# Why don't we have lumbar discs in our necks?

## Patterns of Strain in Intervertebral Discs: Cervical Spine

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## Introduction

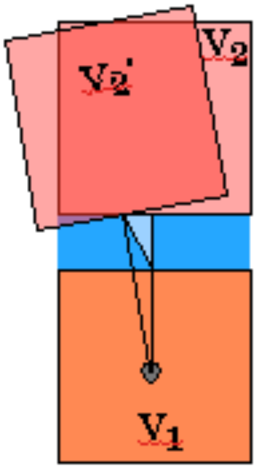
The vertebral column is a chain of interlocking bones connected by ligaments, joint capsules, and muscles. Movements of the spine are the concatenation of the movements of the individual vertebrae with respect to each other. Intervertebral movement is constrained by interdigitation of the bones and connective tissue that binds them together. Interdigitation constrains movement primarily by abutment of one bone upon the other. Binding restrains movement largely by tethering. Both types of constraint must be considered to understand the logic of movement in the spine. This essay will examine how strains in the fibrous structure of the intervertebral disc constrain movement.

### *The Problem*

The published estimates for ranges of motion of the various cervical vertebrae indicate that some of the intervertebral joints allow up to 20° of flexion/extension and about10° of oblique rotation in either direction [White, 1990 #43; Panjabi, 1998 #55]. The question naturally arises as to how that quantity of motion is accommodated by the intervertebral discs and facet joints?

The facet joints are less of a problem, because they are oriented to allow movement in precisely those directions. They act to prevent movement in other directions [Onan, 1998 #60; Milne, 1991 #12].

The intervertebral discs are another matter though. The centers of rotation for salaam of the upper three vertebrae of the lower cervical spine are through the mid to lower part of the subjacent vertebra [White, 1990 #43; Panjabi, 1998 #55]. That configuration gives a swing arm of 0.8 units with a disc that is 0.3 units thick, which means that the superior endplate of the intervertebral disc travels 0.14 units relative to the lower endplate when the joint undergoes 10° of salaam. Since the original distance between the end plates is 0.3 units, a change in the distance between the two ends of a fiber that goes directly from the center of the inferior endplate to the center of the superior endplate is roughly $\sqrt{0.3^2 + 0.14^2} = 0.33$ or 10% increase in length. How is this possible, when a 5% increase in length is a large physiological strain in a ligament? That is the question that will addressed in some detail in this paper.



### *Review of the Anatomy of Intervertebral Discs*

The intervertebral disc varies in its structure, depending upon the level of the spine that is being examined [White, 1990 #43; Williams, 1995 #17]. However, the lumbar disc is generally taken as the norm for all levels. The lumbar intervertebral disc is essentially a ligament that binds one vertebral body to another. It is composed of a circumferential ring of dense, highly fibrous, bands with oppositely aligned fibers, called the annulus fibrosus, and a loose, semi-fluid, mucoprotein/mucopolysaccharide matrix in the center, called the nucleus pulposus. The nucleus occupies 30% to 50% of the horizontal disc cross-section. It tends to occupy more of the disc cross-section in the lumbar and cervical spine, where there is more movement. The superior and inferior interfaces between the disc and the vertebral bodies is largely occupied by a thin layer of hyaline cartilage. The exception is the outer rim, where a narrow cartilaginous zone binds bone to bone (Sharpeys fibers). Fibrocartilage makes up most of the annulus and it binds the hyaline cartilage endplates together. At lumbar levels, the nucleus pulposus is not centrally located. Rather, it is centered about the junction between the anterior two-thirds and the posterior third of the disc.

The annulus fibrosus is laminated in that alternate circumferential bands have dense parallel arrays of collagen fibers that are aligned at about 30° to the vertebral endplates, but running in opposite directions [White, 1990 #43]. Consequently, the fibers in adjacent bands are directed at about 120° relative to each other.

This is the conventional description of the annulus fibrosus and it is probably approximately correct for many intervertebral discs, especially for the lumbar spine. However, there are a few notes that should be made here as they may be relevant in the analysis of strain in the disc. The orientation of the fibers may not always be approximately 30° to the endplate. Inoue found that the obliquity of the fibers of the deeper laminae were different [Inoue, 1973 #58] and Zaki [Zaki, 1973 #59] found that there were vertical fibers in the posterior annulus, which are apt to make those fibers far more apt to tear with most movements, unless they are very loose. Conventional accounts suggest that the laminae of the annulus fibrosus form continuous rings that totally encircle the central disc. In fact there is a complex interdigitation of partial rings of laminae, especially in the posterolateral part of the disc.

