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# Effects of sliding kinematics and normal load on the tribological behavior of metal/polymer contact

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ABSTRACT

Wear and friction simulator with metal cylinder on flat polymer was developed to analyze the tribological behavior of tibial insert used in Total Knee Replacement (TKR). For the kinematics, flexion/extension motion (F/E) was applied to the metal cylinder and anterior/posterior translation (A/P) was applied to the flat polymer. Tests were first carried out with polymethylmethacrylate polymer (PMMA) for which the tribological behavior has been well developed. High density polyethylene (HDPE) was also characterized. In fact HDPE has been firstly used in the tibial insert before the use of ultra high molecular weight polyethylene (UHMWPE). Sinusoidal motions were considered for the F/E and A/P with 8.185 and 5 mm amplitude respectively. F/E and A/P motions were generated separately under a constant applied normal load and 1 Hz frequency. For each test condition, the damage of polymer surfaces was analyzed by following the evolution with the cycle numbers of the friction coefficient, the surface roughness and the micrograph of the wear scar. Whatever the sliding kinematics is, the initial average value of the friction coefficient measured is 0.3 for the steel/PMMA contact and 0.07 for the steel/HDPE contact. These values are similar to those presented in the literature. Specific tribological behavior, which present direct dependence on the sliding kinematics, was identified for each steel/polymer contact.



## 1. Introduction

Total Knee Replacement (TKR) has become a frequent surgical procedure to relieve pain, restore alignment and restore knee function. Recent research works try to ameliorate the survival time of TKR. Even if survival rates better than 90% have been achieved for a 10 years span for some designs [1], failures of the knee prosthesis have been observed to be mainly due to wear and/or loosening of implants components [2–6]. TKR prosthesis generally consists of metal femoral and tibial components separated by tibial insert made from ultra high molecular weight polyethylene (UHMWPE). The concave surface of tibial insert makes contact with the convex counterface of femoral component under compressive load. The contact experiences a very complex kinematics during walking which is a combination of rolling and sliding. The principal motion components are Flexion/Extension (F/E), Anterior/Posterior translation (A/P) and Internal/External rotation (I/E) [7]. Commercial knee joint simulators are intended to test the wear of actual knee prosthesis [8]. These simulators try to reproduce the knee kinematics for the TKR femoral component resting on tibial insert. The resulting wear mechanisms are very complex and difficult to analyze. Simple wear devices, which reproduce wear mechanisms similar to those occurring clinically, are more interesting for basic wear and friction characterization of new materials for the TKR components [9,10]. Based on this idea, a new two axis wear and friction simulator with metal cylinder on flat polymer was developed. Flexion/Extension (F/E) motion and Anterior/Posterior (A/P) translation are the two motions considered for the contact which can be generated simultaneously or separately. The aim of this paper, in a first step, is to validate the results given by our wear and friction simulator. For the polymer material, we have chosen Polymethylmethacrylate (PMMA) whose tribological behavior has been well developed [11]. High density polyethylene (HDPE), which has been previously used for the tibial insert [12], was also considered for the validation. In a second step, this paper aim to analyze the effects of the contact kinematics and the compressive load on the tribological behavior of the two considered steel/polymer contacts.

## 2. Materials and method

The developed wear and friction simulator is shown in Fig. 1. In order to simplify contact geometry, the femoral component was replaced by a steel cylinder of 35 mm of radius and 55 mm of length. The tibial insert was replaced by a flat polymer block of $55 \times 20 \times 15$ mm$^3$ located beneath the steel cylinder. Contact between

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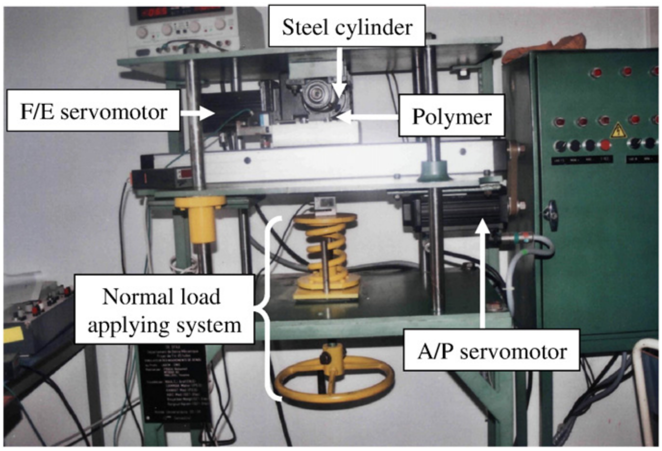


**Fig. 1.** Friction and wear simulator.

the steel cylinder and the flat polymer was done under constant normal load "$F_n$" using helicoidally spring in series with nut–screw system. A load cell placed in the normal load axis allows the control of the "$F_n$" value which ranges from 100 N to 3000 N. Flexion/extension (F/E) motion is applied to the steel cylinder using a servomotor and a gear box. Anterior/posterior (A/P) translation is applied to the polymer cube using another servomotor with a ball–screw system. The resultant tangential load "$F_t$" is continuously measured using a load cell placed in the A/P translation direction. The output of this load cell was stored during each experiment via a data acquisition. Each of the servomotors generating the F/E and the A/P motions is controlled by a servovariator interfaced with a computer. This allows a free choice of the F/E angle $\theta(t)$ as a function of time as well as the A/P translation $\delta(t)$ as a function of time (Fig. 2).

