A COMPARATIVE STUDY ON WEAR BEHAVIOR OF HIP PROSTHESIS BY FINITE ELEMENT SIMULATION

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ABSTRACT

A numerical approach was proposed to investigate the wear behavior occurred in the artificial hip joints in this paper. In the numerical simulations, the wear coefficients taken from pin-on-disk tests were introduced into the wear analysis model to assess the wear rates of polyethylene acetabular cups against metallic or ceramic femoral heads. For the established material combinations, different values of polyethylene wear rates were obtained respectively, which were not necessarily the realistic one as expected in vivo but could be confirmed after further discussion on the wear mechanism involved in wear tests. Current results indicated that the polyethylene/ceramic couples represented better wear performances than the polyethylene/metal couples. Furthermore, the ratio of wear rates for polyethylene cups against alumina and the metallic femoral heads was 0.5, which agreed well with that deduced from clinical studies or laboratory hip simulators. It is obvious that these comparable wear behaviors observed from clinics or laboratory studies also can be found by means of the numerical simulation.

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Keywords: Hip prosthesis; Acetabular cup; Wear coefficient; Wear rate

1. INTRODUCTION

Over the 30 years of total hip replacement, a number of biomaterials including metal, ceramic and polyethylene for artificial hip components have been proven successfully under clinical conditions. However, in spite of the materials used for prosthetic implants, the wear of the articulating surface has been the major problem encountered in clinics. Metallic wear particles have been found to disseminate in the various organs such as lymph node, liver, spleen and bone marrow, which may induce the tissue necrosis [1,2]. Clinical studies [3-5] have shown that the polyethylene wear particles cause the osteoarthritis and periprosthetic bone loss and subsequently, the aseptic loosening of fixation.

To prevent the loosening from fixation, the ceramic, with excellent wear characteristics against polyethylene, was being used as a substituent for prosthetic components. Although ceramic and polyethylene combinations have been reported with lower wear rates than the conventional metallic and polyethylene couples, the incidence of breakage due to low toughness is still the limitation of prevalent usage in clinics.

Seeking for more appropriate biomaterial on prosthesis design is therefore the main concern in bioengineering related communities. However, for any new candidate materials to be paired in hip prosthesis, it is necessary to evaluate their wear performances before clinical trials. For this, laboratory tests using pin-on-disk apparatus [6,7] or hip joint wear simulators [8-10] have been developed. Usually, the essential tribological characteristics of the bearing materials can be obtained through the pin-on-disk wear tests. In hip simulator, the clinically used or designated artificial hip components were soaked in the physiological lubricant, such as bovine serum or distilled water. The forces imposed on the hip joint were also well controlled and synchronized through the hydraulic actuators with digital control system so that the loading profile can be

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replicated in physiological sense to simulate the hip joint forces under normal walking. In addition, the testing duration was set to 4 to 6 million cycles that is equivalent to 3 to 4 years of implantation time. Compared to the results with pin-on-disk, it is therefore believed that the wear test performed on hip simulators can realistically reproduce the physiological wear phenomena in association with the wear mechanism occurred in the resulting artificial prosthesis. However, the costs in equipment and time interval required on hip simulators are the main drawbacks in application on new prosthesis designs.

For investigating the wear behaviors of hip prosthesis with different material combinations in more efficient ways, in this paper, a numerical simulation technique based on three-dimensional contact model and modified Archard's wear law was employed to analyze the wear behavior in hip prosthesis. The volumetric wear rates and linear wear rates of polyethylene acetabular cups against metallic or ceramic femoral heads were assessed through the computational algorithm. The wear patterns of interface of acetabular cups were also drawn for further perception on the wear behavior.

2. WEAR MODEL

2.1 Wear Mechanism in Artificial Prosthesis

For wear simulation by numerical analysis, a proper wear model for assessment of wear amount is prerequisite. Meanwhile, the wear model needs conforming to the wear behavior and wear mechanism involved in the artificial hip prosthesis. Generally speaking, the wear behavior occurred in artificial hip prosthesis is quite complicated to understand because the wear mechanism at articulating surface is affected by factors such as the contact status at the bearing surface, as well as the tribological characteristics of bearing materials and the resulting physiological conditions.

