A Thesis

entitled

Auxetic Spinal Implants: Consideration of Negative Poisson’s Ratio in the Design of an Artificial Intervertebral Disc

By

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Fusion is a common surgery performed to treat those with chronic, severe, low back pain. Currently fusion is being done by replacing the removed disc with an implanted intervertebral cage and bone graft with posterior fixation devices to provide stability until the fusion process has completed. The fusion process limits the range of motion of the spine in the section where fusion has taken place and also generally does not help to reduce pain that is associated with the degenerated disc. This study examined the possibility of using a negative Poisson’s ratio artificial intervertebral disc to replace discs that are degenerating. The hypothesis is that replacing the damaged disc with a negative Poisson’s ratio artificial spinal disc implant will allow for the same range of motion that the natural intervertebral disc allows and additionally will prevent interference with surrounding nerves due to the lack of bulging exhibited by a negative Poisson’s ratio material when compressed.
The initial portion of this study focused on finite element analysis of the L4-L5 motion segment to determine if the stresses, range of motion, and displacement of the intervertebral disc were affected by changing the Poisson’s ratio of the disc. The study focused on examining seven possible movements that can take place in the spine; extension, flexion, left and right lateral bending, left and right axial rotation, and pure compression. Each of these analyses was completed using several Poisson’s ratios for the intervertebral disc; the initial model had a Poisson’s ratio of 0.45 for the annulus fibrosus and 0.4999 for the nucleus pulposus. For all additional analyses the annulus fibrosus and the nucleus pulposus had the same Poisson’s ratio and were examined for Poisson’s ratios of; 0.4999, 0.3, -0.3, and -0.999. These analyses had results that indicate that a negative Poisson’s ratio artificial intervertebral disc will undergo similar stress and range of motion as a natural intervertebral disc, but will additionally have a negative displacement as compared to a bulging effect that can be observed in a positive Poisson’s ratio. However, at some point in the range between -0.3 and -0.999 the beneficially properties are lost.

The second portion of this study focused on compressing medium density polyurethane foam to create foam with a negative Poisson’s ratio. The compression process was achieved through heating the foam while under tri-axial compression. Additionally the microstructures of the original uncompressed foam and the compressed foam were examined through the use of scanning electron microscopy (SEM) and microCT. A small sample of the three dimensional (3D) microstructures of both the original uncompressed foam and the compressed foam were printed using rapid
prototyping, otherwise known as 3D printing. The long term goal of this work is to fabricate an auxetic spinal implant prototype.
For my mother, Toni. Even when Alzheimer’s has taken your memories, I will remember for us both. You have inspired and motivated me in ways you will never know, and for that I thank you.

“A mother will hold her child’s hand for a short time, but their heart forever.” - Anonymous
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Chapter 1

Introduction

1.1 Spine Anatomy

There are thirty-three vertebrae that comprise the spinal column. These vertebrae are divided into five main regions; cervical, thoracic, lumbar, sacral, and coccygeal. Seven vertebrae make up the cervical region, twelve vertebrae in the thoracic region, five vertebrae in the lumbar region, five vertebrae in the sacral region, and four in the coccygeal region. Figure 1-1 below shows the entire spinal column from a lateral view from cervical vertebra 1 through the coccygeal region of the spine. In between each pair of vertebrae there are flexible intervertebral discs, which allow for motion to take place between two vertebrae. The spine has several important functions. It is a protective structure for the spinal cord and also is a supportive structure for the torso and head. The grouping of two vertebrae and the surrounding ligaments connected by one intervertebral disc is referred to as a motion segment, or a functional spine unit (FSU).

This study is focused on the fourth lumbar (L4) and fifth lumbar (L5) vertebrae, the attached ligaments, and the intervertebral disc that connects the L4 and L5 vertebrae. The numbering of the lumbar vertebrae starts at the superior portion and is numbered sequentially from 1 to 5, ending at the inferior portion of the lumbar spine.
The intervertebral discs account for one fourth of the length of the spine [1]. The intervertebral disc that lies between vertebrae is comprised of two portions. The exterior annulus fibrosus is made of lamellae; concentric sheets of collagen fibers which are connected to the vertebral end plates [1]. The interior portion of the intervertebral disc is the nucleus pulposus; this portion of the disc absorbs most of the pressure of the spine. The nucleus pulposus is primarily composed of water and proteoglycans [1].
1.2 Disc Degeneration

Most cases of disc degeneration are related to aging. However, there are other factors that can contribute to disc degeneration such as; autoimmune and biomechanical [2]. The degeneration of intervertebral discs can affect any region of the spine, but is most common in the lumbar and cervical regions. The degeneration of discs typically results with age due to morphologic changes that occur in the vertebral bone and cartilaginous endplate [3]. These changes can interfere with the normal nutrition of the metabolically active disc. As the disc continues to degenerate, there will be greater stresses placed on the surrounding structures of the spine such as the facet joints [3]. In addition to the normal degeneration with age, patients may have an earlier onset of symptoms due to job type, lifting, or trauma for example.

The main symptom in patients with degenerative disc disease is chronic pain in the region where degeneration is occurring. However, there are many patients that are asymptomatic. There may also be episodes of intense pain flare ups, which are referred to as acute episodes [1]. Because of the instability that results from the degeneration of the disc, there are several factors that can lead to the pain that patients may experience. These factors can include mechanical compression of the nerves by the bone, ligaments, or disc material and biochemical mediators that cause inflammation and/or pain [3]. Initial treatments for degenerative disc disease will include noninvasive methods such as physical therapy, chiropractic care, or exercise. If the degeneration continues to progress, the next options for treatment would be surgical. These options include spinal fusion and artificial disc replacement.
1.3 Artificial Disc Replacement

For years, the treatment of choice for degenerative disc disease that has not responded to conservative treatments has been spinal fusion. In spinal fusion, the diseased disc is removed and either autologous or allograft bone grafts are implanted, often along with interbody cages, pedicle screws, and rods, to create a bony fusion between the vertebrae [4]. While patients can benefit from the fusion of spinal vertebrae, there are still many who do not show an improvement in symptoms after the bone fusion. In addition, the purpose of fusion is to limit motion in the diseased portion of the spine. This limiting of motion in turn causes neighboring segments of the spine to have increases in stress and motion [4].

