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Research Article

Verification of the Primary Stability of Bone-Implant Non Manifold Assembly (Prosthetic Joint) using Hertzian Contact Mechanics Model

Gabriel Oladeji Bolarinwa[1], Sam Omenyi[2], Ugochukwu Okonkwo[3]
[1]PhD Student, Mechanical Engineering Department, Nnamdi Azikiwe University, Awka, Anambra State, Nigeria
[2]Professor, Mechanical Engineering Department, Nnamdi Azikiwe University, Awka, Anambra State, Nigeria
[3]Doctor of Philosophy, Mechanical Engineering Department, Nnamdi Azikiwe University, Awka, Anambra State, Nigeria

***Corresponding author**
Gabriel Oladeji Bolarinwa
Email: dejilee2000@gmail.com

Abstract: The problem with hip replacement technology is a challenging one and no addition to that effort is a wasted venture. The aim of this work considering stainless steel SS316L as the implant material was to investigate theoretically, the interaction at the interface between the two materials in contact (Bone and SS316L) using Hertzian Contact Mechanics Model to ascertain the primary stability of the virtual Prosthetic joint.. Hertzian Contact mechanics was applied for the determination of micromotion at the bone-implant interface, the maximum and the minimum values of micromotion obtained were d_{min}=73µm and d_{max}=102µm and when these values were compared with the range of values obtained from literatures, they fell into the range of the recommended values required for good osseointegration. With these values, osseointegration (bone growth) is enhanced, aseptic loosening will not occur and primary stability is ascertained. It also indicates that the prosthesis will not fail within the suggested body weights. The result obtained shows that the assembly has a good initial stability the implant was optimally located and the virtual surgical operation carried out in this work was successful.
Keywords: Micromotion, Osseointegration, Hertzian, Primary stability, Implant-Bone interface.

INTRODUCTION

One of the major factors that determine the success of hip replacement is the primary stability which is the function of the micromotion on the bone-implant interface [1]. Hertzian contact mechanics are defined for elastic, frictionless contact between materials. Within the µm range of displacement, friction can be neglected and Hertzian and Newtonian mechanics could be assumed to hold for the interactions.

Progress in biomechanics has led to the development of the artificial heart and heart valves, artificial joint replacements, as well as a better understanding of the function of the heart and lung, blood vessels and capillaries, and bone, cartilage, inter-vertebral discs, ligaments and tendons of the musculoskeletal systems. The problem with hip replacement technology is a challenging one and no addition to that effort is a wasted venture [2].

Failure of hips replacement may arise from excessive motion at the implant-bone interface under the weight bearing loads. Minimizing the micromotion of the cementless prosthetic components is a key requirement for obtaining bone in-growth. If the initial movement is excessive, bone in-growth into the porous surface will not occur. Few experimental studies are available on implant micromotion largely due to difficulty of simulating loads in-vitro and in-vivo. This study investigated how implant material will affect micromotion theoretically by applying a contact mechanics that characterize the relationship between the bone–implant interfaces. This is to verify the stability of the joint under consideration.

Bolarinwa *et al.* [3] has carried out some research work in this area and their results were employed in this paper. There have not been consolidated values for micromotion, few works have been carried out in this area owing to discrepancies in biological structure of human bones and tissues. The recommended values from different researchers are within the range of 0-200 µm. 200 µm is referred to as the osseointegration threshold. After the finite element analysis, micromotion test was carried out theoretically by employing the Hertzian contact mechanic model. Here, bone was modeled as a hollow cylinder, fully clamped at the base (representing the constraint to the ground), with a conical hole for a conical stem with rounded end to avoid stress singularities at the corners as shown in figure 1 below. The black arrow represents the movement of the bone-implant interface which resulted into what is referred to as Micromotion.

HERTZIAN CONTACT MECHANICS

Hertzian contact mechanics are defined for elastic, frictionless contact between materials. Within the micrometer (μm) range of displacement, friction can be neglected and Hertzian and Newtonian mechanics could be assumed to hold for the interactions [4]. For implants in contact with the canal of the femur, it can be approximated that this relationship was a spherical cross-section in contact with an elastic half-space. Nearly half of all THAs utilize press fit implants. In Hertz's classical theory of contact, he focused primarily on non-adhesive contact where no tension force is allowed to occur within the contact area [5].

The following assumptions were made in determining the solutions of Hertzian contact problems:

i. The strains are small and within the elastic limit.
ii. Each body can be considered an elastic half-space, i.e., the area of contact is much smaller than the characteristic radius of the body.
iii. The surfaces are continuous and non-conforming.