In fact, the wear behaviors have been realized to some extent from analysis of wear debris or examination on surface morphology of worn prosthetic components taken from retrieval implants or laboratory hip simulators. For example, earlier studies in [11-13] and the recent results in [14] have shown that majority of polyethylene wear particles produced in artificial prosthesis were 0.1 to 1 μ m in size and they are round in shape, irrespective of the materials used for these components. The bearing surface of femoral head or acetabular cup displayed the appearance of surface stretching of the form of fibril, which can be attributed to be the typification of micro-adhesive wear [11] or third-body abrasive [13]. These comparable wear morphologies also suggested that in vitro hip simulators, they could provide an equivalent model of the wear of

total hip replacements as in vivo. The similarity in size and morphology of the wear particles further indicated that the same basic wear mechanisms occurred in these hip prosthetic components.

Concluding the investigations on wear mechanisms in [8-9], [15-17], three major wear mechanisms occurred in the artificial hip joints have been identified, namely, adhesive wear, abrasive wear and fatigue wear. These wear mechanisms may occur in interrelating ways with the physiological conditions during the long-term wearing process, but they usually cannot be clarified with each other since they are related to the bearing materials sliding against mutually, the resulting lubrication conditions, and the patient activity. When the shear strength at the interface was higher than those in the soft materials, the adhesive wear can be induced by the shearing of microscopic asperities on soft materials and subsequent adhesion of wear debris to the interface of hard materials. Such wear characteristics have been verified in the wear tests for polyethylene sliding against alumina ceramic in [7] and [18]. Similar wear behaviors were also observed in the combination of metal-on-polyethylene [19], which pointed out that the polyethylene wear rate is controlled by the extent of adhesive transfer from polymer to the metal interface. In [19], the wear behavior of polyethylene sliding against metal discs (Ti-6Al-4V alloy with various surface treatment, AISI 316 L stainless steel and Vitallium) were investigated using an annulus-on-disc oscillating tribometer. However, in another sliding wear tests, it has shown in [20] that no polymer transfer layers were observed on the metallic interface and the adhesion between polyethylene and titanium alloy surface is weak. For hip joint combinations of metal and polymer, it seems that the abrasive wear has the dominance in wear behavior when the hard debris produced from the metallic asperities are served as the third-body particles and entrapped between articulating surface. On the other hand, the authors in [21] reported that the wear mechanisms would have changed from adhesive to abrasive when the metallic interfaces were roughened, either from manufacturing process, surface scratches, or disruption of dioxide layer. For advanced investigation on the wear behavior in artificial prosthesis, the authors in [22] have conducted a series of wear tests for alumina ceramic and CoCr femoral heads with various surface roughness articulating on polyethylene acetabular cups under serum lubricant conducted using a multidirectional motion hip simulator. Their results have also revealed the similar wear morphology reported in [10-14] on the wear debris retrieved from periprosthetic tissues.

2.2 Wear Model

As mentioned above, the wear mechanism involved in artificial prosthesis of different material couples can be considered as the combinations of adhesive

wear and abrasive wear in nature, even with fatigue wear to little levels. From the macroscopic viewpoint, such wear behavior can be referred to as the process of surface material removal due to relative sliding of two mating components. The wear amount can thus be determined from the energy required to remove the material from contact surface, which essentially can be correlated with the sliding distance, frictional force on contact surface and surface properties of mating materials. Based on this concept, the explicit relationship between the wear volume and the contact surface and sliding distance can thus be expressed by the Archard's wear equation, that is,

$$V = K_f S p_n \quad (1)$$

where V is the wear volume removed from the contact surface, S is the sliding distance, p_n is the normal contact force and K_f is the wear coefficient, which indeed imply the factors affecting the wear behavior, such as hardness, and friction of mating materials.

Since the contact statuses as well as wear behaviors in acetabular components indeed have three-dimensional characteristics, the wear depth for a local point is more important substantially than the bulk wear in volume. The Archard's wear equation may therefore be modified into an incremental form for a local point on articulating surface of acetabular cups, that is,

$$dV = \Delta A dh = K_f (\sigma \Delta A) ds, \quad (2)$$

$$dh = K_f \sigma dS, \quad (3)$$

where dh is the infinitesimal wear depth, dS is the infinitesimal sliding distance, and σ is the locally normal contact stress.

