A FEM Analysis for Acetabular Component with Negative Poisson's Ratio in Total Hip Arthroplasty

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1. INTRODUCTION

Poisson's ratio v, which is one of four material constants in isotropic material, depicts a dimensional change in lateral direction to longitudinal direction when a force is applied in longitudinal direction. Most materials become narrower in cross-section when they are stretched ; they have positive Poisson's ratio. It is typically about 1/3 for steel and aluminum, just under 1/2 for rubber, and about 0 for cork. It is possible to have materials that become fatter when stretched because the positive strain energy theory of isotropic elasticity allows Poisson's ratios in the range from-1 to 1/2[1)]. But isotropic material with negative Poisson's ratio has not been reported. Several anisotropic materials are known to have negative Poisson's ratio. These in clude honeycombs with inverted hexagonal cells[2)], a few natural single crystals[3)], some composite laminates[4)], microporous polytetratluorocthylenc−PTFE)[5)], and microporous ultra-high molecular weight polyethylene[6)].

Recently, isotropic polymer[7)] and metallic[8)] foams with negative Poisson's ratio were developed by a transformation from conventional foam with positive Poisson's ratio. This was done by a cell shape change from convex polyhedron to concave(which bulge inward) one. In addition to the negative Poisson's ratio, this new material showed enhancements in several material properties comparted to positive Poisson's-ratio material-impact absorption, damage resistance, damage tolerance, plane strain fracture toughness, resilience, shearing modulus, and indentation resistance[7,8)].

Meanwhile, current trends[9)] in acetabular components of total hip arthroplasty includes UHMWPE cup with a cementless metal backing. In order to increase the initial stability for bone ingrowth, the metal backing is press-fitted into the under-reamed acetabulum or is fixed by screws. Several factors which affect the aseptic loosening of the acetabular component were investigated. Bartel et. al. studied the effect of the thickness of the polyethylene layer[10)]. They suggested that the minimum thickness of the polyethylene layer of eight millimeters should be maintained whenever possible to reduce stresses that lead

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to surface damage. They also found that the stresses were lower in the acetabular component of the twenty-eight-millimeter hip replacement than in the twenty-two-millimeter replacement. Large femoral head were associated with the high rate of acctabular revision in the sense of insufficient thickness of the polyethylene component and great volumetric wear[11]. Murray et al.[12] investigated the influence of the physical surface properties of implants, in particular surface energy and roughness, on bone resorption. It was found that rough hydrophilic surfaces stimulated the most bone resorption via large volumetric wear.

It is only the reaction of tissue to the wear debris that constitutes a significant question in acetabulum components. None of the true wear rates was large enough to cause difficulty with mechanical function during any normal life. The uneven deformation, however, due to the non-uniform contact stress or non-uniform wear can progressively increase the wear rate. Thus, in this study, it is investigated how the above enhanced material properties of negative Poisson's-ratio material affect the stress distribution in the acetabular regions when using a UHMWPE cup with negative Poisson's ratio instead of the conventional UHMWPE cup with positive Poisson's ratio.

2. METHOD

In this study, a thin two-dimensional slice in a plane extending in a superior-inferior direction through the center of the acetabulum is taken for the analysis. The model section is separated into five discrete bony regions in order to account for the distribution of bony density. Material properties are assigned with the simplifying assumption of material isotropy within each region(Fig. 1). A summary of these regional bone characteristics is provided in Table 1. The inner diameter and the thickness of the UHMWPE cup are 28mm and 10mm, respectively. The thickness of metal backing is 2mm. Thus, this model contains the acetabulum with 52mm diameter, which is mostly used in a surgical operation.

For the metal-backed cup, we assumed a cobalt-chramium alloy clastic modulus of 200 GPa and a Poisson's ratio of 0.3. In order to verify the negative Poisson's-ratio effect of UHMWPE, Poisson's ratio of UHMWPE was changed from 0.3 to −0.9. The analyses are conducted using a plane strain assumption with a total hip resultant force of 2500N. directed supero-medially at an angle of 15° from the vertical(Fig. 1). Each contact surface of UHMWPE, metal, and the subchondral bone is assumed to be perfectly bonded to each other. The model has fixed boundary conditions at the superior and inferior ends.

