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***Research Article***

# Analysis of the Wear Behavior of Human Femur Bone- A Taguchi Approach

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***A b s t r a c t***

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The femur is the largest, strongest and most voluminous tubular bone in the human body. This is the principal load-bearing bone in the lower extremity. Femoral fractures are among the most common major injuries that an orthopedic surgeon will be required to treat. During fracture treatment of femur bone the biomaterials are used for fracture healing. Because of the knee and hip joint replacement, the bones are subjected to the conditions of wear. This experimental investigation focuses on the evaluation of wear behavior of femur. The full scale testing of the femur bone has been carried out. The wear studies of the femur head and the condoyle regions have been made using L27 orthogonal array and Taguchi technique. Wear of femur bone has shown maximum dependency on the matrix of the femur and its hardness. The wear resistance of the condoyle region is found to be high.

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## 1. Introduction

In humans femur is the largest, most voluminous and strongest bone. It can support up to 30 times the weight of an adult. It forms a part of hip and knee. In a hip and knee joint, cartilage lies between the femoral head and hip and condoyle and tebia bone to help prevent wear [1-3]. Femur is most responsible for bearing the largest percentage of body weight during normal bearing weight and it is solid inflexible bone. The femur is the most proximal (closest to the body) bone of the leg in vertebrates capable of walking or jumping. The average adult male femur is 48 centimeters (18.9 in) in length and 2.34 cm (0.92 in) in diameter [4- 6].

Musculoskeletal loading influences the stresses and strains within the human femur [7]. One of the main injuries of femur is because of accidents. During many physical activity like jumping, walking and running etc, the body weight is transferred to femur through hip joint and the femur bone is subjected to different loading conditions such as impact, bending, shear, compression and torsion loads and because of these loads lateral forces, twisting stresses and powerful impacts may cause the bone to break or which may lead to bone desorption and thereby affect the clinical outcome [8-10].

The femur is the most proximal bone of the leg in vertebrates capable of walking or jumping and most of the upper weight of the body is supported by femur bone [11-12]. If the femur bones get fractured then the person who suffering from this unable to do many of the physical activity and this will results in the total collapse of the human body[13]. In human femoral bone, different regions are critical for different loads. The common form of “Orthrities and Osteoarthritis” is caused by wear and tear of articular cartilage on the surface of bones in synovial joints in case of hip as well as knee replacement. Trochanteric fracture may occur in elderly patients suffering from osteoporosis and may result from direct trauma such as a fall [14].

Nowadays many varieties of implants can be used for femoral fractures [15]. The mechanical and chemical stability of implanted materials in body fluids are of fundamental importance in the successful treatment of bone fractures, particularly femoral fractures. [16-17]. Metallic biomaterials have their main applications in load-bearing systems such as hip and knee prostheses and for the fixation of internal and external bone fractures. Prosthetic devices are implanted in the human body to replace the affected joint in order to eliminate pain and restore its normal function. During hip replacement surgery, the damaged hip joint or knee joint is removed and replaced with the artificial joint [18]. After implantation, the implant functions just as a normal hip joint and as normal knee joint.

Currently, persistent problems remain to be solved with total hip replacements, including implant wear, aseptic loosening, and osteolysis [19]. During fracture of femur bone the implant materials are used for fracture healing and they are suitable for long term implants within the living tissues and it was reported that bones were subjected to conditions of wear, such as femoral knee or hip modular head components higher amount of coarse debris particles were found in surrounding tissues [20-21]. This may cause some of the reactions such inflammatory response induces periprosthetic bone loss and subsequent loosening of prosthesis. The common form of “Orthrities and Osteoarthrities” is caused by wear and tear of articular cartilage on the surface of bones in synovial joints [22-24].

In the Taguchi method, Design of experiments approach enables to analyze successfully the wear behavior of materials. The design of an experiment (DOE) technique is an optimized technique mainly employed in determining wear behavior of material, which must follow certain sequence for the experiments to yield an improved understanding of product or process performance [25-26].

