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Observation of lubrication mechanisms in knee replacement: A pilot study

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ABSTRACT

The present study introduces a unique experimental approach for in situ observation of lubricant film formation in knee joint replacements. A knee joint simulator was designed and equipped with optical module based on fluorescent optical method for film thickness observation. The contact between the femoral knee metal implant and real-shaped polymer insert mimicking actual contact nature is observed. The shape of the polymer insert was fabricated with respect to the shape of original polyethylene insert to ensure corresponding contact conformity. Simple solutions of albumin and γ-globulin proteins as well as its mixture were used while the film thickness was studied as a function of time considering simplified flexion/extension motion with variable load over the cycle. Adequate fluorescent markers were employed enabling to observe one particular protein during each measurement. The results showed a clear importance of the interaction of proteins since the mixtures showed different results compared to simple solutions. Especially considering albumin protein, its behaviour was substantially affected by adding γ-globulin. Moreover, a satisfactory compliance with previous findings related to hip joint lubrication in terms of the behaviour of both proteins was found. Finally, the motivation for future experimental work is highlighted.

1. Introduction

Total knee arthroplasty (TKA) has become a routine surgical technique for patients suffering from osteoarthritis. According to Health at a Glance: OECD Indicators report [1], 126 operations per hundred thousand inhabitants were performed in 2015. Considering the implant design, some new approaches have been proposed such as metal-free knee implant [2], oxinium knee implant [3], or post-cam design together with multilayer coating known as VEGA [4]. Nevertheless, despite the promising preliminary results, the implant consisting of metal tibial and knee component with polyethylene (PE) insert persists as the most common type of knee replacement [3].

When focusing on the durability of TKA, aseptic loosening, instability and prosthetic joint infection are recognized as the main reasons for reoperations [5,6]. Since aseptic loosening is associated with release of wear particles, it is apparent tribological processes substantially affect the condition of implant. Previously, the main attention of researchers was paid to the evaluation of wear rate and/or friction adopting both commercial and tailor-made simulators [7–11]. However, only a limited attention was paid to the lubrication mechanisms which play an important role as suggested in literature [12].

Following references dealing with lubrication of knee replacements by means of numerical simulations were introduced [13–19]. The pilot study was given by Tandon and Jaggi [13] who proposed an idealized model considering the viscoelastic parameter of the lubricant to capture the increased load capacity caused by an increased concentration of hyaluronic acid (HA) in synovial fluid (SF). The study was subsequently extended by the same authors focusing on the calculation of wear rate, load capacity, and approaching time of the opposing surfaces [14]. It was found that the slip velocity plays an important role regarding the self-adjusting nature of the joint. Later, Jin et al. [15] simulated a walking cycle based on elastohydrodynamic lubrication (EHL) theory using simplified ellipsoid-on-plane numerical model. The authors predicted a transient lubricating film thickness in knee prostheses considering compliant layer between the implant surfaces. A substantial effect of contact geometry on fluid film lubrication was found while the maximum film thickness is expected when contact area of a transverse conjunction is maximized. A minimized risk of starvation due to small stroke is discussed as an another advantage. The published results were in a good qualitative agreement with the experimental investigation given by Ohtsuki et al. [16]. The authors investigated the contact of steel ball and tibial component represented by silicone rubber layer. Degree of separation based on the electrical resistance technique was measured; concluding that ability of fluid film formation was higher in

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the case of transverse geometry compared to longitudinal one.

In a further numerical study given by Mongkolwongrojn et al. [17], a point contact was considered when predicting both film thickness and pressure distribution as a function of load, speed, material and lubricant properties. It was shown that the film thickness during the first cycle is always lower due to time required for film development. In the following cycles, the film is similar and dependent on loading and kinematic conditions related to human motion. Subsequently, Su et al. [18], performed time-dependent EHL analysis of knee implant considering transient loading and kinematic conditions respecting normal walking. As in some previous cases, ellipsoid-on-plane model was adopted. It was found that under the combined effect of squeeze-film and entraining action, the central film thickness decreases during the stance phase. On the contrary, during the swing phase, the film is kept relatively thick. Recently, Gao et al. [19] focused on the numerical prediction of wear and lubrication using ball-on-socket model. For the first time, the authors compared non-textured surface with micro-dimpled surface. Medial and lateral knee compartments were investigated finding that lateral compartment may benefit if the dimples are carefully designed; however, no advantage was found for medial compartment.