HyperMesh pre-processor and NASTRAN solver were used in this analysis. Fournodded, isoparametric quadrilateral element was used throughout the model. And triangular element is utilized geometrically to connect the quadrilateral elements of each side. Piner meshes are used in acetabular components to reveal the stress distribution around the acetabular and adjacent bony regions. The total number of el-

Table 1. Distribution of Material Properties

Region	Volume Fraction	Apparent Density (g /cm^3)	Yield Strength (MPa)	Young's Modulus (MPa)	Poisson's Ratio
Bone-1	0.126	0.252	2.86	40	0.18
Bone-2	0.676	1.352	82.20	6188	0.326
Bone-3	0.260	0.520	12.17	352	0.22
Bone-4	0.373	0.743	24.82	1025	0.247
Bone-5	0.676	1.352	82.20	6188	0.326
UHMWPE			22	500	0.3

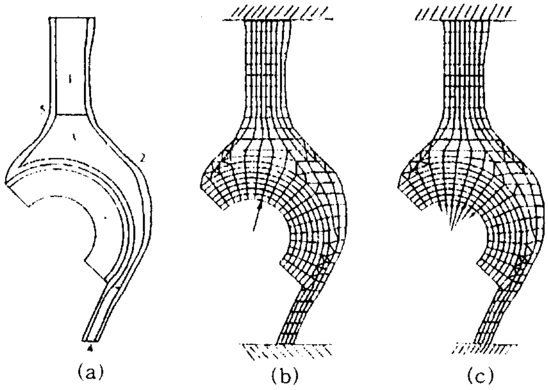

Fig. 1. Material property regions of the model and loading conditions : (a) material property regions, (b) concentrated load, (c) distributed load

ement is 313 and the total number of nodel point is 342. These numbers are enough to verify the convergence of the solution based on the other studies[13].

3. RESULTS

Fig. 2 and 3 shows the variation of the maximum von Mises' stresses transmitted from metal backing to subchondral bone when Poisson's ratio decrcases from 0.3 to −0.9 by 0.1, in case of concentrated and distributed load cases, respectively. This means that negative Poisson's ratio UHMWPE would dissipate more stress and transfer less stresses to the subchondral or peripheral iliace bone, compared to the conventional UHMWPE with Poisson's ratio of 0.3 This effect is best for Poisson's ratio of −0.7 at concentrated load and for Poisson's ratio of −0.5 at distributed load. Poisson's ratio of −0.9 transfers the lowest von-Mises' stress to the medial part of subchondral bone in both loading conditions.

Table 2 shows the percent decrease of maximum stresses occurred in each component of the aseptic region as a result of suing UHMWPE cup with Poisson's ratio of −0.5, compared to normal cup. Numbers indicate the percent decrease for the distributed and concentrated loads. Negative Poisson's-ratio cup reduces the principal stresses and von Mises' stress up to 27% in UHMWPE cup itself as well as metal backing, and subchondral bone. This reduction in periacetabular mechanical stresses would significantly reduce the rate of fatigue failure and consequently reduce the incidence of aseptic loosening of the cup due to wear or bone resorption. The application of the UHMWPE cup with negative Poisson's ratio also results in decreased tensile stresses at the inferior interface between the UHMWPE cup and metal backing. The reduced tensile stresses in this region are likely to decrease a possibility of punchout failures of acetabular components.

Table 2. Percent decrease of maximum stresses occurred in each component when using UHMWPE cup with Poisson's ratio of −0.5 instead of normal cup : numbers : distributed load/ concentrated load

Stress type	Subchondral Bone	Metal Backing	UHMWPE
Max. Tensile Stress	16/17	16/17	27/27
Max. Compressive Stress	15/18	15/18	15/0
Max. von-Mises' Stress	16/17	16/17	24/0

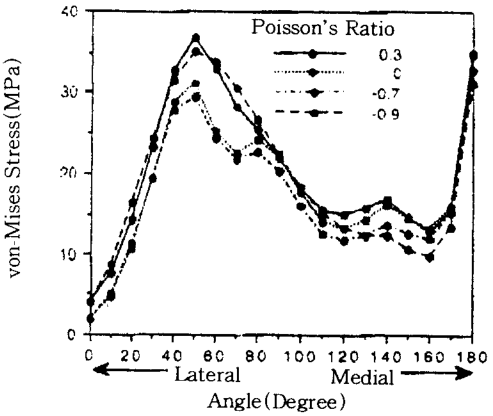

Fig. 2. von-Mises Stress transfer from metal backing to subchondral bone in case of the concentrated loading condition