From the literature survey it is clear that there is lot of scope for the study of wear behavior of femur bone. Hence present study was focused on the dry sliding wear behavior of femoral head and condoyle region. The main aim was to investigate the effect of applied load, sliding distance and sliding speed which mainly influences the dry sliding wear of the femoral head and condoyle region with the help of Taguchi technique under various testing conditions. Furthermore, the analysis of variance (ANOVA) is employed to investigate the testing characteristics of femur bone. Tests were carried out using a pin-on-disc type of apparatus under different conditions. A major step in the DOE process is the determination of the combination of factors and levels which will provide the experimenter with the desired information.

## 2. Material and Experimentation

This experimental study aims at determining wear behavior of human femoral head. This study attempts at providing wear properties of femoral head and condoyle region through series of wear tests. The specimens were extracted from number of dead human (male) femur. Human male femoral bones (dead) of mid age of 20 to 30 have been used. The average adult male femur is 48 centimeters (18.9 in) in length and 2.34 cm (0.92 in) in diameter are been used. The composition of femur bone used is as given in table 1.

Table.1: Composition of the human femur.

| Dry matter | 904 |
|---|---|
| **Organic matter** | 840 |
| **Crude protein** | 144 |
| **Crude fat** | 25 |
| **Crude fibre** | 150 |
| **Ash** | 64 |
| **Calcium** | 11.7 |
| **Phosphorus** | 5.9 |
| **Sodium** | 2.6 |
| **Chloride** | 5.8 |
| **Potassium** | 8.5 |
| **Magnesium** | 1.6 |
| **Iron** | 0.149 |
| **Copper** | 0.005 |
| **Manganese** | 0.044 |
| **Zinc** | 0.155 |

## 2.1. Specimen preparation

The femur bone is the longest bone in the human structure and carries much load. During the course of hip joint and knee replacement, the femoral head and the condoyle portions are subjected to wear loads. Considering the above facts the specimens of the femoral head and condoyle portion are cut for the wear test using a tennon saw. Both the end surfaces of the each specimen are accurately flattened on surface plate. The size of the specimen is 30mm length and average diameter is 32mm. The figure 1 shows the specimen taken for wear test at femoral head region.

a) Femoral head region b) condoyle region

Fig.1 a) femoral head region and b) condoyle region of femur bone

### 2.2. Wear test

Due to the advent of new technologies in the biomedical instrumentations the replacement of hip joint, knee and femoral heads has become most common. The replacement of these elements will be made with the metallic materials like stainless steel, high strength non corrosive steel, ceramics mnemonic alloys. During the course of functioning the natural bone elements will come in contact with these externally implanted metallic bodies. Under the presence of variable amplitude load the basic bone elements may undergo wear. Hence an attempt has been made to analyze the wear behavior of the femoral head and condyle region which is highly prawn to the wear.

The experimentations were carried out in order to determine the wear property of the femur bone. A pin-on-disc test apparatus was used to investigate the dry sliding wear characteristics of the femur bone. The disc used is En-32 steel hardened to 62 HRC, 135mm track diameter and 8mm thick, with surface roughness of 10µm Ra. The tests were conducted by selecting test duration, load and velocity and performed in a track of 115mm diameter is shown in figure 2a. The primary objective of wear test is to determine the wear resistance of human femur bone against metallic implants. The bone specimen used in this study was placed in sliding contact with EN32 steel disc. A 6mm pin is used to hold the specimen firmly in the position, so as to obtain proper sliding contact between specimen and disc. The difference in the weight measured before and after test gives the sliding wear of femur bone specimen and then the volume loss was calculated. The test setup and specimens used for the wear test is as shown in figure 2b.

### 2.3. Taguchi techniques

Taguchi technique is a powerful tool for the design of high quality systems. The Taguchi approach to experimentation provides an orderly way to collect, analyze, and interpret data to satisfy the objectives of the study. By using these methods, in the design of experiments, one can obtain the maximum amount of information for the amount of experimentation used.

