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The Stabilizing System of the Spine. Part II. Neutral Zone and Instability Hypothesis

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Summary: The neutral zone is a region of intervertebral motion around the neutral posture where little resistance is offered by the passive spinal column. Several studies—in vitro cadaveric, in vivo animal, and mathematical simulations—have shown that the neutral zone is a parameter that correlates well with other parameters indicative of instability of the spinal system. It has been found to increase with injury, and possibly with degeneration, to decrease with muscle force increase across the spanned level, and also to decrease with instrumented spinal fixation. In most of these studies, the change in the neutral zone was found to be more sensitive than the change in the corresponding range of motion. The neutral zone appears to be a clinically important measure of spinal stability function. It may increase with injury to the spinal column or with weakness of the muscles, which in turn may result in spinal instability or a low-back problem. It may decrease, and may be brought within the physiological limits, by osteophyte formation, surgical fixation/fusion, and muscle strengthening. The spinal stabilizing system adjusts so that the neutral zone remains within certain physiological thresholds to avoid clinical instability. **Key Words:** Spine stabilizing system—Spinal instability—Neutral zone—Muscle function—Low-back pain.

In studies of the measurements of spinal motion segment behavior, load-displacement curves often appear as nearly straight lines, starting from the origin (12,18,26). We believe that this is a result of preconditioning the specimen two to five times and then zeroing the deformation-measuring system. This practice has been used to minimize the viscoelastic effects in order to get more repeatable results. As a consequence, an important part of the initial phase of the load-displacement curve is lost. What is left of the load-displacement curve is the more or less linear elastic part. In reality, however, the individual ligaments of the spine (1,13), as well as those of many joints [such as the knee (11)], have been shown to have highly nonlinear load-displacement curves.

The result of this nonlinearity is a high flexibility around the neutral position and a stiffening effect toward the end of the range of motion. The nonlinearity of the load-displacement curve is necessary for the proper functioning of the spinal system. It allows spinal movements near the neutral position with minimal expenditure of energy, and yet still provides significant resistance to prevent damaging motion beyond the ends of the physiological range of motion. Therefore, it is surprising to see that this aspect of the load-displacement curve of the spine has been neglected.

The existence of this highly nonlinear behavior of the spine became evident to us in the course of an investigation of the physiological strains in the spinal ligaments (22). The ranges of motion of fresh cada-

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veric lumbar spine specimens were measured in the normal manner—i.e., preconditioning followed by zeroing of the motion-measuring system. We noted that the ranges of motions were *smaller* than the available in vivo measurements. Even allowing for large measurement errors in the in vivo studies, we reasoned that the in vitro motion ought to be larger than the in vivo motion because: (a) the muscles can be expected to produce motion that is well below the threshold that may cause injury or pain; and (b) the in vitro motions were obtained by loading the specimen just below its injury threshold. In a recent study, it has been shown that the lumbar spine ranges of motion obtained with our methodology (23), when compared with previous studies, were indeed closer to the in vivo motion measurements; and the ranges of motion of other studies were smaller. The region of high flexibility or laxity around the neutral position is called "the neutral zone."

The purpose of this paper is to present experimental evidence supporting the existence of neutral zones in intact spine specimens and to explore the effects of injury, muscle force, and instrumentation on the neutral zone. In addition, we offer a hypothesis of spinal instability that incorporates the concept of the neutral zone.

THE NEUTRAL ZONE

Before we describe the basic concepts and experimental observations, it is useful to briefly define and explain a few terms concerned with load-displacement curve. These terms are also illustrated in Fig. 1.

Terms and Concepts

Neutral Position. *The posture of the spine in which the overall internal stresses in the spinal column and the muscular effort to hold the posture are minimal.*

Range of Motion (ROM). *The entire range of the physiological intervertebral motion, measured from the neutral position.* It is divided into two parts: neutral and elastic zones.

Neutral Zone (NZ). *That part of the range of physiological intervertebral motion, measured from the neutral position, within which the spinal motion is produced with a minimal internal resistance.* It is the zone of high flexibility or laxity.

Elastic Zone (EZ). *That part of the physiological intervertebral motion, measured from the end of the neutral zone up to the physiological limit. Within the EZ, spinal motion is produced against a significant internal resistance.* It is the zone of high stiffness.

