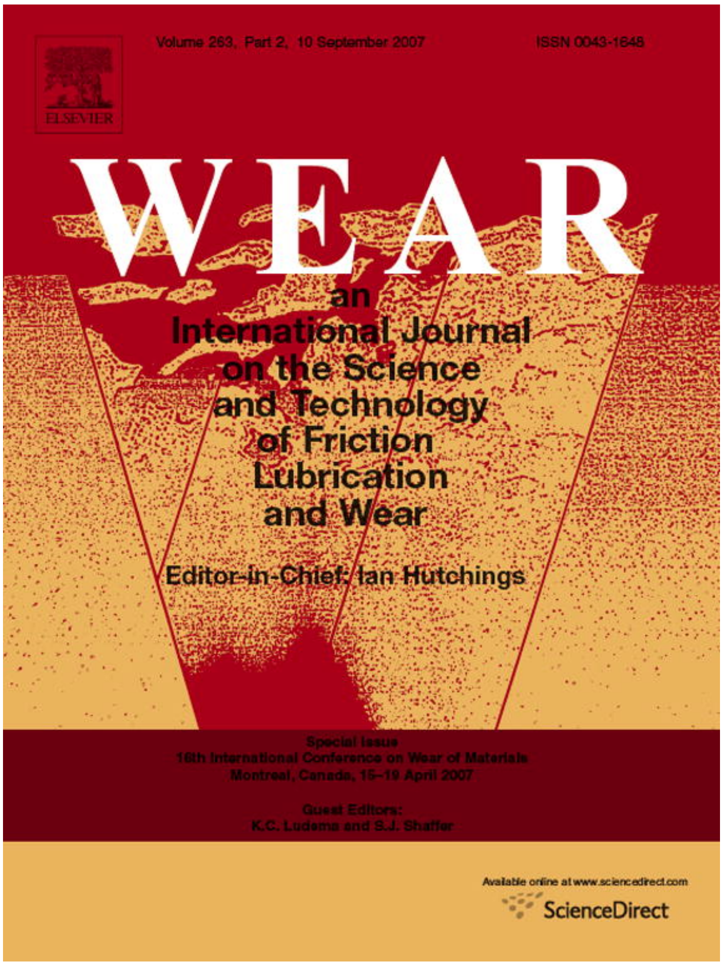

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Short communication

Development of a hip wear simulation rig including micro-separation

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Abstract

Currently, hip joint simulation is an important tool in both testing total hip prosthesis and developing new biomaterials with enhanced tribological properties. During total hip arthroplasty (THA), the ligament of the femoral head (LHF) and the cartilage of the acetabulum pelvic cup are often disrupted or degenerated and are surgically removed. Recent studies have reported that one consequence of the absence of LHF and cartilage dissection on THA patients is the micro-separation between the femoral head and the acetabulum in the artificial hip joint during normal gait. In the present work, a new hip joint simulator was developed, integrating mechanical devices and electronic control. This hip simulator provides a dynamic load close to human body conditions during walking and jogging. Also, micro-separation is included and multidirectional motions with the following amplitudes: flexion-extension (FE) ±23°, abduction-adduction (AA) ±23° and internal-external (IER) ±8°. This machine allows flexibility to use different path loads and different micro-separations amplitudes (1–4 mm) through a pneumatic muscle adapted to a springs system. Using this system is possible to measure the combined effect of micro-separation (micro-impact between the contact surfaces), multidirectional motion and the Paul load peak in a similar lubricated system, allowing more accurate replication of in vivo conditions.

Keywords: Hip joint; Simulator; Micro-separation; Wear; Biotribology

1. Introduction

Nowadays, hip joint simulator studies have become an efficient tool for basic research in biomaterials development, as well for preclinical testing to minimize patients' risk when receiving new implant [1].