Taguchi parameter design can optimize the performance characteristics through the setting of design parameters and reduce the sensitivity of the system performance to the source of variation. This is accomplished by the efficient use of experimental runs to the combinations of variables studied. This technique is a powerful tool for acquiring the data in a controlled way and to analyze the influence of process variable over some specific variable, which is unknown function of these process variables. The most important stage in the plan of experiments is selection of factors. Taguchi technique creates a standard orthogonal array to accommodate the effect of several factors on the target value and defines the

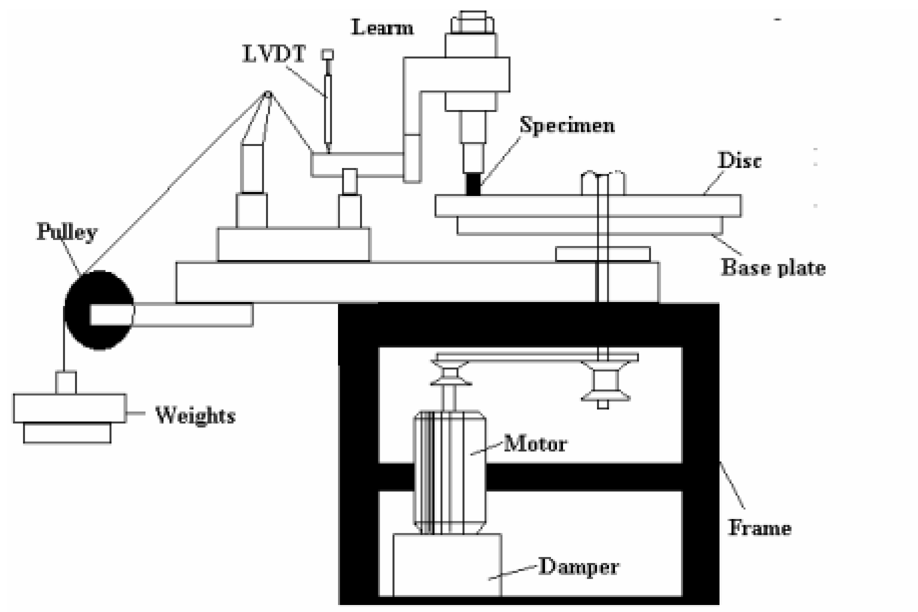


Fig.2a. Dry sliding wear testing machine

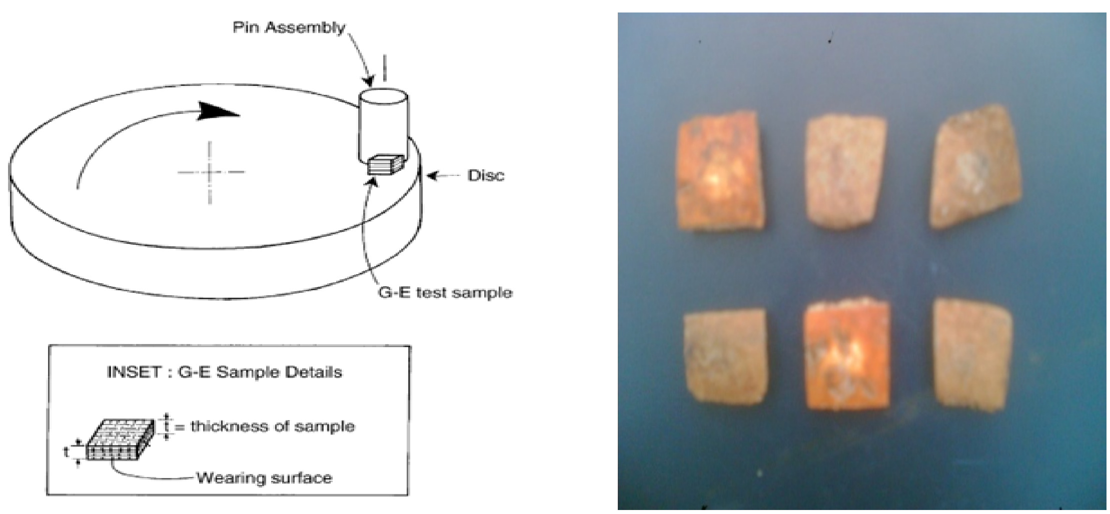


Fig.2b. Dry sliding wear testing machine setup and wear test specimens

Table.2: $L_{27}$ Orthogonal Array

| $L_{27}$ ($3^{13}$) | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **1** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **2** | 1 | 1 | 1 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| **3** | 1 | 1 | 1 | 1 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| **4** | 1 | 2 | 2 | 2 | 1 | 1 | 1 | 2 | 2 | 2 | 3 | 3 | 3 |
| **5** | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 3 | 3 | 3 | 1 | 1 | 1 |
| **6** | 1 | 2 | 2 | 2 | 3 | 3 | 3 | 1 | 1 | 1 | 2 | 2 | 2 |
| **7** | 1 | 3 | 3 | 3 | 1 | 1 | 1 | 3 | 3 | 3 | 2 | 2 | 2 |
| **8** | 1 | 3 | 3 | 3 | 2 | 2 | 2 | 1 | 1 | 1 | 3 | 3 | 3 |
| **9** | 1 | 3 | 3 | 3 | 3 | 3 | 3 | 2 | 2 | 2 | 1 | 1 | 1 |