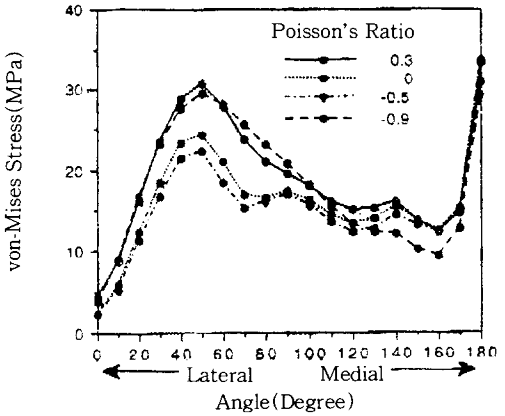

Fig. 3. von-Mises Stress transfer from metal backing to subchondral bone in case of the distributed loading condition

4. DISCUSSION

The stress distributions obtained in the two-dimensional model with positive Poisson's-ratio UHMWPE cup are qualitatively consistent with other numerical[13] and experimental[14] studies. Compressive stresses were created on the lateral wall and tensile stresses were created on the medial wall. In our two-dimensional model, a similar mechanical effect is obtained by the rigidly fixed boundary conditions in the ischium and pubis.

As shown in the major and minor principal stress distributions of the conventional cup with positive Poisson's ratio, resistance to the contact load is supplied partly by direct compression of the polyethylene and partly by tensile at the periphery of the contact area. Negative Poisson's-ratio cup reduces the principal stresses and von Mises' stress up to nearly 30% in polyethylene cup itself, metal backing, and subchondral bone. In theory, this reduction in periacetabular mechanical stresses would lower the rate of fatigue failure and subsequently lead to a decreased incidence of aseptic loosening of the cup.

The stress patterns for the two different modes are difficult to interpret since the failure characteristics of each bone region and each engineering material are vastly different. To rigorously examine the level of stress with regard to the yield stress of each material, one must invoke some kind of failure theory. To allow a preliminary look at the levels of stress relative to yield stress in each material, we have calculated the von Mises' yield stress at each node. The negative Poisson's-ratio cup causes a reduction of von Mises' stress in all the acetabular components and bony regions. This ignores the more complicated failure mechanism of materials such as brittle, elastic-plastic, and nonlinear elastic materials and then must be used carefully. For example, the von Mises' criteria does not account for the greater strength of dense bone in compression than in tension. However, they do provide a relative easy method for the initial review of results from parametric studies.

The stress state in the polyethylene component is not large enough to fracture the component or to cause mechanical difficulty during any normal life time. It is only the polyethylene wear debris that causes the bone resorption and the following loosening at the component-bone interface as a result of the macrophagic inflammatory response to the particle. The hip-joint motion is essentially unidirectional and reciprocal, comparable to uniform gait. While the hip flexes during normal gait, the center of the contact area may move by as much as 15 degrees from its mean position with respect to the acetablum. Points on the surface of the polyethylene component are subjected to cyclic stresses. Thus, cyclic fatigue mechanism gives rise to a large percentage of the total wear in the polyethylene cup through pitting and delamination. The polymer eventually becomes highly oriented and the wear rate may sensitive to occasional changes in direction. However, there is another advantage with negative Poisson's-ratio material in that the stress concentration effect in the vicinity of the unevenly deformed area is diminished due to negative Poisson's ratio. This effect can lessen the wear rate of the polyethylene component and resulting bone resorption.

