DESIGNING AN EXPERIMENTAL STAND TO TEST THE FRICTION TORQUE ON A HIP PROSTHESIS FEMORAL HEAD

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Abstract. *In order to carry out implants' fatigue tests under physiologic loading conditions, it is required to know the forces acting on the hip joint. A wear testing machine which is able to test the actual prostheses is called a hip simulator. Over the years various researches on various kinds of simulators and implants have been performed. The goal of this paper is to present a few versions of hip simulators along with an experimental stand version of our own design, to test the friction torque on the femoral head of a hip prosthesis, which allows simulating the main movements occurring in the hip joint, i.e. flexion-extension, internal rotation - external rotation, microseparation movement.*

Keywords: *stand, loading, joint, implants, wear*

1. INTRODUCTION

Human gait is a cyclic locomotor movement, achieved by successive positioning of one foot in front of the other [1]. During walking one of the lower limbs extends while the other lower limb swings as it leaves the ground in order to be propelled forward and then to be fixed on the ground again in front of the supporting leg, each of the two legs acting alternately as propeller and support.

During walking, when switching the step (that is, when the body is supported by one leg), the gluteus medius muscle (Figure 1, position 2) must develop a force four times bigger than the body weight [2]. Therefore, according to the first order lever laws, a force of 400 kgf will be exerted on the femoral head (Figure 1, position 5) of a person weighing 100 kg.

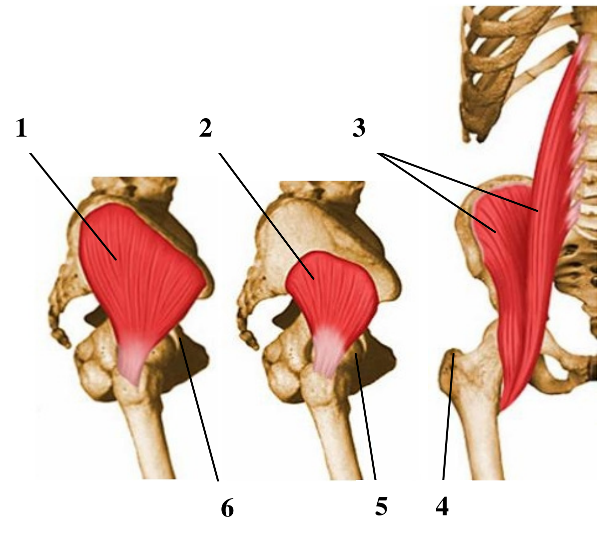

Figure 1. Hip joint:
1. gluteus maximus **2.** gluteus medius, **3.** iliopsoas, **4.** greater trochanter**, 5.** femoral head, **6.** acetabular cup [3]

2. FORCES ACTING ON THE HIP JOINT

In order to carry out implants' fatigue tests under physiologic loading conditions, it is required to know the forces acting on the hip joint. For the functional optimization of implants it is necessary to know these forces. In the unipodal stance, the iliopsoas (Figure 1, position 3) is an anterointernal stabilizer while the gluteus medius (position 2) is a lateral stabilizer of the hip. The gluteus medius is positioned like a set square with the angle towards the inside, forming a lateral muscular belt pressed on the side of the greater trochanter (position 4), thus pressing the femoral head in the acetabular cup (position 6). At the anterior side of the coxofemoral joint, the iliopsoas, due to its positioning and orientation, forms a muscular belt that pushes the femoral head back. The muscle couple formed by the iliopsoas and the gluteus medius creates a balance of forces and causes a reaction in the joint, which adds to that of the body weight itself. Figure 2 [4].