On October 26, 2004, the FDA approved an artificial disc for the treatment of degenerative disc disease at L4 to S1 [5]. There are currently two FDA approved total disc replacements; the Charité™ total disc replacement and the Prodisc®-L total disc replacement [6]. The ideal advantage to total disc replacement verses spinal fusion would be the preservation of motion in the spine. Using the artificial disc will also restore stability and maintain disc height without causing adjacent segment disease [4]. The two total artificial discs that are approved for use in the United States by the FDA both consist of two metal endplates and a plastic inlay that fits between the two endplates. The endplates can then slide over the plastic inlay to allow for motion. In 2010 Depuy ceased manufacturing of the Charité artificial disc in favor of an improved version called the In Motion artificial disc. The new version keeps many of Charité’s features while incorporating some minor modifications to allow for easier implant insertion [7]. These metal on metal or metal on plastic models over time can experience wear due to the
motion. This wear can cause irritation in the body. An implant that is one continuous piece would in theory prevent this wear, however most materials experience bulge in the transverse direction when compressed in the axial direction. This bulge can interfere with surrounding nerves and cause further pain issues. However, there is a class of materials known as negative Poisson’s ratio materials that when compressed, contract in the transverse direction. It is this property that seems to make an artificial intervertebral disc made of a negative Poisson’s ratio material an attractive candidate as a total disc replacement.

1.4 Negative Poisson’s Ratio Materials

The Poisson’s ratio of a material is defined as the ratio of the lateral strain to the longitudinal strain for a material undergoing tension in the longitudinal direction [8]. For a homogeneous, isotropic structure,

\[ v_{xy} = -\frac{\varepsilon_y}{\varepsilon_x} \]

Equation 1-1: Poisson’s Ratio

Where \( \varepsilon_x \) is the strain applied in the x direction and \( \varepsilon_y \) is the resultant tensile strain in the y direction, which is transverse with respect to the x direction [9]. For isotropic materials, \( v_{xy} = v_{yx} = v \) and the range of the Poisson’s ratio lies between \(-1 \leq v \leq 0.5\), anisotropic materials may have Poisson’s ratios that lie outside of this range. Negative Poisson’s ratio materials, or auxetic materials, will undergo longitudinal and lateral extension when a tensile load is applied in the longitudinal direction. Materials with a
positive Poisson’s ratio on the other hand will undergo longitudinal extension and lateral contraction when a tensile load is applied in the longitudinal direction.

![Diagram showing non-auxetic and auxetic materials.](image)

**Figure 1-3:** (a) Depiction of a material with a Positive Poisson's Ratio. (b) Depiction of a Material with a Negative Poisson's Ratio [8]

There is currently a growing list of natural molecular materials and microstructural biomaterials that exhibit a negative Poisson’s ratio. This list includes materials such as; arsenic [10], cadmium [11], cow teat skin [12], and cat skin [13]. In addition to the auxetic materials that occur naturally, there are several man-made auxetic materials. This list includes; a keyed-brick structure, re-entrant honeycombs, microporous polymers, composites, and some compressed foams [8]. The foams that exhibit negative Poisson’s ratios are created by applying tri-axial compression to thermoplastic or metal foams and heating the foam to its softening temperature, then allowing the foam to cool while still under tri-axial pressure.

### 1.5 Purpose of this Study

This study set out to determine if an artificial intervertebral disc with a negative Poisson’s ratio would be beneficial to a patient who suffers from degenerative disc disease. Investigation of the change in displacement, range of motion, and stress on the
intervertebral disc were performed using finite element study of the L4-L5 motion segment. When a negative Poisson’s ratio material is longitudinally compressed, the material will also compress in the transverse direction. This unique property would prevent bulging that could result if an artificial intervertebral disc was designed using a positive Poisson’s ratio material. Bulging could result in interference with the nerves surrounding the spinal column and cause the patient additional pain. The objective of this study was to determine if polyurethane foam could be compressed to yield a negative Poisson’s ratio foam. The compressed foam was characterized through scanning electron microscopy, microCT, and three dimensional printing of the microstructure of the foam.
Chapter 2

Literature Review

This section will review literature related to low back pain and disc degeneration. There will be a discussion of the various pathologies that contribute to degenerative disc disease. In addition, the surgical treatment options of spinal fusion and total disc replacement will be covered. Finally, a review will be done on negative Poisson’s ratio materials with special attention paid to negative Poisson’s ratio foams.

2.1 Low Back Pain

Not only does low back pain have physical effects on patients, but it can also results in socioeconomic problems for the patient as well [14]. The total costs of low back pain in the United States exceed $100 billion per year [15]. The costs that can be associated with low back pain include; health care, missed work, and disability. Each year, the fewer than 5% of the patients who have an episode of low back pain account for 75% of the total costs [15]. Not only does the low back pain affect the patient, but it also has an impact on the family and employer of the patient. Low back pain can be characterized by specific pathologies such as; hernia, infection, inflammation, osteoporosis, rheumatoid arthritis, or fracture [14]. Low back pain can also occur without indication of what is the cause, or non-specific low back pain. The most important symptoms of non-specific low
back pain are pain and disability [16]. Roughly 90% of low back pain cases are non-specific [14]. Figure 2-1 below depicts common pathologies that can be associated with lower back pain; showing the degenerated disc, a bulging disc, a herniated disc, disc thinning, and disc degeneration with osteophyte (bone spur) formation.