| **10** | 2 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 |
| **11** | 2 | 1 | 2 | 3 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 1 |
| **12** | 2 | 1 | 2 | 3 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 |
| **13** | 2 | 2 | 3 | 1 | 1 | 2 | 3 | 2 | 3 | 1 | 3 | 1 | 2 |
| **14** | 2 | 2 | 3 | 1 | 2 | 3 | 1 | 3 | 1 | 2 | 1 | 2 | 3 |
| **15** | 2 | 2 | 3 | 1 | 3 | 1 | 2 | 1 | 2 | 3 | 2 | 3 | 1 |
| **16** | 2 | 3 | 1 | 2 | 1 | 2 | 3 | 3 | 2 | 1 | 2 | 3 | 1 |
| **17** | 2 | 3 | 1 | 2 | 2 | 3 | 1 | 1 | 2 | 3 | 3 | 1 | 2 |
| **18** | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 2 | 3 | 1 | 1 | 2 | 3 |
| **19** | 3 | 1 | 3 | 2 | 1 | 3 | 2 | 1 | 3 | 2 | 1 | 3 | 2 |
| **20** | 3 | 1 | 3 | 2 | 2 | 1 | 3 | 2 | 1 | 3 | 2 | 1 | 3 |
| **21** | 3 | 1 | 3 | 2 | 3 | 2 | 1 | 3 | 2 | 1 | 3 | 2 | 1 |
| **22** | 3 | 2 | 1 | 3 | 1 | 3 | 2 | 2 | 1 | 3 | 3 | 2 | 1 |
| **23** | 3 | 2 | 1 | 3 | 2 | 1 | 3 | 3 | 2 | 1 | 1 | 3 | 2 |
| **24** | 3 | 2 | 1 | 3 | 3 | 2 | 1 | 1 | 3 | 2 | 2 | 1 | 3 |
| **25** | 3 | 3 | 2 | 1 | 1 | 3 | 2 | 3 | 2 | 1 | 2 | 1 | 3 |
| **26** | 3 | 3 | 2 | 1 | 2 | 1 | 3 | 1 | 3 | 2 | 3 | 2 | 1 |
| **27** | 3 | 3 | 2 | 1 | 3 | 2 | 1 | 2 | 1 | 3 | 1 | 3 | 2 |

plan of experiments. The experimental results are analyzed using analysis of means and variance to study the influence of factors. The Experiments were conducted as per the standard $L_{27}$ orthogonal array so as to investigate which design parameter significantly affects the dry sliding wear for the selected combinations of load, sliding speed and sliding distance as shown in the Table 2.