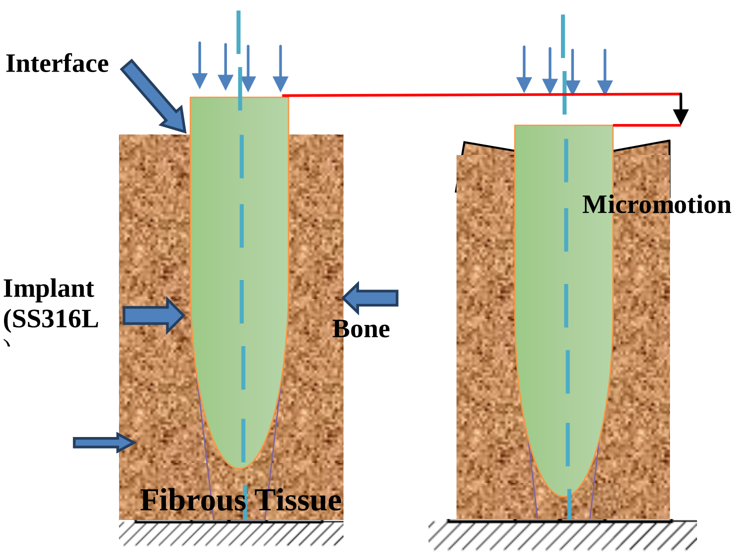

Fig-1: Ideal representation of bone-implant assembly and Micromotion

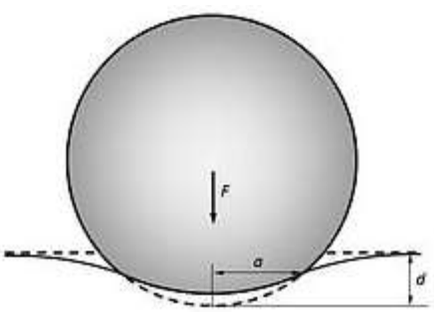

Fig-2: Contact of an elastic sphere with an elastic half-space

For implants in contact with the canal of the femur, it was approximated that this relationship was a spherical cross-section in contact with an elastic half-space. The applied force, F, can then be related to the displacement, d, relating figure 2 to figure1 by the equation;

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$F = \frac{4}{3}E^{*}R^{\frac{1}{2}}d^{\frac{3}{2}}$ -------------------- 1; where

$\frac{1}{E^{*}} = \frac{1-\upsilon^{2}{}_{1}}{E_1} + \frac{1-\upsilon^{2}{}_{2}}{E_2}$ --------------2 therefore;

$d = \left(\frac{3F}{4E^{*}\,R^{\frac{1}{2}}}\right)^{\frac{2}{3}}$ ------------------------3

Here, ν_1 is Poisson ratio of the implant material SS316L = 0.3 ν_2 is the average values of Poisson ratios of the bone from the result obtained in table 1 = 0.28

E_1 is the Young modulus of the implant material = 193MPa
E_2 is the Young Modulus of the cortical part of the bone as obtained in table 1 = 14906 MPa
Inputting the above values into equation 2 gives,

E* = 209 MPa----------------- 4

Table 1: Bone Materials and their Orthotropic Properties [3]

Materials Number	Density (E+9 x kg m^-3)	Young's Modulus (E+9 x Pa)	Bulk Modulus (E+9 x Pa)	Shear Modulus (E+9 x Pa)	Poisson's Ratio	Location
Material 1	1.04987	6.21404	2.0713	3.107	0.3	Proximal End
Material 2	1.21317	.1798	2.3933	3.5899	0.3	
Material 3	1.3762	8.1457	2.7152	4.0728	0.3	
Material 4	1.5394	9.1115	3.0372	4.5557	0.3	Cortical section
Material 5	1.7026	10.0770	3.3591	5.0387	0.3	
Material 6	1.8657	11.0430	3.6810	5.5216	0.3	
Material 7	2.0289	12.0090	4.0030	6.0045	0.3	
Material 8	2.1921	12.9750	4.3249	6.4874	0.3	
Material 9	2.3553	13.941	4.6468	6.9703	0.3	
Material 10	2.518	14.9060	4.9688	7.4532	0.3	
Material 11	1.3762	8.1457	2.7152	4.0728	0.3	Distal End
Material 12	1.2131	7.1798	2.3933	3.5899	0.3	
Material 13	1.04987	6.21404	2.0713	3.107	0.3	

Five different radii were taken randomly on the implant stem
(21.33, 17.86, 8.71, 5.68 and 4.74 all in mm)

The average value of radii, R obtained was approximately12mm.

Substituting **E***, R; equation 3 was reduced to

$d = 1.02E\text{-}6 * F^{2/3}$ ------------------ ------5 **;**

where d is the tangential displacement caused by the resultant force acting on the implant head which results into micromotion. Equation 5 can be rewritten as;

$F = Kd^{3/2}$; -------------------------- 6**;**

where K is a function of the average radius of the implant and the calculated equivalent modulus of elasticity of the bone and implant.

$F \alpha (\sqrt{d})^{3}$ ---------------------------------7;

The displacements were calculated by substituting values of the forces used for analysis into equation 5. The results obtained were shown in table 2 and the graph of the applied load and the displacement were plotted as shown in Figure 3. Figure 3 shows that the micromotion increases as the load (body weight) increases. Because the implant – bone interface is elastic in nature, as the weight or the load increases, the displacement of the surface increases and the implant moves down relative to the effect of the load. The graph represents the behavior of the contact between the implant and the bone surface. Figure 3 was constructed using the recommended values of micromotion obtained from literatures. The numbers 1 through 16 represent the literatures from where the micromotion values that were used for comparison with the result obtained from the research work were obtained.