The nucleus pulposus is a hydrophilic gel that imbibes water when there is less pressure upon the nucleus and releases it when there is increased pressure. This makes the disc slightly thicker upon rising in the morning than it was upon lying down at night. In young spinal columns the nucleus is about 90% water, but, as the disc matures, the proportion of water decreases to about 70%.

The rounded shape of the nucleus pulposus is impressed upon the surrounding annulus so that the laminae bulge peripherally. In situations in which the fibrous laminae are forced to become less concave, they press in upon the nucleus, which may transmit the force to parts of the annulus that are under reduced strain. There may be substantial displacement of the nucleus due to these differential forces. It is thought that the nucleus may act as a soft cushion over which the vertebral bodies may rock and/or glide.

### *Special Features of the Cervical Spine*

The cervical discs are very different from the lumbar discs [Mercer, 1999 #77]. In the adult spine, the concentric laminae are essentially absent in the posterior disc. The annulus fibrosis forms a crescent that is thickest anteriorly and tapers laterally as it approaches the uncinate processes. The posterior disc is deficient posterolaterally and represented posteriorly by a thin layer of vertically oriented fibers deep to the posterior longitudinal ligament. The posterior longitudinal ligament acts as a restraint on flexion of the cervical spine and the anterior longitudinal ligament may act as a restraint upon extension [Przybylski, 1998 #91]. Both ligaments are broad, with multiple component layers and parts.

Most of the substance of the disc is a fibrocartilaginous matrix in which collagen fibers are loosely distributed in a dense gel, something like soap. The relative numbers of fibrous elements probably declines as one progresses centrally into a region that probably corresponds to the nucleus pulposus.

It is known that cervical discs are often, probably normally, fissured with broad clefts that extend in from the lateral margins. These fissures help in the formation of the uncovertebral facet joints, along the lateral margin of the disc for the second through the sixth or seventh cervical vertebrae. Frequently, the fissures extend as far as the nucleus pulposus and divide the posterior part of the disc into two separate plates. While complete fissures are generally seen only in mature spines, the process probably starts in the second decade of life.

Fissuring is common in this type of joint. Similar fissures are found in the pubic symphysis and the manubrio-sternal symphyses. It has been speculated that the fissuring of the cervical disc may represent an adaptation to the need for more rotation in the cervical spine [Bogduk, 2000 #103][Penning, 1989 #47].

### *The Current Approach and its Rationale*

The anatomy of the intervertebral disc is complex and specific. In modeling the disc, it is prudent to start with a simple anatomy and add elements as they are needed to deal with particular discrepancies between the model and actual anatomical measurements. The analysis starts with a model that is like the traditional lumbar disc and problems arising from that approach lead to the rationale for the observed cervical anatomy.

To that end, it will be assumed that the two vertebral endplates are parallel in neutral position and that the fibers of the annulus fibrosus extend from the inferior plate to the superior plate at an angle of 30° to the inferior plate.

For the time being, the nucleus pulposus will be left out of consideration. There is no doubt that it is important to the functioning of the disc in compression and it causes a bowing of the annular fibers that may be critical to allowing the full observed range of motion, but its interaction with the annulus is complex and poorly understood in quantitative terms, therefore the analysis will proceed without it until its import becomes apparent. Clearly, in the cervical spine the biomechanics must be quite different, because the nucleus pulposus is not bound in an annular ring of fibrous tissue, as in the lumbar spine.

The anatomy is also simplified in that it will be assumed that the intervertebral disc is circular. This is also clearly not the case, but, as stated above the reasons for it not being circular should become apparent as the analysis proceeds or there is not a particular reason for the exact shape that it does take.

## Methods

The descriptive model is realized as a collection of program segments expressed in ***Mathematica***. Many of the images are processed through a graphics program, ***Canvas 6***, to add labels and other graphical elements. Text is created and processed in ***Mathematica*** and ***Word***.

The basic form of the model is to view the intervertebral joint as a pair of endplates that are connected by fibers that extend from one to the other in a particular manner. Initially, the fiber trajectory is generally a helical line that moves in a circular arc about a center of rotation. The model involves the selection of an array of these fibers, distributed throughout the disc, calculating their trajectories when the endplates are in neutral position and after the superior endplate has moved relative to the inferior endplate. The length of the fiber is computed prior to the movement and after the movement and the change in length is compared with the original length to give a percent change in fiber length. The distribution of that computed variable is plotted as a function of the fiber's location.