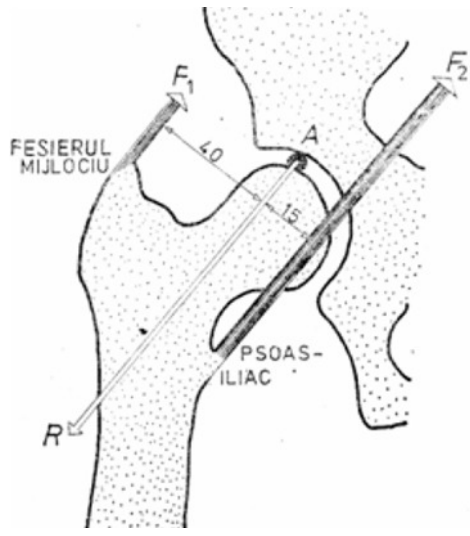

Figure 2. The forces developed by the iliopsoas and the gluteus medius [4]

When the body is supported by one leg, in the equilibrium phase, the following can be noted [4]:

$F1 \times 40 = F2 \times 15$

Where:

F1 = the force developed by the gluteus medius;

F2 = the force developed by the iliopsoas;

40 and 15 = the distances (given in mm) between the forces and the reaction R.

Admitting that F1 = 1 N, it follows that:

$F2 = 1 \times 40/15 = 2{,}66$ N

$R = F1 + F2 = 1 + 2{,}66 = 3{,}66$ N

A movement towards the inside, however small, of the supporting point A, results in an increase of the reaction force. Thus, a movement of only 5 mm leads to:

$F2 = 1 \times 45/10 = 4{,}5$ N

$R = F1 + F2 = 1 + 4{,}5 = 5{,}5$ N

This means that a force of 100 kgf developed by the gluteus medius (F1 = 100 kgf) will result in F2 = 100 x 40/15 = 266.66 kgf, and the reaction force at point A will be R = 366.66 kgf. If the supporting point A moves only by 5 mm towards the inside, then F2 = 100 x 45/10 = 450kgf, and the reaction force of the joint at point A will be R = 550kgf [4].

Anteroposterior and lateral oscillations of the body that are necessary to maintain the balance in standing on one leg are higher than those required to maintain the bipedal position and produce important changes in pressure on the bone segments of the hip joint [4].

As demonstrated by G. Bergmann and other authors, during walking, the forces of the average peaks in the hip joint are of 1800N and the forces of the high peaks are of 3900N. When climbing stairs, the forces of the average peaks are of 1900N and the forces of the high peaks are of 4200N. When stumbling, the highest peaks force is of 11000N [5]. The values obtained are the result of measurements made on a limited number of subjects.

3. TYPES OF HIP SIMULATORS

A wear testing machine, able to test the actual prostheses, is called a hip simulator. Over the years various researches on various kinds of simulators and implants have been performed. Some versions of hip simulators are presented below.

3.1 Experimental stand for tribological study of hip prostheses, made at the Department of Machine Elements and Tribology, University Politehnica of Bucharest

An experimental stand for tribological study of hip prostheses is presented by Tiberiu Laurian [6] (Figure 3).

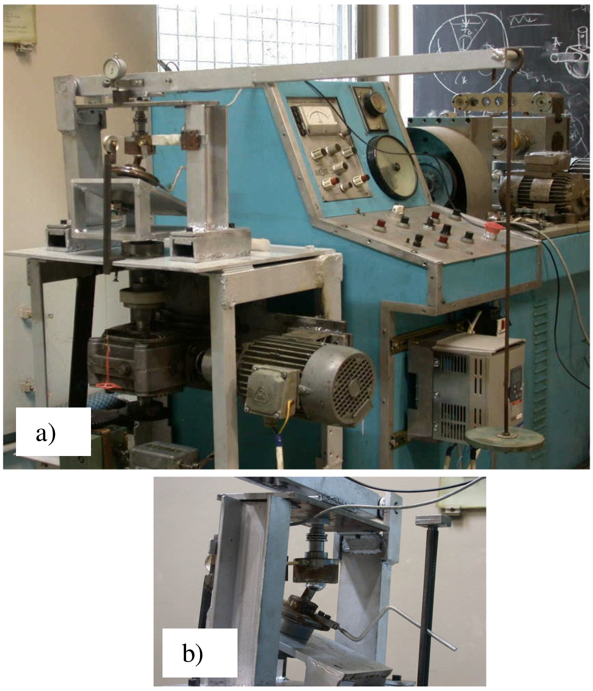

Figure 3. Experimental stand for tribological study of hip prostheses, made at the Department of Machine Elements and Tribology, University Politehnica of Bucharest [6]. a) overview, b) detail

