BIOARTICULAR FRICTION

Ionut Cristian Romanu [1], Emanuel Diaconescu[1]

[1] Department of Mechanical Engineering, University of Suceava, Romania

ionutromanucristian@yahoo.com , emdi@fim.usv.ro

ABSTRACT

The present paper illustrates experimental investigations of bioarticular friction. The first set of experiments was conducted on a pig synovial joint and the second one investigates the friction between a spherical cap made out of cartilage and an elastic half-space. For the experimental investigations, a device was conceived and built that ensures rolling and sliding movements of the joint.

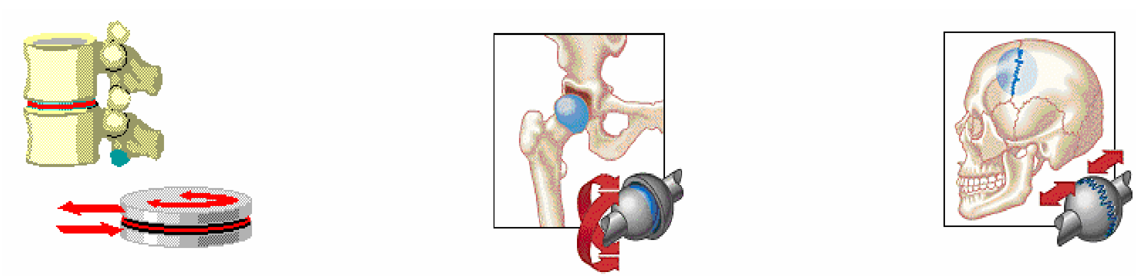
Keywords*: bioarticular friction, friction coefficient, synovial* joints

INTRODUCTION

The human body contains 143 joints that connect skeletal bones. Most of these joints are synovial and represent the object of present study. Human synovial joints are subjected to various and large forces under static and dynamic loading, while executing sliding and rolling movements.
A joint represents the connection between two or more bones, via a fibers and ligaments. Viewed from the mechanical engineer's perspective, joints can be treated as cinematic couplings. A healthy joint must ensure a series of functions such as:
- allowing bone movements in particular directions;
- ensuring low friction between contacting surfaces;
- receiving and transmitting forces;
- shock and vibration damping.

JOINT TYPES

The first to classify the joints into categories was Bichat [3]. Using physiological characteristics as a criterion, Bichat suggested that joints are either: mobile joints (later named diarthrosis by Galien [5]) or fixed joints (also named synarthrosis). Another type of joint can be distinguished, having less mobility, it is called amphiarthrosis.



Amphiarthrosis *Diarthrosis* *Synarthrosis*

Figure 1**:** Types of joints [3]

EXPERIMENTAL SET-UP

Experimental investigations were conducted on a joint from an approximately 250 days old pig. For preservation, the joint was kept in a container filled with 0.98% saline solution, at constant temperature and in darkness.
Mechanically, the joint was clamped on an adjustable arm at one end and to a stiff enough elastic lamella at the other. The elastic lamella is rigidly bound to the mobile core of an electro-dynamic actuator. Once the actuator is turned on, the joint is subjected to both rolling and sliding movements.
Besides the mechanical part ensuring joint movements shown in figure 2, the experimental set-up consists of the following auxiliary components: signal generator, audio amplifier, strain indicator, oscilloscope and PC.

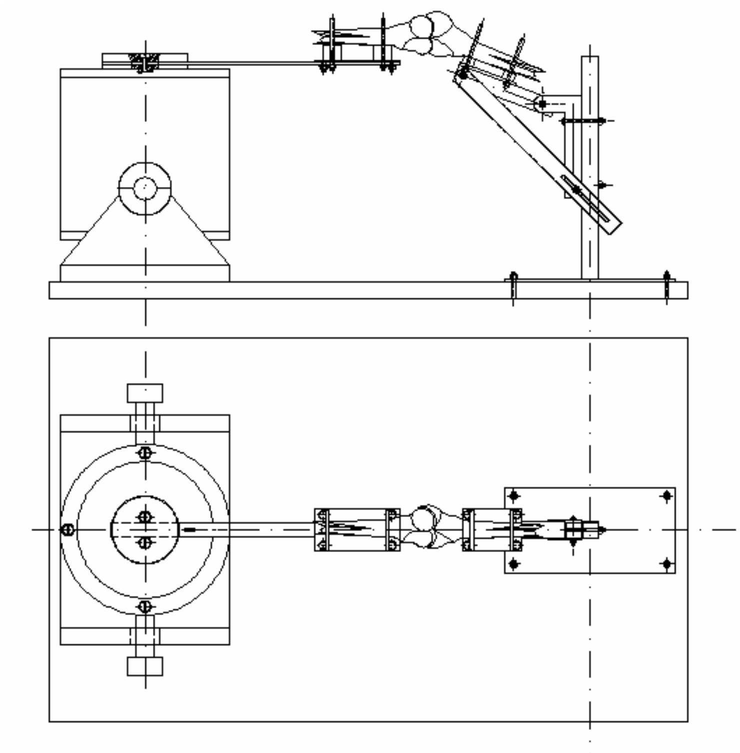


Figure 2: Experimental set-up

The devices used in the experimental installation are connected one to another as illustrated in figure 3:

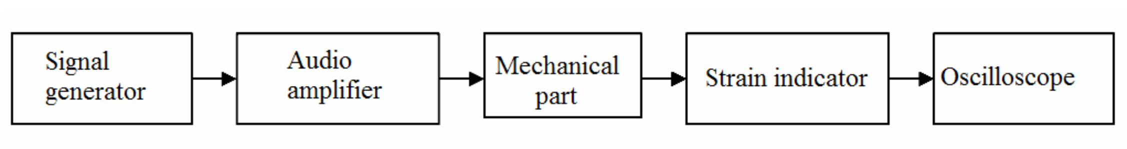


Figure 3: The connections between devices.

The first step of presented experimental investigations was calibration of the measuring devices. To that end, the strain indicator is first set to indicate „0" when subjected no load, and a sinusoidal signal with a frequency of 3 Hz and an amplitude of 0.8V is programmed at the signal generator's output. In order to quantitatively assess forces transmitted in joints, the elastic lamella was loaded using dead weights of known mass and the values indicated by the strain indicator were written in the table 1.

Table 1: Loading device calibration values

Weight [g]	Strain indicator value [mV/V]	Equivalent load [N]
5	0.002	0.05
10	0.004	0.1
20	0.007	0.2
25	0.008	0.25
30	0.01	0.3
50	0.016	0.5
100	0.031	1
150	0.046	1.5
200	0.061	2

After calibrating the measuring apparatus, the joint was fixed into position on the device as described before, and measurements were taken under different conditions.

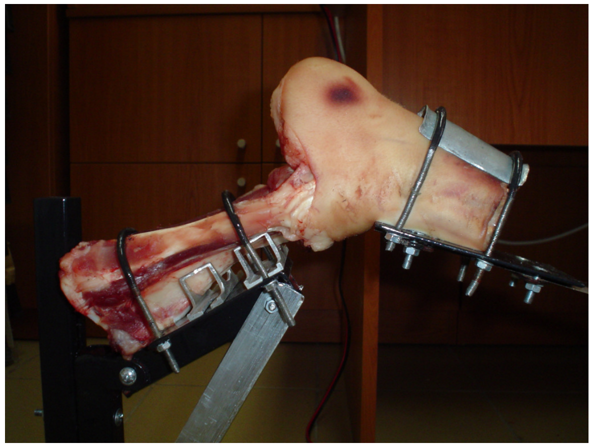


Figure 4: Joint clamped on the experimental apparatus

Experimental measurements of friction were made for several different frequencies, in the form of oscilloscope graphical charts, as the one illustrated in figure 5.

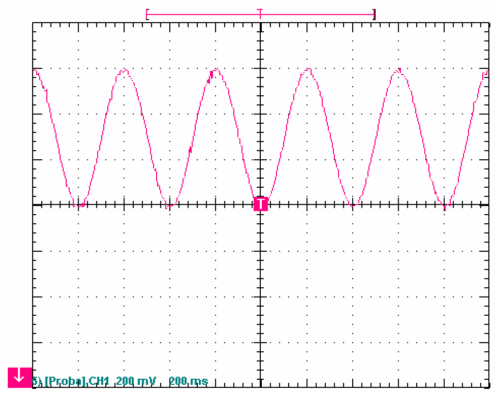


Figure 5: Friction curve at 2Hz.

In order to calculate joint friction, the 2Hz chart was considered. This frequency corresponds to a 1,80m tall man having an average step width of 0,8m / step, at a frequency of 2 steps / s. This means he would walk at a speed of 1.6m / s or 5.7 km / h, which represents the average speed at which a normal human is moving most of the time. The graph in figure 5 indicates peak to peak signal amplitude is 410mV, and 205mV for a half alternation respectively. When comparing the obtained charts with values from when the device was statically loaded for calibration, it is shown that for a load of 100g (1N), an output voltage of 220 mV is generated. That way, it is possible to graphically conclude that maximum joint friction occurs when the signal reaches a maximum. For such maximum the force can be evaluated as shown in eq. (1):

$$F_f = \frac{1 \cdot 205}{220} = 0.931N \qquad (1)$$

Thus, for a 2 Hz frequency, the friction force was evaluated at 0.931N. This measured force is the result of both cartilage friction and loss due to friction between articular tissue linings.
To better assess friction force between bone ends in a joint, a second experimental rig described in [7] and [8] was employed to study the contact between a bone end and a flat glass surface. The investigations are based on contact mechanics theory, according to which the contact between two spherical punches (bone ends in this case) can be replaced by the contact of an equivalent punch pressed against half-space (represented by the glass plate).