The wear parameters chosen were (1) sliding speed (2) Load (3) sliding distance and their levels indicated in Table 3. The experiments consist of 27 tests (each row in the $L_{27}$ orthogonal array) and first column in table was assigned to load (L), second column was assigned to sliding speed (S), third column was assigned to sliding distance (D).

Table.3: Process parameters and their levels

| Levels | Speed (rpm) | Load (N) | Sliding distance(m) |
|---|---|---|---|
| **1** | 200 | 9.81 | 500 |
| **2** | 250 | 19.62 | 1000 |
| **3** | 300 | 29.45 | 1500 |

## 3. Results and Discussion

During the course of functioning the natural bone elements will come in contact with these externally implanted metallic bodies. Under the presence of variable amplitude load the basic bone elements may undergo wear. The common form of “Orthrities and Osteoarthritis” is caused by wear and tear of articular cartilage on the surface of bones in synovial joints. The experiments were conducted with an aim of relating the influence of sliding speed(S), applied load (L) and sliding distance (D) with dry sliding wear of both the head and condoyle specimens. On conducting the experiments as per the orthogonal array, the dry sliding wear results for various combinations of parameters were obtained as shown in table 4.The purpose of statistical analysis of variance (ANOVA) is to investigate which design parameter significantly affect the wear characteristic. Based on ANOVA the optimal combinations of process parameter are predicted.

### 3.1. Design of Experiments

The experiments were conducted with an aim of relating the influence of sliding speed (S), applied load (L) and sliding distance (D) with dry sliding wear of both the head and condoyle region of femur bone under study.

Table.4: Results for dry sliding wear test for head and condoyle specimens

| $L_{27}$ ($3^{13}$) | Speed (rpm) | Load (N) | Sliding distance(m) | Wear (mg) head | Wear (mg) condoyle |
|---|---|---|---|---|---|
| **1** | 200 | 9.81 | 500 | 0.4 | 0.5 |
| **2** | 200 | 9.81 | 1000 | 3.1 | 0.6 |
| **3** | 200 | 9.81 | 1500 | 0.6 | 0.7 |
| **4** | 200 | 19.62 | 500 | 0.4 | 0.6 |
| **5** | 200 | 19.62 | 1000 | 2.0 | 1.6 |
| **6** | 200 | 19.62 | 1500 | 5.5 | 0.8 |
| **7** | 200 | 29.43 | 500 | 1.8 | 1.0 |
| **8** | 200 | 29.43 | 1000 | 4.2 | 3.9 |
| **9** | 200 | 29.43 | 1500 | 3.7 | 3.3 |
| **10** | 250 | 9.81 | 500 | 1.7 | 0.5 |
| **11** | 250 | 9.81 | 1000 | 0.7 | 1.0 |
| **12** | 250 | 9.81 | 1500 | 1.5 | 3.9 |
| **13** | 250 | 19.62 | 500 | 1.6 | 2.0 |
| **14** | 250 | 19.62 | 1000 | 1.6 | 3.0 |
| **15** | 250 | 19.62 | 1500 | 1.8 | 1.3 |
| **16** | 250 | 29.43 | 500 | 5.9 | 0.8 |
| **17** | 250 | 29.43 | 1000 | 3.8 | 1.8 |
| **18** | 250 | 29.43 | 1500 | 6.6 | 5.0 |
| **19** | 300 | 9.81 | 500 | 0.9 | 0.5 |
| **20** | 300 | 9.81 | 1000 | 1.2 | 1.5 |
| **21** | 300 | 9.81 | 1500 | 1.2 | 1.4 |
| **22** | 300 | 19.62 | 500 | 1.8 | 0.6 |
| **23** | 300 | 19.62 | 1000 | 2.8 | 2.4 |
| **24** | 300 | 19.62 | 1500 | 1.9 | 2.6 |
| **25** | 300 | 29.43 | 500 | 3.3 | 1.2 |
| **26** | 300 | 29.43 | 1000 | 3.7 | 0.9 |
| **27** | 300 | 29.43 | 1500 | 5.8 | 5.5 |