The wear depth h at any point on the interface after wearing path S , then can be assessed from the integral equation,

$$h = \int_0^S K_f \cdot \sigma \cdot dS. \quad (4)$$

Recalling the wear coefficient K_f in above equations, which is defined as the wear volume per unit load and sliding distance, can be determined by experiments. In pin-on-disk testing machine, the polyethylene pin members are held to slide against the metallic or ceramic interface in unidirectional or multidirectional motion under different lubricated conditions. Unlike the hip simulators, the results from pin-on-disk wearing tests can not reveal the real wear behavior in hip prosthesis, however, the essential wear characteristics under specified testing environments can be easily quantified by the wear coefficient from the measured wear amount.

3. WEAR ESTIMATION

3.1 Model Description

Considering the simplification and efficiency in

numerical simulations, the finite element model of the artificial hip joint consists of only acetabular cup and femoral head without the stem. The acetabular cup is made of ultra high molecular weight polyethylene (UHMWPE) with interior diameter of 32, 28, and 22 mm and outer diameter of 50 mm, while the paired femoral head with different materials is simulated by a hollow spherical geometry with the interior surface constrained. The whole finite element model is meshed with hexahedron brick elements, as shown in Fig. 1. Since the acetabular cup is fixed to the pelvis bony part, a layer of compact bone, with Young's modulus of 17 GPa and Poisson ratio of 0.46, is applied to the outer surface of the acetabular cup. At the possible contact regions such as bone/cup and cup/head region, the element discretization is finely meshed and proper numbers of contact element are added. Material properties such as Young's modulus (E) and Poisson ratio (ν) are $E=0.8$ GPa, $\nu=0.47$ for polyethylene, $E=190$ GPa, $\nu=0.305$ for stainless, $E=230$ GPa, $\nu=0.33$ for CoCrMo alloy and $E=380$ GPa, $\nu=0.32$ for alumina ceramic. The wear coefficients for polyethylene-metal and polyethylene-ceramic under certain environments are listed in Table 1.

3.2 Loading Conditions

The physiological loading profile, analyzed from gait analyses, is imposed on the hip joint model in numerical simulations. Generally speaking, the main activities of foot are flexible and extendable in the walking direction, while other activities such as abduction or adduction, and femoral rotation, are negligible [23]. Therefore, the force component induced by flexion and extension of foot is mainly considered in this study. Meanwhile, the load profile for one gait cycle is taken from experimental data used by Saikko [24] in five-station hip joint simulator. Each gait includes two phases, namely, standing and swing phases, in the mean time the swing angle of foot is 23° in the for-

Fig. 1 Solid model with mesh overlay of artificial hip joint.

Table 1. Wear coefficients for polyethylene sliding against metallic and ceramic counterface in different lubricants

No	Mating materials	Wear coefficient ($10^{-7} \text{ mm}^3/\text{Nm}$)	Lubricant
PS1	Polyethylene / Stainless steel	8.00	Bovine serum [24]
PS2	Polyethylene / Stainless steel	1.81	Bovine serum [25]
PC1	Polyethylene / CoCrMo alloy	3.50	NaCl Water [26]
PA1	Polyethylene / Alumina ceramic	3.10	Bovine serum [7]
PA2	Polyethylene / Alumina ceramic	1.01	Bovine serum [25]

ward and backward directions for flexion/extension actions [23,27]. The maximum load is 3500 N corresponding to five times of body weight of 71.4 kg. In addition, the load profile is divided into sixteen load stages, shown in Fig. 2, with the relative directions applied to the femoral head in Fig. 3. Thus, the contact stress can then be calculated at discrete locations respectively, rather than the whole gait cycle. Once the contact stresses have been calculated, they are served as input for the subsequent wear estimation.

3.3 Computational Process

A computational algorithm developed in our previous studies [28] is followed to evaluate the wear rate of the acetabular cup. This algorithm includes three major parts, namely, determination of contact stress at the articulating surface, estimation of local wear depth, and updating the contact geometry. The real contact status will vary with the gait cycles since the contact geometry will become nonconforming from the initial conforming state when wear occurs. It is therefore necessary to update the contact geometry of the bearing surface to reflect the wearing effects, which can be down by incorporating the wear amount into the model geometry. The magnitude of forces applied to the arti-

ficial hip joint in every stage of each gait cycle can thus lead to the real contact status. Besides, the wear simulation is an iterative process and need to be repeated for a required gait cycles. In this paper, the total gait cycles defined for the assessment of wear behavior is 1.5 million walking cycles per year, among which the wear amount is estimated for every 100 thousand gait cycles. It followed that the modification on contact surface and recalculation of contact stress is carried out. Finally the volumetric wear loss values, determined from the difference of volume of unworn and worn acetabular cups, were converted to the linear wear rate by means of the equation $h = V / \pi R^2$, in which V is the wear volume, R is the cup radius and h is the linear penetration.

