COMPARISON OF ENERGY ABSORPTION BETWEEN LUMBAR SPINE IMPLANTS DURING DAILY ACTIVITY

University of Manitoba
Mohammad Hodaei, Pooneh Maghoul, and Nan Wu
hodaeim@myumanitoba.ca

ABSTRACT

A contact model has been offered to compare the effect of roughness on energy absorption in different lumbar spine implants. In this research, we develop a statistical contact model to investigate interaction of Lumber implant surfaces, ball and socket, from L1 to L5 including normal contact load in which the effect of roughness is included. It is found that the energy absorption between lumbar implant increases from lumbar 1 to lumbar 4, L1 to L4, and decreases from lumbar 4 to lumbar 5,L4 to L5, as it has effect on design performance and durability of implants.

Introduction

The biomechanical and cartilaginous structure of spinal column in human body makes it strong to withstand the high level of mechanical loads. Any injury to spinal column can influence the functionality of human body. The replacing injured spinal columns are the most important application of implants [1,2]. Therefore, it is important to evaluate the design and wear condition of implant, which is not only beneficial for patient but will help to avoid further injury.

The objective of this research is to investigate the effect of surface roughness in lumbar spine implants and compare energy absorption induced by roughness in lumbar implants, L1-L5.

Material and Method

Figure 1 illustrates the schematic diagram of spine implant. Any force transfer to the spine will increase the contact force between the spine components. There is an approximation for shape of implant as it is assumed a semi-sphere with radii of curvature R_1 and R_2 respectively for its components, ball and socket.

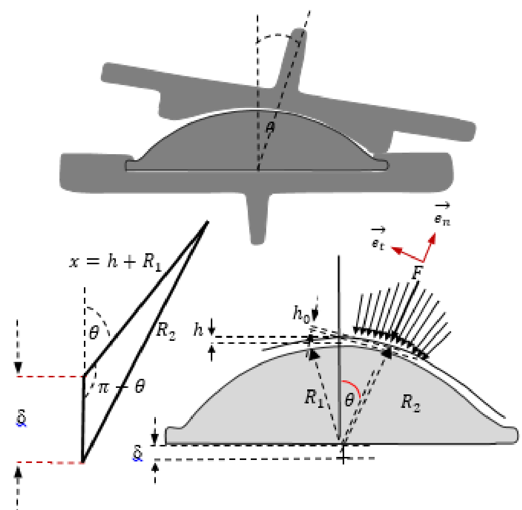

Figure 1. Lumbar components in contact [5]

The values for lumbar spine are generated for various ball radii [3, 4]. With regards to the schematic drawing of semi spheres for ball and socket contacts, for the minimum separation of two contact surfaces h_0, the offset of two semi spheres centers, δ, can be expressed in terms of h_0 [5]. The expression of force per unit area between two components are given as below [6]

$$P(h) = P_e(h) + P_p(h) \tag{1}$$

h, $Pe(h)$, and $P_p(h)$ are mean surface separation, elastic, and plastic force respectively as they have been derived from previous research [5]. Some parameters mentioned in the previous research relevant to this research are defined by Greenwood and Williamson (1966) [7]. The plasticity index for a surface is given as follow:

$$\psi = \frac{E}{H}\sqrt{\frac{\sigma}{R}}$$

where R is the average asperity summit radius of curvature, E is the equivalent modulus and H is the hardness of the softer material. Greenwood and Williamson also define critical interference as

$$\omega_c = \left(\frac{H}{E}\right)^2 R$$

To obtain contact force along a particular direction, summing components of infinitesimal contact force along the particular direction can lead to total contact force along with that direction. Summation of the force components parallel to radial line of symmetry with respect to nominal contact area is done,

$$F = \int_0^{2\pi} \int_{\frac{-\pi}{2}}^{\frac{\pi}{2}} P(h) R^2 \sin\theta \, \cos\theta \, d\theta d\phi , \quad [2]$$

where R is the equivalent radius of curvature of the ball and socket radii of curvatures. To get rid of calculation for different radius along with different plasticity index, it is better to find an approximate relation between contact forces F and the minimum separation h_0 that the contact force can be estimated using function of the form