Figure 6: Second experimental set-up [7]

The second experimental set-up consists of a mechanical part that ensures loading and movement of the bone pressed against a glass plate, strain indicator, oscilloscope and PC.
As before, the test rig was first calibrated, obtaining for the elastic lamella used in friction measurements a calibrating curve as the one shown in figure 7.

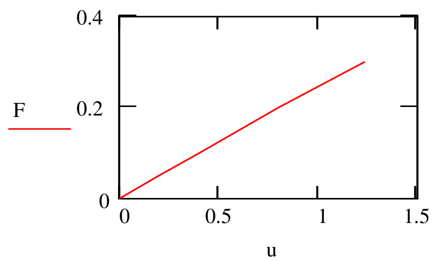


Figure 7: Elastic lamella calibration curve

In the experimental investigations the following steps were covered:
- Cleaning the glass disc;
- Connecting the experimental device to the power supply and strain indicator;
- Interfacing oscilloscope and strain indicator;
- Calibrating strain indicator
- Equipment functionality was checked before fixing bone end;
- Fixing bone end on the support by screw
- Lowering the glass disc until contact with bone end is established.
- Operating the test rig, thus creating bone end movements, and recording friction charts as the one in figure 8.

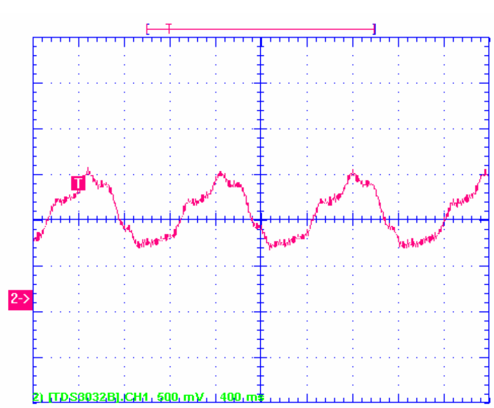


Figure 8: Friction curve at 15 N loading

The chart in figure 5 indicates peak to peak signal amplitude of 0,8V, value obtained during calibrations at a 20 g weight, which corresponds to a 0,2N applied force.
In order to validate the experiments, friction coefficient was calculated and compared against literature values. Thus, for a friction force of 0.2 N at a 15N load, the resulting friction coefficient is:

$$\mu = \frac{F_f}{N} = \frac{0.2}{15} = 0{,}013 \qquad (2)$$

This value was found to be close to friction coefficient values from literature.
Another set of tests involved placing water between the bone end and glass plate, thus better modeling real life lubrication conditions. A typical resulting friction curve is shown in figure 9:

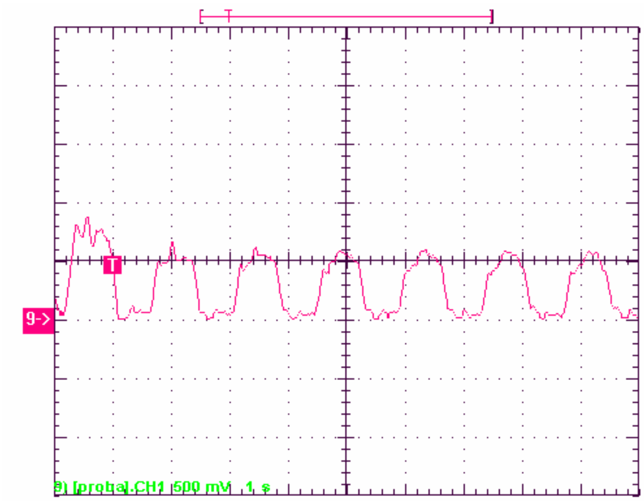


Figure 9: Friction curve (with water lubrication)

According to the chart signal amplitude is 0.6V, which corresponds to a static load of 0.15N, leading to a friction coefficient value as follows:

$$\mu = \frac{F_f}{N} = \frac{0.15}{15} = 0{,}01 \qquad (3)$$

From these results it can be concluded, that in the presence of a lubricating layer (in this case water), friction decreases up to 70% from its initial value. Water was chosen as lubricant because synovial fluid is 90% water.

CONCLUSIONS

The work reported here can be summarized by a few conclusions listed below:
The first experiment aimed to determine joint friction without separating joint elements. Several measurements were taken at different frequencies and friction force was calculated at 2 Hz, frequency corresponding to a 1,8 m tall man walking at 5.7km per hour. For these conditions a friction force of 0.931N was determined to appear in the joint.
At first glance such friction value may seem high, but this value includes the friction between cartilage covered bone ends and that between tissues lining the joint.
Graphical results show an increase in friction with frequency, which can be attributed to intra-articular fluid viscosity.
For better determination of friction, a second test rig was employed, in which cartilage covered bone ends moves against a flat glass surface. From this second experiment, friction forces were evaluated at 0.2 N for dry contact and at 0.15N when a liquid (water) was used as lubricant respectively.
On the second rig, measurements were taken at the same frequency (given by the motor drive of the device), but contact load varied.
Linear dependence of friction to load could be observed.
In order to validate obtained results, friction coefficients were calculated and found to be in good agreement with literature values.

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