inappropriate activation amplitude may produce instability (if passive stiffness is not sufficient), or at least unstable behaviour could result from inappropriate activation at lower applied loads. Quantification of stability in vivo is further complicated by several phenomena which have a critical influence on column stability—for example ‘thixotropy’. It is well known that passive tissue compliance is a function of the number and type of preceding loadings—as is muscle stiffness (and is therefore thixotropic—since it depends on previous movements and activation). For example, Lakie [19] reporting earlier work, showed in the wrist that the history of previous movement (previous stretch, concentric contraction, eccentric contraction) modulates muscle stiffness—and this modulation is not accompanied by any change in EMG amplitude. These issues, together with many more, must be sorted out to better quantify spine stability and interpret the laboratory and clinical implications.

3. Sufficient stability

How much stability is necessary? Obviously insufficient stiffness renders the joint unstable but too much stiffness and co-activation imposes massive load penal-

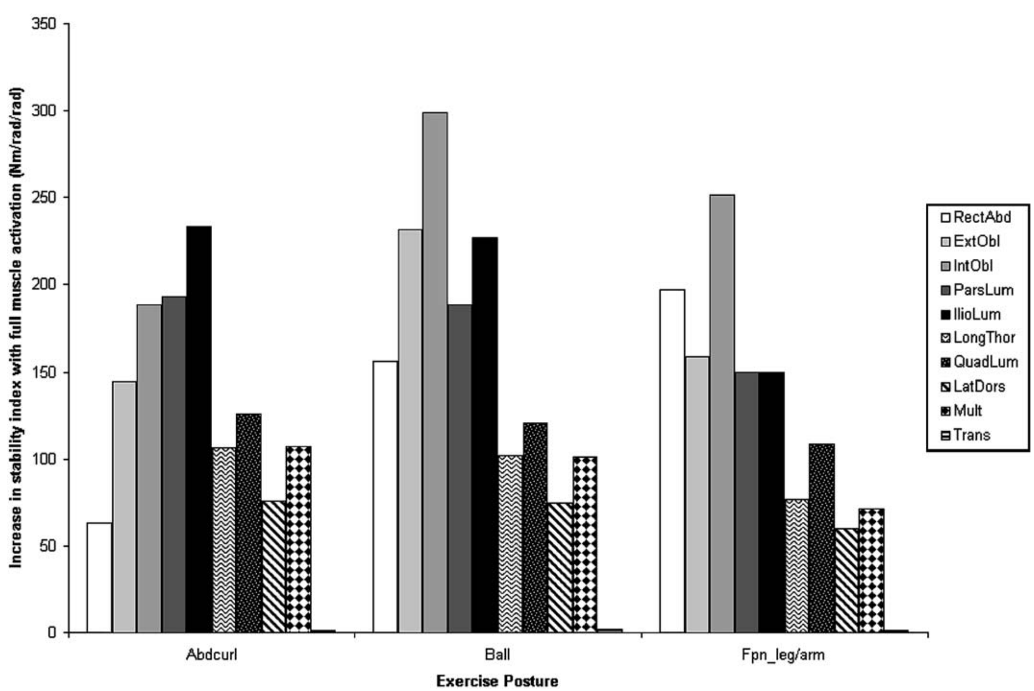

Fig. 1. In an attempt to understand the role of each muscle pair on spine stability, the increase in the stability index is shown as a function of setting each muscle pair activation in turn to 100%MVC. Note that the relative order of muscles that increase stability changes across exercises. As well, in flexion tasks, the pars lumborum (in this example) plays a larger stabilizing role over the rectus abdominis. In contrast, during the extension tasks the opposite holds true suggesting a task dependent role reversal between moment generation and stability. The exercises were: Abcurl—curl-up on the stable floor, Ball—sitting on a gym ball, Fpn—leg/arm—four point kneeling while extending one leg and the opposite arm.

ties on the joints and prevents motion. 'Sufficient stability' is a concept that involves the determination of how much muscular stiffness is necessary for stability, together with a modest amount of extra stability to form a margin of safety. Granata and Marras [13] have shown simultaneous co-activation of many muscle groups around the spine produce stiffness and that the co-activation cannot be explained in terms of moment generation. Interestingly enough, given the rapid increase in joint stiffness with modest muscle force, large muscular forces are rarely required to ensure sufficient stability.