Figure 2-1: Common Disc Problems [1]

In the United States, low back pain is the second most common cause of disability in adults [17]. The adverse affects that low back pain has on the population are numerous. These affects include 149 million days of work lost per year. Roughly two-thirds of the costs associated with low back pain are due to decreased wages and productivity [17]. Low back pain can be associated with the muscles, bones, or nerves. The pain can be as simple as a muscle strain that will subside in a short time, just like other muscles in the
body, or could be attributed to a larger problem. Chronic back pain is often defined as back pain that lasts for longer than 7-12 weeks [18]

There are several underlying sources that could attribute to low back pain. These possible sources of pain include; herniated discs, spondylolisthesis, degeneration of the vertebral body, stenosis, or degenerative disc disease. A herniated disc is a split or rupture in the intervertebral disc which allows the nucleus pulposus to leak out. Spondylolisthesis is a forward slippage of one vertebra relative to another [1]. Degeneration of the vertebral body is simply a deterioration of the bone that makes up the vertebrae. This can be caused by age or another underlying disease such as osteoporosis. Stenosis is a narrowing of the spinal cord canal. Although the precise cause of low back pain is disputed, degeneration of the intervertebral disc is believed to play an important role [19]. Degenerative disc disease will be covered in detail in the next section.

2.2 Disc Degeneration

The North American Spine Society refers to degenerative disc disease as “a clinical syndrome characterized by manifestations of disc degeneration and symptoms thought to be related to those changes” [20]. Deterioration of the osseous and soft tissue structures of the spine is a normal consequence of the aging process and can be predisposed to or accelerated by a variety of developmental and acquired factors [21]. Degenerative disc disease can be caused by a number of factors. An intervertebral disc functions as a shock absorber for the spine. As a disc degenerates, it loses both proteoglycans and water that make up the nucleus pulposus [22]. This loss of fluid decreases that ability of the intervertebral disc to act as a shock absorber. As a result, instability in the motion
segment occurs because the disc has lost some of its stiffness. Most patients with
degeneration of the disc have some degree of abnormal spinal flexibility, but further
investigation into the relationship between kinematics and flexibility need to be
performed [22].

As the disc degenerates, it leads to changes in the surrounding anatomy as well. The
disc will lose height, causing the facet joints into malalignment [23]. In addition to the
increased forces of the facet joints, a degenerating disc and fact changes will likely have
an effect on the posterior ligaments. As the disc degenerates, it leads to a vicious cycle
which can include degenerative disc disease, facet arthrosis, ligamentous and capsular
hypertrophy, spine instability, and lumbar stenosis [23].

Disc degeneration occurs in three stages; dysfunctional, instability, and stabilization.
The dysfunctional stage is characterized by circumferential fissuring or tearing of the
outer annulus fibrosus [24]. This stage of disc degeneration is accompanied by acute
episodes of low back pain or phases where the back “goes out”. In the instability stage,
intervertebral disc changes occur as the result of multiple annular tears and delamination
of the layers. This results in vertebral segment instability [24]. The instability will result
in further decline in proteoglycans and water loss. The final stage, stabilization, is
characterized by further resorption of the nucleus pulposus which leads to more
intervertebral disc space narrowing, fibrosis, endplate irregularities, and osteophyte
formation [24].
2.3 Fusion

There are several options for the treatment of low back pain and degenerative disc disease. Initial treatments will be of the conservative approach, such as physical therapy. If these options fail to treat the pain, surgical options will then be investigated. If the main cause of pain is compression on the nerve root, a decompression surgery can be done. Techniques commonly used in decompression surgeries include laminectomy and laminotomy. If compression on the nerve root is not causing the patient’s pain, a spinal fusion may be performed. In spinal fusion, the damaged intervertebral disc would be removed and then an interbody cage and bone grafts would be placed in between the vertebrae in order to promote bone growth that would fuse the adjacent vertebrae together. There are several surgical techniques that can be used in order to fuse the vertebrae. These techniques include; posterolateral fusion, anterior lumbar interbody fusion, posterior lumbar interbody fusion, transforaminal lumbar interbody fusion, and extreme lateral interbody fusion. A brief description of the above mentioned procedures will follow in upcoming sections.

Spinal fusion should eliminate motion at the instrumented segment [25]. A major problem with fusion is that the elimination of motion in one segment will lead to increases in loading in the adjacent segments. As the loads in adjacent segments increase, this can lead to increases in degeneration in those adjacent segments [25]. A study by Ghiselli et al. found that 59 of 215 patients had degeneration adjacent to their fusion site that would require additional surgical procedures. The study also predicts that over time 16.5% of patients who have had fusion surgery will have degeneration at the adjacent level that will require surgery after five years, and after ten years that percentage
will be 36.1% [26]. In a second study, Lehmann et al. found that in patients that had undergone fusion at L3 or lower, there was significant instability above the fusion level in 15 of 33 patients in a long-term follow-up study [27].

2.3.1 Laminectomy

Laminectomy is a surgery to remove the lamina, or the back part of the vertebra that covers your spinal canal. The goal of laminectomy is to relieve pressure on the spinal column caused by stenosis by enlarging the spinal canal [28].

2.3.2 Laminotomy

A laminotomy is a procedure that can be used to remove the ligamentum flavum. Spinal stenosis has been attributed to this ligament located in the spinal canal [29]. The goal of a laminotomy is also to relieve pressure on the spinal column.

2.3.3 Posterolateral Fusion

Posterolateral fusion is a process that aims to create stability in the affected spine segment through a posterior entry surgery. In a posterolateral fusion, the damaged intervertebral disc material is not removed, but a bone graft is attached between the transverse processes to encourage growth across the vertebrae [30].

