

ACHIEVING SPINE STABILITY: BLENDING ENGINEERING AND CLINICAL APPROACHES

Stuart M. McGill

Faculty of Applied Health Sciences, Department of Kinesiology
University of Waterloo, Waterloo, Ontario, N2L 3G1, Canada

INTRODUCTION

Lumbar stability, and low back stabilizing exercises, are popular topics related to optimal athletic/occupational performance, and to the rehabilitation of painful backs. The objective of such exercise is to enhance the function of these critical torso muscles in a way that spares the spine from damage. The intention of this presentation is to develop a synthesis of the scientific foundation and formalization of the notion of stability as it pertains to the lumbar spine, and then provide specific guidelines for enhancing stability to advance spine rehabilitation. For the interested reader, more extensive references together with tabulated data of specific muscle activation profiles, resultant spine loads, etc., can be found in the authors review chapters and original papers listed at:
www.ahs.uwaterloo.ca/kin/kinfac/mcgill.html.

In most traditional approaches to designing low back exercise, an emphasis has been placed on the immediate restoration, or enhancement, of spine range of motion and muscle strength. Generally, this approach has not been sufficiently efficacious in reducing back troubles, in fact a review of the evidence suggests only a weak link with improving back symptoms while some studies suggest a link with negative outcome in significant numbers of people (McGill, 1998). It appears that the emphasis on early restoration of spine range of motion continues to be driven by legislative definitions of low back disability - namely loss of range of motion. Thus, therapeutic success is often judged on motion restored. The underlying theme of this paper, reflects the developing philosophy based on mechanisms of injury and stability - that a spine must first be stable before moments and forces are produced to enhance performance but to do so in a way that spares the spine from potentially injurious load.

The meaning of the words "spine stability" 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 and attempt to alter one, or a few, muscle activation profiles. Several groups have made contributions to the stability issue but only a very few have attempted to actually quantify stability and joint moment and force demands. This presentation is biased towards efforts to quantify stability and develop clinical notions based on direct biomechanical evidence of stability indexes, resultant joint and paraspinal tissue loads, and measurements of processed muscle activation and joint motion patterns.

THE INJURY PROCESS - MOTOR CHANGES

Those reporting debilitating low back pain conclusively suffer simultaneous changes in their motor control systems. Recognizing these changes is important since they effect the stabilizing system and are therefore are a focal point for optimal rehabilitation. Richardson et al (1999) have produced quite a comprehensive review of this literature together with making a case for targeting specific muscle groups during rehabilitation. Specifically, their objective is to re-educate faulty motor control patterns post injury. The challenge is to train the stabilizing system during steady state activities together with stabilizing during rapid voluntary motions and to withstand sudden surprise loads. It is this collection of evidence that strongly supports approaches to stabilization exercises that promote patterns of muscular co-contraction observed in with fit spines.

INSTABILITY AS A CAUSE OF INJURY

While biomechanists have been able to successfully explain how strenuous exertions cause specific low back tissue damage, explaining how injury occurs from tasks such as picking up a pencil from the floor has been more challenging. Recent evidence suggests that such injuries are real, and result from the spine "buckling" or exhibiting unstable behaviour. But this buckling mechanism can occur during far more challenging exertions as well.

A number of years ago we were investigating the mechanics of power lifter spines while they lifted extremely heavy loads using video fluoroscopy to view their vertebrae in the sagittal plane. During their lifts, even though the lifters outwardly appeared to fully flex their spines, in fact their spines were two to three degrees per joint from full flexion, thus explaining how they could lift magnificent loads without sustaining injury - the risk of disc and ligamentous damage is greatly elevated when the spine is fully flexed (which the lifters skilfully avoided). We happened to capture one injury on the fluoroscopic motion film - the first such observation that we know of. During the injury incident, just as the semi squatting lifter had lifted the load about 10 cm off the floor, only the L2/L3 joint briefly rotated to the full flexion calibrated angle and exceeded it by one-half a degree, while all other lumbar joints maintained their static positions (not fully flexed) (Cholewicki and McGill, 1992). The spine buckled! Sophisticated modelling analysis revealed that buckling can occur from a motor control error where a short and temporary reduction in activation to one, or more, of the intersegmental muscles would cause rotation of just a single joint so that passive or other tissues become irritated or possibly injured (Cholewicki and McGill, 1996).