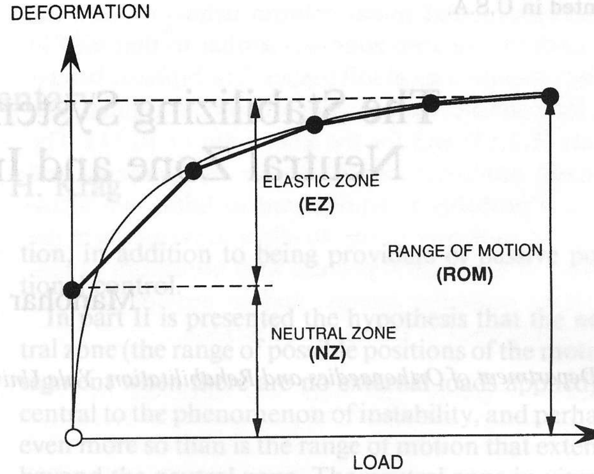

FIG. 1. The load-deformation curve of a soft tissue or a body joint is highly nonlinear. The joint is highly flexible at low loads; it stiffens as the load increases. To analyze this nonlinear biphasic behavior, the load-displacement curve is divided into two parts: neutral zone (NZ), the region of high flexibility; and elastic zone (EZ), the region of high stiffness. The two zones together constitute the physiological range of motion (ROM) of a joint.

All of the above quantities exist for each one of the six degrees-of-freedom of motion, i.e., three rotations and three translations.

Measurement Method

When a spinal specimen is loaded physiologically repeatedly in a particular direction, on release of the load, the specimen does not return to its initial position but exhibits a certain residual displacement. We have used this phenomenon as the basis for a standardized procedure for the quantification of the neutral zone. The process consists of loading three times to the estimated maximum physiological load, in several incremental steps. The load-displacement values are recorded only during the third load cycle, which begins 30 s after removal of the load at the end of the second load cycle, to allow for viscoelastic creep. The process is then repeated by loading in the opposite direction. The residual displacements present just before the beginning of the third load cycle in one direction, and the third load cycle in the opposite direction, define the ends of the neutral zone. The neutral position is defined as the point midway between these two values. The elastic zone, for each of the loads, is obtained from the respective load-displacement curve (on the third load cycle). The two ranges of motion

TABLE 1. *Typical values of NZ (deg), EZ (deg), ROM (deg), and NZR (%) for a few levels of the spine*

	Flexion				Extension				One-side lat. bend				One-side ax rotation			
	NZ	EZ	ROM	NZR	NZ	EZ	ROM	NZR	NZ	EZ	ROM	NZR	NZ	EZ	ROM	NZR
C0–C1	1.1	2.4	3.5	31.4	1.1	19.9	21.0	5.2	1.5	4.0	5.5	27.3	1.6	5.6	7.2	22.2
C1–C2	3.2	8.3	11.5	27.8	3.2	7.7	10.9	29.4	1.2	5.5	6.7	17.9	29.6	9.3	38.9	76.1
Low cervical	10.4	6.9	17.3	60.1	3.6	3.5	7.1	50.7	9.3	4.3	13.6	68.4	5.8	9.2	15.0	38.7
Lumbar	1.5	6.1	7.6	19.7	1.5	2.3	3.8	39.5	1.6	5.0	6.6	24.2	0.7	1.7	2.4	29.2
L5–S1	3.0	7.0	10.0	30.0	3.0	4.8	7.8	38.5	1.8	3.7	5.5	32.7	0.4	1.0	1.4	28.6

NZ = neutral zone, EZ = elastic zone, ROM = range of motion, NZR = neutral zone ratio.

are computed as the sums of the respective neutral and elastic zones. A parameter that is useful for the purpose of comparison is the neutral zone ratio (NZR), which is equal to NZ/ROM × 100.

Some Values of NZ, EZ, ROM, and NZR

Typical values of these four kinematic parameters for flexion, extension, lateral bending, and axial rotation, for selected spinal levels are given in Table 1. The data were taken from published in vitro studies (20,29) and an experimental work on the cervical spine not yet published. The table does not contain data from the thoracic region, because these data are presently not available. The neutral zone ratio (NZR) is plotted in Fig. 2.