$$F_{na}(h_0) = \left[a(\psi) R_1^{\,2}\right] e^{-c(\psi) h_0^{\,1.21}} \quad [3]$$

$$a(\psi) = a_3\psi^3 + a_2\psi^2 + a_1\psi + a_0 \, . \quad [4]$$

$$c(\psi) = c_3\psi^3 + c_2\psi^2 + c_1\psi + c_0 \quad [5]$$

Approximate functional relationship between a and plasticity index, ψ, are established for plasticity index ranging 0.6 to 1.3 for all lumbar implants, L1-L5. For surfaces characterized by $0.6 < \psi < 1$, the surface is viewed as elastic plastic. Table 1 and 2 show coefficients, a's and c's, for loading and unloading parts. The max error between fitted function and original function for elastic-plastic contact is less than 6% over the entire range of parameters considered shown in the figure 2.

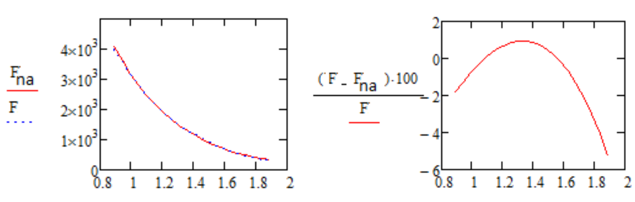

Figure 2. The max error between approximate function and exact function

Energy Loss in Lumbar Implants

The contact between the ball and socket implant surfaces consists of asperities experiencing elastic and plastic deformation. A close look at the loading and unloading process reveals that both damping and elastic recovery are involved in the process. During the increase in contact load both elastic and plastic deformations can occur at asperity deformation level. However, unloading asperities undergo only elastic recovery. Therefore, the load and unload process will follow different paths, resulting in hysteresis type energy loss in the spine joint contact.

The approximate equations can be employed for elastic-plastic contact, and the purely elastic contact is used to represent the loading and unloading process mathematically. The force during loading is denoted as, $F_{nL} = \alpha_{1L} e^{\alpha_{2L} h_0^{\alpha_{3L}}}$, and that during unloading is, $F_{nU} = \alpha_{1U} e^{\alpha_{2U} h_0^{\alpha_{3U}}}$. Based on the results of the previous section, the respective coefficients of contact force during loading and unloading are as follows,

$$\alpha_{1L} = a(\psi) R_1^{\,2} \quad [6]$$

$$\alpha_{2L} = -c(\psi) \quad [7]$$

$$\alpha_{3L} = \alpha_{3U} = 1.21 \quad [8]$$

$$\alpha_{1U} = a(\psi) R_1^{\,2} \quad [9]$$

$$\alpha_{2U} = 1.2 \quad [10]$$

To study energy loss and storage in a spine joint, an equilibrium contact force is considered. A disturbance from equilibrium is denoted as *x.* Therefore, to study the behavior of the contact near an equilibrium state, the contact force equations above can be used. Depending on the nature of the disturbance, the load may increase from equilibrium or decrease from it. The following expressions will be adequate to account for either load change scenarios,

$$F_{nL}(h_0, x) = \alpha_{1L} e^{\alpha_{2L} (h_0 - x)^{\alpha_{3L}}} \quad [11]$$

$$F_{nU}(h_0, x) = \alpha_{1U} e^{\alpha_{2U} (h_0 - x)^{\alpha_{3U}}} \, .$$

[12]

When the disturbance is small, the above force equations can be written in linear form using truncated Taylor series expansion of F_{nL} and F_{nU} about the equilibrium minimum separation.

$$FL_{nL}(h_0, x) = -\left(\frac{h_0^{\,\alpha_{3L}-1} \alpha_{1L}\, \alpha_{2L} \alpha_{3L} e^{h_0^{\,\alpha_{3L}} \alpha_{2L}}}{1!}\right) x + \alpha_{1L}\, e^{\alpha_{2L} h_0^{\,\alpha_{3L}}}$$

[13]

$$FL_{nU}(h_0, x) = -\left(\frac{h_0^{\alpha_{3U}-1}\alpha_{1U}\,\alpha_{2U}\alpha_{3U}e^{h_0^{\alpha_{3U}}\alpha_{2U}}}{1!}\right)x + \alpha_{1U}\,e^{\alpha_{2U}h_0^{\alpha_{3U}}}$$

[14]

Based on the dissipated energy formula, the plot of two terms loading and unloading forces can show the damped energy of the system. Figures 5 to 9 show the dissipated energy loss for Lumbar 1 to 5 when plasticity index changes from elastic zone to plastic zone respectively (0.6 to 1.3). The area between both unloads and load forces will be expanded with increasing plasticity index.

