Tribological testing of implants-bone pair and coefficient of friction of coated knee implants

Relevant for: tribology, pin-on-disk, implants, bone

The bone-implant interface plays an important role in the osseointegration of metallic implants. While the mechanical properties of implants and bone are generally well known, the frictional properties at the bone-implant interface are much less understood despite strongly affecting post-operative integration. This application report begins with a tribological study where the coefficient of friction between hip implant materials and bone was measured in relevant physiological conditions. The report is completed by a tribological study of coated knee implants against an Ultra high molecular weight polyethylene (UHMWPE) counterbody in bovine serum.

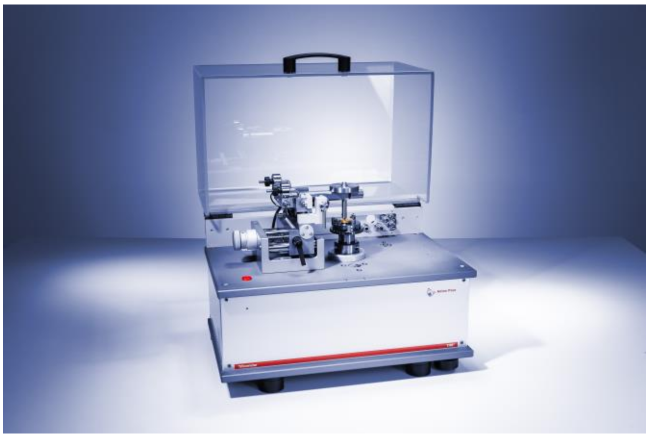

Figure 1 - The Anton Paar pin-on-disk tribometer.

1 Friction between bone and hip implant shaft

The bone-implant interface (Figure 2) plays a key role in the clinical success of orthopedic and dental implants. The desired secondary stability of such implants relies on extensive osseointegration which is a direct result of the primary stability achieved during surgical implantation. While the mechanical properties of the bone dominate the structural behavior of the bone-implant complex, friction between bone and implant may contribute to primary stability. Although frictional behavior has been explored in isolated studies, its systematic investigation is lacking. Several authors have measured coefficient of friction values ranging between 0.14 to 1.75 for a variety of test conditions (pressure, dry/liquid, material) between bone and assorted metallic counterbodies [1,2]. To fill this gap of knowledge, we investigated the influence of applied load, sliding speed, material and surface treatment on the tribological behavior of bovine bone with common metallic implant materials. These results should allow for more realistic modelling of the bone-implant interface during the primary post-operation period [3].

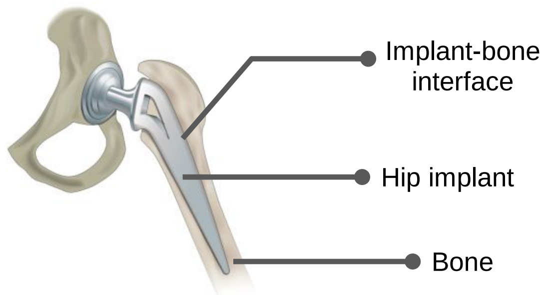

Figure 2 – Schematic illustration of the bone-implant interface for hip implant (Source: www.bonesmart.org).

1.1 Experimental setup

Tribological experiments were performed using the Anton Paar TRB^3 pin-on-disk system in linear reciprocating mode (Figure 3) and the coefficient of friction (CoF) was recorded. The conditions for the tribological tests were selected in order to simulate real life conditions occurring during the post-operational period. The applied load spanned from 1 N which corresponds to the purely elastic regime of bone, to 50 N which causes irreversible plastic deformation of bone. The sliding velocity ranged from 10^2 to 10^5 µm/s where the lowest speed imitates the micro-motions between implant and bone during walking and the highest speed represents an occasional sudden drop or shock. The bone samples were prepared from healthy bovine tibiae in the form of a 20 mm x 40 mm block. To ensure the same contact conditions, the surface of the bone subject to friction was polished using diamond paste and cleaned by ultrasonic bath to remove debris.

Three implant materials were tested: 316L steel, Ti6Al7Nb and pure Ti. In addition, pure Ti was provided with different surface treatments. As the most common implant material, 316L stainless steel was easiest to obtain in the required quality; therefore, the effects of sliding speed and normal load were compared for this material. To simulate real conditions all experiments were done in saline solution at room temperature. The results were analyzed with descriptive statistics in order to determine the effects of the test parameters.