4. RESULTS AND DISCUSSION

For each different material combination of hip prosthetic components, we first calculated the normal

Fig. 2 Forces acting on the hip joint in one gait cycle. **Fig. 3 Loading directions for 16 stages in one gait cycle.**

Fig. 4. Growth of wear depth with gait cycles for polyethylene acetabular cup against stainless steel, CoCrMo and alumina femoral head. (refer to Table 2 for material couples PS1,PC1,PA1; 32 mm in head size).

pressures applied to the compact bony part for each load stage according to the 16 loading stages for one gait cycle. The contact elements were added to the interface of the bone/cup and cup/head regions to determine the contact stress and then assess the wear rate. The growth of wear depth and wear volume with gait cycles for polyethylene acetabular cup against specified femoral head (32 mm in size) are shown in Fig. 4 and Fig. 5. In addition, the polyethylene wear rates for different material combinations estimated by presented model are summarized in Table 2. For polyethylene acetabular cups coupled with stainless steel, wear rates in vivo are usually in the range 0.1–0.2 mm per year. To compare with the data in the presented study, the linear wear rates fall within the wide ranges of 0.019 to 0.110mm/year (with mean value 0.052), in which the lower and upper values are estimated under two different wear coefficients quoted in presented wear model. The influences on wear rates and meanings of wear coefficients will be discussed later. For polyethylene acetabular cups against CoCrMo heads, the linear wear rates per year are within the ranges of 0.036 to 0.048mm (with mean value 0.040). With 32 mm CoCr heads, the hip simulator reported the wear rate 0.043 mm per 1 million cycles [9]. It can be seen that reasonable agreements exist between numerical results and clinical observations or laboratory studies. Obviously, as an interface of polyethylene, CoCrMo alloy shows better wear characteristics than stainless steel.

On the other hand, for polyethylene acetabular cup coupled with ceramic femoral head, the average linear wear rates are within the ranges of 0.011 to 0.042 mm (with mean value 0.024). Current results in-

Fig. 5. Growth of wear volume with gait cycles for polyethylene acetabular cup against stainless steel, CoCrMo and alumina femoral head. (refer to Table 2 for material couples PS1,PC1,PA1; 32 mm in head size).

dicate that the hip prosthesis with polyethylene/ ceramic couples yield lower wear rates than those with polyethylene/metal couples. Similar tendency can be found in volumetric wear rates. Comparative wear rates for hip prosthesis with different material combinations have been reported in literature, and they are summarized in Table 3. These wear results were usually measured by means of different methods including radiographic measurement in clinic, dimensional change of explanted acetabular cups, or laboratory hip simulators.

In the case of polyethylene acetabular cup paired with a stainless steel femoral head (22mm in size), the mean wear rates obtained from clinical studies [8, 29–32] or the hip simulator [23,33] roughly fall within the wide range of 0.1 to 0.2 mm/year in wear depth, and 45 to 75 mm³/year in volume loss. In our work, the corresponding wear rates are 0.111 to 0.029mm/year in wear depth and 11.28 to 42.03 mm³/year in volume loss, which have great accordance with the laboratory or clinical results. However, the above results are estimated with different wear coefficients taken from the pin-on-disk apparatus. Especially the wear coefficient of $0.8 \times 10^{-6} \text{ mm}^3 \text{ N}^{-1} \text{ m}^{-1}$ yields the wear rates of 0.111 mm/year, which is close to the clinical results [29]. It is obviously that the wear coefficients directly affect the wear rates of polyethylene acetabular cups, nevertheless, they unnecessarily yield the real wear results of hip prosthesis. It is therefore worth noting the significance implied in the wear results associated with the wear coefficient while proceeding wear simulations. In other words, whether the wear mechanism occurred in the pin-on-disk testing environments conforming to that involved in hip prosthesis is of the