Cholewicki's work [4,5] has demonstrated that sufficient stability of the lumbar spine is achieved, in an undeviated spine (neutral posture), in most people with modest levels of co-activation of the paraspinal and abdominal wall muscles. This means that people, from patients to athletes, must be able to maintain sufficient stability in all activities - with low, but continuous, muscle activation. Thus, maintaining a stability 'margin of safety' when performing tasks, particularly the tasks of daily living, is not compromised by insufficient strength but probably insufficient endurance, and probably insufficient control. The mechanistic pathway of those studies showing the efficacy of endurance training for the muscles that stabilize the spine is beginning to be understood. Having strong abdominals does not necessarily provide the prophylactic effect that had been hoped for - but several works suggest that endurable muscles reduce the risk of future back troubles (for example [2,21]). Finally, the Queensland group (e.g. [32]) together with several others (e.g. [27]) have noted the disturbances in the motor control system following injury. These disturbances compromise the ability to maintain sufficient stability. In summary, stability comes from stiffness, passive stiffness is lost with tissue damage, and active stiffness throughout the range of motion may be compromised by disturbed motor patterns following injury.

4. Stability myths, facts and clinical implications

From the explanation of spine stability above, several issues can be clarified to enhance clinical decisions.

4.1. How much muscle activation is needed to ensure sufficient stability?

The amount of muscle activation needed to ensure sufficient stability depends on the task. Generally for most tasks of daily living, very modest levels of abdominal wall co-contraction is sufficient. Again, depending on the task, co-contraction with the extensors (including quadratus lumborum, and latissimus dorsi) and the abdominals (rectus abdominis, the obliques and transverse abdominis) will ensure stability [18]. But if a joint has lost passive stiffness due to damage, more co-contraction is needed to make up the deficiency. Crisco and Panjabi [8] simulated injuries in osteoligamentous spine which produced a decreased buckling load.

4.2. Is any single muscle most important?

Several clinical groups have suggested focussing on one or two muscles to enhance stability. This would be similar to emphasizing a single guy wire in the fishing rod example. It may help or it may be detrimental for achieving the balance in stiffness needed to ensure stability throughout the changing task demands. In particular, there has been much emphasis on multifidus and transverse abdominis by clinical groups. This may be at the expense of achieving stability in the optimal way, given that muscles also impose a compressive load to the spine when contracting. Grenier and McGill [15] have shown that muscles enhance stability of the column not only by acting as 'guywires' but also by contributing compression, which acts to stiffen in all degrees of freedom [11,17,32a].

4.3. What are stabilization exercises?

'Stability exercises' and a 'stable core' are often discussed in exercise forums. What are stabilization exercises? The fact is that any exercise can be a stabilization exercise—but it depends on the way in which it is performed (examples are provided in [26]). Ensuring sufficient joint stiffness is achieved by creating specific motor patterns. To adapt a phrase popular in motor control circles, 'practice does not make perfect—it makes permanent'. Ideally, good stabilization exercises that are performed properly produce patterns that are practiced while other demands are satisfied simultaneously. Any exercise that grooves motor patterns that ensure a stable spine, through repetition, constitutes a 'stabilization' exercise [25]. But then some stabilization exercises are better than others—again it depends on the objectives. For example, the resultant load on the spine is rarely considered—one key to improving bad backs is to select stabilization exercises that impose the lowest load on the damaged spine. The stability index versus compressive load are ranked over several such exercises are provided in Fig. 2 as an example to give guidance for clinical decisions on which exercise would provide the most appropriate challenge for a specific individual.

4.4. Can those who are poor stabilizers be identified?

From a qualitative perspective, Hodges et al. [16] have observed aberrant motor patterns in low back pain patients which would compromise the ability of the affected person to stabilize efficiently. From a quantitative perspective, we have tried to find ways to identify those who compromise their lumbar stability from spe-