The simulator allows measuring two parameters defining the tribological behavior of the studied torque. These are the moment of friction in the joint and the relative proximity between the acetabular and the femoral components – a proximity monitored throughout the test. [6]

3.2 The HJS simulator

Another version of simulator is presented by VAGonzalez-Mora et al. (2009) [7]. The HJS type simulator is a three-operating position system with a type of biaxial rocking motion, Figure 4.

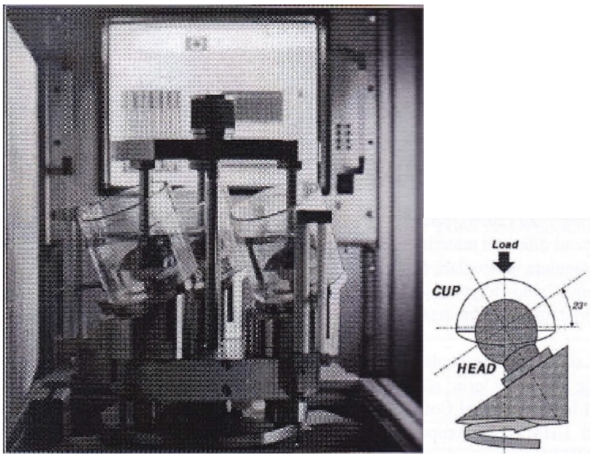

Figure 4. HJS simulator with three operating positions [7].

A biaxial swinging motion of the femoral heads is applied on the HJS simulator, through a rotational angle block fitted under the femoral head. This provides a practical engineering application of walking, in vitro, simulating the flexion-extension and the abduction-adduction movements [7].

The abduction-adduction movement range is four times larger than the actual movement of abduction-adduction of the human hip joint in walking. In this way the walking kinematics is estimated exaggeratedly [7]. However, the HJS device was designed to provide a practical simulation of the motions and loads on the hip joint during a typical walking cycle [7].

3.3 The Leeds II hip simulator

Another type of hip simulator is presented Elhaidi Sariali et al. (2010) [8]. The selected type of hip simulator is Leeds II, for which there was developed, using the ADAMS software, a three-dimensional model simulating a controlled microseparation similar to the movement that occurs during the swinging phase of the walking cycle [8]. The microseparation has been simulated in vitro with a modified hip simulator using springs (figure 5) [9].

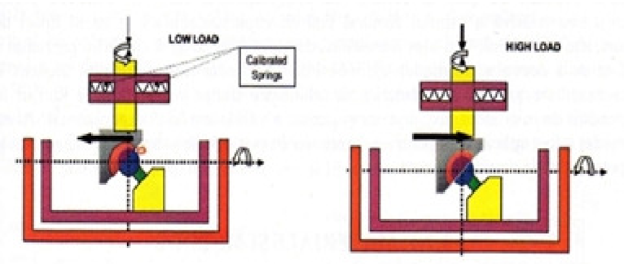

Figure 5. Modified simulator for microseparation movement [8]

The Leeds II simulator consists of two major parts: the upper part that supports the cup and the lower part that supports the femoral stem. The cup-supporting part allows a rotation around a vertical axis and two translations, an anteroposterior one and a mediolateral one. The cup rotation reproduces the external-internal rotation of the hip. The mediolateral translation is controlled by two springs which limit its motion range to 500µm [8]. The preload of the springs was set at the start of each simulation to control the amplitude of the separation. The lower part supporting the femoral stem allows a rotation around a horizontal axis and reproduces the flexion / extension of the hip [8].

On the Leeds II simulator the separation was reproduced using two calibrated springs placed on either side of the cup-supporting part. These springs impose a medial separation of the cup-supporting part of maximum 500µm. If the load increases during the stance phase, this forces the cup-supporting part to reposition itself over the femoral head. If, on the contrary, the force decreases during the swinging phase, the springs impose a medial translation of the carriage and thus the lateralization of the femoral head takes places [8].