Because of the viscoelastic properties of the polyethylene, the sliding velocity of the femoral head on the polyethylene cup affects the friction force to a certain extent. In case the contact surface between two bodies moves with motion as hip joint, this effect is more pronounced. Low sliding velocity causes relatively high fictional force by an increase of the contact area with time due to the viscoelastic behaviors of the polyethylene. However, high sliding velocity under a certain contact stress leads to an increase in temperature at the contact surface because polymers usually have low thermal conductivity compared to metallic materials. The increase in temperature at the contact surface can increase the contact area and activate adhesive wear mechanism between two bodies. The effect by high sliding velocity will be more severe in wear than that by low sliding velocity. The contact surface between the polythylene cup and the metal femoral head is lubricated by body fluids in vivo. Most polymers including the polyethylene are swollen by lubrications, even if it differs from material to material ; such swelling deteriorates its mechanical properties and can lead to an increase in wear. This is explained by the fact that lubricants diffuse into the polymer and reduce the surface-film strength, and this, in turn, leads to an increase in wear in the contact area. No research has been doing for these phenomena even though the surface weakening problems by high sliding velocity and lubricant diffusion would be main causes of wear problem in hip prostheses. Later work investigating these effects would be helpful to fully understand the wear mechanism of the polyethylene component in hip prostheses.

In cups worn for a short time, for example on year, the high wear area is smaller than theoretically predicted one due to surface irregularities. After surface irregularities, which prevent complete surface contact, are removed, there appears a sharp ridge between the high and low wear areas. This means that the UHMWPE cup meets with a concentrated load over a small contact area. Furthermore, the addition of a metal backing may create a more concentrated distribution of contact stresses at the cup surface. Because of the high loads over a small region during weight-bearing, permanent deformation adds significantly to the loss of thickness from apparent wear in the area. On the other hand, negative Poisson's-ratio material resist shape changes(large G value) but easily undergo volume change(small K value) ; the opposite is true in case of postive Poisson's ratio. For example, two roller balls in pressure contact deform in a way of not obviating from the original sphere when $v=-1$; they preserve their shape during contact. This suggests that the lowest possible Poisson's ratio is desirable in such a loading condition because the stress is more evenly distributed inside the material with negative Poisson's ratio.

The honeycombs and foams manufactured so far need to be highly porous to achieve negative Poisson's ratios. They are therefore substantially less stiff than the solids from which they are made. Negative Poisson's-ratio materials should have stiffness as high as the compact solids in order to be used in any structural application. As a closing remark of the present study, an isotropic compact solid with high stiffness and negative Poisson's ratio may be envisaged by the following considerations. At first, make hollow microspheres that are smaller than tens of micrometer in size. And then, applying a proper pressure and temperature to the hollow microspheres, they can be crushed into a concave shape. This concave polyhedron resembles the three-dimensional re-entrant unit cell which was proved to give negative Poisson's ratio effect[15]. The packed material with the three-dimensional re-entrant unit cells also showed negative Poisson's ratio isotropically. Therefore, the concave polyhedrons are lumped together into a compact solid by solidification procedures such as compaction or sintering. This treatment excludes the extrusion or expansion procedures which result in anisotropic materials. Thus, we can obtain an isotropic microporous material with negative Poisson's ratio and high stiffness. In the mean time, we plan to synthesize this material following the above procedures. In case of metallic material, we can imagine an isotropic material with high stiffness and negative Poisson's ratio by controlling material's grain boundary.

This new material can be applied to other areas in human body which require the capabilities of even stress distribution or impact absorption such as total knee replacement, knee pad, and intervetebral disc. According to Bartel et. al.[16], the center of the contact area in knee postheses moves farther from its mean position than in hip prostheses during normal gait and contact stresses are greater for non-conforming surfaces such as knee prostheses than for conforming surfaces such as hip prostheses. Consequently, the combination of the higher stress and the moving contact area is more likely to cause surface damage due to fatigue in tibial components than in acetabular components. Thus, the effect of negative Poisson's-ratio polyethylenc component will be more noticeable in knee prostheses than in hip prostheses.

5. CONCLUSIONS

Based on the present FEM study for negative Poisson's-ratio UHMWPE, the following conclusions seem expected.

1) Negative Poisson's-ratio UHMWPE transfers less stresses to the subchondral or peripheral iliac bone, compared to the conventional UHMWPE with Poisson's ratio.

2) Negative Poisson's-ratio cup reduces stresses in UHMWPE cup itself as well as metal backing, and subchondral bone.

3) The reduction in periacetabular mechanical stresses would significantly reduce the rate of fatigue failure and consequently reduce the incidence of aseptic loosening of the cup due to wear or bone resorption.

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