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Experimental Stress Analysis

Design of Experimental Device for Loading the Femur When Standing on One Leg

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Abstract: The contribution presents the context of the need to address biomechanical problems in human society. Some dysfunctions are solved by replacing the bone contact surfaces with implants (TEP, hip resurfacing, Proxima DePuy). With the aid of computer modeling, we can predict the behavior of implants in the human body with a certain degree of simplification. These computer simulations, however, could not be carried out without experimental verification. The output of the work is an experimental device that allows for loading the femur with a known load with measuring the response variables – strain on the bone surface.

Keywords: Experimental, Hip Joint, Loading device

1. Introduction

The need for biomechanical problems is obvious from the well known phenomena such as extending the active life of the human population, increasing numbers of trauma and unilaterally oriented way of life leading to unbalanced mental and physical activity. For solving the biomechanical problems we can use experimental and computational modelling.

In this paper we consider an experiment whose purpose is to verify the computational model of the thigh bone (femur) to load the appropriate standing on one leg. This model is used to resolve stress-strain states of different hip joint implants ([1], [2] and [3]):

- Compared with the physiological state of the implant.
- The establishment (alignment) of the implant components in the bone.
- Incidence and description of phenomena: the impingement, notching and stress-shielding.

2. Problem formulation

The problem is the verification of computer modelling by the experimental device, which will load the sample (femur) to match the load of standing on one leg. Furthermore, the definition of response variables for comparative analysis with computational models and suggest measuring chain for determining this variable. Objectives of the solution:

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- Construct an appropriate device. Design of: clamping and loading the sample, scanning the applied load, measuring chain.
- Propose a method to capture response variable, the deployment of sensors and measuring chain.
- Debugging of test equipment and measuring chains.

3. Materials and methods

3.1. Description of the loaded object (optional supports from a mechanical standpoint)

The loading analysis assumes free body diagram of the femur bone from the human body. Significant interactions we could consider in the proximal femoral head and the pelvic hole, than the trochanteric protrusion of the femur and ischium muscle group. In the opposite side (distal side of femur) we could consider the transposed contact force acting on the lower surface of the foot to the knee (Fig. 1). Where we use the following description: g - gravitational acceleration; F_S – force reaction from seating system of muscles, F_J - force acting from the acetabulum socket, F_P – given force from the pad, M_P - the moment of the resulting shift of force F_P, distance x.

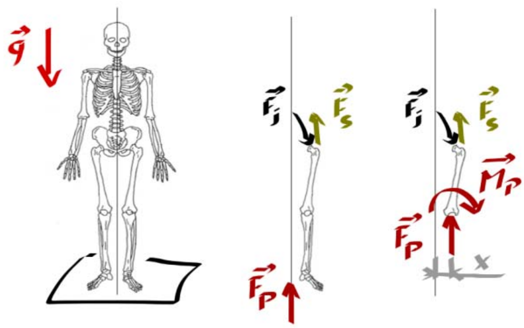

Fig. 1. Free body diagram for femur

For simplicity, consider a planar state. Under this assumption, consider the femur of the following supports:

- Acetabulum and femoral head → spherical support.
- Trochanteric protrusion and ischium muscles → link support.
- Distal end of femur → sliding support (loading of bone strength and twisting effect).

3.2. Constructing the device

The initial design idea was done based on previous work ([4] - [9]) and analysis in the previous chapter. Long discussion about the sample loading and how to measure the necessary variables yielded the final design of the device (Fig. 2).

Realization of 3D supports is shown in the picture. Possible moves for the establishment of the device are shown on Fig. 2. Description of the supports:

- Spherical support: the femoral head fits into the load system socket. Required load is applied by downward movement of the socket, which is done by rotating the load screw. Alignment of the socket against to the femoral head is corresponding to the physiological condition of the hip (anteverse 15°, 45° inclination, from [10]).
- Link support. The proximal part of the bone is anchored by steel wires. The other ends of the wires are mounted in loading system, which allows us to set the preload of each wire.