Apparently, there is very limited knowledge in terms of experimental investigation of lubrication in knee joint replacements. Nevertheless, some assumptions can be defined based on the lubrication of hip prosthesis, which have been extensively in recent years. In particular, it was found that contact conformity plays a key role while better compliance of the surfaces ensures better lubrication performance [20]. Later, focusing on the effect of constituents of SF, a clear effect of HA and HA and phospholipids was observed [21]. Focusing on the role of individual fluid components, fluorescent optical method was introduced and successfully validated examining the formation of albumin and γ-globulin lubricant film [22]. The method was recently adopted when investigating the lubrication mechanisms within hard-on-soft bearing surfaces [23]. As the results enabled clear explanation of film formation, the same method is used in the present study.

Based on the above references, it can be assumed that only a limited attention was paid to the lubrication of knee joint replacement. Most of the so far published studies are numerical, while some level of simplification in terms of geometry or lubricant behaviour is necessary in such case. The limitations of numerical simulations and the need of experimental validation was mentioned by Gao et al. [19]. Moreover, some effects such as protein adsorption or agglomeration cannot be considered in the models at all. Since the impact of lubrication on friction and wear is indisputable, the motivation of the performed study is to develop a methodology for in situ film thickness observation in knee replacement considering real geometry of rubbing surfaces.

2. Materials and Methods

The experiments were carried out using the knee joint simulator enabling to apply transient loading and kinematic conditions. In general, flexion/extension (F/E), anterior/posterior (A/P) translation, internal/external (I/E) rotation, and axial (AX) load can be controlled. Nevertheless, since this is a pilot study, simplified kinematic and loading conditions were applied, as is shown in Fig. 1. The F/E range was from 0° to 58° which corresponds to ISO 14243-3:2014 standard for wear testing of knee prosthesis while AX load varied from 270 N to 310 N. A/P translation as well as I/E rotation were fixed. The contact is realized between the real femoral knee implant component and transparent counterface insert enabling direct in situ observation. The optical module is mounted in an inverted arrangement and is composed of halogen illuminator, fluorescent microscope, high-speed camera, and PC. The model of the test device with the detail of the contact couple is displayed in Fig. 2. Photos of the contact zone illuminated by mercury lamp are shown in Fig. 3.

The contact bodies are represented by original CoCrMo femoral knee component (cruciate retaining implant, Zimmer Biomet) and the insert made from transparent poly(methyl) methacrylate (PMMA). PMMA was chosen since its mechanical properties are relatively close to conventionally used PE. However, PE is not transparent so the direct observation of the contact is not possible. The shape of the PMMA insert corresponds to real PE tibial plateau. The original geometry was obtained using 3D optical scanning method [24]. Subsequently, the sample was manufactured by micro-chip machining technology using computer numerical control shape generator. Single point diamond turning (SPDT) method was applied enabling to reach the accuracy equal to fractions of nm. Surface topography was evaluated using 3D optical profilometer based on phase shifting interferometry. The Ra parameter of both the contact surfaces is similar varying from 6 nm (average value for PMMA insert) to 10 nm (for femoral knee component). The elastic modulus and Poisson's ratio of metal alloy and PMMA are as follows: $E_{metal} = 230$ GPa, $\nu_{metal} = 0.28$; $E_{PMMA} = 4$ GPa, $\nu_{PMMA} = 0.37$. It should be noted that elastic constants of ultra-high molecular weight polyethylene (UHMWPE) are approximately $E_{UHMWPE} = 700$ MPa, $\nu_{UHMWPE} = 0.35$, respectively.

Due to the nature of PMMA which is poorly reflective and is not conductive, routine techniques such as optical interferometry [21] or electrical resistance method [16] could not be applied. Therefore, the fluorescent microscopy method was implemented [22]. The method was recently successfully validated when examining the lubrication mechanisms within hard-on-soft hip replacements where the same materials (metal vs. PMMA) were considered [23]. The evaluation of film thickness is based on the observation of fluorescent intensity as a function of time. It was previously proved in literature that the intensity is proportional to the layer of the lubricant [25]; therefore, the intensity is considered as a dimension-less film thickness. It means that the higher intensity corresponds to higher film thickness and vice versa. Therefore, based on the detected fluorescent emission, it is possible to assess the development of lubricant layer between the surfaces. Although the specific proteins were fluorescently stained, it is apparent that the proteins are uniformly distributed in the base fluid. It means that the whole fluid appear to be dyed. This is the reason why thickness of albumin/γ-globulin layer throughout the observed zone could be detected. To determine the overall film thickness, both the proteins would have to be fluorescently stained at the same time.