Elastic properties for the steel cylinder and for the flat polymer (PMMA and HDPE) are summarized in Table 1 [13–15]. TR 200 Hand-held Roughness Tester was used for the topography control of the considered surfaces. The obtained mean values of the Ra roughness are 0.9 µm for the steel cylinder, 0.007 µm for the PMMA and 1.8 µm for the HDPE.

In order to explore the effect of the normal load on the tribological behavior of the considered steel/polymer contacts, two levels of the applied normal load "$F_n$" were considered (500 N and 1000 N). For these considered normal load levels, both PMMA and HDPE polymers are under their plastic flow limit in the static condition [16]. Hertz elastic theory [16] was also used for estimating the width of the contact band for each of the considered polymers and normal loads. Results are summarized in Table 2.

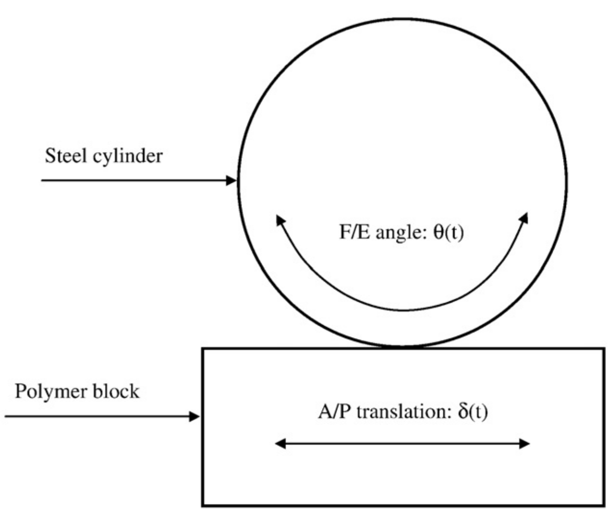


**Fig. 2.** Schematic representation of the contact kinematics; $\theta(t)$: F/E angle, $\delta(t)$: A/P translation.

**Table 1**
Elastic properties for the steel cylinder and for the flat polymer.

| | Steel | PMMA | HDPE |
|---|---|---|---|
| Young modulus (MPa) | 210,000 | 3300 | 965 |
| Poisson coefficient | 0.3 | 0.35 | 0.35 |
| Plastic flow stress (MPa) | – | 82 | 25.9 |

The tribological behavior of the steel/polymer contact was analyzed under two different kinematics. The first motion, *A/P translation*, consisted in a sinusoidal translation $\delta(t)$ with 5 mm amplitude and 1 Hz frequency applied to the flat polymer while the steel cylinder was kept fixed (Fig. 3-a). The second motion, *F/E motion*, consisted in a sinusoidal oscillation $\theta(t)$ with 8.185° amplitude and 1 Hz frequency applied to steel cylinder while the flat polymer was kept fixed (Fig. 3-b). The amplitude of the F/E motion was selected in order to provide the same sliding distance between the contacting bodies when compared with the A/P translation.

## 3. Results and discussion

Typical evolution of the tangential load with time for the first 2 cycles in the case of A/P translation is given in Fig. 4. A similar evolution is obtained for the F/E motion. For each half cycle, the monotonous region between points A and B corresponds to the partial slip condition and the stationary region between B and C corresponds to the gross slip condition. The small fluctuations of the tangential load for the gross slip condition are related to the stick/slip phenomenon. The friction coefficient $\mu$ is calculated as the ratio of the mean tangential load value $F_{tMax}$ for the gross slip condition by the normal load $F_n$: $\mu = \frac{F_{tMax}}{F_n}$.

### *3.1. A/P translation*

The mean initial value of the friction coefficient is 0.3 for the steel/PMMA contact and 0.07 for the steel/HDPE contact. These values are similar to those presented in the literature [17–19]. The evolutions of the friction coefficient $\mu$, normalized by the initial value $\mu_1$, with the number of cycles for the considered two polymers and normal loads are shown in Fig. 5. A progressive increase of the friction coefficient is obtained as the number of cycles increases. The same trends for the friction coefficient evolution are obtained for the two considered steel/polymer contacts. No significant effect of the normal load on the friction coefficient evolutions is obtained.

Microscopic analysis of the polymer surface wear scar was also developed for different number of cycles. Fig. 6 presents a set of typical micrographs in the case of PMMA polymer. The initial wear mechanism is abrasive for which the PMMA surface is scratched by the steel cylinder asperities. The scratches depth increases as the number of cycles increases. The first PMMA particles detached from the surface appear around 1000 cycles. The density of detached particles increases as the number of cycles increases and seems to be constant by about 5000 cycles. Some of the detached particles are trapped between the stripes which attenuate the wear severity. In the case of HDPE polymer, a set of typical micrographs for different number of cycles are presented in Fig. 7. Damage in the form of micro-

**Table 2**
Width of the contact band for each of the considered polymers and normal loads.

| | Steel/PMMA | | Steel/HDPE | |
|---|---|---|---|---|
| Normal load (*N*) | 500 | 1000 | 500 | 1000 |
| Contact width 2a (mm) | 1.09 | 1.55 | 2.02 | 2.85 |