Table 2. Wear rate for polyethylene acetabular cups against metallic and ceramic femoral heads

Mating materials	Volumetric wear rate (mm ³ /year)				Linear wear rate (mm/year)				Wear coefficient (10 ⁻⁷ mm ³ /Nm)
	Head size (mm)				Head size (mm)				
	32	28	22	mean value	32	28	22	mean value	
Stainless steel	16.89	11.89	11.28	13.3	0.021	0.019	0.030	0.024	1.81
	58.42	52.07	42.03	50.84	0.073	0.085	0.111	0.089	8.00
CoCrMo alloy	29.13	23.0	18.2	23.44	0.036	0.037	0.048	0.040	3.50
	Average wear rate				0.043	0.047	0.063		
	Overall average linear wear rate for metallic head = 0.051								
Alumina ceramic	11.03	6.59	5.23	7.62	0.014	0.011	0.014	0.013	1.01
	26.28	20.35	16.13	20.92	0.033	0.033	0.042	0.036	3.10
	Average wear rate				0.024	0.022	0.028		
Overall average linear wear rate for ceramic head=0.024									

same importance as the wear coefficient. For instance, the wear coefficient taken from the circularly translating pin-on-disk (CTPOD) test in [24] was higher than that for other reciprocating pin-on-disk tests [25], even if these tests were performed in bovine serum lubricant. However, it brings to different wear rates in current wear estimations. By analyzing the worn surface and wear particles, authors in [24] believed that the induced wear mechanisms in CTPOD wear test were similar to those observed in retrieved polyethylene acetabular cups, which therefore yield the wear coefficient close to that obtained in clinical studies [34]. It has been proven in the current wear simulation that this reasonable wear coefficient brings to realistic polyethylene wear rates.

Similar circumstances also can be found in the case of the polyethylene acetabular cup against the alumina femoral head. The schemes in [7] and [25] also employed a pin-on-disk machine to investigate the tribological behaviors in such material combinations. The polyethylene wear coefficients were found to be $1.01 \times 10^{-7} \text{ mm}^3 \text{ N}^{-1} \text{ m}^{-1}$ in bovine serum lubrication and $3.1 \times 10^{-7} \text{ mm}^3 \text{ N}^{-1} \text{ m}^{-1}$ in water lubricant, respectively. In the presence of bovine serum lubrication, polymer debris was found to adhere to the alumina interface, which was the appearance of adhesive wear. While in water lubricant, the abrasive wear were initiated by the plowing action of the ceramic contact asperities into polymer for a definite time, and then polymer transfer film was gradually formed on ceramic interface with time. It is apparent that distinct wear mechanisms might occur under various testing conditions and hence brought wear rates to different level. With these wear coefficients introduced into cur-

rent model, different values of mean wear rates (with head sizes of 22, 28, and 32 mm) are estimated to be 0.013 (in the range of 10.7 to 13.8) mm/year and 0.036 (in the range of 32.7 to 42.4) mm/year, respectively. Such wide varieties in wear rates were also found on laboratory hip simulators [23, 35-38].

The comparative wear resistance of polyethylene against ceramic and metallic also can be clearly declared by summarizing the current results. Further discussion can also be made. The shaded images of wear depth at the interface of acetabular cups are shown in Figs. 5 to 7. For polyethylene cup against stainless head, the main wear apparently concentrates on the central contact zone and diminishes in outward direction circumferentially with different extents. It can be expected that the tunneling effect will occur if femoral head persistently penetrates into acetabular cup. Furthermore, that may result in the nonconformity of contact geometry between femoral head and acetabular cup, and hence increase in subsequent wear. Similar, but lessened, wear behaviors also can be found for CoCrMo femoral head paired with the polyethylene cup. For polyethylene cup against alumina ceramic head, the wear rates are not significantly reduced when compared with CoCrMo alloy/polyethylene couples. However, the wear depth distributes more uniformly over the interface of acetabular cups, which may have the interface to retain conforming contact geometry. The average wear rates of polyethylene against ceramic and metallic heads with head size 32 mm are 0.023 mm and 0.043 mm, respectively; the ratio being 0.534. While the average wear rate for the ceramic and metallic heads with diameter 22 mm are 0.0281 mm and 0.0626 mm respectively; the ratio being 0.45. It is