3.4 The Manchester simulator

Another type of simulator, "Simulator solutions, Manchester, UK", with a single testing position, is presented by Claire Brockett et al. [10], Figure 6.

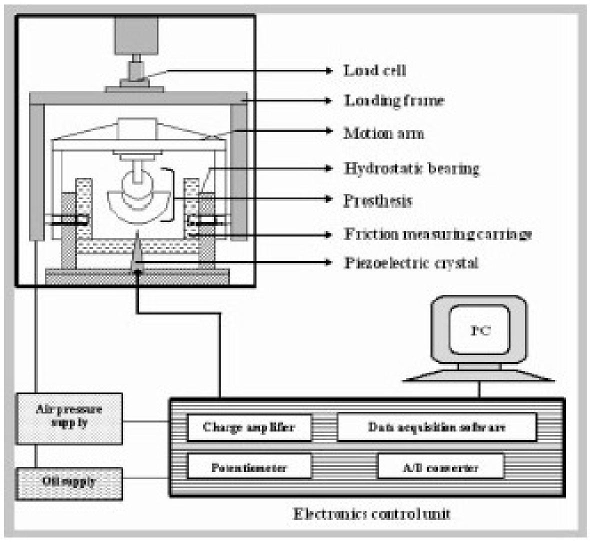

Figure 6. Manchester simulator [10]

In the simulator mentioned in the paper, the implants were reversed from the anatomical position. The tests were carried out on the forward and backward directions using the same loading conditions. To determine the friction torque the following equation [10] was used:

$M = (M1-M2)/2$, where:
M is the real friction torque
M1 is the friction torque measured on the twisting "forward" direction
M2 is the friction torque measured on the twisting "backward" direction

The friction coefficient is calculated based on the actual friction torque, using the formula:

$\mu = M / R N$

where: R is the radius of the cup, and N is the maximum load.

There are professional systems for the dynamic multiaxial testing of hip implants (Figure 7), but they are very expensive, their price exceeding EUR 150,000.

Since Romania does not produce hip implants on an industrial scale and professional simulators are expensive, we have designed an experimental stand to test the friction torque affecting the femoral head of a hip prosthesis. The stand is designed to allow the simulation of the main movements occurring in the hip joint, namely: the flexion-extension, internal rotation - external rotation and microseparation movements.

Figure 7. Professional system for dynamic multiaxial testing

4. EXPERIMENTAL STAND DESIGNED TO TEST THE FRICTION TORQUE AFFECTING THE FEMORAL HEAD OF A HIP PROSTHESIS

Hip simulators should be able to provide testing conditions very close to the proper physiological, kinematic and anatomical conditions, similar to those of the human joints. In actual fact, no simulator meets exactly such quality.

In terms of kinematics there are three distinct categories of hip simulators:

- motion simulators with independent movements on each of the three axes - X, Y and Z
- biaxial oscillatory motion simulators
- single-motion simulators (reproducing the flexion-extension movement)

The stand was designed so as to allow the simulation of the main movements occurring in the hip joint, namely:

- the flexion-extension movement,
- the internal rotation - external rotation movement
- the microseparation movement

The experimental stand designed to test the friction torque on the femoral head of a hip prosthesis consists of the following 17 elements (Figure 8).