- Sliding support allows us to control the rotation of the distal end of the bone by adjustable screws in directions Rx, Ry, while Rz is fixed. Furthermore, it allows free displacement in the x-axis, the other are fixed. With these degrees of freedom will be the end of the distal femur loaded by force and force couple. The design includes force sensors so that each sensor transmits only axial load.

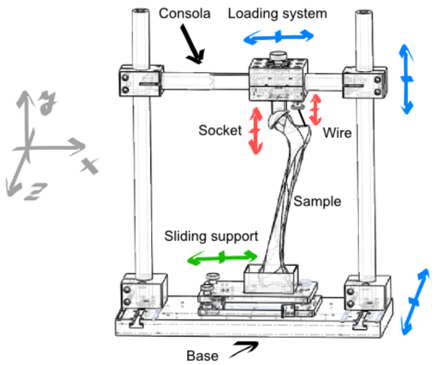

Fig. 2. Design of the experimental device

3.3. The method of determining the load

Thanks to the used supports the load is determined by:

- Force sensors (the principle of strain gauges) at the sliding support (forces F_1, F_2, F_3, see Fig. 3).
- Detection of the acting forces in wires (link support) by electromagnetic sensor.

For purposes of measuring HBM MGCplus station was used. Signal processing was done (preamp, etc.) by device AP815 I, followed by used 24-bit AD converter ML 801 B. The force transducers (HBM-C9B 1kN) are connected to full bridge. For signal evaluation HBM Catman software was applied.

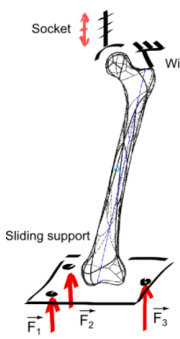

Fig. 3. Forces acting on the sliding support

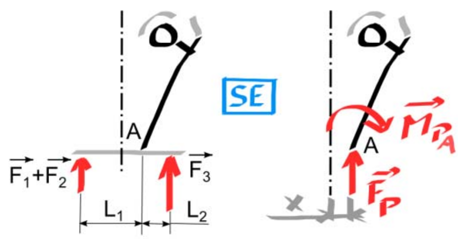

Fig. 4. Principle of loading the femoral head compared to free body diagram

A certain problem arises if we want to measure the acting forces in the steel wires during sample loading. Steel wires are relatively short so the integration of any strain gauge is not possible. It acceded to the approximate measurements of these forces acoustic path. Approximate, thanks to the problematic behaviour of steel wire. Brook Taylor relationship is used to determine the load force thanks to known frequency:

$$f = \frac{1}{2 \cdot l} \cdot \sqrt{\frac{F}{m\prime}} \quad (1)$$

where: f – frequency [Hz], F – load force [N], l – length of wire [m], m'- mass per unit length [kg · m^{-1}].

The problem is to determine the unit weight of steel wire, where it is difficult to gauge the density. It is easier to determine the weight values divided by length (and get m'). But even this procedure is unsuccessful probably due to the fact that the derived relationship is valid for prismatic beam of the string character (length >> diameter).

The m' were experimentally determined using a universal load testing machine ZWICK. Steel wire was clamped in the jaws of the machine and loaded by a known tensile force. Wire was stroked by impulse and the following oscillation was captured. The time dependence of oscillation was followed by FFT - convert the signal into the frequency domain, with an indication of the base frequency f. Sequence of measurements:

- Scanning acoustic vibrations excited in the wire (use an electromagnetic sensor FOCUS-H involvement coils in parallel).
- Verification by acoustic microphone (Bruel & Kjaer, type 4189 with amplifier type 2669).
- Implementation of FFT (Fast Fourier Transfer - transfer the signal from time domain to frequency domain) in the freeware program Audacity (version 1.2.6). The microphone signal was processed in the program HBM Catman.
- Frequency evaluates.
- Determination of unit weight.

3.4. Measured values for comparison with computational model

Strain was determined for monitoring the response on loading. For this purpose is used a strain rosette (HBM RY11-3/120). Each of strain gauge is in four-wire connection (this set compensate the effects of temperature on the wiring) into one-quarter bridge. Which means that the measuring system is not compensate to the effect of temperature on the rose. We have neglected the change of temperature and strain rosette sample, for the relatively rapid progress of measurement. Following variables will be compared with computational models: Previously mentioned forces (F1, F2 a F3) and forces in wires; Strain on the bone.