Human hip joint kinematics can be analyzed in three different planes, sagital, frontal and transversal with the following motions: flexion-extension (FE), abduction-adduction (AA) and internal-external rotation (IER), respectively. Measurements of the hip joint during normal gait by Johnston and Smidt [2] postulated the design basis for wave forms, with the following amplitudes: ±23° for FE, ±5° for AA and ±7.5° for IER, see Fig. 1.

Several researchers had studied the forces acting in human hip joint during normal gait [3–5]. Therefore, through treadmills and electrogoniometry, articular reaction load peaks could be determinated, as well as its muscular activity specific correlation. In such studies, it was seen that two load peaks are produced during normal gait, see Fig. 2. The first one is produced before heel-strike and the second just before toe-off. Also during the total support phase, i.e. when the full sole lies on the floor, it was observed a decrease in the articular reaction force, below the body weight. This is expected because in this phase the body's gravity centre suffers a displacement.

In vivo wear of artificial hip joints varies strongly between patients because wear is influenced by several factors such as patient activity, weight and bone quality [1]. Joint simulators should aim to reproduce the physiological motion, loading and environment of the replacement joint in vivo as closely as possible. A hip joint simulator aims to reproduce the physiological conditions of time-dependent loading and complex three-dimensional articulation at the bearing surfaces. Important considerations include the speed, sliding distance and direction of movement; frequency, direction and magnitude of loading; the chemical composition of the test fluid and the temperature in the contact zone [6].

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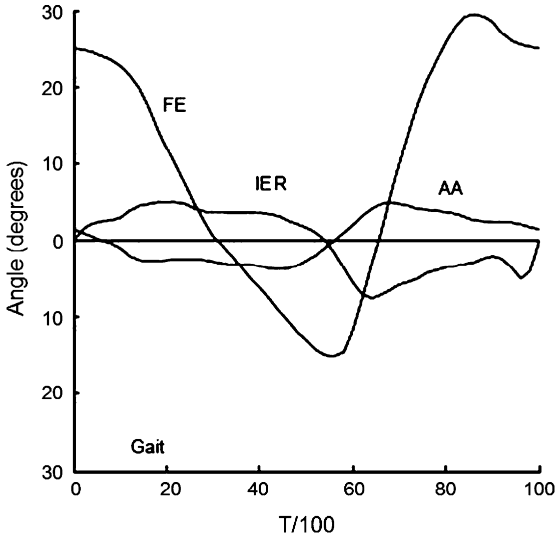

Fig. 1. Motion wave forms during normal gait [2].

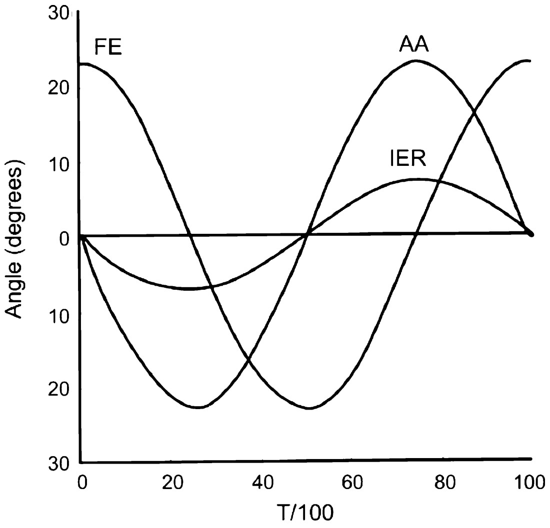

Fig. 3. Motion wave forms used in the computation of slide tracks in BRM with offset lever [19].

Natural hip joint kinematics are more closely simulated by three axes machines [6–13], than by forerunner single axis machines, executing purely flexion-extension movement [14].

More recently, video fluoroscopy has been used to determine the in vivo kinematics of the hip joint [15,16]. The investigators in these studies assumed that the motions of normal and implanted hip joints would differ since many of the soft-tissue supporting structures of the hip joint are altered by total hip arthroplasty [15–17]. The fluoroscopic studies indicated that the femoral head may slide away from the medial aspect of the acetabular component during gait and with active hip abduction and adduction, and activity [15–17]. This phenomenon is known as micro-separation [18].