2.3.4 Posterior Lumbar Interbody Fusion

As with posterolateral fusion, posterior lumbar interbody fusion is a surgery that aims to return stability to the affected spinal region through a posterior entry surgery. In posterior lumbar interbody fusion, the damaged intervertebral disc is removed, and bone grafts are placed to promote growth between the vertebrae [30].
2.3.5 Anterior Lumbar Interbody Fusion

For an anterior lumbar interbody fusion, the vertebrae are fused after the removal of the affected intervertebral disc and replaced with bone grafts to promote growth. Unlike the posterior lumbar interbody fusion, the anterior surgery is performed through and incision in the abdomen as opposed to the back [31].

2.3.6 Transforaminal Lumbar Interbody Fusion

Transforaminal lumbar interbody fusion is also an open back surgery during which the intervertebral disc is removed and replaced with bone grafts. This surgery differs from posterior lumbar interbody fusion in that the disc is removed from the sides of the vertebrae as opposed to the back [32].

2.3.7 Extreme Lateral Interbody Fusion

Extreme lateral interbody fusion is a minimally invasive surgical approach that fuses the affected vertebrae with a side approach surgery that avoids that major back and abdominal muscles [7]. Again this surgery removes the affected intervertebral disc and replaces it with bone grafts to promote growth between the vertebrae.

2.4 Nucleus Arthroplasty

Currently, the FDA considers the term nucleus arthroplasty as a term that applies to any device that replaces the nucleus pulposus while preserving the surrounding annulus fibrosus [33]. This option differs from total disc replacement which will be discussed later in that only the inner portion, nucleus, of the disc is removed. With total disc replacement the entire disc is removed and an implant is placed to preserve disc height.
and motion. As of 2006, there were several companies that had nucleus arthroplasty devices in FDA investigational device exemption (IDE) studies. These companies included Spine Wave, Inc., Raymedica, LLC, Disc Dynamics, Inc., and Pioneer Surgical Technology [33].

2.5 Total Disc Replacement

Due to increases in adjacent segment loading that are seen in spinal fusions, it was important to move to the next frontier in surgical options for treatment of intervertebral disc degeneration. Total disc replacement has increased in popularity as an alternative for lumbar fusion [34]. Total disc replacement aims to completely remove the damaged intervertebral disc and replace the disc with an artificial disc which will still allow for motion in that segment of the spine as opposed to spinal fusion which would eliminate the motion of the segment. It is the goal of total disc replacement to maintain the disc height, reduce pain associated with the diseased area, not increase loading in the adjacent segments of the spine, and in turn prevent deterioration of the adjacent segments because of increased loads [35]. Figure 2-2 shows the two devices that are currently FDA approved for total disc replacement surgery, the Charité™ total disc replacement by Depuy Spine, and the Prodisc®-L total disc replacement by Synthes Spine, Inc.

Figure 2-2: The Charité Artificial Disc (left) and the Pro-Disc L artificial disc (right) [6]
A study performed by Cinotti et al. reported on 46 patients who underwent total disc replacement with Charité disc prosthesis. Follow-up was performed between 2-5 years after surgery, 63% of the patients reported satisfactory results [36]. O’Leary et al. performed a study that found that the Charité total disc replacement restored near normal quantity of flexion-extension range of motion under constant preload, however the quality of segmental motion differed from the intact case over the flexion-extension range [37]. In another study, performed by Tropiano et al., 64 patients who underwent lumbar total disc replacement with the Pro-Disc prosthesis were followed up with a mean of 8.7 years after surgery, 55 patients, or 86%, participated in the follow-up. The authors reported significant improvement in back pain and disability. Thirty-three patients reported excellent results, eight had good results, and 14 had poor results [38]. A study performed by Tumialán et al. found that patients in the military who underwent total disc replacement experienced results comparable to spinal fusion, but that the total disc replacement patients were able to return to active duty at a faster rate than patients who underwent the spinal fusion process [39].

Disc arthroplasty devices are classified by their articulating surfaces as either metal-on-metal or metal-on-plastic. In order for a total disc replacement to be performed, the patient must have intact ligaments and integrity of the facet joints. It is also important for the vertebral bodies with intact end plates and good bone quality to be present [40]. During the FDA investigational device exemption (IDE) clinical trials, patients were randomly selected to undergo either total disc replacement or spinal fusion with titanium interbody cage. The patients involved in the FDA IDE trials who underwent artificial disc replacement experienced shorter recovery periods, with shorter hospital stays, and
faster pain relief. All of which resulted in higher patient satisfaction, when compared with the patients who underwent spinal fusion [4].

2.6 Negative Poisson’s Ratio

Negative Poisson’s ratio materials have many tasks for which they can be used. An auxetic form of polytetrafluoroethylene (PTFE) has been used to manufacture prosthetic arteries [41, 42]. Due to the nature of auxetic materials, they should have improved fracture toughness, shear modulus, hardness, sound absorbing properties, and impact resistance when compared with positive Poisson’s ratio materials with the same Young’s modulus. For any material, the Poisson’s ratio is related to the geometry and deformation mechanisms of its microstructure. Therefore, the design of auxetic materials at any length scale must begin at the microstructure level [43].

![Diagram of compression properties of non-auxetic versus auxetic materials]

Figure 2-3: Compression Properties of Non-auxetic versus Auxetic Materials [8]

There are several microstructures that are worth evaluating when discussing auxetic materials. The first microstructure that should be considered is the two dimensional re-entrant honeycomb structure. This was first manufactured by Gibson and Ashby [44]; in
this case, it is the pleating of the ribs that allows for the auxetic nature of this design. In addition to the re-entrant honeycomb structure, the node-fibril design which is based on the microstructure of expanded microporous PTFE, also displays auxetic behavior. A final microstructure that has been known to exhibit auxetic behavior is the rotating square model [45]. Figure 2-5 shows the rotating squares microstructure in both its deformed and undeformed configurations.