Table 3. Comparison of wear rate of polyethylene acetabular cup obtained from clinical measurements, experimental procedures and numerical methods

Mating materials	Technique / model	Head size (mm)	Average linear wear rate (mm/year)
Stainless steel	Clinical observation [8,29-33]	22	0.005~0.623 (mean 0.1~0.2)
	Hip simulator [23,34]	22.5 , 22	0.15; 0.108
	Current numerical model	22	0.029; 0.111
Alumina ceramic	Hip simulator [35]	22	0.038
	Current numerical model	22	0.0138; 0.0424
CoCrMo	Clinical observation [36]	28	0.247
	Hip simulator [14]*	28	0.091
	Current numerical model	28	0.037
Alumina ceramic	Clinical observation [36]	28	0.098
	Hip simulator [14]*	28	0.084
	Current numerical model	28	0.011, 0.033
Stainless steel	Clinical observation [29]	32	0 ~ 0.32 (mean : 0.10)
	Hip simulator [19,36]	32	0.036; 0.032~0.0592(m)
	Current numerical model	32	0.073
CoCrMo	Hip simulator [9,19,27]	32	0.053; 0.022; 0.03
	Current numerical model	32	0.0362
Alumina ceramic	Clinical observation [39]	32	0.02~0.20
	Hip simulator [23,35,36]	32	0~0.016; 0.027; 0.034~0.072
	Current numerical model	32	0.013; 0.033

*Original wear data were reported in mass loss and transferred into wear volume (= mass loss/0.94 mg mm⁻³) and linear wear rate(= wear volume/ πr^2).

interesting to note that the ratios of the overall estimated polyethylene wear rates for acetabular cup against alumina and the metallic femoral heads are 0.5, which is identical to the clinical measurement in [39]. In addition, according to the comparative investigation in [40], the author collected the results from other clinical studies and hip simulator tests, the ratio of polyethylene wear rates also behaved wide variation, being in the range of 0.29 to 0.71. For acetabular cups against ceramic heads and metallic heads, a comparative ratio 0.5 also could be deduced. It is obvious that these comparable wear behaviors observed in clinic or laboratory also can be found by means of the numerical simulation and shows good agreements in these results.

5. CONCLUSION

In this paper, a numerical approach was proposed to investigate the wear behavior occurred in the artificial hip joints. In numerical simulations, the wear coefficients taken from pin-on-disk tests were introduced into the wear analysis model to assess the wear rates of

polyethylene acetabular cups against metallic or ceramic femoral heads. While for designated material combinations in artificial hip components, dissimilar wear coefficients were derived under various lubricated conditions or testing configurations. These wear coefficients not only implied the essential tribological characteristics of polyethylene against various materials in the presence of different lubricant, but also brought the polyethylene wear rate to different values when used in wear simulations. Therefore, the estimated wear rates were not necessarily the realistic one as expected, however, that could be confirmed after further discussion on the wear mechanism involved in the wear test.

For the simulated material combinations, although the estimated wear rates of polyethylene acetabular cups behaved different values, as observed in clinical or laboratory studies, the polyethylene/ceramic couples showed better wear performance than the polyethylene/metal couples. Furthermore, the ratios of wear rates for polyethylene cups against alumina and the metallic femoral heads were 0.5, which are similar to that reported in literatures. It is obvious that these comparable wear behaviors can be found by

Fig. 6 Shaded-image of wear depth of polyethylene acetabular cup against stainless steel femoral head (32 mm, wear coefficient = $0.8 \times 10^{-6} \text{ mm}^3 \text{ N}^{-1} \text{ m}^{-1}$).

Fig. 8. Shaded-image of wear depth of polyethylene acetabular cup against alumina ceramic femoral head (32 mm, wear coefficient = $3.1 \times 10^{-7} \text{ mm}^3 \text{ N}^{-1} \text{ m}^{-1}$).

Fig. 7 Shaded-image of wear depth of polyethylene acetabular cup against CoCrMo alloy femoral head (32 mm, wear coefficient = $3.5 \times 10^{-7} \text{ mm}^3 \text{ N}^{-1} \text{ m}^{-1}$).

means of numerical simulations. Contrary to the time and cost consuming on the hip simulator, the numerical simulation combined with pin-on-disk wear test has been proven to be an efficient and reliable manner in the validation of wear characteristic for artificial prosthesis with new designs.

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