Other evidence linking poor motor co-ordination with higher risks for the lumbar spine reaching critical points of instability exists, and is revealing. Cholewicki and McGill (1996) have identified through a modeling analysis, the nodal points, or specific spinal joint, where buckling could occur from specific motor control errors. Such inappropriate muscle sequencing has been observed in men who are challenged by holding a load in the hands while breathing 10% CO₂ to elevate breathing. On one hand the muscles must co-contrast to ensure sufficient spine stability, but on the other, challenged breathing is often characterized by rhythmic/contraction/relaxation of the abdominal wall (McGill, 1997). 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). Fit motor systems appear to meet the simultaneous breathing and spine support challenge - unfit ones may not. All of these deficient motor control mechanisms will heighten biomechanical susceptibility to injury or reinjury.

In vitro, a ligamentous lumbar spine buckles under compressive loading at about 90 Newtons (about 20 lbs) highlighting the critical role of the musculature to stiffen the spine against buckling (the critical work and analysis of the passive tissues being performed by Crisco and Panjabi (1992). Anatomical arrangement of muscle around the spine, coupled with critically important patterns of activation, enables the spine to bear a much higher compressive load as it stiffens and becomes more resistant to buckling but in so doing, the spine bears even more load due to the "stiffening" muscle activity. As noted above, aberrant patterns of activation can result in instantaneous spine instability and acute tissue overload. But over the longer term, the Queensland group have developed a tissue damage model which suggests chronically poor motor control (and motion patterns) initiates microtrauma in tissues which accumulates leading to symptomatic injury. Injury leads to further deleterious change in motor patterns such that chronicity can only be broken with specific techniques to re-educate the local muscle-motor control system. Both acute and chronic instability-tissue models have been proposed. But given the wide range of individuals and physical demands, question remain as to what is the optimal balance in terms of stability, motion facilitation and moment generation - if stability is achieved through muscular co contraction, how much is necessary and how is it best achieved?

On Stability: The Foundation. This section shall formalize the notion of stability from a spine perspective. During the 1980's, Professor Anders Bergmark of Sweden, very elegantly formalized stability in a spine model with joint stiffness and 40 muscles (Bergmark, 1987). In this classic work he was able to formalize mathematically, the concepts of "energy wells", stiffness, stability and instability. For the most part, this seminal work went unrecognized largely because the engineers who understood the mechanics did not have the biological -- clinical perspective, and the clinicians were hindered in the interpretation and implications of the engineering-mechanics. This pioneering effort, together with its continued evolution by several others will be synthesized here - the current author has attempted to encapsulate the critical notions without mathematical complexity.

The concept of stability begins with potential energy, which for the purposes here, is of two basic forms. In the first form, objects have potential energy by virtue of their height above a datum.

$$PE = \text{mass} * \text{gravity} * \text{height}$$

Critical to measuring stability are the notions of energy "wells" and minimum potential energy. If a ball is placed into a bowl it is stable, because if a force was applied to the ball (or a perturbation) the ball will rise up the side of the bowl but then come to rest again in the position of least potential energy at the bottom of the bowl - or the "energy well". As

noted by Bergmark, "stable equilibrium prevails when the potential energy of the system is minimum". The system is made more stable by deepening the bowl and/or by increasing the steepness of the sides of the bowl (see figure 1). Thus, the notion of stability requires the specification of the unperturbed energy state of a system followed by study of the system following perturbation - if the "joules" of work done by the perturbation is less than the "joules" of potential energy inherent to the system then the system will remain stable (i.e., the ball will not roll out of the bowl). The corollary is that the mechanical system will collapse if the applied load exceeds a critical value (determined by potential energy and stiffness).

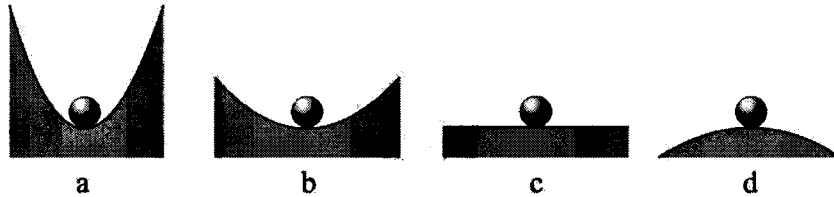


Figure 1. The continuum of stability - "A" is most stable where "D" is least stable. The ball in the bowl seeks the "energy well" or position of minimum potential energy ($m \cdot g \cdot h$). Deepening the bowl or increasing the steepness of the sides increases the ability to survive perturbation - this increases stability.