Table 2: Applied forces and the resulting displacement

LOAD APPLIED (N)	DISPLACEMENT (μm)
600	72.56 **(d_{min})**
700	80.41
800	87.90
900	95.08
1000	102.00 **(d_{max})**

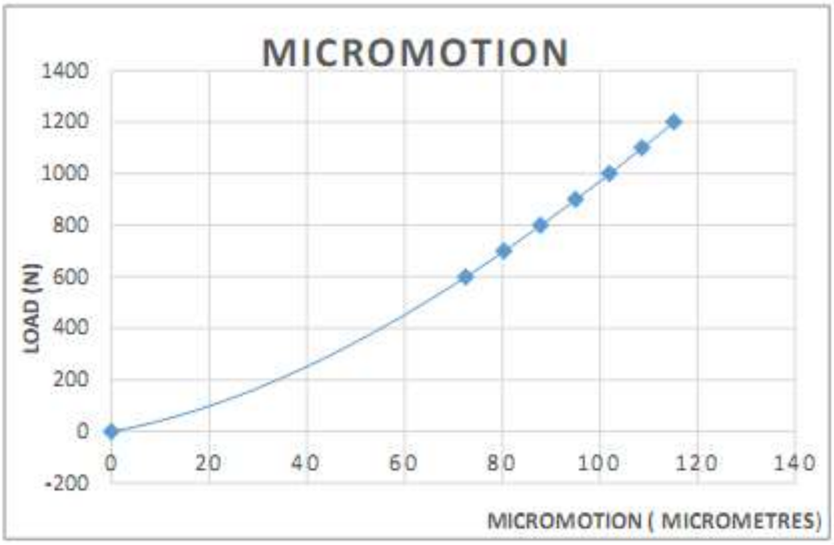

Fig-3: Relationship between the applied load and the Micromotion

The three different regions named Bone, Bone/Bone-Fibro Cartilage and fibrous encapsulation were used to represent osseointegration transitional movement (fig 4). Assuming that the direction of the implant motion is towards the blue arrow, within the micromotion values ranging from 0-28 μm, bone only is expected to be growing; here, the fixation is very strong. From the range of 28 - 200μm, osseointegration of both the Bone and Fibro Cartilage will occur. From the literature, 200μm is mostly used as the Osseointegration (bone in-growth) threshold; the implant is still averagely stable. Above the osseointegration threshold value, aseptic loosening begins, the implant begins to loose and the surgery begins to fail. At this region, fibrous encapsulation occurs instead of osseointegration, it is also known as bone healing. The 73 μm and 102μm values that were displayed on the above developed chart represent the minimum and maximum values of micromotion obtained from this research study.

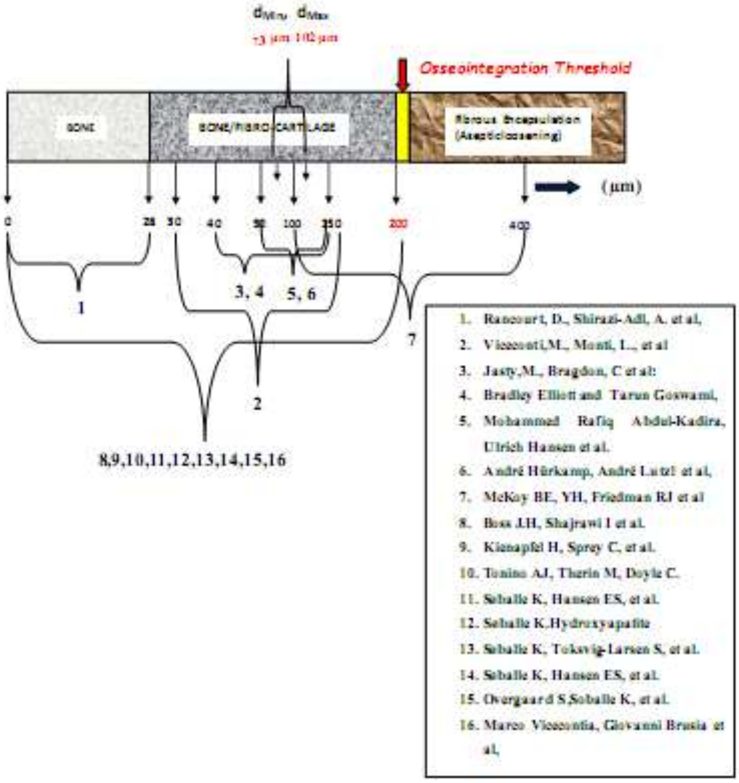

Fig-4: Comparison of different magnitudes of Micromotion obtained from literatures and the research results

CONCLUSION

The Hertzian Contact mechanics models adopted in this work helps to determine the micromotion that occurred at the bone-implant interface and to describe the mechanical characteristics and the phenomenological changes in the interface of the osseointegration process. The feasibility of verifying micromotions at the bone–stem interface and primary stability of an implant have been established. The method could be used to validate finite element models and the primary stability of the stem. The result obtained shows that the assembly has a good initial stability the implant was optimally located and the virtual surgical operation carried out in this work was successful.

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