It should be emphasized that the quantitative film thickness could not be evaluated due to some limitations discussed in a detail in previous study [23]. However, the particular value of film thickness is not decisive, as the laboratory investigation can hardly involve all the processes occurring within the body. Nevertheless, the trend of film thickness development as well as the understanding of the interaction of the SF constituents is of a great importance when clarifying the lubrication mechanisms between knee articulating surfaces.

To verify the designed methodology and to capture the mutual influence of SF constituents, various proteins solutions were used as the test lubricants. Initially, simple solutions of bovine serum albumin (A2153, Sigma-Aldrich) and γ-globulin from bovine blood (G5009, Sigma-Aldrich) were applied. The proteins were fluorescently stained in order to determine its role in film formation process. Albumin was stained by Rhodamine-B-isothiocyanate (283,924, Sigma-Aldrich) and γ-globulin was doped by Fluorescein-isothiocyanate (F7250, Sigma-Aldrich). The proteins were initially dissolved in phosphate-buffered saline (PBS). Subsequently, the proteins were mixed together. In each specific measurement, only one of the proteins was doped by corresponding fluorescent marker. This approach allows to determine the mutual interaction of the constituents enabling to determine the role of specific proteins in film formation process. The lubricants are summarized in Table 1. The overall volume of the test lubricant was 4 ml ensuring fully flooded conditions at the beginning of the test. To avoid any inaccuracies of film thickness development due to adsorbed protein film from the previous experiment, attention was paid to the cleaning procedure of the test samples. Before and after tests, the specimens were rinsed in water and washed by 1% solution of sodium dodecyl

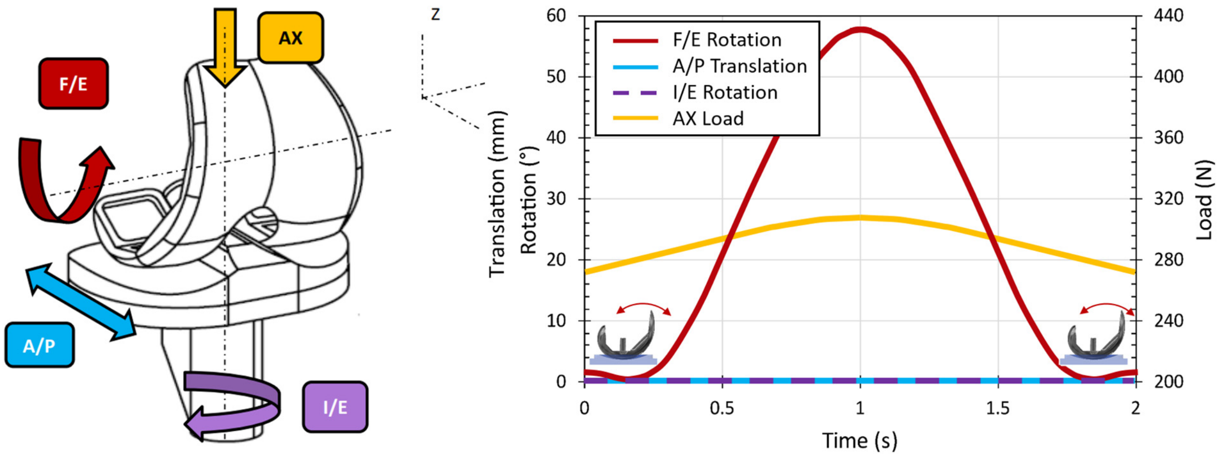

Fig. 1. A schematic illustration of the applied kinematic and loading conditions.

sulphate. Then, it was rinsed by deionized water, and washed in isopropyl alcohol.