The movements of the superior endplate are expressed as a rotation about an axis of rotation that passes through a center of rotation. The actual mathematical techniques, are based upon quaternion analysis, which has been developed elsewhere [Langer, 2003 #35].

## Results

Since the intent of this analysis is to discover general principles, rather than to model a particular joint, the model starts with a very simple anatomy that has a great deal of symmetry and which can be dealt with using fairly simple mathematics. As needed the model can be altered to include more realistic anatomy, but often at the expense of intuitive understanding of the details of the calculation. As the anatomy becomes more realistic it is necessary to move from analytic methods to numerical solutions.

For the most part, what is studied is not the disc, *per se*, but an analytic probe that allows one to test the behaviour of the disc fibers under different conditions and in various parts of the disc. It is not so important that the detailed anatomy is correct, but that the fibers have an appropriate orientation and the relative distance between plates is approximately correct. In many situations, the fibers in only a portion of the probe are relevant to the points under investigation. To emphasize that the computed entity is a probe, rather than an actual disc the computed probe will be called a p-disc.

### *The model*

The initial model is quite simple. It is assumed that the joint is expressed as the relative movements of two circular endplates, that are parallel in neutral position. The inferior endplate will generally be taken as immobile, so the joint's configuration will be expressed as the movement of the superior endplate relative to the inferior endplate. The separation between the endplates will be three units. This is primarily because the relative thickness of the intervertebral discs in the cervical and lumbar spinal columns are about 30% of the vertebral segment. Consequently. the vertebral body would be about 7 units thick, rostro-caudally.

The two endplates are connected by fibers that extend between them, but traverse the interval by following a course that is helical about an axis through the centers of the endplates, with an inclination of 30° relative to the inferior endplate. This means that fibers close to the center of the p-disc will travel through a large circular arc as they extend from the inferior plate to the superior plate. If the fiber is about 0.83 units from the center of the p-disc, then it will complete a circle as it travels between the plates. Its superior end will be directly above its inferior end.

Fibers 1.66 units out will complete a half circle and fibers 3.3 units out will complete a quarter circle.

Since fibers are distributed in space, their location will be arbitrarily set to be their midpoint in neutral position for the joint. So a fiber that lies 3.3 units directly lateral to the center of the p-disc will extend from 45° anterior to the center of the disc at one end to 45° posterior to the center of the disc at its other end.

For any fiber at a given distance from the center of the p-disc, it is possible to compute its trajectory between the plates. In addition, it is possible to numerically integrate the fiber to determine its length, which will always be the same in neutral position, unless the p-disc varies in thickness, as real one do. The same numerical integration, applied after the joint is moved, will also give a length, which will depend on the location of the fiber and the nature of the joint movement. The strain upon the fiber can be expressed as the relative change in fiber length, which generally will be expressed as the percent change from the length in neutral position. Since the locations of the ends of the fiber are known it is also possible to determine the span between them. The span is the minimal distance between the ends of the fiber, therefore the shortest length that the fiber can have if it is to bridge the gap. The ratio of the span to the initial fiber length in neutral position is the minimal strain possible under the current conditions. A stretched fiber will tend to deform in the direction that will bring it closer to its minimal strain, but the other fibers in the same and different laminae and the incompressibility of the nucleus pulposus would tend to resist that deformation.

Initially, it will be assumed that the alternating, concentric, laminae of fibers have straight walls. It is commonly noted that the actual walls are bowed so that they bulge peripherally. This is obviously a way to maintain length in fibers that would otherwise be compressed. It is also a way of obtaining more fiber length when a fiber would be stretched beyond it normal limit. However, the bowing of the laminar walls is a difficult feature to build into a quantitative model, because there are not quantitative descriptions of the amount of bowing under various conditions and it would be very difficult to do such a study.