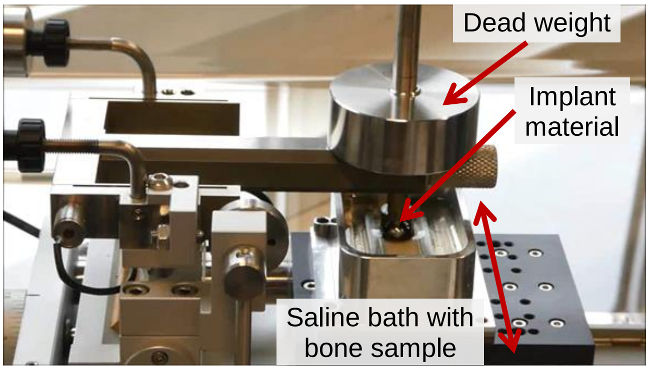

Figure 3 – Tribological setup showing the saline bath with the fixed bone sample, counterbody from implant material, and dead weight (after [3]).

1.2 Tribological test results

The results of the tribological experiment show that the CoF between bone and implant depends mainly on load and sliding speed. Their influence is however different: to achieve the same change of CoF the load has to be increased by a factor of fifty whereas an almost thousand-fold increase in sliding speed is needed for a similar change of CoF (Figure 4). Under conditions relevant to post-operation activities (walking), the CoF was found to be ~0.4 for the 316L stainless steel and ~0.6 for the Ti-based materials. The effect of different surface treatment of the Ti implants on CoF was much smaller as compared with the effect of either load or sliding speed.

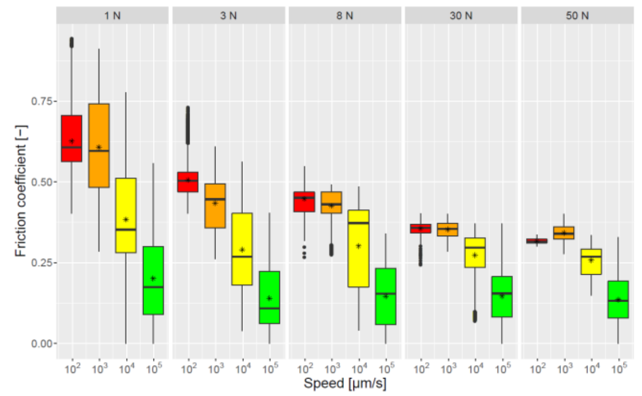

Figure 4 – CoF as a function of load and sliding speed for the 316L stainless steel [3].

The observed decrease of CoF with increasing load is very likely related to surface conditions: despite being polished, the bone surface retains some asperities and pores. As the load on the bone increases, these asperities become flattened and the surface becomes smoother, leading to a lower coefficient of friction. The frictional behavior cannot be described using the Stribeck model as the influence of speed indicates mixed lubrication whereas the influence of load would suggest hydrodynamic lubrication.

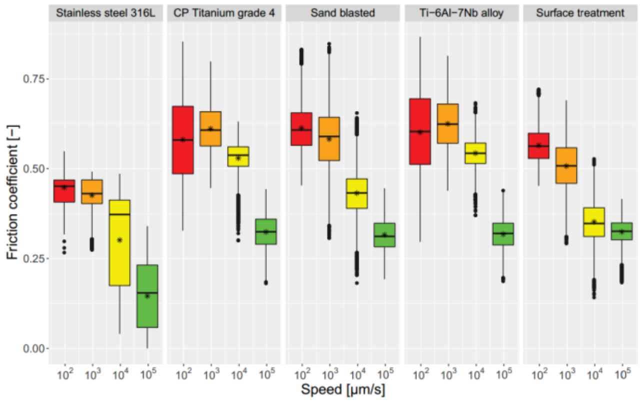

Figure 5 – CoF for 8 N load and various sliding speeds for all tested implant materials and surface modifications [3].

The effect of material type (Figure 5) and surface finish is more obvious and can be explained by intrinsic material stiffness. The 316L stainless steel has an elastic modulus approximately two times higher than the Ti alloys. Thus, for the same normal load the 316L steel deforms less than the Ti alloys, which leads to a smaller contact area and therefore lower CoF. This is shown in Figure 5 where the CoF of steel is ~0.45 at 8 N and 0.1 mm/s speed whereas the CoF of the Ti alloys is ~0.6. Note that different surface treatments of Ti led to only minor changes in CoF and therefore the main factor for changes in CoF is the material stiffness.