To be able to compare the results of fluorescent intensity of two different components doped by different markers, normalization of the data had to be performed. This step is fundamental since it also eliminates the effects such as settings of light source, ambient light conditions or settings of fluorescent filters. The process of normalization is based on a simple division/multiplication. At the beginning of data analysis, the initial intensity is found for each measurement. To avoid any effect of the random variation of intensity, several tens of images within the first seconds of the test are analysed. Subsequently, independently of the performed test, the initial value is normalized to 1000. Therefore, the division/multiplication constant for each test is found. Then, all the rest of the data corresponding to the given measurement are divided/multiplied by the constant. This approach enables to compare the data independently of the used lubricant type or its concentration. The methodology was validated in our previous paper investigating hip replacement considering the same contact materials (metal vs. PMMA) [23].

Since the simulator is newly developed and its function was not verified so far in terms of complex test with transient loading and kinematics, simple flexion-extension test was designed for the purpose of the present study. The PMMA insert was fixed in the simulator frame and the femoral component swung in the range from 0° (initial vertical position displayed in the bottom right corner of Fig. 2) to 58°. Frequency of the stroke was 0.5 Hz. The maximum applied load throughout the cycle was 310 N resulting to maximum contact pressure of approximately 36 MPa. With respect to standards for knee implant testing, the maximum load should be up to 2600 N. However, this is a peak value while the average load throughout the cycle is around 900 N. Assuming the simplified loading cycle employed within the present study, and noting that the elastic modulus of PMMA is around six times higher compared to UHMWPE, the resulting contact pressure should be similar considering metal-PMMA and metal-PE contact. Moreover, the presented data of maximum contact pressure are in accordance with expected pressures in knee replacement considering

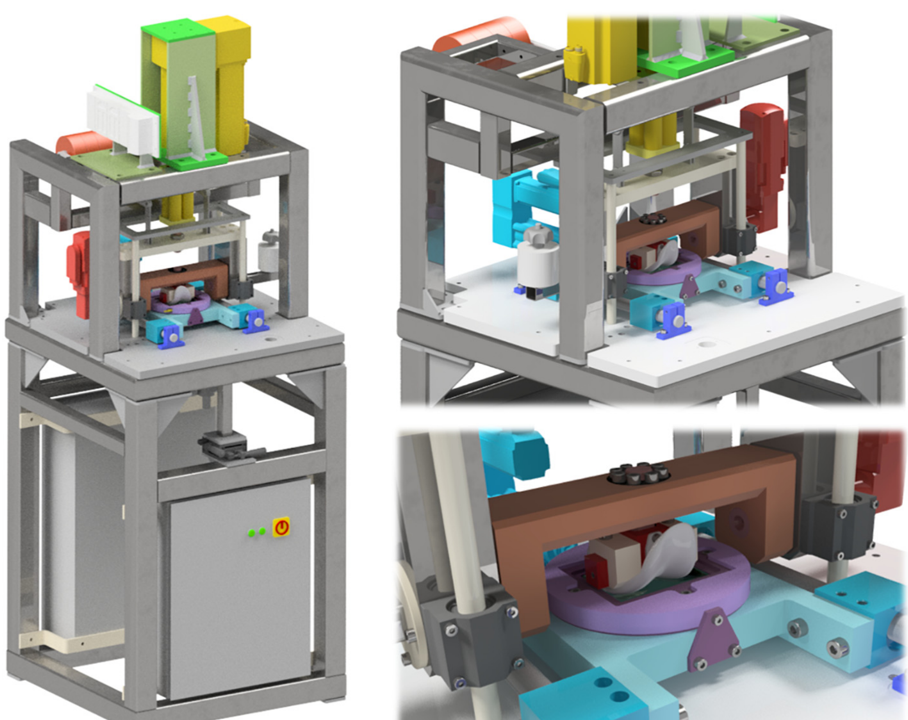

Fig. 2. Model of the test device with the detail of the contact couple and optical module.