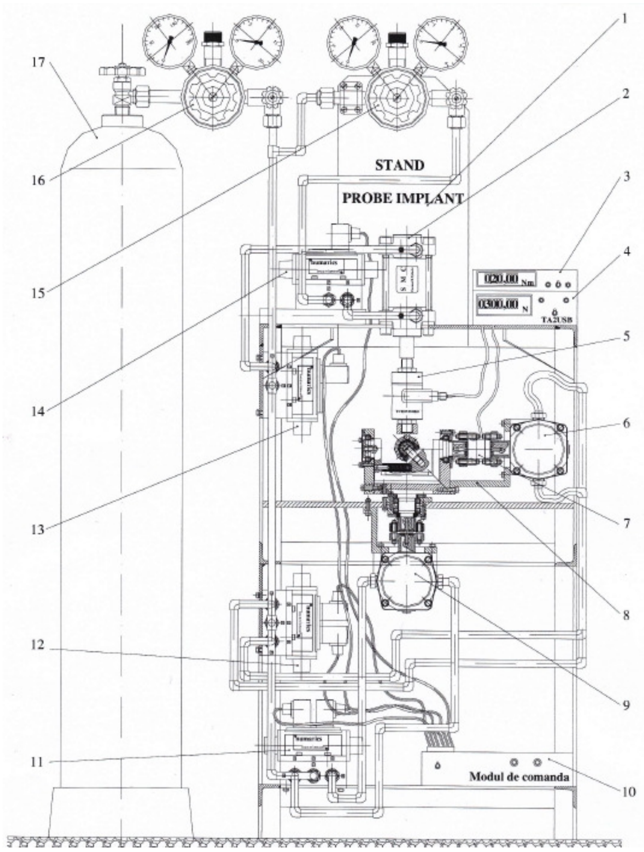

Figure 8. Experimental stand for testing the friction torque on the femoral head of a hip prosthesis

1-Bed,
2-Linear pneumatic motor,
3-Time display,
4-Force display,
5-Force sensor,
6-Rotary pneumatic motor 1,
7-Moment sensor,
8-Oscillating plate,
9- Rotary pneumatic motor 2,
10-Command module,
11-Distributor 1,
12-Distributor 2,
13-Distributor 3,
14-Distributor 4,
15-Regulator class II,
16-Regulator class V,
17-Nitrogen container

The overall dimensions of the experimental stand are: 1498 mm x 981 mm x 652 mm.

4.1 Rotation and translation movements

For the motion simulating the pressing on the femoral head there was used a SMC type double action pneumatic linear motor (Figure 9, position 2); the translation movement follows the Y axis.

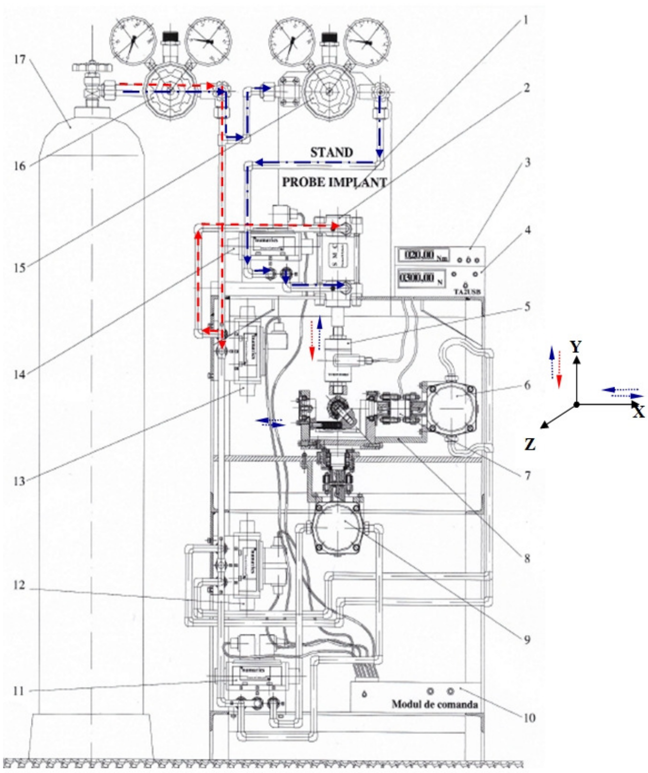

Figure 9. The circuit of the fluid used for the translation movement on the Y axis

For the flexion-extension movement, the rotation angle follows the X-axis and is limited to 150°. To obtain this type of movement, a Parker RA pneumatic rotary motor is used (Figure 10, position 6).