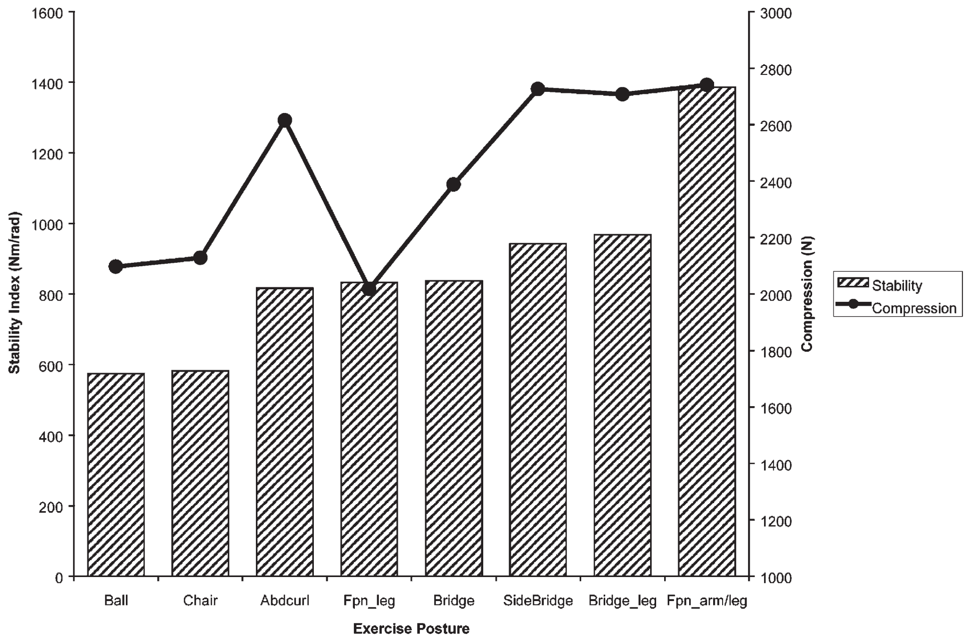

Fig. 2. Stability versus L4-L5 compression for eight different stabilization exercises. All exercises were performed with the abdominal wall active and were as follows: Ball—sitting on a gym ball, Chair—sitting on a chair, Abcurl—curl-up on the floor, Fpn—leg—four point kneeling while extending one leg at the hip, Bridge—back bridge on the floor, SideBridge—side bridge with the elbow and feet on the floor, Bridge—leg—back bridge but extending the knee and holding one leg against gravity, Fpn—arm/leg—four point kneeling while extending one leg and the opposite arm. Exercises are rank ordered based on increasing lumbar spine stability.

cific motor control errors using modeling analysis. Such inappropriate muscle sequencing has been observed in men who are challenged by holding a load in the hands while breathing 10% CO_2 to elevate breathing. This is an interesting task because on one hand the muscles must co-contract to ensure sufficient spine stability, but on the other, challenged breathing is often characterized by rythmic/contraction/relaxation of the abdominal wall [24]. Thus, the motor system is presented with a conflict—should the torso muscles remain active isometrically to maintain spine stability or will they rhythmically relax and contract to assist with active expiration (but sacrifice spine stability). Those with 'fit' motor systems (i.e., have the ability to meet any task challenge but not risk losing sufficient stability) appear to meet the simultaneous breathing and spine stability challenge with less variance of stability during the task permitting an overall lower level of stability [14]. 'Less fit' motor systems in this task result in a high degree of variability in stability sometimes forcing greater co-activation (consequently compression is also higher) to keep stability high (see Fig. 3) or could even result in temporary losses in stiffness [24]. All of these deficient motor control mechanisms may heighten biomechanical susceptibility to injury or re-injury [4].

4.5. Stability is a dynamic objective

Achieving stability is not just a matter of activating a few targeted muscles be they multifidus or any other.