The previous ball analogy is a two dimensional example. This would be analogous to a hinged skeletal joint that only has the capacity for flexion/extension. Spinal joints can rotate in three planes and translate along 3 axes requiring a 6 dimensional bowl for each joint - mathematics enables the examination of a 36 dimensional bowl (6 lumbar joints with 6 degrees of freedom) representing the whole lumbar spine. If the height of the bowl were decreased in any one of these 36 dimensions, the ball could roll out. In clinical terms, a single muscle having an inappropriate force (and thus stiffness), or a damaged passive tissue, which has lost stiffness, can cause instability that is both predictable and quantifiable.

While potential energy by virtue of height is useful for illustrating the concept, potential energy as a function of stiffness and storage of elastic energy is actually used for musculoskeletal application. Elastic potential energy is calculated from stiffness (k) and deformation (x) in the elastic element:

$$PE = 1/2 \cdot k \cdot x^2$$

In other words the greater the stiffness (k) the greater the steepness of the sides of the bowl (from the previous analogy), and the more stable the structure. Thus stiffness creates stability (see figure 2). Active muscle produces a stiff member and in fact the greater the

activation of the muscle, the greater this stiffness - it has long been known that joint stiffness increases rapidly and non-linearly with muscle activation such that only very modest levels of muscle activity create sufficiently stiff, and stable joints. Furthermore, joints possess inherent joint stiffness as the passive capsules and ligaments contribute stiffness particularly at the end range of motion. The motor control system is able to control stability of the joints through coordinated muscle co-activation and to a lesser degree by placing joints in positions, which modulate passive stiffness contribution. However, a faulty motor control system can lead to inappropriate magnitudes of muscle force, and stiffness, allowing a "valley" for the "ball to roll out" or clinically, for a joint to buckle or undergo shear translation. But mechanical systems, and particularly musculoskeletal linkages, are limited to analysis of "local stability" since the energy wells are not infinitely deep and the many anatomical components contribute force and stiffness in synchrony to create "surfaces" of potential energy where there are many local wells. Thus local minima are located from examination of the derivative of the energy surface. Spine stability then, is quantified by forming a matrix where the total "stiffness energy" for each degree of freedom of joint motion is represented by a number (or eigenvalue) and the magnitude of that number represents its contribution to forming the "height of the bowl" in that particular dimension. Eigenvalues less than zero indicate the potential for instability. The eigenvector (different from the eigenvalue) can then identify the mode in which the instability occurred while sensitivity analysis may reveal the possible contributors allowing unstable behavior, (Gardner-Morse et al (1995) have initiated interesting investigations into eigenvectors by predicting patterns of spine deformation due to impaired muscular intersegmental control) or for clinical relevance - what muscular pattern would have prevented the instability?

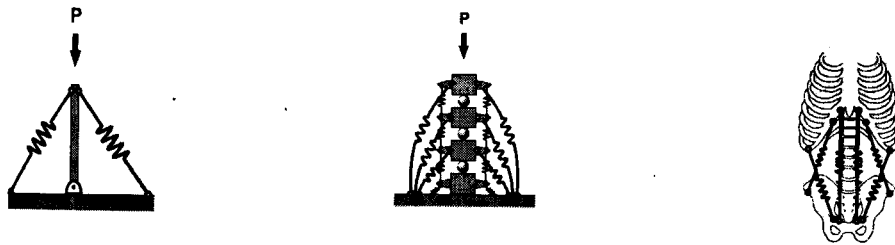


Figure 2. A) Increasing the stiffness of the cables (muscles) increases the stability (or deepens the bowl) and increases the ability to support larger applied loads "p" without falling. B) Spine stiffness (and stability) is achieved by a complex interaction of stiffening structures along the spine and C) those forming the torso wall (right panel).

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 together with generation of the required moment and desired joint movement. But only one muscle with inappropriate activation amplitude may produce instability, or at least unstable behavior could result at lower applied loads.

How much stability is necessary -- obviously insufficient stiffness renders the joint unstable but too much stiffness and co-activation imposes massive load penalties 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. Interestingly enough, given the rapid increase in joint stiffness with modest muscle force, large muscular forces are rarely required. In our recent papers, stabilization exercises were quantified and ranked for muscle activation magnitudes together with the resultant spine load. (Quantification of individual tissue loads in the spine is a complex procedure and an issue outside the constraints of this article - the interested reader is directed to reference McGill, 1992). Furthermore, Cholewicki's work (2000) has demonstrated that sufficient stability of the lumbar spine is achieved, in an undeviated spine, 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 rather insufficient endurance. We are now beginning to understand the mechanistic pathway of those studies showing the efficacy of endurance training for the muscles that stabilize the spine. 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 (e.g. Biering-Sorensen, 1984).