Experimental Observations

Both the neutral zone and range of motion are measures of displacement. Which one is a better indicator

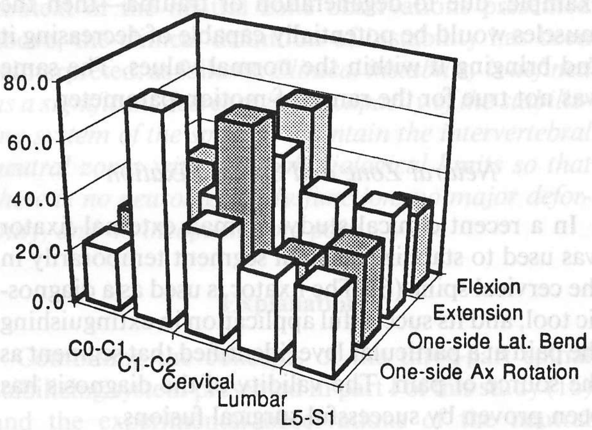

FIG. 2. Representative neutral zone ratios (%) of the spine. Neutral zone ratio, defined as the neutral zone divided by the range of motion, is plotted as a function of both the spinal level and motion type.

of spinal instability? Several experimental studies support the view that the neutral zone is a more sensitive parameter than the range of motion in characterizing spinal instability. A summary of these studies is presented below.

Neutral Zone and Disc Degeneration

Although there is no conclusive evidence, there are some indications that there may be a relation between the neutral zone increase and disc degeneration. In an in vitro study using fresh cadaveric lumbar spine specimens, certain motion parameters were found to be correlated to disc degeneration (21). The neutral zone, in some cases, was found to be a more sensitive parameter than the range of motion in relating to degeneration of the disc. For example, although the range of motion in flexion/extension did not change with increasing disc degeneration, the neutral zone increased significantly. In a recent in vivo study, a relationship was posited between disc degeneration and the risk for low-back pain problems (27).

This finding that the "neutral zone increases with degeneration" in flexion-extension motion supports the in vivo clinical observations of increased anterior-posterior spinal motion seen in low-back pain patients (5,8,9).

Neutral Zone and Spinal Injury

In a high-speed trauma experiment using porcine cervical spine specimens, both the neutral zone and range of motion were found to increase with the severity of injury (17). However, in a direct comparison between the neutral zone and range of motion parameters, the neutral zone increases (measured as a percentage of the intact behavior) were larger than the corresponding increases in the range of motion for the same injury. For example, in extension-compression trauma, the neutral zone for the axial rotational instability increased by 540%, while the corresponding range of motion increase was only 240%. In the latest study on this subject from our laboratory, in which spine specimens were subjected to high-speed trauma of increasing severity, we found the increase in flexion-extension neutral zone to be the first indicator of the onset of injury (15). This was not true for the increases in the corresponding range of motion.

Neutral Zone and Compression Fractures

In an independent study from another laboratory, instability of the experimentally produced fresh cadaveric thoracolumbar compression fractures was measured before and after the experimental trauma (2). Physiological moments were applied in the vertical planes: sagittal plane, frontal plane, and several planes in between, in the presence of 400 N of preload. Neutral zones were measured in each plane. The authors plotted the neutral zones on a graph, with flexion-extension on x-axis and lateral bending on y-axis. Both the intact and postinjury values were plotted. The lines joining the points were found to form approximate rectangles. The rectangles were quantified by the area and the distance of the centroid from the origin. The best correlation was found between the reduction in the vertebral height due to trauma and the change (from the intact to the traumatized) in the distance of the centroid from the origin. Ching et al. therefore suggested that the neutral zone centroidal shift may be a good indicator of the potential kyphotic deformity. Thus, a neutral zone parameter was found to be an indicator of another aspect of compression fractures.

Neutral Zone and Burst Fracture

In a study from another institute, experimental spinal trauma of burst fractures was produced in the laboratory (25). Fresh cadaveric thoracolumbar human spine specimens were utilized. Stiffness was measured in flexion, lateral bending, and axial rotation, both before and after the trauma. The authors found all load-displacement curves to be bilinear—i.e., having two distinct regions of constant stiffness values. In the initial phase, the load-displacement curve showed low stiffness; whereas, in the latter phase, it showed high stiffness. These two behaviors are predictable from our concepts of neutral and elastic zones, respectively. For all three motion types, the initial-phase stiffness decreased much more significantly than did the latter-phase stiffness. This is equivalent to saying, using the terms proposed here, that for all three instability tests, the neutral zones increased much more than did the corresponding elastic zones. For flexion, lateral bending, and axial rotation, the elastic zones increased respectively by 20%, 42%, and 61%. The corresponding increases for the neutral zone were 49%, 80%, and 87%. Slosar et al. further noted that all NZ increases (over the intact values) were statistically significant, whereas none of the EZ increases were significant. This study clearly shows the neutral zone to be an important and sensitive parameter to indicate injury.