### *Movements of the joint*

If the inferior endplate is fixed, then the superior plate can move in a number of different ways. If a frame of reference is defined and the plates are horizontal in neutral position, then the superior plate moves about an axis of rotation , ***R***, through an angle of excursion, $\alpha$. If the axis of rotation is a transverse axis, then the movement is flexion ($\alpha > 0$) or extension ($\alpha < 0$). If it is about a sagittal axis, then the movement is sideflexion and, if about a vertical axis, the movement is lateral rotation, of turning. The axis of rotation may have any orientation. For instance, in the lower cervical spine, one of the two permitted axes of rotation is an oblique axis in the sagittal plane that runs from anterior and inferior to posterior and superior. In addition to its orientation, an axis of rotation has a location, that is, there is a center of rotation. The center of rotation may be any point on the axis of rotation, but there is usually a particular point that simplifies the calculations and that point is usually chosen for the center of rotation. In summation, to describe a rotatory movement, it is necessary to give a center of rotation, an axis of rotation, and an angular excursion about that axis.

Most of what follows is concerned with how fibers, which are defined by their location, obliquity, and direction relative to the two end plates, are affected by movement of their superior ends about an axis of rotation.

### *Initialization of the Fiber*

The first program segment illustrates how the various attributes of the disc and the fiber combine with the movement to lead to a measurement of the strain. Words in bold are variables in the calculation.

The disc has a superior/inferior thickness, **depth**, of 3 units. The slope of the fibers, or **fiberSlope**, is 60° off vertical , 30° relative to the inferior plate, in neutral position.

**alpha** is the angular offset of a radial vector. When there is no offset, the vector points straight ahead, or anteriorly. When **alpha** = 0°, it points along the **r** axis. When **alpha** = 90° it points along the **s** axis.

The **twistAngle** is 2π radians times half the thickness of the disc, times the tangent of **fiberSlope**, divided by the circumference of a circle with the same radius. In other words, it is half the angle subtended by an arc that extends through the thickness of the disc at an angle that is equal to the slope of the fibers of the disc; the angle subtended by the part of a fiber between its middle and one end.

The radial vector, **middle**, that is half way through the thickness of the disc is obtained by computing the effect of rotation of the radial vector with a length equal to the **radius** which points in the positive **r** direction, about an axis that points in the positive **t** direction, though an angle of **alpha**. It points to the middle of the fiber. The **superiorEnd** is the vector produced by rotating **middle** through the **twistAngle** in a positive direction and setting it at the top of the disc. The **inferiorEnd** is the vector that results from rotating **middle** through an angular excursion of **twistAngle** in the negative direction and placing it at the bottom of the disc.

The length of the fiber, **lengthFiber**, is the depth of the disc times the reciprocal of the sine of the **fiberSlope**. It can be computed easily, since the fiber lies in a cylindrical surface, which is topologically a plane. After the tilt, the metric of the curve is distorted and the length must be computed by integrating the curve. That is done by numerically integrating the curve, which is approximated by a series of 20 line segments.

The **distance** between the ends of the fiber, **spanFiber**, is the norm of the **superiorEnd** minus the **inferiorEnd**. It is actually computed by computing the tensor of the difference quaternion.

### A Program Segment to Compute the Configuration of a Single Fiber

```
alpha =90*Pi/180;
fiberSlope = 60;
radius = 3.3;
depth = 3.0;
twistAngle = Pi*depth*Tan[fiberSlope*Pi/180]/(2*Pi*radius);
twistQuat = Quaternion[Cos[twistAngle] ,0, 0, Sin[twistAngle]];
antitwistQuat = Quaternion[Cos[-twistAngle], 0, 0, Sin[-twistAngle]];
```

```
middle = Quaternion[0, radius*Cos[alpha], radius*Sin[alpha] ,0];
superiorEnd = twistQuat**middle+Quaternion[0, 0, 0, depth];
inferiorEnd = antitwistQuat**middle;

lengthFiber = depth/Sin[(90-fiberSlope)*Pi/180];

spanFiber = tensorQ[superiorEnd - inferiorEnd];
```

It is not known how the disc is distorted by movement, but it is probably roughly proportional to the distance from the fixed attachments. When the superior plate is tilted or sheared relative to the lower plate the amount of shear at intermediate depths is assumed to be proportional to the distance from the inferior plate. If the point is a tenth of the distance from the inferior plate to the superior plate, then it will move through about a tenth of the angular or linear excursion that the superior plate experiences.

First, the previous program section is generalized to compute a series of points, **fiberArray**, along the curve between the two endpoints.

