In Vitro Assessment of Allowable Bone Loss for Implantation of a Zweymuller Stem for Total Hip Arthroplasty Revision Surgery

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Abstract:
Total hip arthroplasty patients typically experience some degree of stress shielding and subsequent bone remodeling during the life of the primary femoral stem. If a patient experiences pain, subsidence of the stem, or stem loosening, a revision surgery is necessary. The purpose of this experiment is to determine, by finite-element modeling and in-vitro testing, what amount of bone loss in the proximal femur is permissible for a Zweymuller stem to be achieve stability..

Introduction:
Normally, in revision surgery due to proximal bone loss, a cemented stem is used, as the cement helps to reduce stress in the proximal femur to prevent femoral fracture. However, uncemented Zweymuller stems have been shown to be more effective in reducing stress shielding [1] and therefore have been more effective at maintaining bone stock [2]. This is due to the fact that they can transfer more force through the proximal end of the femur, as opposed to the cemented stem, which tends to disperse the stress along the femur and therefore reduce the stress at the proximal end, leading to bone loss. Poor bone stock has been shown to exacerbate conditions such as loosening and subsidence when an uncemented primary stem is used in a revision surgery [3]. Salymer et. al reported that bone formation occurred in certain patients that used uncemented stems in revision surgery, provided that the initial bone loss was not too great [4]. Peters et. al suggested that a primary cemented stem provides a poor environment for a revision uncemented stem due to the bone loss incurred with the cemented stem [5].

Methods:
The Zweymuller stem will be implanted into a cadaveric femur and tested under cyclic loading and the micromotion will be recorded. The micromotion measurements help to predict the life of the implant. The femur would first be tested with full bone stock, and then the bone would be removed in approximately 1 cm horizontal layers and retested to simulate proximal bone loss, as shown in Figure 1.

This setup will also be produced in finite-element modeling software to validate results obtained by the in-vitro tests.

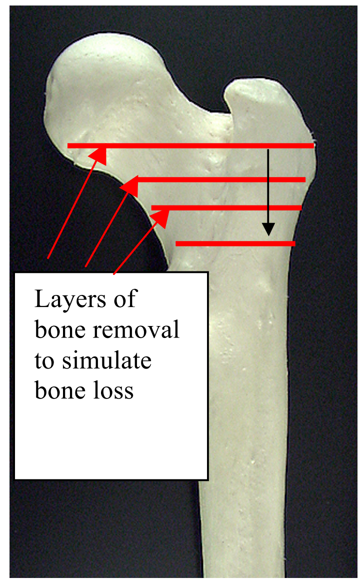

Figure 1: Simulation of Bone Loss.

A simplified 2D model of the femoral stem was created to get a rough estimate of the amount that the stresses would increase following bone loss. It is shown in Figure 2.

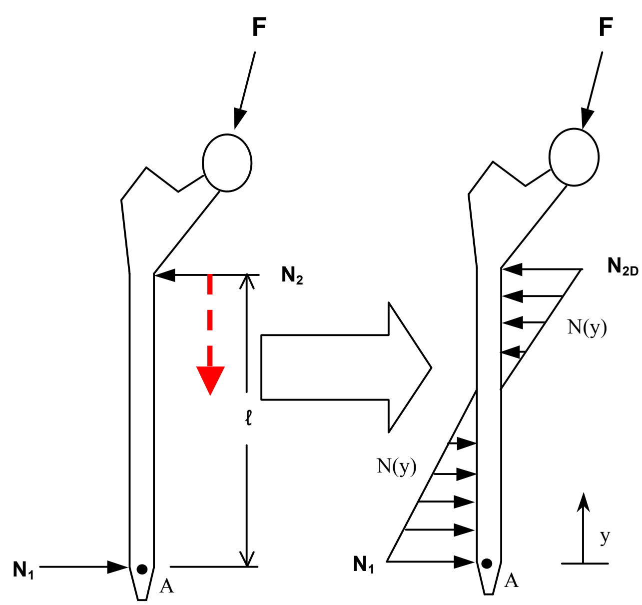

Figure 2: Simplified 2D Model of Femoral Stem

The analysis used to determine the maximum distributed force at the bottom (N_{1D}) and the top (N_{2D}) of the stem is shown below. The forces and the moments about point A for both figures are set to be equal to each other.