Figure 2-4: Comparison of Conventional Honeycomb (a) to Re-entrant Honeycomb (b) [8]

Liquid Crystalline Polymer consists of chains of rigid rod molecules connected by flexible spacer groups along the chain lengths [46]. Figure 2-6 depicts the theoretical structure of liquid crystalline polymer.
In 2005, Martz et al., designed and characterized an artificial intervertebral disc with an anisotropic negative Poisson’s ratio. The prosthesis incorporates the negative Poisson’s ratio to prevent bulge which might impinge nerves [47]. The disc was designed based on the re-entrant honeycomb structure and was made from high density polyethylene. The re-entrant honeycomb structure in this case was created by drilling holes through the high density polyethylene so they formed the inverted honeycomb.
structure. Figure 2-7 below shows the implant with re-entrant honeycomb formed through drilled holes.

![Diagram of artificial disc design](image)

Figure 2-7: Artificial Disc Design Proposed by Martz et al. [47]

2.7 Negative Poisson’s Ratio Foams

Negative Poisson’s ratio foams are isotropic in nature, and have been created using polymeric foams [8 48 49 50 51] and metallic foams [48]. In order for foam to be transformed to a negative Poisson’s ratio foam, the cell structure of the foam will need to become re-entrant. To create a re-entrant cell structure in polymer foam, the foam must be tri-axially compressed and heated to its softening point. This softening will allow the cell walls to cool in their re-entrant shape and hence convert the foam from a positive Poisson’s ratio material into a negative Poisson’s ratio material. The re-entrant structure of auxetic foams is similar to the structure of the re-entrant honeycomb. Figure 2-8 shows what would be an idealized re-entrant cell.
In 1987, Lakes first transformed polyester foam into re-entrant negative Poisson’s ratio foam [48]. The foam that Lakes transformed initially had a Poisson’s ratio of 0.4, a Young’s modulus of 71 kPa, a density of 0.03 g cm$^{-3}$, and a cell size of 1.2 mm. After heating the foam above the softening temperature while tri-axially compressed and then allowing the foam to cool in the mold, the Poisson’s ratio was -0.7. This method has been used to compress a number of different types of polymer foams.
Figure 2-9: Scanning Electron Micrographs of Uncompressed (top) and Compressed (bottom) foams [50]

Figure 2-9 shows SEM images of foams as received and after the completion of the compression process as performed by Loureiro and Lakes in 1997. In addition to polymer foams, metal foams have also been manufactured with a negative Poisson’s ratio. The transformation of metallic foams is done by successive applications of small increments of plastic deformation in three orthogonal directions in a vice [49].
Chapter 3

Finite Element Study of L4-L5 Motion Segment

3.1 Materials and Methods

This portion of the study was a finite element analysis (FEA) of the L4-L5 motion segment within Abaqus CAE.

3.1.1 Model

The model used was a L4-L5 motion segment consisting of the L4 vertebra, L5 vertebra, the L4-L5 intervertebral disc, and the surrounding ligaments. The model was obtained from the lab of Dr. V. K. Goel. The L4-L5 model adapted from a previously validated L3-S1 model used in published studies [52, 53, 54, 55, 56]. The original model was created from 1.5 mm thick transverse slices from computed tomography scans of a healthy cadaver spine [57]. The final mesh of the finite element model can be seen in Figure 3-1.
3.1.2 Motions

The model was run under several different scenarios in order to create all of the possible motions of the intact spine in the human body. These motions include; pure compression, flexion, extension, right lateral bending, left lateral bending, right axial rotation, and left axial rotation.

3.1.3 Loads

The pure compression model was a load of 600 N applied in the downward axial direction. All other loads consisted of the same pure compression load of 600 N applied in the downward axial direction followed by a 7.5 Nm moment applied in the appropriate direction to obtain the desired motion.

3.1.4 Intervertebral Disc Properties

Table 3.1 outlines the Young’s Moduli and Poisson’s ratios for all of the possible Poisson’s ratios that were used in this study.
Table 3.1: Young’s Moduli and Poisson’s Ratios used in Study

<table>
<thead>
<tr>
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<th>Young’s Modulus (MPa)</th>
<th>Poisson’s Ratio</th>
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</thead>
<tbody>
<tr>
<td>Original</td>
<td></td>
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</tr>
<tr>
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<tr>
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<td>0.4999</td>
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<td>Nucleus Pulposus</td>
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<td>0.3</td>
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<tr>
<td>Annulus Fibrosus</td>
<td>4.2</td>
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<tr>
<td>Nucleus Pulposus</td>
<td>4.2</td>
<td>0.3</td>
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<td>-0.3</td>
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<tr>
<td>Annulus Fibrosus</td>
<td>4.2</td>
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<td>Nucleus Pulposus</td>
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<td>Annulus Fibrosus</td>
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<td>Nucleus Pulposus</td>
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3.2 Results and Discussion

After the finite element models were run; the range of motion, the stress on the intervertebral disc, and the displacement between nodes on the intervertebral disc were investigated in order to determine if there would be a benefit to using an artificial intervertebral disc when compared with the native intervertebral disc or with a positive Poisson’s ratio artificial intervertebral disc.

3.2.1 Visual Comparison of Deformed and Undeformed Models

The deformed and undeformed shapes of the L4-L5 motion segment can be seen in Figures 3-2 through 3-22. Figure 3-2 shows the model with the original properties for the intervertebral disc run in compression. The model depicts bulging of the intervertebral disc with the original properties of the model. Figure 3-3 is of the model run in compression with a Poisson’s ratio of -0.3. Comparing the deformed shape of this model to the deformed shape of the original model shows that the intervertebral disc does not
bulge with a negative Poisson’s ratio. Figure 3-4 shows the model run in compression with a Poisson’s ratio of -0.999. This deformed model shows little compression of the intervertebral disc due to the increased impact resistance associated with negative Poisson’s ratio materials.