1.3 Conclusions and comments

Our investigations suggest that the frictional behavior between implant and bone can be simulated by a tribological experiment provided that the test conditions are similar to loads and speeds seen in a real scenario. The pin-on-disk tribometer can simulate a broad range of dynamic conditions from walking to sudden drops with a large range of contact pressures available, all in physiologically relevant conditions. The most important finding is that the CoF depends primarily on the bone-implant pressure (load): the lower the pressure, the higher the CoF. Increasing the sliding speed on the other hand leads to a decrease in CoF. The CoF between bone and 316L stainless steel at walking conditions and medium pressure (8 N) is ~0.45. These results contribute to a more accurate model of this contact problem which may further be used for the design and optimization of new metallic implants.

2 Frictional behavior of coated knee implants

While the majority of metallic joint implants (hip, knee, or shoulder) use bare metals without surface coating, there are an increasing number of implants with coatings. The implants are coated for two primary reasons:

- Improved osseointegration
- The prevention of allergic reactions resulting from metal ion release in vivo

In this second study we focused on implants with hard ceramic coated surfaces designed to prevent ion release. These coatings are usually based on titanium or zirconium nitrides and oxides which generally have thicknesses in the range of one to several micrometers [4,5]. Some of these coatings are composed of several layers where the layer(s) near the substrate ensure good adhesion to the metallic substrate and the surface layer(s) impart favorable frictional properties. Since the coated parts of implants (prosthesis part on femur, Figure 6) functionally replace the articular joint, they are in moving contact with a counterbody. This counterbody is usually made from Ultra high molecular weight polyethylene (UHMWPE) polymer (Figure 6, prosthesis part on tibia). It is therefore important to know the coefficient of friction of the contacting surfaces (coating against UHMWPE).

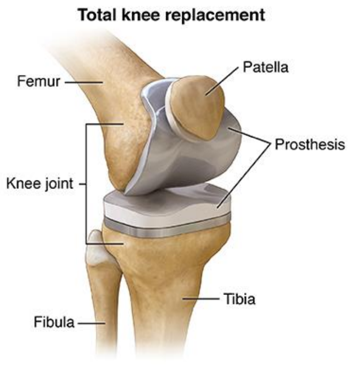

Figure 6 – Illustration of knee implant: upper part on femur is made of coated metal while the lower part on tibia is made of UHMWPE (Source: www.uhhospitals.org).

2.1 Friction of coated knee implants – experimental setup

To evaluate these materials we measured the coefficient of friction of several knee implants with various coatings. The measurements on coated implants were compared with measurements on two uncoated metallic substrates which are commonly used for knee implants. Tribological measurements were performed using the Anton Paar TRB^3 pin-on-disk tribometer in the linear reciprocating configuration – see Figure 7. The coated (TiN-based coating type A, TiN-based coating type B and ZrN-based coating) and uncoated samples (Ti6Al4V and CoCrMo) were cut from the knee implant, mounted on a steel shaft using epoxy glue and fixed in a special holder. This holder was then fixed in the TRB^3 and put into contact with a UHMWPE block. All experiments were done in calf serum at room temperature. The applied load (5N) corresponded to a real pressure of ~30MPa and the sliding speed corresponded to the relative movements of the knee joint during average walking conditions. The goal of the experiment was to measure the coefficient of friction between coated and uncoated implants and the UHMWPE counterbody in a steady state (i.e. where the CoF remains constant). Additional details and results of this study can be found in [3].

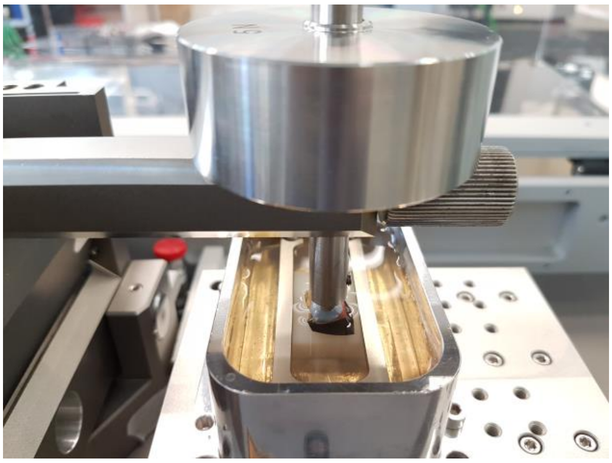

Figure 7 – Tribometer setup for measurement of coefficient of friction between coated knee implant and UHMWPE counterpart in bovine serum.