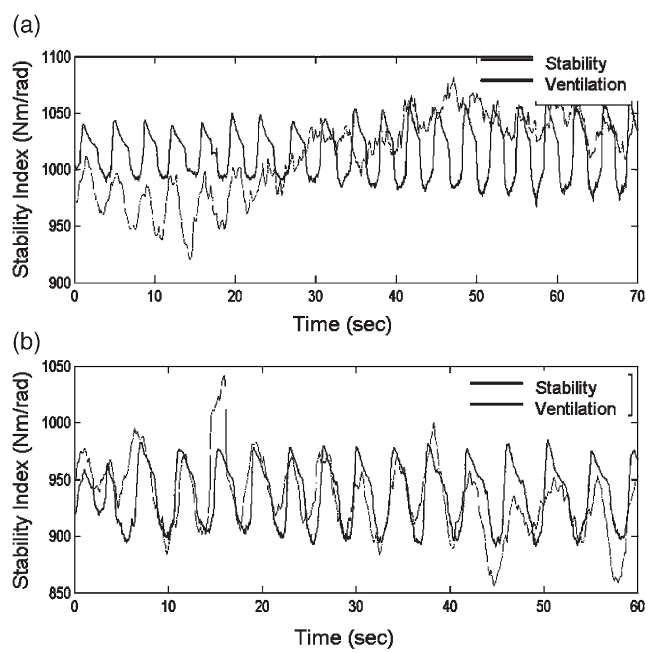

Fig. 3. Stability index together with ventilation during challenged breathing (top panel) and when breathing ambient air (bottom panel). In this subject with a history of low back troubles, stability increases suddenly (at 25 s) in response to an increase in muscle activation, but this at the cost of increased compression. Note that oscillation of stability ceases at this point, whereas this occurs throughout the ambient air trial. Ventilation (air flow) units have been scaled to superimpose stability. Stability units are Nm/rad. Ventilation is coupled to stability when breathing ambient air (bottom panel).

Achieving sufficient stability is a moving target, which continually changes as a function of the three-dimensional torques needed to support postures, and the necessary stiffness needed in anticipation of enduring unexpected loads, or to prepare for the need to move quickly, or to ensure sufficient stiffness in any degree of freedom of the joint which may be compromised from injury. Motor control fitness is essential to achieving the stability target under all possible conditions for performance and injury avoidance.

Consider sudden and/or unexpected loading on the lumbar spine that may occur for example when a worker slips or trips while handling heavy materials or if the handled object shifts unexpectedly. A very high level of trunk muscle co-contraction would have been necessary prior to such loading to prevent spine buckling and injury. Likely to occur is a motor control response with appropriate muscle inhibition and activation immediately following such a perturbation [6]. This rapid response of various muscles must still conform to a coordinated recruitment pattern discussed earlier both in their timing and their force magnitude. Otherwise, the incorrect response will further compound the effects of suddenly applied load on the spine and may lead to self-injury.

Motor control response to sudden spine loading relies on proprioceptive feedback from a variety of mechanoreceptors including muscle spindles, Golgi tendon organs, joint receptors, cutaneous receptors, and other sensory organs. What if sensory feedback is inherently poor or compromised by prior injury? Certainly impaired motor control could lead to spine instability especially under sudden loading conditions. It is well documented that patients suffering from low back pain have diminished lumbar position sense [12,29,33], poor postural control [22,31], and longer trunk muscle reaction latencies [23,30]. However, presently it is not known whether this impairment in motor control is a predisposing risk factor (cause) or a result of low back injuries and damage to tissues containing sensory organs (effect). In either case, the intervention aimed at restoring adequate motor control may be beneficial in preventing and rehabilitating low back injuries as well as in halting the progression from an acute injury to a chronic low back problem.

5. Looking forward

There is no single muscle that is the best stabilizer of the spine—the most important muscle is a transient definition that depends on the task. Further, virtually all muscles work together to create the 'balance' in stiffness needed to ensure sufficient stability in all degrees of freedom (or to maintain the appropriate level of potential energy of the spine). With the evidence supporting the importance of muscle endurance (not strength) and 'healthy' motor patterns to assure stability, both basic and applied work must continue. Specifically, applied work is needed to: (1) understand the role of various components of the anatomy to stability—and the ideal ways to enhance their contribution; (2) understand what magnitudes of muscle activation are required to achieve sufficient stability; (3) examine post-buckling behaviour, the associated eigenvectors and the cause of unstable events; (4) identify the best methods to re-educate faulty motor control systems to both achieve sufficient stability and to reduce the risk of inappropriate motor patterns occurring in the future. Basic work is needed to (5) understand the influence of thixotropy on muscle stiffness; (6) determine the biomechanical implications of the several options available to calculate a 'stability index'; (7) develop dynamic models of spine stability capable of simulating sudden loading events. Much remains to be done.