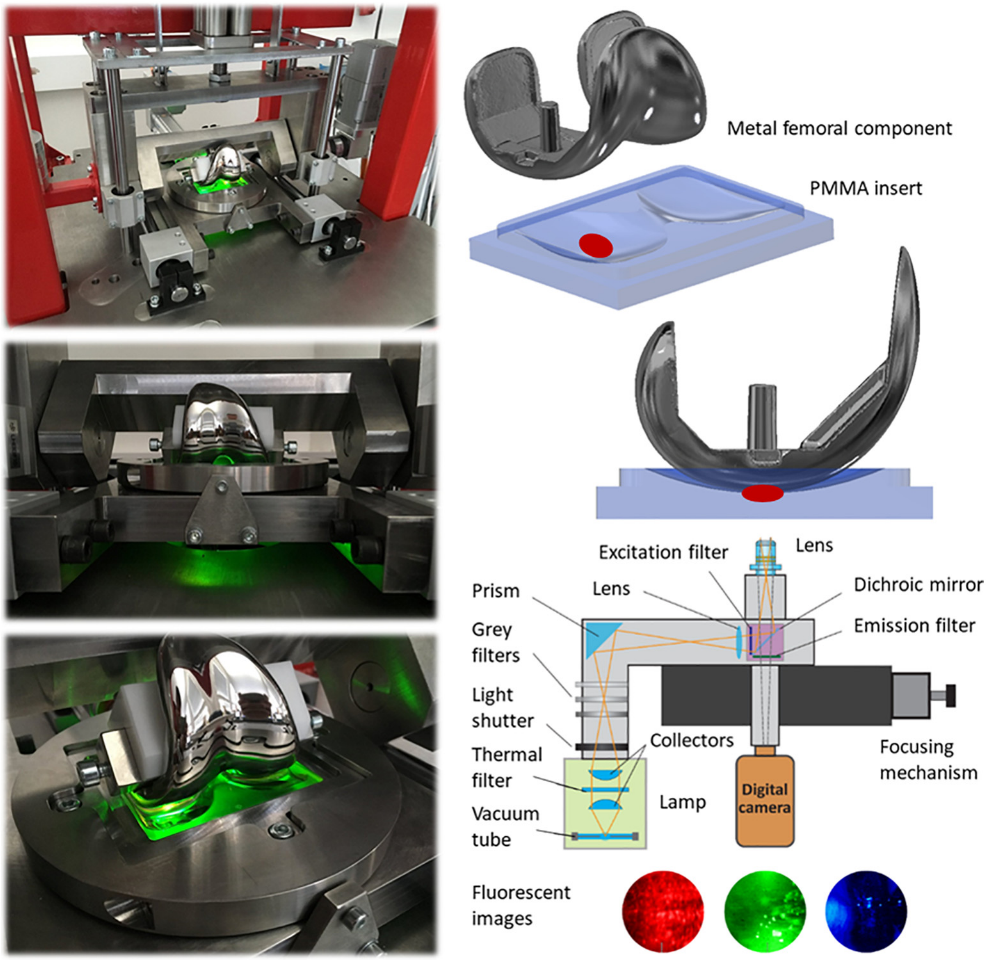

Fig. 3. Photo of the contact zone illuminated by mercury lamp. The red spot on the top right images indicate the observed zone where the film thickness is evaluated. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

various references [26,27]. The contact area is an ellipse having the major and minor axis equal to 2.62 mm and 0.88 mm, respectively. The evaluated intensity is an average value over observed ellipse-shaped area depicted in Fig. 3 having length 2 mm and width 1.54 mm. The intensity is always evaluated in the zero position (when the position of the femoral component is vertical). The experiments were carried out under ambient temperature of 22 °C since it was shown in literature that an increase of lubricant temperature to 37 °C does not affect film formation [28].

3. Results and Discussion

The dimension-less film thickness was studied as a function of time. The corresponding fluorescence intensities for all the test lubricants considering lateral condyle are plotted in Fig. 4a. As can be seen, albumin film has a strongly increasing tendency during the first part of the experiment. Then, it continuously decreases and until the end of the experiment. Almost identical behaviour of albumin film was previously observed even in the case of hip replacement [23]. When the fluorescently stained albumin was mixed with non-stained γ-globulin; surprisingly, the film became lower than that of pure albumin. The maximum film thickness was almost around half, while initial increase was followed by slight drop. However, contrary to pure albumin, the film formed by the mixture of the proteins showed much better lasting effect indicating better lubrication performance in long-term time interval. This phenomenon is very important. It should be emphasized that maximum film thickness in the case of few-minutes experiment is not as decisive parameter. Nevertheless, the ability of film formation over a long time is particularly important. The described behaviour supports our previous findings and suggestions highlighting the importance of the interaction of SF constituents in film formation process [21]. Moreover, it is expected that lower film thickness results in slightly higher friction which is in coincidence with our previous observation. Focusing on metal-polyethylene sliding test, it was found that a mixture

Table 1
Summary of the test lubricants.