4. Results

4.1. Stages of sample loading

The sample is loaded by force action and by a twisting effect (force couple). In this paper we will only consider providing force effect of contact forces F_1, F_2 and F_3.

Loading was carried out using a screw that allowed the socket movement. This creates a pressure load of the bone head. On the load dependency could be seen following step of increasing the load, than force value comparison of F_1 and F_2.

Forces determination from sliding connection:

Given: $L_1 = 80$ [mm], $L_2 = 230$ [mm], $F_1 = F_2 = 140$ [N], $F_3 = 530$ [N].

Analyses of forces from the sliding support see Fig. 4.

$$F_P = \left|F_1 + F_2 = F_{1,2}\right| = \frac{F_{1,2}+F_3}{2} = \frac{280+530}{2} = 405\ [N] \quad (2)$$

This force is approximately half the weight of a person (40.5 kg)

4.2. Measurement of strain on the surface of the femur

The monitored variables are the strain of the reference point on the surface of the bone neck. These values will be used for comparison with computational models (see Fig. 5 and Fig. 6).

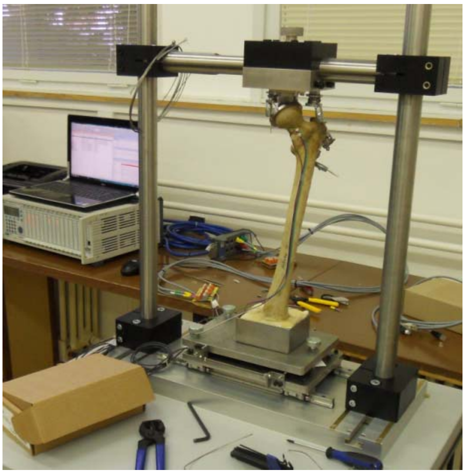

Fig. 5. Experimental device during the measurement

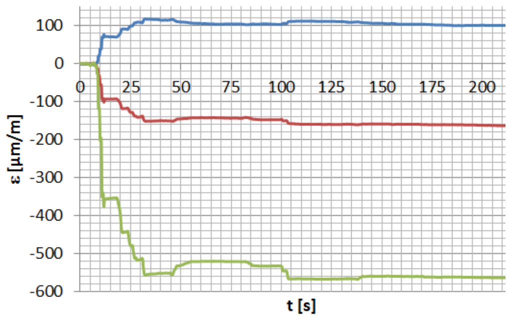

Fig. 6. The strain measured on the strain rosette applied on the bottom femoral neck

4.3. Determination of forces in the wires

In the time of writing this paper, only the debugging of method was done. Direct determining of the forces, when loading the femur, has not been performed.

The experiment was aimed to determine the material characteristics under known load and the known length of strings (L = 135 mm) from the equivalent relationship:

$$m' = \frac{F}{4 \cdot l^2 \cdot f^2} \quad (3)$$

Table 1. Recommended mathematical element sizes

Frequency [Hz]		Loading force [N]	Evaluated material property: m' [kg.m^{-1}]
Electromagnetic sensor	Acoustic microphone		
731	730	210	9.197E-3
984	991	410	9.763E-3
1161	1166	610	10.525E-3

5. Conclusion

The paper presents the results of work in the field of biomechanical problems related to the hip joint. The work is focused on the construction design of experimental equipment for loading the thigh bone (femur) with the aim of simulating loading in human body as close as possible. Results can be organized into the following points:

- Creation of experimental device for loading the femur.
- Implemented test measurements for debugging during loading.
- Debugging of measuring chains needed to detect the load. Preparation of a methodology for determining forces which acts in steel wires by acoustic method.

The device can be used for:

- Loading the long bones (device allows for modification of the working space).
- Measuring the responses related to loading the long bone.
- Strain gauges can be applied on bone.

Future procedure:

- Small design modifications required for the installation of wiring and easy manipulation of connectors for connecting the measuring station.
- Loading of "fresh" pig bones for the different material characteristics of the currently used bone.
- Loading of the femur which involves some of hip joint implant (e.g. resurfacing).

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