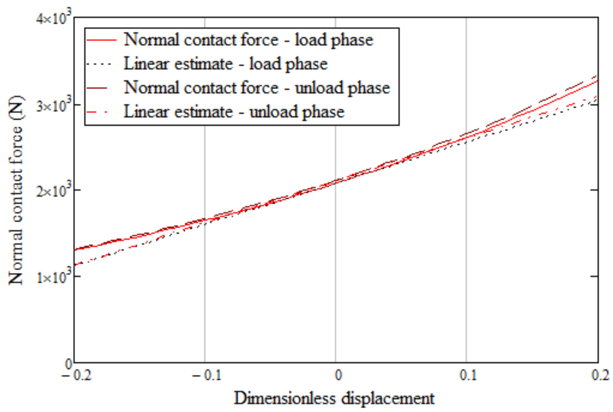

Figure 3a. Load – unload phase in low plastic zone ($\psi = 0.6$) for spine implant L1

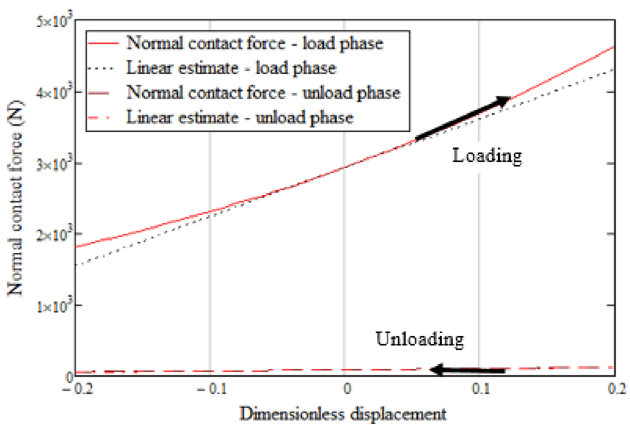

Figure 3b. Load – unload phase in low plastic zone ($\psi = 1.3$) for spine implant L1

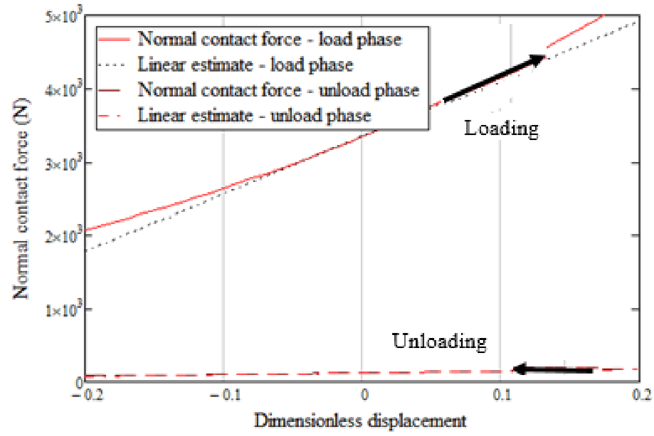

Figure 4. Load – unload phase in low plastic zone ($\psi = 1.3$) for spine implant L2

For other lumbar spine, the energy loss is plotted just for plasticity index 1.3 and we neglect plotting energy loss with low plastic zone, $\psi = 0.6$, because the graphs are similar and just with different amount of normal contact force. The procedure of load-unload for Lumbar 3 to 5 is the same as Lumbar 1 and 2. With regard to two different types of plasticity i.e., 0.6 and 1.3, it can be seen that for high plasticity, the dissipative energy is also higher. Additionally, the energy loss increase from L1 to L4 and decreases from L4 to L5. It means the the surface area gradually increases from L1 to L4 and reduces from L5 to L4. The mentioned results confirm the results obtained by previous researcher about the changes of surface area in the lumbar [8,9].