Lubricant no.	Labelled constituent (concentration)	Non-labelled constituent (concentration)	Total concentration	Base fluid (total amount)
1	Albumin (24.9 mg/ml)	–	24.9 mg/ml	PBS (4 ml)
2	Albumin (24.9 mg/ml)	γ-globulin (6.1 mg/ml)	31 mg/ml	PBS (4 ml)
3	γ-globulin (6.1 mg/ml)	–	6.1 mg/ml	PBS (4 ml)
4	γ-globulin (6.1 mg/ml)	Albumin (24.9 mg/ml)	31 mg/ml	PBS (4 ml)

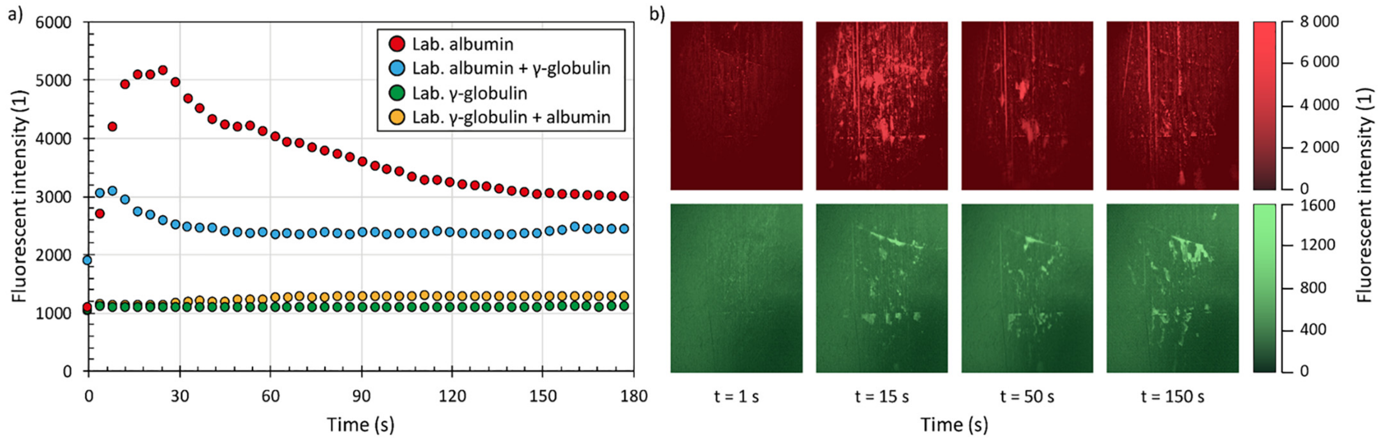

Fig. 4. a) Development of non-dimensionless film thickness (fluorescent intensity) as a function of time for various test fluids; b) Images of the observed zone at defined time steps for albumin (red) and γ-globulin (green). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