Neutral Zone and Muscles

Consider the neutral zone to be of two kinds: passive and active. The spinal column in vitro, devoid of musculature, exhibits neutral zones. These are the passive neutral zones. The active neutral zones are present in vivo, under the action of resting muscle tone. Although no measures of the active neutral zones are presently available, we believe these are smaller than the corresponding passive neutral zones measured in vitro. In two recent studies, one an in vitro experiment (19) and another a mathematical model of the spine (14), the application of simulated deeper muscular forces to the injured spinal specimen was investigated. In both studies, sequential injuries of the spinal column components resulted in corresponding increases in neutral zones and ranges of motion. The application of an anteriorly-inferiorly directed force vector to the middle of the spinous process decreased the neutral zone to the near intact value, but the range of motion did not decrease. Thus, if there was an increased passive neutral zone—for example, due to degeneration or trauma—then the muscles would be potentially capable of decreasing it and bringing it within the normal values. The same was not true for the range-of-motion parameter.

Neutral Zone and Spinal Fixation

In a recent clinical study, a small external fixator was used to stabilize a spinal segment temporarily in the cervical spine (6). The fixator is used as a diagnostic tool, and its successful application in extinguishing the pain at a particular level identified that segment as the source of pain. The validity of the diagnosis has been proven by successful surgical fusions.

To quantify the underlying motions responsible for pain, we conducted an in vitro study using fresh cadaveric human cervical spine specimens (23). In this preliminary study, the specimen was first tested intact for its three-dimensional flexibility using normal protocols for this purpose. The pins were inserted into the lateral masses of C5 and C6, using the surgical technique, and the fixation was applied to prevent motion at C5–C6. Then the specimen was tested a second time with the same protocol. Results were expressed as the percentage decrease in motion, due to the application of the fixator. Following preliminary conclusions were drawn. For the motions of flexion-extension, bilateral rotation, and bilateral lateral bending, the ranges of motion decreased by 47%, 54%, and 17%, respectively. Similar decreases for the neutral zones were 80%, 75%, and 57%, respectively. On average, combining all of the results, the range of motion decreased by only 38%, whereas the neutral zone decreased by 71%.

From these findings one may hypothesize that the motion parameter that decreased the most—i.e., the neutral zone—is better correlated to the pain that may be eliminated by the application of the fixator. To our knowledge, this is the first attempt in a human subject to relate a quantified motion parameter—namely, the neutral zone—to neck pain. If these results are supported by further studies, then the present hypothesis of increased ranges of motion as indicators of instability may be questioned.

A HYPOTHESIS OF INSTABILITY

Clinical instability has been defined as the loss of the ability of the spine under physiologic loads to maintain its pattern of displacement so that there is no initial or additional neurological deficit, no major deformity, and no incapacitating pain (28). In the context of the neutral zone observations presented above, the clinical definition of instability has been reinterpreted, as follows: *Clinical instability is defined as a significant decrease in the capacity of the stabilizing system of the spine to maintain the intervertebral neutral zones within the physiological limits so that there is no neurological dysfunction, no major deformity, and no incapacitating pain.*

Explanation

Combining the concepts of the three-part spinal stabilizing system presented in part I of this study (16) and the experimental observations of the neutral zone, the instability definition may be presented graphically (Figs. 3A and B). The experimental observations concerning the spinal column, of an increase in the neutral zone with injury to the spinal column and a decrease with spinal column augmentation (fixation), are conceptualized as shown in Fig. 3A. Also shown is the region of the neutral zone that is physiological, pain-free, and neurologically intact. A similar diagram, describing the experimentally observed interaction between the muscle force and the neutral zone, is shown in Fig. 3B.