References

[1] A. Bergmark, Mechanical stability of the human lumbar spine: a study in mechanical engineering, Acta Orthop. Scand 230 (Suppl.) (1989) 1–54.
[2] F. Biering-Sorensen, Physical measurements as risk indicators for low back trouble over a one year period, Spine 9 (1984) 106–119.
[3] J. Cholewicki, S.M. McGill, Lumbar posterior ligament involvement during extremely heavy lifts estimated from fluoroscopic measurements, J. Biomech. 25 (1) (1992) 17–28.
[4] J. Cholewicki, S.M. McGill, Mechanical stability of the in vivo lumbar spine: implications for injury and chronic low back pain, Clin, Biomech 11 (1) (1996) 1–15.
[5] J. Cholewicki, M.M. Panjabi, A. Khachatryan, Stabilizing function of trunk flexor-extensor muscles around a neutral spine posture, Spine 22 (19) (1997) 2207–2212.
[6] J. Cholewicki, A.P.D. Simons, A. Radebold, Effects of external trunk loads on lumbar spine stability, J. Biomech 33 (11) (2000) 1377–1385.
[7] J. Cholewicki, J.J. VanVliet III, Relative contribution of trunk muscles to the stability of the lumbar spine during isometric exertions, Clin. Biomech 17 (2) (2002) 99–105.
[8] J.J. Crisco, M.M. Panjabi, Euler stability of the human ligamentous lumbar spine, part I theory 1992; 7: 19-26 and part II, experiment, Clin. Biomech 7 (1992) 27–32.
[9] M. Gardner-Morse, I.A.F. Stokes, J.P. Laible, Role of the muscles in lumbar spine stability in maximum extension efforts, J. Orthop. Res. 13 (1995) 802–808.
[10] M. Gardner-Morse, I.A.F. Stokes, The effects of abdominal muscle coactivation on lumbar spine stability, Spine 23 (1) (1998) 86–91.
[11] M. Gardner-Morse, I.A.F. Stokes, Trunk stiffness increases with steady state effort, J. Biomech. 34 (2001) 457–463.
[12] K.P. Gill, M.J. Callaghan, The measurement of lumbar proprioception in individuals with and without low back pain, Spine 23 (3) (1998) 371–377.
[13] K.P. Granata, W.S. Marras, Cost–benefit of muscle cocontraction in protecting against spinal instability, Spine 25 (2000) 1398–1404.
[14] S.G. Grenier, S.M. McGill, On the influence of compressive preload, muscle and passive tissue stiffness to limit post-buckling displacement magnitude in the lumbar spine, submitted for publication.

[15] S.G. Grenier, S.M. McGill, Complex neuromuscular tasks affect spine stability and tissue loads: differences between normals and low back pained people, submitted for publication.

[16] P.W. Hodges, C.A. Richardson, Altered trunk muscle recruitment in people with low back pain with upper limb movement at different speeds, Arch. Phys. Med. Rehab 80 (1999) 1005–1012.

[16a] P.W. Hodges, G.L. Moseley, Pain and motor control of the lumbopelvic region: effect and possible mechanisms, J. Electromyogr. Kinesiol. 13 (2003).

[17] J. Janevic, J.A. Ashton-Miller, A.B. Schultz, Large compressive preloads decrease lumbar motion segment flexibility, J. Orthop. Res. 9 (1999) 228–236.

[18] N. Kavcic, S. Grenier, S.M. McGill, Quantifying tissue loads and spine stability while performing common stabilization exercises, submitted for publication.

[19] M. Lakie, Muscle tone, tension and thixotropy, J. Physiol 511 (1998) 31.

[20] D. Lucas, B. Bresler, Stability of the ligamentous spine, in: Tech report no 40, Biomechaics Laboratory, University of California, San Francisco, 1961.

[21] S. Luoto, M. Helioraara, H. Hurri, M. Alaranta, Static back endurance and the risk of low back pain, Clin. Biomech 10 (1995) 323–324.

[22] S. Luoto, H. Aalto, S. Taimela, H. Hurri, I. Pyykko, H. Alaranta, One-footed and externally disturbed two-footed postural control in patients with chronic low back pain and healthy control subjects. A controlled study with follow-up, Spine 23 (19) (1998) 2081–2089.

[23] M.L. Magnusson, A. Aleksiev, D.G. Wilder, M.H. Pope, K. Spratt, S.H. Lee, V.K. Goel, J.N. Weinstein, Unexpected load and asymmetric posture as etiologic factors in low back pain, Eur. Spine J. 5 (1) (1996) 23–35.