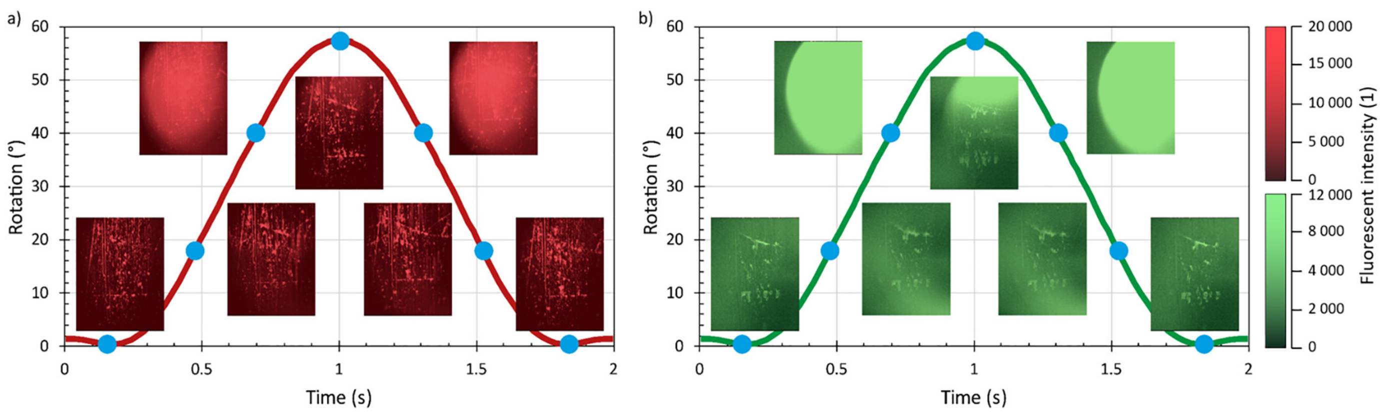

Fig. 5. Detail of the images of the observed part of the contact zone over the cycle: a) albumin; b) γ-globulin.

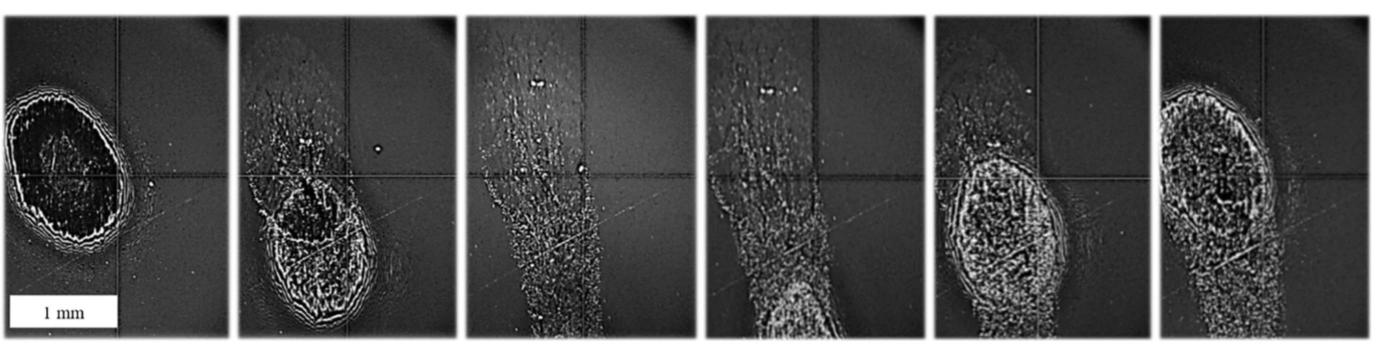

Fig. 6. Macroscopic observation of migrating contact zone.

of albumin and γ-globulin shows higher friction than simple protein solutions. In addition, the thickness of the adsorbed film was lower in the case of protein mixture which corresponds to current results [29].

Second set of experiments was performed with γ-globulin-based lubricants. Simple protein showed very limited lubrication ability while only a negligible increase of film thickness due to protein agglomerations could be observed. When albumin was added, the lubricant layer slightly increased (see Fig. 4a); nevertheless, the film was substantially lower than that of albumin-based model fluids (the thickness was less than half). This corresponds to findings related to lubrication of hard-on-soft hip implants [23]. However, in contrast to some previous observations, simple albumin formed thicker protein film compared to simple γ-globulin [21,30] which proves the importance of the contact mechanics related to contact conformity (1) and soft nature of metal-on-PMMA contact (2).

The fluorescent images of the observed part of the contact zone for albumin and γ-globulin solutions are displayed in Fig. 4b. As can be seen, the appearance of the images corresponds well to the results of film thickness (Fig. 4a). In the case of albumin, rapid increase of intensity could be observed within the first 15 s. This is attributed to strong agglomeration of proteins at the early phase of the experiment. Subsequently, part of the proteins is removed/squeezed out from the contact, leading to thinning of the lubricant layer. In the later part of the experiment, small scratches can be observed on PMMA surface. Surprisingly, these scratches were not so substantial in the case of γ-globulin. This might be related to better lubricity of γ-globulin despite the thinner lubricant film, ensuring lower coefficient of friction. This partially corresponds to previously published friction results [31]. As can be seen, only a limited protein formation can be observed in the case of γ-globulin solution. It should be emphasized that the fluorescent intensity plotted in Fig. 4a corresponds to average intensity over the whole observed zone. Therefore, it is evident that these limited localized protein clusters have quite limited impact on overall film thickness.