WHAT ARE THE STABILIZERS OF THE LUMBAR TORSO?

While many muscles have been regarded as primary spine stabilizers, confirmation of their role requires two levels of analysis. First, engineering - stability analysis must be conducted on anatomically robust spine models to document the ability of each component to stiffen and stabilize. Second, electromyographic recordings of all muscles (even deep muscles requiring intramuscular electrodes) are necessary to confirm the extent that the motor control system involves each muscle to ensure sufficient stability. From our limited intramuscular EMG and modelling studies, and those of others, we suspect that virtually all torso muscles play a role in stabilization. However, while multifidus, the other extensors, and the abdominal wall, have been highlighted before, the architecture of quadratus lumborum suggests that it can be a stabilizer. This notion is further strengthened by some earlier observation that the motor control system involves this muscle together with the abdominal wall when stability is required in the absence of major moment demands. The fibres of quadratus lumborum cross-link the vertebrae; they have a large lateral moment arm via the transverse process attachments, and traverse to the rib cage and iliac crests. Thus, the quadratus could buttress shear instability, and be effective in all

loading modes, by design. Typically, the first mode of buckling is lateral - the quadratus can play a significant role in local lateral buttressing. Further, activation profiles support the notion of the stabilizing role of quadratus. It is active during a variety of flexion dominant, extensor dominant and lateral bending tasks. Specifically, Andersson et al (1996) found the QL did not relax with the extensors during the flexion-relaxation phenomenon. The flexion-relaxation phenomenon is an interesting task since there is no substantial lateral or twisting torques and the extensor torque appears to be supported passively - suggesting some stabilizing role for QL. Other very limited data suggest (our laboratory techniques to obtain quadratus lumborum activation were rather imprecise at the time) that in an experiment where subjects stood upright, but held buckets in either hand where load was incrementally added to each bucket, the quadratus lumborum appeared to increase its activation level (together with the obliques) as more stability was required. This task forms a special situation since only compressive loading is applied to the spine in the absence of any bending moments. The three layers of the abdominal wall are also important for stability together with muscles, which attach directly to vertebra - the multisegmented longissimus and iliocostalis and the unisegmental multifidii. Cholewicki and McGill (1996) has also presented an argument for the role of the small intertransversarii in producing small but critical stabilizing forces. On the other hand, psoas activation appears to have little relationship with low back demands - the motor control system activates it when hip flexor moment is required (data is presented by Andersson et al (1995) and Jucker et al (1998)). So which are the wisest ways to challenge and train these identified stabilizers? These will be shown during the presentation.

ANOTE AN ABDOMINAL HOLLOWING AND BRACING

In this authors opinion, there appears to be some confusion in the broad interpretation of the literature regarding the issue of abdominal "hollowing" and "bracing". Richardson's group has evaluated hollowing - observing that the "drawing in" of the abdominal wall recruits transverse abdominis. Given that transverse abdominis has been noted to have impaired recruitment following injury (Hodges and Richardson, 1996), Richardson's group developed a therapy program designed to re-educate the motor system to activate transverse abdominis in a normal way in LBP patients. Hollowing was developed as a motor re-education exercise and not necessarily as a technique to be recommended to patients who require enhanced stability for performance of the ADL, which has perhaps been misinterpreted by some clinical practitioners. Rather, abdominal bracing, that activates the three layers of the abdominal wall (external oblique, internal oblique, transverse abdominis), with no "drawing in" is much more effective at enhancing spine stability. Specifically, the lumbar torso must prepare to withstand steady state loading (which may be a complex combination of flexion-extension, lateral bend and axial twisting moments), withstand sudden unexpected complex loads together with loads that develop from prehensive ballistic motion. The abdominal brace is required to ensure sufficient stability using the oblique cross bracing although high levels of co contraction are rarely required - probably about 5% MVC co contraction of the abdominal wall during performance of ADL and up to 10% MVC during rigorous activity.

THE BEGINNER'S PROGRAM THROUGH TO ADVANCED TECHNIQUES FOR STABILIZATION

Stabilization exercises are virtually any type of exercise that grooves motor patterns that ensure sufficient stability for the task at hand. However, given populations of patients through to athletes, the preferred exercise changes from those that spare the spine to those that are designed to enhance athletic performance. A sampling of these techniques will be demonstrated.