On conducting the experiments as per the orthogonal array, the dry sliding wear results for various combinations of parameters were obtained and shown in Table 4. The ANOVA allows analyzing the influence of each variable on the total variance of the results. Table 5 and 6 shows the results of ANOVA for the wear of the test samples. This analysis was performed with a level of significance of 1% and 10% i.e. for a level of confidence of 99% for both Head and Condoyle regional specimens respectively. The last column of the table shows the contribution % (P) of each variable in the total variation indicating the influence degree on the wear of contact pair. If the "Test F" value is greater than the F (1%) column value, then the assigned variable is statistically significant.

Table.5: ANOVA results for head specimens

| Source of Variance | SS | DOF | Variance | Test F | F | $P^a$(%) |
|---|---|---|---|---|---|---|
| D | 0.44 | 2 | 0.22 | 43.13 | $5.27^b$ | 52.41 |
| L | 0.06 | 2 | 0.03 | 5.08 | $5.27^b$ | 6.070 |
| S | 0.01 | 2 | 0.005 | 0.98 | - | - |
| SXL | 0.05 | 4 | 0.0125 | 3.43 | $2.875^c$ | 3.6 |
| SXD | 0.05 | 4 | 0.0125 | 3.43 | $2.875^c$ | 3.6 |
| LXD | 0.03 | 4 | 0.0075 | 1.47 | - | 1.17 |
| Pooled Error | 0.18 | 35 | 0.0051 | | | 33.15 |
| Total | 0.82 | 53 | | | | |

One can observe from the ANOVA table 5 that the sliding distance (p=52.41%) and applied load (p=6.07%) has great influence on the wear. The speed has no influence on the wear of head specimens. However the interaction between sliding speed and applied load (3.6%) and sliding speed and sliding distance(3.6%) also as an influence on the wear and other interactions sliding distance and load(1.17%) has less significant effect (both physical and statistical) on the dry sliding wear so it is neglected. The pooled error associated in the ANOVA table is approximately about 33.15%. The sliding distance of the head region contributes much to wear of femur is due to reason that the disc material used was harder than the hardness of the femur bone. Due to rubbing of the bone against harder disc material lead to weight loss of bone. Also as applied load increases the friction at the contact surface of the material and rotating disc obviously increases the wear loss also increases.

It can be observed from the ANOVA table 6 that the sliding distance (p=29.23%) and applied load (p=17.69%) has great influence on the wear. The speed has negligible influence on the wear of condoyle specimens. However the interaction between sliding speed and applied load (0%) and sliding speed and sliding distance(0%) as no influence on the wear and other interactions sliding distance and load(10.38%) has less significant effect (both physical and statistical) on the dry sliding wear so it is neglected. The pooled error associated in the ANOVA table is approximately about 40.40%. The sliding distance of the condoyle region contributes much to wear of femur is due to reason that the disc material used was harder than the hardness of the femur bone. Due to rubbing of the bone against harder disc material lead to weight loss of bone. The contribution of applied load is greater which may be due to the sufficiently induced stress at contact area within the experimental conditions. Also mechanical properties like hardness and wear characteristics vary from region to region because of its matrix composition. Thus the wear of condoyle is more compared to head region.