To be able to assess the recovery of the lubricant film during the swinging cycle, images of the contact zone over one cycle during 30th second (maximum albumin intensity) were taken. The illustrative images at various phases of F/E rotation are shown in Fig. 5. When focusing on the first and the last picture (the left and the right) along the cycle, it can be seen that the appearance of the contact zone at the beginning and the end of the cycle is very similar. This is an important verification regarding the methodology. Due to complicated geometry of the femoral implant, the contact migrates during the cycle. This can be clearly seen in terms of overexposed images. In that phase of F/E, the contact disappears for very short time outside the observed zone. However, in the subsequent back-swing, the contact returns to the initial position. The image corresponding to maximum deflection might be bit confusing; however, in that case, the contact area is the largest. Therefore, for a very short moment, the contact reaches the observed zone. This is the reason why only a small part of the image (when F/E = 60°) is overexposed.

The migrating contact zone shown in Fig. 6 is one of the limitations of the performed study. Microscopic images of the migrating contact were taken using no-magnification lens under transient load (maximum 400 N) to get better imagination about the contact motion over the cycle. Therefore, the camera holder mechanism will be redesigned in the future; thus enabling to observe the contact zone over the whole cycle. Thus, the development of film thickness in various phases of F/E will be evaluated. Another limitation is that we focused on lateral compartment when observing the lubricant film formation. However, it was pointed out in literature that in terms of wear, the behaviour of both lateral and medial compartments is different [19]; therefore, the future study should involve this suggestion and verify the findings in terms of lubrication. Further, it should be highlighted that the present study was focused mainly on the development of the knee joint simulator, experiment design, and methodology of evaluation of lubricant film formation. For this purpose, only simple and mixed protein solutions were employed to understand some fundamentals. Nevertheless, it was showed in the studies focused on hip joint lubrication that these simple solutions are not able to mimic the behaviour of complex model SF [21,23,28]. Therefore, more SF constituents have to be taken into account; e.g. HA and phospholipids, in particular.

Finally, relatively simple shape cycle was designed for this introductory study. Following the real joint kinematics and loading conditions, more complicated motion as well as more variable load over the cycle have to be taken into account. It is particularly complicated to confront the preliminary results coming from the performed study with literature dealing with knee replacements. The main reason is that so far there is only one experimental study while the authors used simplified geometry and different technique to determine the surface separation [16]. Other above-mentioned experimental works are mostly focused on wear and/or friction evaluation [8–12]. The references related to lubrication mechanisms are exclusively numerical [13,15,17–19]; while it can hardly involve the complexity of geometry; non-Newtonian behaviour of SF [30], or adsorption and agglomeration of proteins [23,32]. Therefore, further experimental investigation is necessary to be able to understand and clarify the lubrication mechanisms of knee implants in a more complex way.

4. Conclusion

The knee joint simulator enabling in situ observation of the contact zone was introduced in the present study. The methodology based on fluorescent observation was employed while it was shown that the approach might help to significantly extend the knowledge about the lubrication of knee implants. Real geometry of rubbing surfaces was considered while a clear interaction of albumin and γ-globulin in terms of dimension-less film thickness was presented. The main goal of the present paper was to design and verify the method for lubricant film formation investigation in knee joint replacement. In particular, it was found that albumin layer is considerably thicker compared to γ-globulin. This is caused by higher concentration of albumin. In addition, it emphasizes the issue of contact mechanics since the results go partially against previous findings for hard-on-hard implants. However, it should be highlighted that maximum film thickness is not a decisive parameter as the function of replacement is a long term-process. Therefore the lasting effect of the lubricant (ability to form stable lubricating layer) was of a greater interest. Independently of the stained fluid component, it was found that mixture of the proteins exhibits better lubrication performance. This proves the importance of the interaction of the molecules contained in SF. The motivation for future study is to consider more complex model of SF together with transient kinematic and loading conditions with respect to various motion activities. In addition, the contact migration throughout the cycle will be issued and both the compartments should be considered into the analysis.

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