Figure 3-2: Compression with the Original Model Properties
Figure 3-3: Compression with a Poisson’s ratio of -0.3

Figure 3-4: Compression with a Poisson’s ratio of -0.999
Figure 3-5 shows the model with the original properties for the intervertebral disc run in extension. The model depicts bulging of the intervertebral disc with the original properties of the model. Figure 3-6 is of the model run in extension with a Poisson’s ratio of -0.3. Comparing the deformed shape of this model to the deformed shape of the original model shows that the intervertebral disc does not bulge with a negative Poisson’s ratio. Figure 3-7 shows the model run in extension with a Poisson’s ratio of -0.999. This deformed model shows little change in the intervertebral disc due to the increased impact resistance associated with negative Poisson’s ratio materials.
Figure 3-6: Extension with a Poisson's ratio of -0.3

Figure 3-7: Extension with a Poisson’s ratio of -0.999
Figure 3-8 shows the model with the original properties for the intervertebral disc run in flexion. The model depicts bulging of the intervertebral disc with the original properties of the model. Figure 3-9 is of the model run in flexion with a Poisson’s ratio of -0.3. Comparing the deformed shape of this model to the deformed shape of the original model shows that the intervertebral disc does not bulge with a negative Poisson’s ratio. Figure 3-10 shows the model run in flexion with a Poisson’s ratio of -0.999. This deformed model shows little change in the intervertebral disc due to the increased impact resistance associated with negative Poisson’s ratio materials.

Figure 3-8: Flexion with the Original Model Properties
Figure 3-9: Flexion with a Poisson’s ratio of -0.3

Figure 3-10: Flexion with a Poisson’s ratio of -0.999
Figure 3-11 shows the model with the original properties for the intervertebral disc run in left lateral bending. The model depicts bulging of the intervertebral disc with the original properties of the model. Figure 3-12 is of the model run in left lateral bending with a Poisson’s ratio of -0.3. Comparing the deformed shape of this model to the deformed shape of the original model shows that the intervertebral disc does not bulge with a negative Poisson’s ratio. Figure 3-13 shows the model run in left lateral bending with a Poisson’s ratio of -0.999. This deformed model shows little change in the intervertebral disc due to the increased impact resistance associated with negative Poisson’s ratio materials.
Figure 3-12: Left Lateral Bending with a Poisson’s ratio of -0.3

Figure 3-13: Left Lateral Bending with a Poisson’s ratio of -0.999
Figure 3-14 shows the model with the original properties for the intervertebral disc run in right lateral bending. The model depicts bulging of the intervertebral disc with the original properties of the model. Figure 3-15 is of the model run in right lateral bending with a Poisson’s ratio of -0.3. Comparing the deformed shape of this model to the deformed shape of the original model shows that the intervertebral disc does not bulge with a negative Poisson’s ratio. Figure 3-16 shows the model run in right lateral bending with a Poisson’s ratio of -0.999. This deformed model shows little change in the intervertebral disc due to the increased impact resistance associated with negative Poisson’s ratio materials.
Figure 3-15: Right Lateral Bending with a Poisson’s ratio of -0.3

Figure 3-16: Right Lateral Bending with a Poisson’s ratio of -0.999
Figure 3-17 shows the model with the original properties for the intervertebral disc run in left axial rotation. The model depicts bulging of the intervertebral disc with the original properties of the model. Figure 3-18 is of the model run in left axial rotation with a Poisson’s ratio of -0.3. Comparing the deformed shape of this model to the deformed shape of the original model shows that the intervertebral disc does not bulge with a negative Poisson’s ratio. Figure 3-19 shows the model run in left axial rotation with a Poisson’s ratio of -0.999. This deformed model shows little change in the intervertebral disc due to the increased impact resistance associated with negative Poisson’s ratio materials.

Figure 3-17: Left Axial Rotation with the Original Model Properties
Figure 3-18: Left Axial Rotation with a Poisson’s ratio of -0.3

Figure 3-19: Left Axial Rotation with a Poisson’s ratio of -0.999
Figure 3-20 shows the model with the original properties for the intervertebral disc run in right axial rotation. The model depicts bulging of the intervertebral disc with the original properties of the model. Figure 3-21 is of the model run in right axial rotation with a Poisson’s ratio of -0.3. Comparing the deformed shape of this model to the deformed shape of the original model shows that the intervertebral disc does not bulge with a negative Poisson’s ratio. Figure 3-22 shows the model run in right axial rotation with a Poisson’s ratio of -0.999. This deformed model shows little change in the intervertebral disc due to the increased impact resistance associated with negative Poisson’s ratio materials.

Figure 3-20: Right Axial Rotation with the Original Model Properties
Figure 3-21: Right Axial Rotation with a Poisson’s ratio of -0.3

Figure 3-22: Right Axial Rotation with a Poisson’s ratio of -0.999
3.2.2 Range of Motion

The range of motion graphs for all six directions of motion can are shown in Figures 3-23, 3-24, 3-25, 3-26, 3-27, and 3-28. In general, the model with a Poisson’s ratio of 0.3 has a similar range of motion in flexion, extension, left and right lateral bending, and left and right axial rotation as the original model. There is no more than a 1.5 degree increase in range of motion over all six motions depicted. The range of motion was most similar for the left and right axial rotation when compared with the original model. The range of motion for the -0.3 model showed the most increase in flexion and extension. When comparing the intervertebral disc modeled with a Poisson’s ratio of -0.999 with the model with the original properties, it is evident that there is very little motion for all six movements that are depicted.