$$F_{x,\text{point}} = F_{x,\text{distribued}}$$

$$N_1 - N_2 = \int_0^{\ell} N(y)dy$$

$$M_{A,\text{point}} = M_{A,\text{distribued}}$$

$$N_2 \ell = -\int_0^{\ell} yN(y)dy$$

Solving for N_{1D} and N_{2D} :

$$N_{1D} = \frac{2}{\ell}(2N_1 + N_2)$$

$$N_{2D} = 6\ell(N_1 + N_2) - \frac{2}{\ell}(2N_1 + N_2)$$

Since this is a 2D model, the units of N_{1D} and N_{2D} are force/length. The depth (or anterior-posterior thickness) of the stem is approximately 1cm, and therefore the stresses at the top and bottom of the stem can be estimated. Also, taking the assumption that the shear is distributed, the following equation gives the shear force per unit length along the stem (which then can be converted to shear stress, given a measurement of the depth of the stem).

$$V_D = \frac{F\cos(\theta)}{2\ell}$$

Once the shear and normal stresses on the top and bottom of the stem are found, maximum normal stresses can be calculated by using the following equation:

$$\sigma_{1,2} = \frac{\sigma_x + \sigma_y}{2} \pm \sqrt{\left(\frac{\sigma_x - \sigma_y}{2}\right)^2 + \tau_{xy}^{\ 2}}$$

Results:
Using these calculations, the relationship between bone loss and maximum normal stresses can be seen in Figure 3.

The dramatic increases in stress with only a few centimeters of bone loss with an angle of 10 degrees suggest that a well-designed FE analysis as well as an in-vitro experiment could be very beneficial in determining the feasibility of using an uncemented Zweymuller stem in revision surgery.

Discussion:
Crowninshield et. al conducted a finite element analysis of a cemented stem and reported maximum compressive stresses of 10Mpa at the proximal end on the medial side using a joint load of 3000N at an angle of 20 degrees [6].

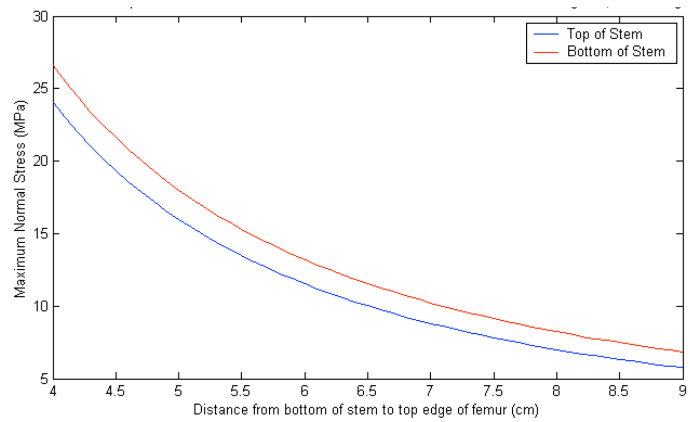

Figure 3: Maximum Normal Compressive Stresses on Femoral Stem Interface with Joint Force at 10 degrees, Stem Length of 12cm.

It should be emphasized that this model assumes linear distribution of normal stress in the proximal femur and distributed shear along the stem. Distributed shear is not necessarily an accurate assumption although it could come close depending on the extent of bone ingrowth. Also, this model does not account for forces on the anterior and posterior sides of the stem, which could be substantial depending on the amount of bone ingrowth and the angle of application of the joint reaction force. Despite these drawbacks, the model is a reasonable first approximation.

References:
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