In the present work, a hip joint simulator has been developed that not only reproduces the kinematic and load conditions during normal gait, but also the micro-separation phenomenon which involve a contact mechanism change between femoral and acetabular components, due to micro-impact. The problem of micro-separation has not been fully addressed by most of the hip joint simulators.

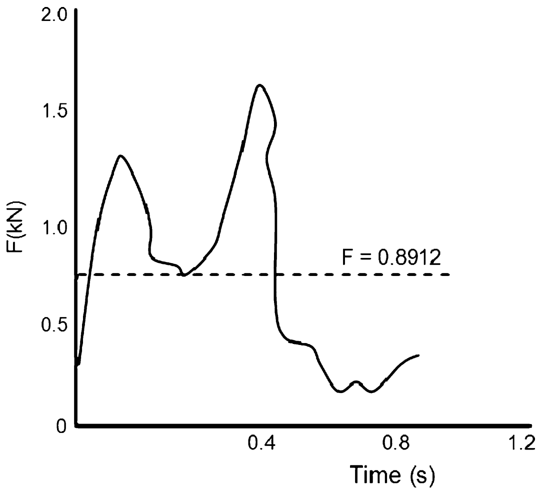

Fig. 2. Load cycle during normal gait [5].

2. Materials and methods

2.1. Kinematics

In the present work, a hip joint simulator with a biaxial rocking motion (BRM) and internal-external rotation (IER), was designed and constructed. The BRM + IER is one of the most commonly used wear-testing device for prosthetic hips around the world [19].

This hip joint simulator has four stations. All stations are loaded by one pneumatic muscle connected to a mechanical system to distribute the load to each station. Each one of the test stations, which are driven by gears, incorporates three rotational axes. The variable rotational movement is driven by an electrical motor articulating a gear box, providing an adjustable frequency with a range of 1.2–1.4 Hz. This machine will be able to reproduce a jogging cycle at a maximum frequency of 1.4 Hz along with a severe load cycle profile. The maximum range of motion is ±23° for flexion-extension, ±23° for abduction-adduction and ±7.5° for internal-external rotation as shown in Fig. 3.

The cup and the head are set in their holders respectively through screws. The cup is seated on the femoral head, which is positioned at 23° to the horizontal axis, see Fig. 4. Prior to testing, the components are individually set to the correct height to match the rotation axis of the head with the cup's load axis.

2.2. Load cycle

To reproduce the load cycle recorded during normal gait [2], the hip joint simulator uses a load system including a pneumatic muscle, which is controlled by a proportional valve that follows

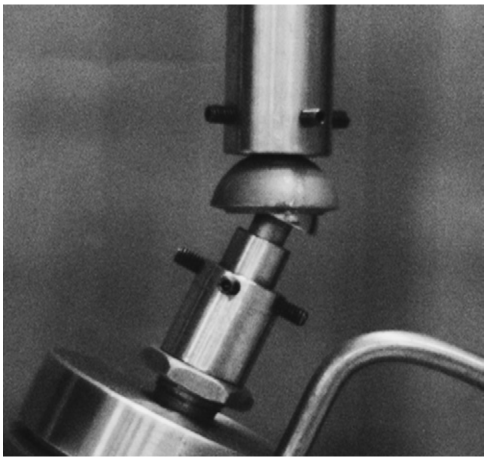

Fig. 4. Detail of the hip joint simulator station, illustrating the holders of the femoral head and the acetabular cup.

an exact real-time generation of the load profile, Fig. 5a. The proportional valve is controlled by a software.

The pneumatic muscle is a flexible membrane and it is resistant to the traction generated by air. The rate between load and mass is approximately 400:1. The pneumatic muscle was chosen because it can work at a frequency of up to 3 Hz and is capable of applying loads up to 4 kN within ±1% accuracy.

A control and monitoring system was designed for the performance of the pneumatic muscle. It can be described in two parts:

- Dynamic load control.
- Input data.