### A Program Segment to Compute the Fiber Curve in Neutral Position and in The Stressed Position, Compute the Length of Each and Compute the Percent Change in Length.

```
alpha =90*Pi/180;
fiberSlope = 60;
radius = 3.0;
depth = 3.0;
twistAngle = Pi*depth*Tan[fiberSlope*Pi/180]/(2*Pi*radius);

middle = Quaternion[0, radius*Cos[alpha], radius*Sin[alpha], 0];

fiberArray = Array[r, {21,3}];
Do[(
twist = twistAngle*k/10;
```

```
twistQuat = Quaternion[Cos[twist], 0, 0, Sin[twist]];
fiberPoint = twistQuat**middle+Quaternion[0, 0, 0, ((1+k/10)*depth/2)];
fiberArray[[k+11, 1]] = fiberPoint[[2]];
fiberArray[[k+11, 2]] = fiberPoint[[3]];
fiberArray[[k+11, 3]] = fiberPoint[[4]]
),{k,-10,10,1}];

lengthFiber1 =0.0;
Do[(
lengthR = fiberArray[[k+1,1]] - fiberArray[[k,1]];
lengthS = fiberArray[[k+1,2]] - fiberArray[[k,2]];
lengthT = fiberArray[[k+1,3]] - fiberArray[[k,3]];
length = Sqrt[lengthR^2 + lengthS^2 + lengthT^2];
lengthFiber1 = lengthFiber1 + length),{k,1,20,1}];

lengthR = fiberArray[[21,1]] - fiberArray[[1,1]];
lengthS = fiberArray[[21,2]] - fiberArray[[1,2]];
lengthT = fiberArray[[21,3]] - fiberArray[[1,3]];
length = Sqrt[lengthR^2 + lengthS^2 + lengthT^2];
spanFiber1 = length;

centerRot = Quaternion[0, 0, 0, -5];
rotationV = Quaternion[0, 0, 1 ,0];
angleExcursion = 10*Pi/180;

pi = Quaternion[0, fiberArray[[1,1]], fiberArray[[1,2]], fiberArray[[1,3]]]

fiberArrayTransform = Array[r,{21,3}];

fiberArrayTransform[[1, 1]] = pi[[2]];
fiberArrayTransform[[1, 2]] = pi[[3]];
```

```
fiberArrayTransform[[1, 3]] = pi[[4]];

Do[
(point = Quaternion[0, fiberArray[[k,1]], fiberArray[[k,2]], fiberArray[[k,3]]];
ps = point;
psRot = ps - centerRot;
beta = angleExcursion*(k-1)/20;
rotationQ = Quaternion[Cos[beta/2], Sin[beta/2]*rotationV[[2]],
Sin[beta/2]*rotationV[[3]], Sin[beta/2]*rotationV[[4]]];
ps = euler[rotationQ, psRot] + centerRot;

fiberArrayTransform[[k, 1]] = ps[[2]];
fiberArrayTransform[[k, 2]] = ps[[3]];
fiberArrayTransform[[k, 3]] = ps[[4]]), {k,2,21,1}];

lengthFiber2 =0.0;
Do[
(lengthR = fiberArrayTransform[[k+1,1]] - fiberArrayTransform[[k,1]];
 lengthS = fiberArrayTransform[[k+1,2]] - fiberArrayTransform[[k,2]];
 lengthT = fiberArrayTransform[[k+1,3]] - fiberArrayTransform[[k,3]];
 length = Sqrt[lengthR^2 + lengthS^2 + lengthT^2];
 lengthFiber2 = lengthFiber2 + length),{k,1,20,1}];

percentChangeLength = 100*((lengthFiber2 - lengthFiber1)/lengthFiber1);

lengthR = fiberArrayTransform[[21,1]] - fiberArrayTransform[[1,1]];
lengthS = fiberArrayTransform[[21,2]] - fiberArrayTransform[[1,2]];
lengthT = fiberArrayTransform[[21,3]] - fiberArrayTransform[[1,3]];
length = Sqrt[lengthR^2 + lengthS^2 + lengthT^2];
spanFiber2 = length;
```

This can then be generalized to an array of fibers, where the **percentChangeLength** is stored in the array **dataArray**. The function **computeRing** is used to create a table from a column of **dataArray** that can be passed as an argument to a plot function to plot the individual rings for 10 steps of radius (from 1.0 to 3.25 in 0.25 steps). Finally, all the individual rings are plotted together in one coordinate system.