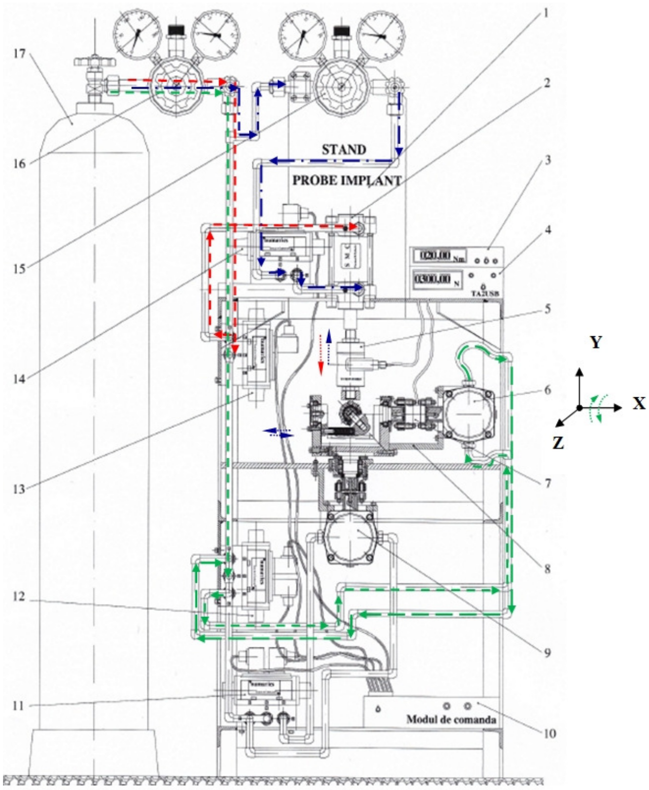

Figure 10. The circuit of the fluid used for the flexion-extension movement

For the the internal-external rotation movement the angle of rotation is around the Y-axis and is limited to 50°. The movement is simulated on the stand using a Parker RA pneumatic rotary motor (Figure 11 position 9).

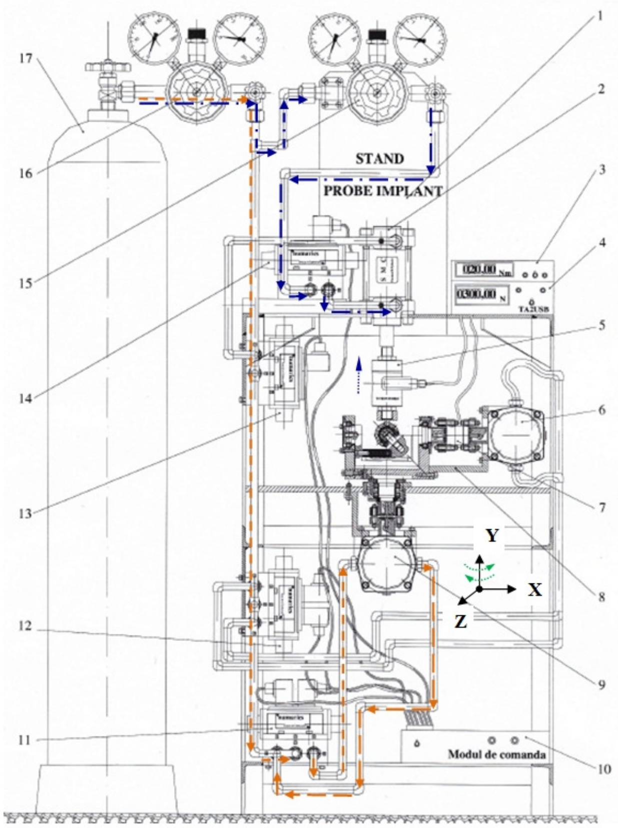

Figure 11. The circuit of the fluid used for the internal rotation-external rotation movement

The microseparation movement is produced on the Y-axis with a 500μm stroke and takes place during the swinging phase of the walking cycle. The microseparation is obtained applying a constant force on the Y-axis direction.