A circuit board is used to control the dynamic load. Another circuit board is used for monitoring such load in the pneumatic muscle. The load cells were integrated to measure the load variations.

2.3. Dynamic load control

Control circuit generates a voltage signal varying in time. This signal is connected to the proportional valve, which controls the pneumatic muscle. Establishing a relationship between time and load in a cycle, a dynamic load is produced. The load produced by the pneumatic muscle is transmitted to each station through a mechanical system.

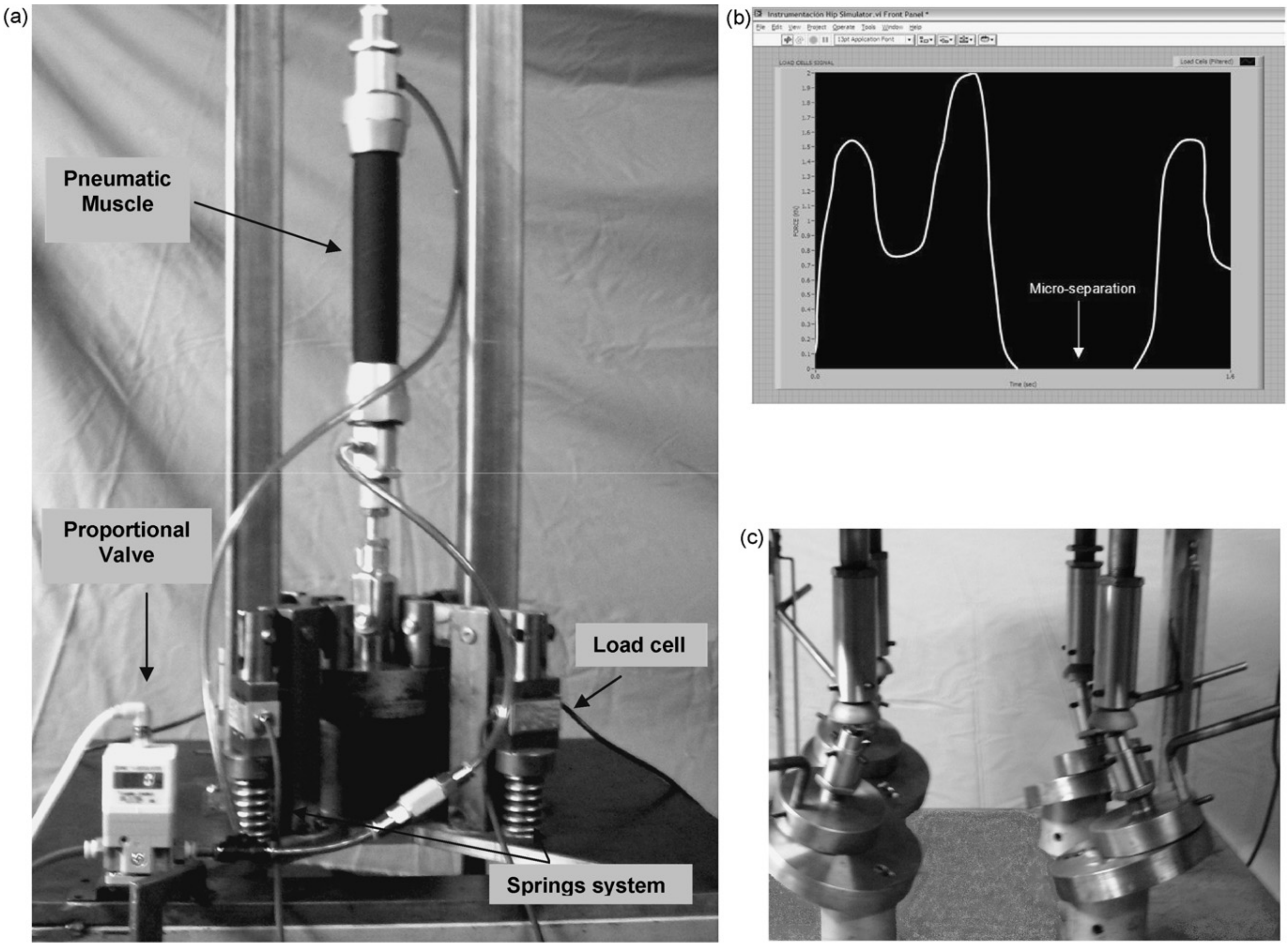

Fig. 5. Hip joint simulator FIME II illustrating: (a) load and springs system; (b) load profile obtained from load cell; (c) four stations of hip joint simulator FIME II.

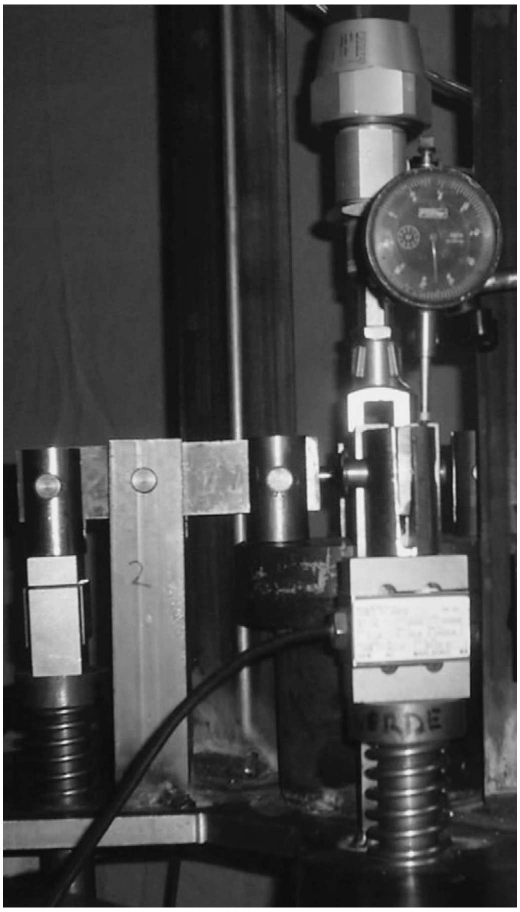

Fig. 6. Preload and calibration test of the hip joint simulator to adjust a micro-separation.

2.4. Input data

The load cells are connected to the input data circuit to get the voltage variation. This voltage variation is converted into a digital signal and is interpreted by a computer.

2.5. Micro-separation

In order to achieve micro-separation between the contact surfaces, a synchronized performance of the mechanical and control systems is required. A preload and calibration test is necessary in the setup of the hip joint simulator to adjust a micro-separation in a range from 0 to 4 mm, Fig. 6, which is the separation between the femoral and acetabular components, already estimated by in vivo studies [15–17].

During the load profile application, the surfaces of the samples are in contact. In the last part of the load cycle, where there is not load applied due to the swing phase during normal gait, Fig. 5b, the micro-separation is produced between head and cup in each station by the force generated by a spring system, Fig. 5a.

2.6. Lubricant

This new simulator will allow to conduct wear tests under lubricated conditions using bovine serum diluted to 25% in distilled water. The protein content of the bovine serum is 15.2 g/l adding 0.6 wt% streptomycin and 1% fungizone. The amount of serum to be used in each test is 125 ml, it is contained in a plastic bowl in a temperature range of 36 ± 4 °C and renewed every 100,000 cycles.