### Compute the Strains in the Disc for a Collection of Fibers Distributed in Several Layers and Many Directions

```
dataArray = Array[r,{36,10}];
Do[
alpha =theta*Pi/180;
fiberSlope = 60;
 (* radius = 3.0;*)
depth = 3.0;
twistAngle = Pi*depth*Tan[fiberSlope*Pi/180]/(2*Pi*radius);
twistQuat = Quaternion[Cos[twistAngle], 0, 0, Sin[twistAngle]];
middle = Quaternion[0, radius*Cos[alpha], radius*Sin[alpha], 0];

fiberArray = Array[r, {21,3}];
Do[(
twist = twistAngle*k/10;
twistQuat = Quaternion[Cos[twist], 0, 0, Sin[twist]];
 fiberPoint = twistQuat**middle+Quaternion[0, 0, 0, ((1+k/10)*depth/2)];
 fiberArray[[k+11, 1]] = fiberPoint[[2]];
 fiberArray[[k+11, 2]] = fiberPoint[[3]];
 fiberArray[[k+11, 3]] = fiberPoint[[4]]), {k,-10,10,1}];

lengthFiber1 =0.0;
Do[
(lengthR = fiberArray[[k+1,1]] - fiberArray[[k,1]];
 lengthS = fiberArray[[k+1,2]] - fiberArray[[k,2]];
```

```
 lengthT = fiberArray[[k+1,3]] - fiberArray[[k,3]];
 length = Sqrt[lengthR^2 + lengthS^2 + lengthT^2];
 lengthFiber1 = lengthFiber1 + length),{k,1,20,1}];

lengthR = fiberArray[[21,1]] - fiberArray[[1,1]];
lengthS = fiberArray[[21,2]] - fiberArray[[1,2]];
lengthT = fiberArray[[21,3]] - fiberArray[[1,3]];
spanFiber1 = Sqrt[lengthR^2 + lengthS^2 + lengthT^2];

centerRot = Quaternion[0, 0, 0 ,-5];
rotationV = Quaternion[0, 0, 1, 0];
angleExcursion = 10*Pi/180;

pi = Quaternion[0, fiberArray[[1,1]], fiberArray[[1,2]], fiberArray[[1,3]]];

fiberArrayTransform = Array[r,{21,3}];

fiberArrayTransform[[1, 1]] = pi[[2]];
fiberArrayTransform[[1, 2]] = pi[[3]];
fiberArrayTransform[[1, 3]] = pi[[4]];

Do[
(point = Quaternion[0, fiberArray[[k,1]], fiberArray[[k,2]], fiberArray[[k,3]]];
ps = point;
psRot = ps - centerRot;
beta = angleExcursion*(k-1)/20;
rotationQ = Quaternion[Cos[beta/2], Sin[beta/2]*rotationV[[2]],
Sin[beta/2]*rotationV[[3]], Sin[beta/2]*rotationV[[4]]];
ps = euler[rotationQ, psRot] + centerRot;

fiberArrayTransform[[k, 1]] = ps[[2]];
```

```
fiberArrayTransform[[k, 2]] = ps[[3]];
fiberArrayTransform[[k, 3]] = ps[[4]]), {k,2,21,1}];

lengthFiber2  = 0.0;
Do[
(lengthR = fiberArrayTransform[[k+1,1]] - fiberArrayTransform[[k,1]];
 lengthS = fiberArrayTransform[[k+1,2]] - fiberArrayTransform[[k,2]];
 lengthT = fiberArrayTransform[[k+1,3]] - fiberArrayTransform[[k,3]];
 length = Sqrt[lengthR^2 + lengthS^2 + lengthT^2];
 lengthFiber2 = lengthFiber2 + length),{k,1,20,1}];

percentChangeLength = 100*((lengthFiber2 - lengthFiber1)/lengthFiber1);

lengthR = fiberArrayTransform[[21,1]] - fiberArrayTransform[[1,1]];
lengthS = fiberArrayTransform[[21,2]] - fiberArrayTransform[[1,2]];
lengthT = fiberArrayTransform[[21,3]] - fiberArrayTransform[[1,3]];
length = Sqrt[lengthR^2 + lengthS^2 + lengthT^2];
spanFiber2 = length;

dataArray[[1+theta/10,4*(radius-1)+1]] = percentChangeLength;), {radius, 1,3.25,.25},{theta,0,350,10}];
```