4.2 The command module

The command module is a semi-automated technical system that allows adjusting the parameters required in the implant testing process as well as developing the actual test cycles.The actuation within the system is pneumatic and is based on three pneumatic motors, of which two are rotary and one is linear. Each of these motors is controlled by a pneumatic electro-distributor. The two rotary motors are controlled by two 3/5-way distributors each, while the linear motor is controlled by the 2/5-way distributors. The necessity to use two different pressure levels in the linear motor operation implies the use of two pressure regulators from different classes. Each distributor will be controlled by the electronic control unit (ECU). This synchronizes the operation of the three motors and adjusts the rotation speed of the two rotary engines. The speed is adjusted by controlling the flow with the help of a voltage controlled electro-distributor, as seen in Figure 12. To change the direction of rotation on the two motors, there are used, as can be seen in the same figure, the two control voltage intervals:10V ÷ 0-5V ÷ 5V.

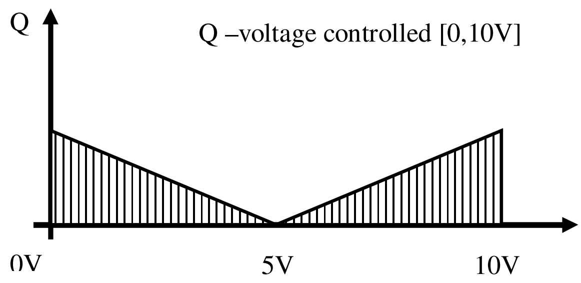

Figure 12. Control feature of the electro-distributors

The electronic control unit is provided also with an interface that enables a human operator to program the load parameters (time, force, orientations, directions, strokes) and the number of test cycles.

4.3 Electronic diagram

The electronic diagram consists of electronic devices used for the process control, adjustments, measuring, etc. Figure 13 shows a schematic diagram of the electronic control unit for the experimental stand intended to test the friction torque on the femoral head of a hip prosthesis.

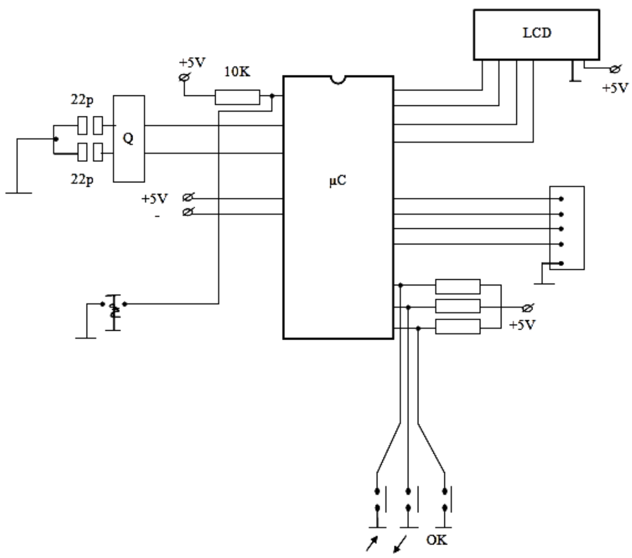

Figure 13. The electronic diagram of the control unit

The microcontroller (μC) is provided with an interface for the operator, consisting in a graphics display and three buttons enabling the user to scroll through the menu.

5. CONCLUSIONS

According to the first order lever laws, during walking a force four times bigger than the weight of a human body is developed, which means that a force of 400 kgf is exerted on the femoral head of a person weighing 100 kg. In order to carry out implants' fatigue tests under physiologic loading conditions, knowledge of the forces acting on the hip joint is required.

The designed experimental stand will allow simulating the main movements occurring in the hip joint, namely:
- the flexion-extension movement,
- the internal rotation - external rotation movement
- the microseparation movement

For the experimental stand we chose a pneumatic actuator due to the following advantages:
- high operating speeds and feed rates and low inertia,
- it allows setting installations operating in automatic cycle, using logic elements or electro-pneumatic convectors that provide higher productivity,
- the forces, moments and speeds of the pneumatic motors can be adjusted easily using simple devices to modify the pressures,
- the compressed air is relatively easy to produce and transported through networks, it is non-polluting and non-flammable and can be stored in high-pressure containers.

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