![Flexion Graph](image)

Figure 3-23: Range of Motion in Flexion for Various Poisson's Ratios
Figure 3-24: Range of Motion in Flexion for Various Poisson's Ratios

Figure 3-25: Range of Motion in Left Lateral Bending for Various Poisson's Ratios
Figure 3-26: Range of Motion in Right Lateral Bending for Various Poisson's Ratios

Figure 3-27: Range of Motion in Left Axial Rotation for Various Poisson's Ratios
3.2.3 Intervertebral Disc Stress

Figures 3-29 through 3-35 depict the von Mises stresses on the intervertebral disc during the seven different motions; compression, flexion, extension, left and right lateral bending, and left and right axial rotation. In general, the intervertebral discs show localized increases in stress when compared with the disc from the original model. The disc from the model with a Poisson’s ratio of -0.999 also show increases in stress when compared with the original model.
Figure 3-29: Stress on the Intervertebral Disc in Compression
Figure 3-30: Stress on the Intervertebral Disc in Flexion

Figure 3-31: Stress on the Intervertebral Disc in Extension
Figure 3-32: Stress on the Intervertebral Disc in Left Lateral Bending
Figure 3-33: Stress on the Intervertebral Disc in Right Lateral Bending

Figure 3-34: Stress on the Intervertebral Disc in Left Axial Rotation
3.2.4 Displacement of Intervertebral Disc

Nodes were selected on the major and minor diameter of the intervertebral disc. The distance between these nodes both in the undeformed and deformed state of the model were calculated by Abaqus CAE, once the values were obtained with Abaqus, the change in distance between the nodes were calculated. The change in distance for the original model and the models with Poisson’s ratios of 0.4999 and 0.3 showed increases. The change in distance for the models with Poisson’s ratios of -0.3 and -0.999 showed decreases. These are the values that would be expected based on the properties of materials with negative Poisson’s ratio. Again with the change in distance between nodes
for the model with a Poisson’s ratio of -0.999 showing a very small decrease lends itself to further supporting the idea that if a Poisson’s ratio goes too negative it will not lead to the desired effect. The change in distance results are graphically depicted in Figures 3-36 through 3-42.

Figure 3-36: Displacement Compression
Figure 3-37: Displacement Flexion

Figure 3-38: Displacement Extension
Figure 3-39: Displacement Left Lateral Bending

Figure 3-40: Displacement Right Lateral Bending
Figure 3-41: Displacement Left Axial Rotation

Figure 3-42: Displacement Right Axial Rotation
3.3 Conclusions

The finite element analysis yielded results that supported the belief that using an intervertebral disc with a negative Poisson’s ratio would be beneficial. The theory is that the decrease in transverse motion would prevent the impingement of nerves by the intervertebral disc. The range of motion and the stress on the intervertebral disc had similar values when comparing the original model with the model with a Poisson’s ratio of -0.3. The change in distance between nodes in the diameters of the disc showed a decrease which supports the hypothesis. On the other hand, when investigating the intervertebral disc with a Poisson’s ratio of -0.999 showed an increase in stress, a decrease in range of motion, and not a significant decrease in change in distance on the intervertebral disc. These three factors lead toward the conclusion that at a certain point in the negative range of isotropic Poisson’s values, the benefits of a negative Poisson’s ratio would begin to be outweighed by the increase in stress and decrease in range of motion.
Chapter 4

Compression of Polyurethane Foam

4.1 Materials and Methods

4.1.1 Cutting of Foam

High density polyurethane foam was obtained from the local fabric store. The foam slab was initially 5 inches in thickness. Foam was cut using a cylindrical can with a 5 inch diameter with a sharpened edge. The sharpened edge was placed on top of the thickness of the foam and using constant pressure and a twisting motion, the can cut through the thickness of the foam to yield a cylinder five inches in height and 5 inches in diameter. Figure 4-1 shows the process of cutting the uncompressed polyurethane foam.

Figure 4-1: Process of Cutting Foam
4.1.2 Compression Chamber

A stainless steel compression chamber was designed and built by the Mechanical, Industrial, and Manufacturing Engineering (MIME) Machine Shop at the University of Toledo. The compression chamber consists of one 3 inch diameter stainless steel tube one foot in length, two 3 inch diameter stainless steel end caps, and a stainless steel piston that is used to mechanically compress the foam in the vertical direction within the tube. Figure 4-2 shows the compression chamber that was designed by the MIME machine shop.

Figure 4-2: Compression Chamber
4.1.3 Compression Process

In order to obtain foam with a re-entrant structure, high density polyurethane was cut to a 5” height with a 5” diameter and placed inside a compression chamber built by the MIME machine shop. Low density polyurethane had previously been compressed by Loureiro and Lakes [33]. The inner diameter of the compression tube was 2.8” and the foam was then compressed to a height of 3.5” by using the interior piston. Once the foam had been mechanically compressed, it was placed in a 177°C furnace for 60 minutes in order to obtain permanent compression. Once the 60 minute time frame had passed, the compression tube was removed from the furnace, the foam was allowed to completely cool inside the tube in order to prevent an incomplete compression. Figure 4-3 shows the compression chamber, the original cylinder of uncompressed foam, and a sample of the complete compressed foam cylinder after it was cooled and removed from the compression chamber.

Figure 4-3: Compression chamber (right), Uncompressed foam (left), and Compressed foam (center)
4.1.4 Characterization of Foam

4.1.4.1 Scanning Electron Microscopy Analysis

Both the original uncompressed foam and the compressed foam were characterized by scanning electron microscopy (SEM) using a Hitachi S-4800 UHR SEM. An accelerating voltage of 3 kV was used to capture the images. Prior to analysis all the samples were sputter coated with gold using a Cressington 108 auto coater (Ted Pella Inc., Redding, CA).

4.1.4.2 MicroCT

MicroCT images of the microstructure of the foam were obtained using an uCT 35, made by Scanco Medical AG in Switzerland. All software which we use is supplied by the same company. Foam samples were 8x8x16 mm prisms scanned at 6 micrometer resolution and using isometric voxel. The scan length was 3 mm (500 slices), the number of samples was 4096, the number of projections was 1023, and sample time (integration) was 500 ms. X-ray tube energy was 70 kV and intensity was 114 micro A. Obtained images were viewed in Solidworks in order to determine continuity of the foam microstructure before three dimensional printing was completed.