### A function to load the array of points to be plotted

```
computeRing[ring_,radius_] := (Do[(
plotListArray[[change, 1]] = radius*Cos[(change-1)*Pi/18];
plotListArray[[change, 2]] = radius*Sin[(change-1)*Pi/18];
plotListArray[[change, 3]] = dataArray[[change, ring]])
,{change,1,36,1}];

change = 1;
plotListArray[[37, 1]] = radius*Cos[(change-1)*Pi/18];
```

```
    plotListArray[[37, 2]] = radius*Sin[(change-1)*Pi/18];
    plotListArray[[37, 3]] = dataArray[[change, ring]];)
```

## Plotting the Individual Rings

```
    plotListArray = Array[r,{37,3}];
    ring =1;
    radius =1;
    computeRing[ring,radius];
    list = Table[{plotListArray[[k,1]], plotListArray[[k,2]], 0.1*plotListArray[[k,3]]},
{k,1,37}];
    ring1 = ScatterPlot3D[list, PlotJoined -> True, PlotStyle  ->  Thickness[0.005] ]

    ring =2;
    radius =1.25;
    computeRing[ring,radius];
    list = Table[{plotListArray[[k,1]], plotListArray[[k,2]], 0.1*plotListArray[[k,3]]},
{k,1,37}];
    ring2 = ScatterPlot3D[list, PlotJoined -> True, PlotStyle  ->  Thickness[0.005] ]
```

***and so on for rings 3 through 10***

```
    Show[{ring1, ring2, ring3, ring4, ring5, ring6, ring7, ring8, ring9, ring10},
    ViewPoint->{10.000, 10.000, 2.00}];
```

The analysis now turns to using this program to examine a number of particular cases that bear upon the strains in intervertebral discs when the joint is moved in particular ways.

## Strains in Lumbar-like p-discs

### *The Case of Flexion/Extension with Vertical Fibers*

The first situation that will be considered is very simple anatomy, one that does not actually exist in the lumbar spine. The reason for considering it is to show why it is not used in there.

Consider a p-disc in which the fibers extend directly from the inferior plate to the superior plate by the shortest possible path. This is equivalent to setting the obliquity to 0°. Only flexion/extension will be considered so the axis of rotation is aligned with the **s**-axis. The center of rotation is first chosen to lie at the center of the p-disc.

It is easily seen that the posterior fibers in the disc are stretched and the anterior fibers are shortened or compressed. If the flexion is 10°, then the fibers three units posterior to the center of the disc are stretched 3 * tan 10° = 0.53 units, so the most posterior fibers would have to stretch to 118% their length in neutral position in order to bridge the gap. Ligaments generally do not stretch anywhere near this amount. A strain of 5% is probably a large physiological strain.

Consider a second situation, where the center of rotation is about the center of the inferior vertebra, 3.5 units below the inferior plate. This approximates the actual situation for the upper vertebrae in the lower cervical spine. If we look at the strain as a function of fiber location (Figure 1), then the distribution of strain is fairly simple, a flat disc that is tilted up about 21% at three units posterior to the center of the disc. This would rip the disc as soon as the joint flexed, but we know that 10° of flexion is not an unreasonable amount of flexion at many spinal levels. This leads to a consideration of how the disc's anatomy allows such a movement to occur.

### *The Case of Flexion/Extension With Oblique Fibers*

It is clear from the previous example that a ligament in which the fibers extend directly from one plate to the other will not allow any appreciable movement unless the ligament is very long relative to the surfaces that it connects. One of the most notable features of the intervertebral disc is that the fibers are obliquely oriented, very oblique. Consider what the pattern of strain is in a disc that has this arrangement of its fibers.

In the next example the fibers are oblique with a obliquity of 30° relative to the inferior plate and the superior plate flexes 10° about a transverse axis though the center of the disc. The maximal strain, three units posterior to the center of the disc, is less than 5% (Figure 2A). If the centre of rotation is shifted five units inferiorly, then the pattern of strain is initially unexpected (Figure 2B). The fibers that are maximally strained are those that lie posterior and lateral. The greatest strain is for fibers located 45° posterior to the coronal plane through the center of the disc. The reason for this distribution is that the superior plate not only tilts down in front, but it is also translated anteriorly. The fibers that lie posterior and lateral are stretched by the posterior part of the plate tilting superiorly and by the superior end of the fibers moving anteriorly, approximately along the long axis of the fiber. The most posteriorly located fibers are stretched by the tilt and the translation, but both movements are approximately orthogonal to the long axis of the fibers, therefore have much less potential for lengthening the fiber.