SUMMARY AND 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 symmetric stiffness needed to ensure sufficient stability in all degrees of freedom (or to keep the appropriate level of potential energy of the spine). Rehabilitation endeavors are continuing to embrace techniques that consider notions of lower torso stability. While there is no question that first a system must be stable before presented with a physical challenge, the enhancement of low back health and the avoidance of troubles have motivated scientific inquiry into the mechanics of stability. Many groups continue to work to understand the contributions to stability of various components of the anatomy at particular joints - and the ideal ways to enhance their contribution; to understand what magnitudes of muscle activation are required to achieve sufficient stability; to identify the best methods to re-educate faulty motor control systems to both achieve sufficient stability and reduce the risk of inappropriate motor patterns occurring in the future. Motor patterns to achieve stability appear to be different depending on whether the activity is steady state (with or without combined loads), or with dynamic motion, which may involve rapid voluntary motions or unexpected loading requiring reaction. Understanding stability in all of these unique conditions is the global goal. Finally, the efficacy studies to date, although promising, can only be considered to provide preliminary data. Rigorous efficacy trials are needed on populations of patients who have been sufficiently examined to be categorized into pathological groups, and on athletes classified by performance goals. Much remains to be done.

Acknowledgments

The author wishes to acknowledge the contributions of several colleagues who have contributed to the collection of works reported here: Daniel Juker, M.D., Craig Axler, M.Sc., Sylvain Grenier, M.Sc., and Jack Callaghan, Ph.D. and in particular Professor Jacek Cholewicki. Also the continual financial support from the Natural Science and Engineering Research Council, Canada has made this series of work possible.

REFERENCES

1. Andersson, E., Oddsson, L., Grundstrom, H., Thorstensson, A., The role of the psoas and iliacus muscles for stability and movement of the lumbar spine, pelvis and hip, *Scand.J.Med.Sci.Sports* 1995; 5: 10-16.
2. Andersson, E.A., Oddsson, L.I.E., Grundström, H., Nilsson, J., EMG activities of the quadratus lumborum and erector spinae muscles during flexion-relaxation and other motor tasks, *Clin.Biomech.* 1996; 11(7): 392-400.
3. Bergmark, A., Mechanical stability of the human lumbar spine, Doctoral Dissertation, Department of Solid Mechanics, Lund University, Sweden, 1987.
4. Biering-Sorensen, F., Physical measurements as risk indicators for low back trouble over a one year period, *Spine* 1984; 9: 106-119.
5. Cholewicki, J., and McGill, S.M., Lumbar posterior ligament involvement during extremely heavy lifts estimated from fluoroscopic measurements, *J. Biomech.* 1992; 25(1): 17-28.
6. Cholewicki, J., and McGill, S.M., Mechanical stability of the in vivo lumbar spine: Implications for injury and chronic low back pain, *Clin. Biomech.* 1996; 11(1): 1-15.
7. Cholewicki, J., Simons, A.P.D., and Radebold, A., Effects of external trunk loads on lumbar spine stability, *J. Biomech.* 2000; 33(11): 1377-1385.
8. Crisco, J.J. and Panjabi, M.M., Euler stability of the human ligamentous lumbar spine, Part I Theory 1992; 7: 19-26 and Part II, Experiment, *Clin. Biomech.* 1992; 7: 27-32.
9. Gardner-Morse, M., Stokes, I.A.F., Laible, J.P., Role of the muscles in lumbar spine stability in maximum extension efforts, *J. Orthop. Res.* 1995; 13: 802-808.
10. Hodges, P.W., Richardson, C.A., Inefficient muscular stabilisation of the lumbar spine associated with low back pain: a motor control evaluation of transversus abdominis, *Spine* 1996; 21: 2640-2650.
11. Juker, D., McGill, S.M., Kropf, P., Steffen T., Quantitative intramuscular myoelectric activity of lumbar portions of psoas and the abdominal wall during a wide variety of tasks, *Med. Sci. Sports Ex.* 1998; 30(2): 301-310.
12. McGill, S.M., A myoelectrically based dynamic three dimensional model to predict loads on lumbar spine tissues during lateral bending, *J. Biomech.* 1992; 25: 395-414.
13. McGill SM. ISB Keynote Lecture-The biomechanics of low back injury: Implications on current practice in industry and the clinic, *J Biomech* 1997; 30: 465-475.
14. McGill, S.M., Low Back Exercises: Evidence for improving exercise regimens, *Physical Therapy*, 1998; 78: 754-765.
15. Richardson, C., Jull, G., Hodges, P., Hides, J., Therapeutic exercise for spinal segmental stabilization in low back pain. Churchill-Livingston, Edinburgh, 1999.