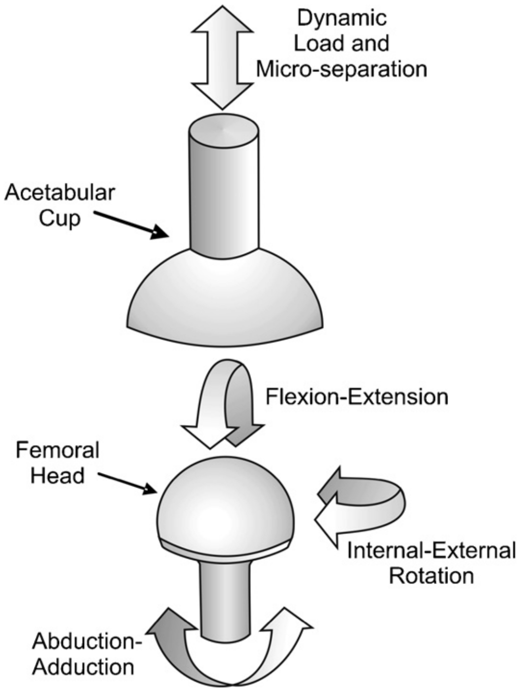

Fig. 7. Samples used in the hip joint simulator, illustrating dynamic load and micro-separation; and three axis motion.

2.7. Samples

The samples used in this simulator are the femoral head and the acetabulum prototype samples, see Fig. 7. The acetabular cups have a 7 mm thick wall and an 18 mm rod, with 20 mm length. This rod helps to set the cups in their holder. The femoral heads have a 30 mm diameter with a 12.5 rod [20].

2.8. Wear measurements

During the experiments performed in this hip joint simulator, wear is measured by the actual weight loss of the specimens using a high precision balance at a nominal precision of 0.1 mg. Readings are taken every 100,000 cycles in each sample. Samples are carefully cleaned and prepared before weight loss measures.

2.9. Surface analysis

The contact surface of each sample is analyzed first by low magnification optical microscope and followed by scanning electron microscopic analysis in order to determine the surface damage in each sample. Roughness is measured with a profilometer set at 0.48 mm of measuring length. Surface topography is determined by means of an atomic force microscope (AFM).

3. Results and discussion

In a human hip joint, the femoral head is retained within the acetabulum by numerous supporting soft-tissue structures, including the fibrous capsule, the acetabular labrum, the ligament of the head of the femur, and the iliofemoral, ischiofemoral, pubofemoral, and transverse acetabular ligament. During total hip arthroplasty, the ligament of the head of the femur is surgically removed. Additionally, a portion of the remaining supporting soft-tissue structures is transected or resected to facilitate surgical exposure. It is therefore, logical to assume that the kinematics of the implanted hip are different from those of a normal hip. Femoral head separation is potentially detrimental and it may play a role in the complications observed after total hip arthroplasty, including premature wear, prosthetic loosening and instability. Micro-separation, included in the present hip joint simulator, may contribute to describe the multidirectional wear vectors observed in retrieved acetabular components [17]. Several authors [21–28] hypothesize that the difference between multidirectional wear pathways produced by hip joints simulators commonly used, and the wear pathways observed in retrieved similar prosthesis, can be due to micro-separation, and may result in accelerated wear due to increased shear forces [15].

There are a number of different tribological hip joint simulators and techniques that have been extensively employed to evaluate the performance of different prosthesis in several movement conditions [6–14]. However only a few hip joint simulators have addressed the problem of micro-separation and micro-impact.

In this new hip joint simulator, achieving micro-separation was possible. A similar load profile following Paul's cycle is applied to each station, when it concludes in every cycle, the springs system can separate up to 4 mm between the prosthetic couples. Load information from load cells was obtained in order to have a close micro-separation control, Fig. 5b. In addition repeatability parameter studies of this machine were completed, resulting a repeatability of $r = 0.91$.

This new simulator has the flexibility to achieve different levels of micro-separation, which can be used to reproduce a closer approximation to in vivo behavior of natural hip micro-separations [15–17].

4. Conclusions

A hip joint simulator, type BRM + IER with range of motion of ±23° for flexion-extension, ±23° for abduction-adduction and ±7.5° for internal-external rotation was built. This hip simulator with a range of frequency of 1.2–1.4 Hz includes a lubrication system and a dynamic load system, which can reproduce different load patterns and micro-separations. This hip simulator provides a dynamic load close to human body conditions during walking and jogging.

Acknowledgements

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