There is a considerable amount of strain when the center of rotation is displaced 5 units inferior to the inferior plate, about 15% more fiber length than in neutral position, but that is still less than for a rotation about a center of rotation at the center of the disc when the fibers were vertical.

This example illustrates the benefit of the oblique fibers, but indicates that even that benefit can not prevent tearing in the posterior third of the disc. In the lumbar spine, that is the most common region for tearing of the annulus. Curiously, the posterior lateral part of the intervertebral part of the disc is where the unco-vertebral joints and lateral fissure tend to form in the lower cervical spine. It is a region largely deficient of annulus fibers in the mature cervical spine [Mercer, 1999 #77].

The anterior part of the strain surface is mostly compression, but, the actual disc is thicker anteriorly in both the cervical and lumbar spine, so there is more material to absorb the compression. The disc is less apt to be damaged by compression. In the cervical spine, the intervertebral discs are generally under compression due to the weight of the head and the pulling of the cervical muscles, which tend to compress the neck.

Extension produces a reversal of the strain plots for flexion. The maximal values are for fibers that lie anterior and lateral in the disc. While the band of dense fascicles is thin in this region in the cervical spine, it is present and it is largely in the portion of the disc that lies immediately subjacent to the alar part of the anterior longitudinal ligament. These fibers are also more vertically oriented than is usually said to be the case. This appears to be a situation that would place maximal stress upon the fibers. Still, these fibers last well into old age, therefore there must be something wrong with the assumptions of the model. The problem is may lie in the placement of the axis of rotation, in the assumption that the fibers will not stretch much beyond 5% of their rest length, or our understanding of the dynamics of the disc; probably all three.

### *The Case of Oblique Rotations*

The cervical intervertebral discs seem to be formed in a manner that allows more flexion that one would expect, based upon the simple circular annulus model. However, it must also allow oblique rotations. These are probably somewhat smaller in range, usually less than 7.5°.

The next example considers the strains introduced by oblique rotation about an axis that lies in the sagittal plane, at a 45° angle to the coronal plane of the vertebra, tilted so the superior end lies posteriorly. The center of rotation is taken to lie at the center of the p-disc.

Whereas the fibers in the alternating laminae of the annulus had strain surfaces that were symmetrical across the midline when the joint was flexed or extended, the strain in the two sets of laminae is similar for oblique rotations. The surface is a like a sheared bowl with the rim being higher on the side that the superior endplate is approaching. In the conventional manner of naming movements, a right rotation causes greater strain in the left side of the p-disc.

The amount of strain is proportional to the horizontal distance from the center of rotation, therefore the strain is greatest lateral to the center of the disc. I the center of rotation is moved posteriorly, then the greatest potential strain would occur at the unco-vertebral joints, where there are no fibers.

## Strains in Cervical-like p-discs

Up to this point, the problems with disc with vertical fibers have been explored and some reasons that the cervical may take the form it does have been proposed. However, when the anatomy of the cervical spine is examined, it becomes clear that the p-discs considered so far are not representative of actual cervical discs. Unlike lumbar discs, the fibers in cervical discs are more vertical and they are distributed only to the anterior rim of the intervertebral space. The most superficial fibers are almost vertical. The deeper fibers are at about 45° to the superior and inferior plates, tilted so that the superior ends are medial to the inferior ends. In the anterior midline, the two sets of fibers from the two sides are interwoven.

It should also be noted that in mature cervical spines, the portion of the superior and inferior surfaces that have fibers is the part that tends to be tilted anteriorly. The superior vertebral body forms a lip along its anterior inferior margin so that its inferior surface is directed posteriorly and inferiorly. The anterior superior margin of the inferior vertebral body is reciprocally contoured so that its surface is directed superiorly and anteriorly. The fibers that pass between the two lips are nearly vertical, tending to run medially as they run superiorly. The fibers in the overlying anterior longitudinal ligament are mostly vertical in the medial part of the ligament and they tend to fan out inferiorly and laterally in the alar portions. The obliquity is about 45° to the inferior and superior plates.

Posteriorly, the annular fibers form a thin and comparatively narrow band in the midline of the disc. These fibers are essentially vertical. They are covered by the posterior longitudinal ligament, which is thicker and more extensive. As with the anterior longitudinal ligament, there is a thicker and denser fascicle of vertical fibers in the midline and a thin web of oblique fibers that extend posteriorly and laterally to either side in an alar component. The alar fibers have variable obliquity, depending on how far their endpoints are situated along the superior/inferior axis of the spine.