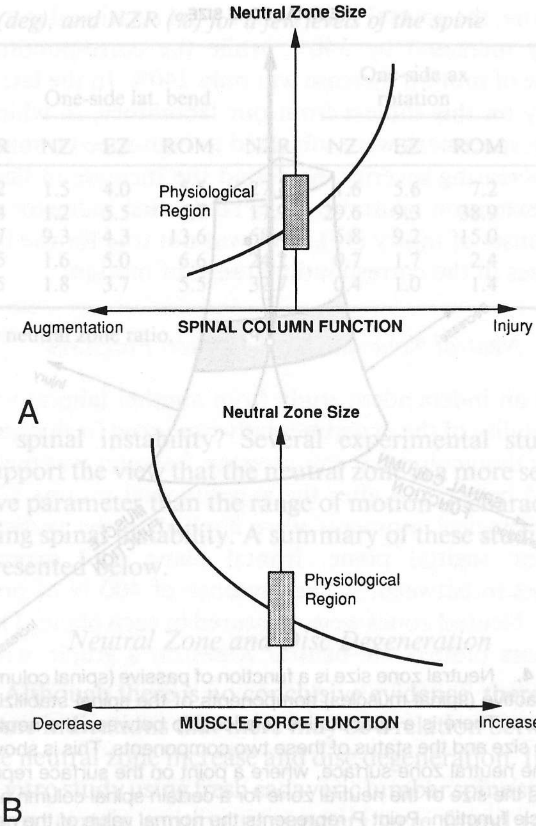

FIG. 3. A: Neutral zone size as a function of spinal column injury and augmentation is shown. Also indicated is the physiological region for the neutral zone. **B:** Neutral zone size as a function of increase and decrease in the muscle force function is shown. Also graphed is the physiological region for the neutral zone.

Combining Figs. 3A and B, a three-dimensional neutral zone surface plot may be generated, as shown in Fig. 4. The two horizontal axes represent the spinal column function and muscle function, while the vertical axis shows the neutral zone size. Injury and augmentation of the spinal column are shown in the opposite directions on the spinal column function axis. In a similar manner, the increase and decrease in muscle function are shown in the opposite directions on the muscle force function axis. The upper limit of the neutral zone surface is defined by the maximum injury to the spinal column and the minimum muscle

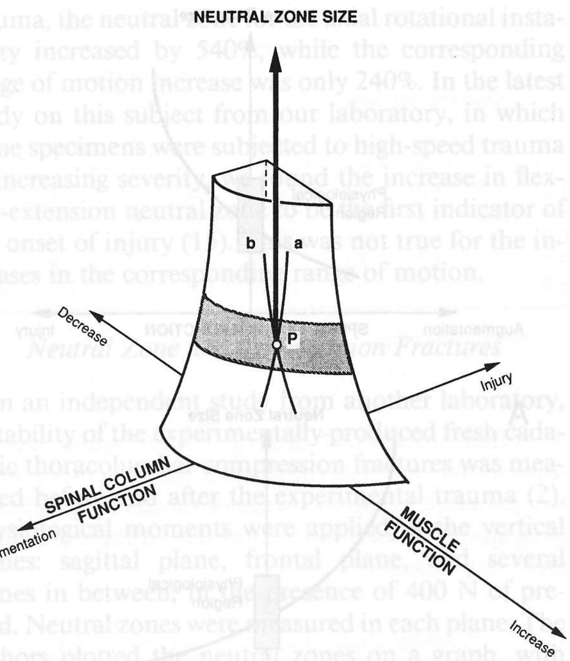

FIG. 4. Neutral zone size is a function of passive (spinal column) and active (spinal muscles) components of the spinal stabilizing system. There is a quantitative relationship between the neutral zone size and the status of these two components. This is shown by the neutral zone surface, where a point on the surface represents the size of the neutral zone for a certain spinal column and muscle function. Point P represents the normal value of the neutral zone for an individual for a particular spinal motion. If there is an injury or augmentation of the passive components, then point P moves, respectively, up or down on the surface (line a). On the other hand, if there is a decrease or an increase in the muscle function, then point P moves, respectively, up or down, but on a different path (line b). Using the instability surface representation, one may chart the stability region for normal functioning of the spine, the physiological region (shaded area). The neutral zone surface may be utilized to visualize the functioning of the stabilizing system of the spine in case of an injury. For example, a moderate injury to a component of the spinal column may bring point P outside the physiological region, but it may likewise be brought within by strengthening the muscle function. A severe injury, however, may displace point P so far away that the increase in the spinal muscle function needed to compensate may be beyond the capacity of the system, leading to clinical problems—e.g., low-back pain.

function, whereas the lower limit is set by osteophytic formation and the maximum muscle effort.