4.1.4.3 Three Dimensional Printing

MicroCT images were converted to files for use with a three dimensional printer or rapid prototype machine, the stratasys FDM3000. 1x1x1 millimeter samples were scaled up to 1x1x1 inch samples and both the compressed and uncompressed foam microstructures were printed.
4.2 Results and Discussion

4.2.1 Foam Compression

The original dimensions of the uncompressed foam cylinders were a height of 5 inches and a radius of 5 inches. The density of the uncompressed foam was 0.25 g/cm$^3$. The compressed samples had a height of 3.78 inches and a radius of 1.47 inches. The density of the compressed foam was 0.09 g/cm$^3$. The compressed foam samples showed transverse expansion when longitudinally expanded, indicative of a negative Poisson’s ratio. The original uncompressed foam when longitudinally expanded, contracts in the transverse direction. This change from transverse contraction to transverse expansion is a result of the re-entrant cell structure that can be seen in SEM images and in the three dimensional models. Figure 4-4 shows the transverse expansion of a compressed foam sample when pulled in the longitudinal direction.

Figure 4-4: Unexpanded compressed foam (left) and Expanded compressed foam (right)
4.2.2 Scanning Electron Microscopy

Images of the compressed foam samples show the microstructure of the foam has a re-entrant cell structure when compared with the images of the uncompressed foam samples.

Figure 4-5: SEM images of Uncompressed Polyurethane Foam

Figure 4-5 shows two different samples of the uncompressed polyurethane foam that were taken with a scanning electron microscope. The samples show the initial open cell structure of the foam. The struts that make up the cells are relatively straight with minimal bending. Figure 4-6 shows three different samples of the compressed polyurethane foam that were taken with the same scanning electron microscope. These samples show bends in the struts that resulted from the tri-axial compression of the foam followed by the heating and cooling process within the compression chamber. It is these bends in the struts that create the re-entrant cell structure of the compressed foam and allow the compressed foam to exhibit a negative Poisson’s ratio.
Figure 4-6: SEM images of Compressed Polyurethane Foam Samples

4.2.3 MicroCT

Foam samples were also examined through the use of MicroCT. Figure 4-7 shows the uncompressed foam structure. This scan shows the open cell structure of the uncompressed foam.
Figure 4-7: MicroCT Scan of Uncompressed Foam

Figure 4-8 shows the MicroCT of the compressed foam microstructure. This scan shows the bent struts and the re-entrant cell structure that is exhibited by the compressed foam. When compared to the uncompressed foam the increased density of the cell structure in the area can be seen.
4.2.4 Three Dimensional Printing

The three dimensionally printed versions of the microstructure of the foam also show that the compressed foam samples have a re-entrant cell structure when compared with the uncompressed foam samples. These three dimensional samples show that it is possible to print the microstructure on a large scale and in a fragile incompressible polymer. The three dimensionally printed version of the uncompressed microstructure can be seen in Figure 4-9. The uncompressed sample is comprised of one cell from the original foam.
The three dimensionally printed microstructure of the compressed foam can be seen in Figure 4-10. The compressed sample is made of several cells with bent struts exhibiting the re-entrant cell structure of the negative Poisson’s ratio foam.

Figure 4-9: 3D Printing of the Uncompressed Foam Microstructure

Figure 4-10: 3D Printing of the Compressed Foam Microstructure
4.3 Conclusions

The compressed foam visually exhibits a negative Poisson’s ratio. This negative Poisson’s ratio allows for the material to compress in the transverse direction when longitudinally compressed, which would be ideal for an artificial intervertebral disc, because this property would prevent the artificial disc from impinging on the surrounding nerves in the spinal column. The negative Poisson’s ratio that the foam exhibits can be attributed to the re-entrant cell structure that was created using a heating method in conjunction with tri-axial compression of the original foam samples. This re-entrant structure has been detailed in both the SEM images taken of the compressed and uncompressed foam samples as well as in the three dimensional printings that were created using the rapid prototyping machine.
Chapter 5

Concluding Remarks

The objectives that were set forth with this study were met by completing a finite element study on the effects of Poisson’s ratio of the intervertebral disc on the range of motion, stress, and change in distance between nodes on the intervertebral disc was completed. In addition, compression of polyurethane foam.

The first portion of this study concentrated on a finite element study of the Poisson’s ratio of the intervertebral disc. This study concluded that there would be benefits to using an artificial disc with a negative Poisson’s ratio. Further finite element studies will need to be performed when a complete artificial disc with a negative Poisson’s ratio is designed, replacing the native disc with the artificial disc within the model. In order to have a completed artificial disc it will again be essential to obtain a three dimensionally printed sample that is not rigid and also for movements similar to the native intervertebral disc. Once a disc is printed, the Poisson’s ratio of that disc will need to be calculated in order to determine if the microstructure determines the functioning of the samples. The artificial three dimensionally negative Poisson’s ratio disc will also need to have a fixation method to secure the intervertebral disc between the vertebrae. Once an implant has been manufactured, in vitro testing can be completed to determine how the implant responds to different circumstances.
The uncompressed and compressed foam samples were characterized through several methods such as; scanning electron microscopy, microCT, and three dimensional printing. The microstructure of the compressed foam samples visually exhibited a re-entrant cell structure which lends itself to a negative Poisson’s ratio material. In addition to the microstructure showing a re-entrant cell structure, the foam could be manually stretched in the longitudinal direction and would show expansion in the transverse direction. Additional testing of these compressed foam samples needs to be performed to determine the precise Poisson’s ratio of the samples. Further three dimensional printing of the microstructure should be completed in order to obtain samples that have been printed in a less rigid material. This will involve further investigation to find a suitable material and a rapid prototyping machine that can print the detailed microstructure to scale.
References


33. **Stiegman, G. A. III.,** Chapter 3: Nucleus Arthroplasty Technology from the U.S. regulatory viewpoint.