Table.6: ANOVA results for condoyle specimens

| Source of Variance | SS | DOF | Variance | Test F | F | $P^a$ (%) |
|---|---|---|---|---|---|---|
| D | 0.16 | 2 | 0.08 | 20.00 | $5.27^b$ | 29.23 |
| L | 0.09 | 2 | 0.05 | 12.5 | $5.27^b$ | 17.69 |
| S | 0.02 | 2 | 0.01 | 2.50 | $2.465^c$ | 2.30 |
| SXL | 0.02 | 4 | 0.005 | 1.25 | - | - |
| SXD | 0.02 | 4 | 0.005 | 1.25 | - | - |
| LXD | 0.07 | 4 | 0.0175 | 4.375 | $2.465^c$ | 10.38 |
| Pooled Error | 0.14 | 35 | 0.0040 | | | 40.40 |
| Total | 0.52 | 53 | | | | |

SS- Sum of squares DOF- Degree of freedom

a- percentage of contribution.

b- 99% confidence level

c- 95% confidence level

d- 90% confidence level

Design of experiments approach by Taguchi method enabled us to analyze successfully the wear behavior of the femur bone on load, sliding distance and sliding speed as test variables. In view of the fact that the theory claims that sliding distance and applied load are most important factors affecting the sliding process. For both femoral head and condoyle region however sliding distance exerted greatest effect on sliding wear which is followed by applied load. There was no weight loss effect of sliding speed on the wear.

### 3.2. Regression Analysis

Linear regression technique was used to study the dry wear weight loss of the bone specimens. The generalized linear regression equation for the experiment can be written as,

$$Y = a_0 + a_1 x_1 + a_2 x_2 + a_3 x_3 + a_4 x_1 x_2 + a_5 x_2 x_3 + a_6 x_3 x_1 + a_7 x_1 x_2 x_3 \qquad (1)$$

The factorial design of experiments and the values of the response variables corresponding to each set of trials are represented in equation 1 for the head specimens and where Y is the wear weight loss. The variables $x_1$, $x_2$, $x_3$ are the L, D and S respectively. The $a_1$, $a_2$ and $a_3$ are the coefficients of the independent variables $x_1$, $x_2$ and $x_3$ respectively. The $a_4$, $a_5$, $a_6$, and $a_7$ are the interaction co-efficient between $x_1$ and $x_2$, $x_2$ and $x_3$, $x_1$and $x_3$ and $x_1$, $x_2$ and $x_3$ respectively with the selected levels of each variable. After calculating each of the coefficients of equation 1, the final linear regression equation for the wear rate of Head specimens and Condyle specimens when tested against a pin on disc set up can be expressed as follows

The regression equation for head specimen is

$$Y = = - 1.9 + 0.0073\, S + 0.00443\, D - 0.028\, L - 0.000019\, S \times D + 0.00041\, S \times L + 0.000018\, D \times L + 0.000000\, S \times D \times L \qquad (1)$$

Regression Analysis; wear versus S, D, L, S×D, S×L, D×L, S×D×L

The regression equation for condoyle specimen is

$$Y = = - 1.71 + 0.0093\, S - 0.00073\, D + 0.225\, L + 0.000002\, S \times D - 0.00104\, S \times L - 0.000059\, D \times L + 0.000001 S \times D \times L \qquad (2)$$

It is note from these equations that the coefficients of applied load, sliding distance, sliding speed and their interactions are positive which indicates that wear increases with the increase in the wear parameters. It indicates that sliding distance is the main factor on wear rate for femur bone.

It is followed by load while the sliding speed was less effective than the other parameters. The interaction coefficients between load/sliding speed, load/sliding distance, sliding speed/sliding distance are negative. This indicates that combined effects of these combinations are less effective on the wear rate. Also the interactions between the three variables are positive which will effect on the wear rate.

## 4. Conclusions

From the experimental analysis carried out on human male femoral bone of age 20-30. The following conclusions have been drawn.

i) During normal activities, the femur is sensitive to different types of loads and different regions of femur process have different mechanical properties. These mechanical properties like hardness, wear characteristics vary from region to region because of its composition.

ii) The hardness of the femur shaft increases from proximal to distal region.

iii) Hardness of femoral bone influences on the wear rate. The wear rate of the condyle region specimens is less compared to head region.

iv) Wear rate of femur bone increased with increasing sliding distance, load and their interactions and wear rate of material is depend on the hardness of bone.

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