The physiological region of the neutral zone, shown by the shaded area in Fig. 4, also has upper and lower limits. The upper limit is set by either the microdeformations of the soft tissues causing pain or the stretching and compression of the neural elements due to the deformation of the spinal column, causing neurological deficit. The lower limit of the physiological neutral zone is defined by either excessive muscle effort (causing muscle fatigue) or spinal column stiffening caused by osteophyte formation and other degenerative effects. Although the NZ in general was equated to instability, micromovements within the physiological NZ region may provide the necessary signal to the neuromuscular system for the proper functioning of the spinal stabilizing system.

DISCUSSION

The basic hypothesis proposed here is that the size of the neutral zone is a better indicator of clinical spinal instability than is the overall range of motion. Because the neutral zone in vivo has not been measured, there is no direct evidence yet to prove the hypothesis; there is, however, significant indirect evidence to support it.

A solid posterior fusion does not always relieve back pain, possibly because of the continued presence of micromotion anteriorly between vertebral bodies. This motion, which is repetitive in nature, may cause microstrains in annular fibers and ligaments and even rubbing of the nerve root by the contacting soft tissue. Anterior fusion may completely eliminate the microstrain in annular fibers; but if the pain originates in posterior structures, such as the capsular ligaments, again the pain may not be relieved. Because of the flexibility of the posterior elements, well documented both in vitro (24) and in vivo (4), a solid fusion at one place does not guarantee the elimination of micromotion at another place within the functional spinal unit.

Our in vitro biomechanical studies have indicated that the application of a cervical spine external fixator at one level reduces the neutral zones much more effectively (~70%) than it does the ranges of motion (~38%). The same fixator applied clinically has been found to eliminate chronic pain in patients. This leads to the hypothesis that the reduction in NZ motion produces a sufficiently large reduction in strain in the pain-generating tissue, and that this in turn produces pain relief in the patient.

In an in vitro study and a mathematical model, the application of the simulated muscle force to an injured functional spinal unit was found to selectively reduce the neutral zone to the intact values. We may hypothesize that the muscles are capable of restoring spinal stability after an injury. To test this hypothesis clinically, it is possible to train muscles surrounding the spinal column in patients who have suffered spinal column injury and observe the clinical outcome.

The spinal column exhibits nonlinear load-displacement behavior, and the behavior is such that the spine is highly flexible in the vicinity of the neutral posture.

This fundamental spinal column behavior—i.e., the presence of a neutral zone—is similar to that seen in many other biological soft tissues. The biphasic behavior, for example, has been documented for spinal ligaments (1,3,13) and for the knee joint (7,10,11). The biphasic nonlinear behavior seen in ligaments and joints is probably a requirement to fulfill two seemingly contradictory needs: to allow movements in the vicinity of the neutral posture with minimum expenditure of muscular energy, and to provide stability toward the ends of the range of motion.

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Commentary

By Martin H. Krag

These two papers, by an individual who has successfully applied his substantial creativity and intellect to the field of spinal instability for years, provide a very useful contribution to this field: the first to pull together and to bring sharply into focus concepts that are touched upon here and there in other writings; the second to propose an innovative and intriguing new hypothesis.

In part I, the spine stabilizing system is envisioned as consisting of three components (passive, active, and neutral control), each of which functions in a highly dynamic, interdependent manner. The adaptability of each component can augment the overall functioning of the system, or can make up for deficiencies in other components, but only up to a limit, beyond which dysfunction of the overall system results.

In addition to the clarification of these concepts, part I provides a useful emphasis upon the active and dynamic aspects of the spine stabilizing system, which leads to an appreciation of the complexity involved in the stabilizing function. Also presented are some interesting hypotheses concerning the function of ligaments as the providers of position or force information, in addition to being providers of passive positional control.

In part II is presented the hypothesis that the neutral zone (the range of possible positions of the motion segment when there are no external loads applied) is central to the phenomenon of instability, and perhaps even more so than is the range of motion that extends beyond the neutral zone. The neutral zone in vitro is seen to increase with disc degeneration and various experimentally produced injuries, and to decrease with the addition (by modeling) of muscle forces and spinal instrumentation. These neutral zone changes are greater than the accompanying changes in range of motion.

This hypothesis is intriguing not only because of the observations it explains, but because of the questions it raises. How relevant is the concept of a neutral zone in vivo when muscle activity dominates positional control? Does the in vivo environment result in a disc hydration change that significantly alters the neutral zone?

Clearly, much remains to be established in this area, but these papers represent two important steps forward.