2.2 Friction of coated and uncoated knee implants – results

After several preliminary tests we found that an experimental duration of ~2h50 (corresponding to a sliding distance of 450 m) was sufficient for stabilization of the coefficient of friction: only minor variations of CoF were observed afterwards. For some coatings and substrates an initial run-in phase was observed but generally the coefficient of friction stabilized after the first ~50 m. Comparison of the evolution of the CoF for all tested samples is shown in Figure 8: the CoF of all coated samples is very close to ~0.08, which means that the coefficient of friction is very low with the exception of the Ti6Al4V uncoated substrate which has a significantly higher coefficient of friction (~0.14) than other samples. This is very likely due to a larger contact area of the titanium alloy resulting from a lower elastic modulus (114 GPa) as compared to CoCrMo alloy (240 GPa). A larger contact area results generally in higher CoF (similar behavior was observed during the friction between bone and implant, see above). The measured coefficient of friction of the coated (and uncoated CoCrMo substrate) samples agrees very well with the results published by Barceinas-Sanchez in [6]. The authors used a 316L stainless steel ball which was rubbed against UHMWPE in very similar conditions (pin-on-disk setup, fetal bovine serum, contact pressure ~20 MPa). Their results are shown in Figure 9.

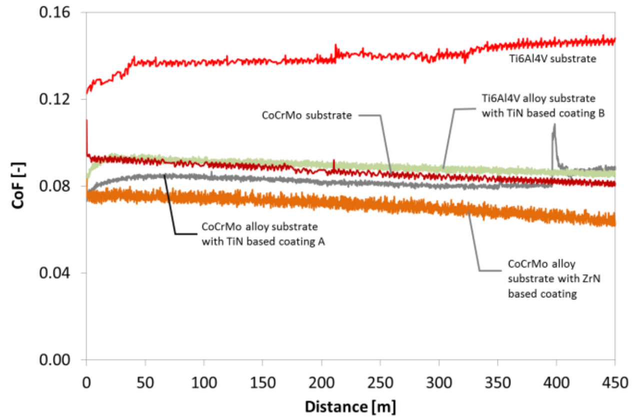

Figure 8 – Evolution of coefficient of friction between coated and uncoated knee implants against UHMWPE versus time.

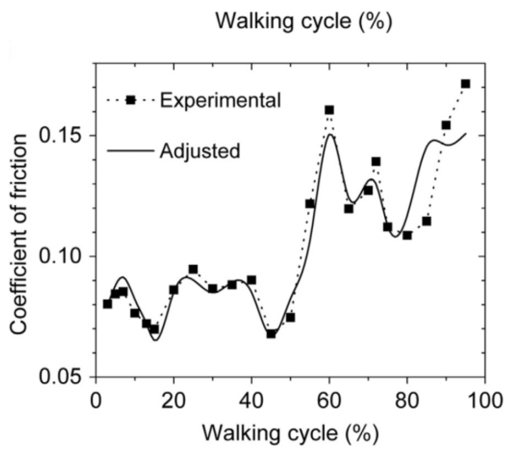

Figure 9 – Coefficient of friction in knee implant prosthesis (316L against UHMWPE) published in [6]. Our values were in the range of ~0.08 (except for the Ti6Al4V substrate).

2.3 Friction of coated knee implants – conclusions

The results of simple benchtop tribological investigations of frictional behavior of coated and uncoated metallic knee implants in realistic conditions have shown that the coefficient of friction of the coated implants is similar, if not lower, than for the uncoated implants. Of particular interest was the CoF of Ti6Al4V which was significantly higher than for all other tested material systems. The pin-on-disk method can therefore be a fast and efficient tool for preliminary screening of frictional properties of metallic implants.

Authors

This application report was written by Jiri Nohava, PhD. The experimental work and analysis of results in the bone-implant study was performed by Mrs. Charlotte Voutat during her master thesis at the University of Bern (CH). The samples for the coated knee implants were provided and the results were discussed with Ms. Maria Crackau M.Sc. from the Otto von Guericke University in Madgeburg (DE).

3 References

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