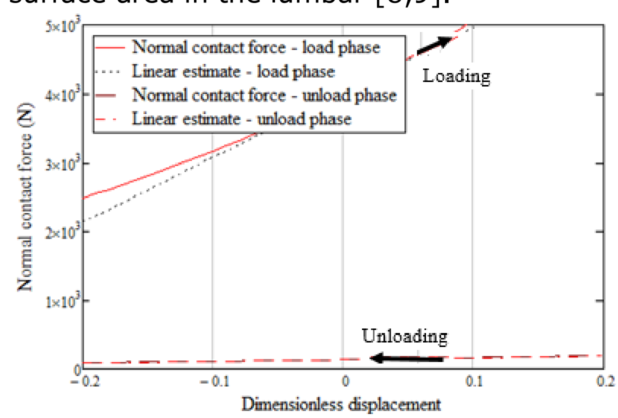

Figure 5. Load – unload phase in low plastic zone ($\psi = 1.3$) for spine implant L4

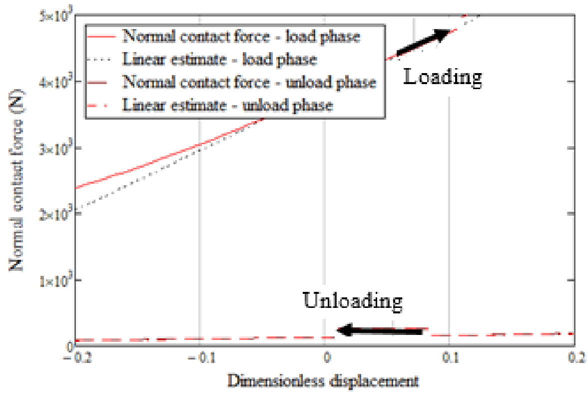

Figure 6. Load – unload phase in low plastic zone $(\psi = 1.3)$ for spine implant L5

Table 1. Loading coefficients of L1 to L5.

Co.	a_0	c_0	a_1	c_1	a_2	c_2	a_3	c_3
L1	5.73e-3	1.447	-0.014	1.573	0.018	- 1.474	-6.73e-3	0.554
L 2	5.73e-3	1.447	-0.014	1.573	0.018	- 1.474	-6.72e-3	0.454
L 3	5.73e-3	1.447	-0.014	1.573	0.018	- 1.474	-6.72-3	0.454
L 4	5.72e-3	1.447	-0.014	1.573	0.018	- 1.474	-6.72e-3	0.454
L 5	5.72e-3	1.447	-0.014	1.573	0.018	- 1.474	-6.71e-3	0.454

Table 2. Unloading coefficients of L1 to L5

Co.	a_0	c_0	a_1	c_1	a_2	c_2	a_3	c_3
L1	2.62e-3	1.245	1.43e-3	3.028	-3.88e-3	-3.859	9.43e-4	1.348
L2	-1.94e-3	1.245	0.018	3.028	-0.024	-3.859	8.47e-3	1.348
L3	- 1.949e-3	1.245	0.018	3.028	-0.024	-3.859	8.473e-3	1.348
L4	- 1.948e-3	1.245	0.018	3.028	-0.024	-3.859	8.467e-3	1.348
L5	- 1.948e-3	1.245	0.018	3.028	-0.024	-3.859	8.467e-3	1.348

Closing Remarks

An elastic-plastic contact model of spine joint implant is developed in this paper. The vertebral body of spine implants, Lumbar 1 to 5, are modeled using semi-spherical solids in internal conformal contact and accounting for the effect of roughness of both surfaces. Statistical integration of contact pressure over contact region of effective interaction between two semi-spherical rough surfaces finds an equation relating force to minimum mean surface separation. The approximate equation is used to find closed-form equation for contact energy loss per cycle. It is obtained that energy loss in lumbar 1 to 4 increases and decreases from L4 to L5. There is confirmation of the obtained results by previous research about the increasing surface area of contact from L1 to L4 and decreasing from L4 to l5. In fact, there are more roughness in wider surface as it can lead to more energy loss after contact and the energy loss can decrease when less roughness or smaller surface come to each other.

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