[24] S.M. McGill, M.T. Sharratt, J.P. Seguin, Loads on the spinal tissues during simultaneous lifting and ventilatory challenge, Ergonomics 38 (9) (1995) 1772–1792.

[25] S.M. McGill, Low Back Stability: From formal description to issues for performance and rehabilitation, Exerc. Sports Sci. Rev 29 (1) (2001) 26–31.

[26] S.M. McGill, Low Back Disorders: Evidence Based Prevention and Rehabilitation, Human Kinetics Publishers, Champaign, Ill, 2002.

[27] P. O'Sullivan, L.T. Twomey, G.T. Allison, Altered pattern of abdominal muscle activation in chronic back pain patients, Aust. J. Physiother 43 (1997) 91–98.

[28] T.R. Oxland, M.M. Panjabi, E.P. Southern, J.S. Duranceau, An anatomic basis for spinal instability: a porcine trauma model, J. Orthop. Res. 9 (1991) 452–462.

[29] T.M. Parkhurst, C.N. Burnett, Injury and proprioception in the lower back, J. Orthop. Sports Phys. Ther 19 (5) (1994) 282–295.

[30] A. Radebold, J. Cholewicki, M.M. Panjabi, T.C. Patel, Muscle response pattern to sudden trunk loading in healthy individuals and in patients with chronic low back pain, Spine 25 (8) (2000) 947–954.

[31] A. Radebold, J. Cholewicki, G.K. Polzhofer, H.S. Greene, Impaired postural control of the lumbar spine is associated with delayed muscle response times in patients with chronic idiopathic low back pain, Spine 26 (7) (2001) 724–730.

[32] C. Richardson, G. Jull, P. Hodges, J. Hides, Therapeutic exercise for Spinal Segmental Stabilization in Low Back Pain, Churchill-Livingston, Edinburgh, 1999.

[32a] I.A.F. Stokes, M. Gardner-Morse, Spinal stiffness increases with load: another stabilizing consequence of muscle action, J. Electromyogr. Kinesiol. 13 (2003)

[33] S. Taimela, M. Kankaanpaa, S. Luoto, The effect of lumbar fatigue on the ability to sense a change in lumbar position. A controlled study, Spine 24 (13) (1999) 1322–1327.

[34] J.H. van Dieën, L. Selen, J. Cholewicki, Trunk muscle activation in low-back pain patients, an analysis of the literature, J. Electromyogr. Kinesiol. 13 (2003).

Stuart McGill is a spinal biomechanist and Professor in the Department of Kinesiology at the University of Waterloo. He has been the author of over 200 scientific publications that address the issues of lumbar function, low back injury mechanisms, investigation of tissue loading during rehabilitation programs, and the formulation of work-related injury avoidance strategies. Much of his work is summarised in his recent book 'Low Back Disorders: Evidence Based Prevention and Rehabilitation'.

Sylvain Grenier has recently completed a PhD. (Stabilization strategies of the lumbar spine in vivo) at the University of Waterloo. He is now an assistant professor at Laurentian University in Sudbury, Canada.

Natasa Kavcic is a researcher at the University of Waterloo in Ontario, Canada. She completed her undergraduate degree in Kinesiology and she has recently finished her Masters of Science degree in Spinal Biomechanics under Dr Stuart McGill. She currently works in the Spine Biomechanics Laboratory where her focus is in quantifying the neuromuscular mechanics involved in commonly performed rehabilitation exercises.

Jacek Cholewicki is a spinal biomechanist and Associate Professor of Orthopaedics and Rehabilitation at Yale University School of Medicine in New Haven, Connecticut. He holds cross-appointments to the departments of Mechanical Engineering and Biomedical Engineering where he teaches a graduate and undergraduate course in biomechanics. He received his Bachelor, Masters, and PhD degrees in Kinesiology from the University of Waterloo in Canada in 1986, 1990, and 1994, respectively. His research addresses the issues of lumbar and cervical spine function, spine injury mechanisms, tissue loading, and biomechanical modeling using both in vivo and in vitro experimental approaches. His current research interests include motor control of spine stability and the effectiveness of abdominal belts.