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Wear Prediction of UHMWPE Cup Against Commercially Pure Titanium Hip Implant With The Nonlinear Load and Contact Area Wear Equation

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Abstract. Hip implants are prostheses designed for severe hip arthritis patients. One of its components, acetabular cup is mostly made from ultra-high molecular weight polyethylene (UHMWPE). This polymer has a wear problem. Its debris would cause osteolysis followed by implant failures. Numerical studies of this problem were commonly used a linear contact pressure wear equation. Recently it was found not suitable to model the polymer wear in hip implants. This study used a nonlinear equation to predict the UHMWPE volumetric wear. It states a nonlinear relation between wear, load and contact area. The computation model was a biaxial rocking motion hip simulator assembly with UHMWPE acetabular cup sliding on commercially pure titanium femoral head. Multidirectional pin on disc experiments conducted to obtain wear factor and coefficient of friction data for the computations. Commercial finite element software calculated the other parameters. Predicted volumetric wear has a good agreement with the experimental data. Lowest numerical error was found 0.53 %.

Keywords: wear prediction, hip implant, UHMWPE, cp Ti.

1. Introduction

Hip implants are lower limb prostheses useful to help patients regain their productivities. The products replace the hip joints of patients with severe arthritis or injuries. The materials of the implants must meet several critical requirements to function properly. It must be biocompatible, have moderate strengths to avoid stress shielding at the femur and wear resistant. One of the most popular biomaterials used is the metal on polymer (MOP) [1]. It consists of artificial metallic femoral head and polymer acetabular cup. Many products designed and used with sophisticated reliability for decades. This is now challenged by a trend of the increased number of younger patients undergo hip replacement surgeries. The products must be able to be in service in much longer time than before. Wear problem especially of the polymers arises. Studies shown a high volumetric wear rate of the mostly used polymer, ultra high molecular

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weight polyethylene (UHMWPE) leads to osteolysis and bone resorption [2, 3]. These in vivo mechanisms caused implant failures [4].

Attempts to improve wear resistant need data obtained from the tribological tests. Experimental setups to study the biomaterial wear behavior must be able to mimic the in vivo conditions. The obstacles are the cost and time duration [5]. It is costly to build simulators able to wear test biomaterials in tens or even hundreds of stations simultaneously. The cyclic frequency of the simulators is one Hertz [6] and it takes millions of cycles to obtain adequate wear data. There is another method available to shorten wear test time duration. It is the computer modeling and simulation. This process use a wear model describes the wear behavior of biomaterial pairs. One of the models mostly used is the Archard equation. The use of this equation needs a wear factor obtained experimentally and contact mechanic parameters computed numerically.

The purpose of this research is to predict volumetric wear of UHMWPE acetabular cup paired with cp Ti femoral head in the hip simulator. The reasons to choose cp Ti are the excellent biocompatibility, low modulus of elasticity compared to other metals and its high fracture toughness [7]. Unlike other previous works [8, 9, 10], this prediction used the nonlinear load and contact area wear model from [11]. This model adapts the Ratner-Lancaster relation. It states that wear rate is not linearly proportional with contact pressure as assumed in Archard equation. The nonlinear model predicts that wear rate is independent from the sliding distance. This model is unique and specially developed for the untreated UHMWPE materials multidirectional sliding in the hip simulator. Inputs for the model was the calculated contact mechanic parameters obtained with Abaqus commercial finite element software. Experimental verification from literature [12] conducted to compare the precision of both models.

2. Materials and Methods

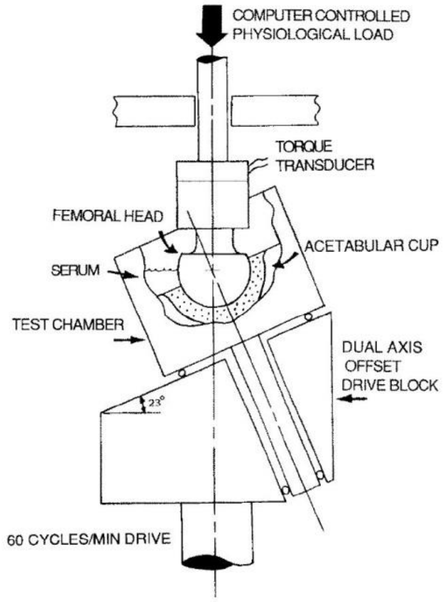
Realistic wear simulations need wear factors for specific tribological conditions. The process to determine the factor usually requires various experimental wear tests. This study uses the same process for cp Ti - UHMWPE pairs designed as hip implant biomaterials. The wear tests were in a multi directional sliding mode as experienced by hip implants [11]. The tests used a three stations multidirectional pin on disc tribotester. UHMWPE pins have dimensions of 9 mm diameter and 17 mm length. The counter faces are 50 mm thick cast cp Ti discs. The lubricant is a simulated body fluid (SBF) solution made from 25 % v/v bovine serum, distilled water and 0.03 % wt sodium azide [13, 14, 15, 16]. Continuous tests ran with 2 MPa and 3 MPa contact pressures and a 1 Hz cyclic sliding for one million cycles. A temperature controller managed the heaters to maintain the lubricant from 37 to 39 centigrade. The purpose is to mimic the in vivo human body fluid. Wear tests were in the incremental steps of 250,000 cycles. The intention was to avoid unrealistic wear rate due to protein adsorption at the surface of the discs [17]. Specimens were dismounted, cleaned and weighted at each incremental step. Wear factor calculations for the nonlinear contact model used the equation below [11]:

$$K_1 = \frac{\Delta V}{W^{2/3}\, A^{1/3}\, N} \tag{1}$$

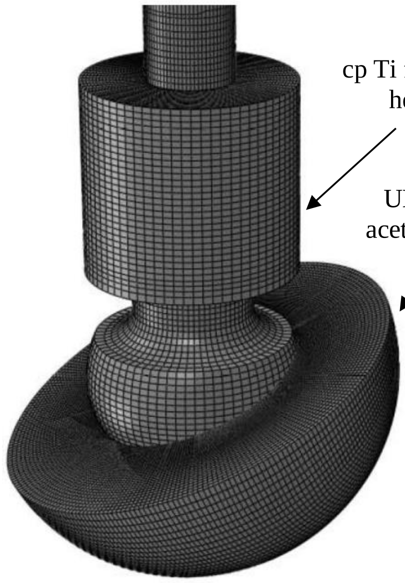
with ΔV, W, A and N are the volumetric loss, applied load, contact area and number of cycles respectively. Equation (1) is different compared with the Archard equation which wear factor is:

$$K_2 = \frac{\Delta V}{W\, L\, N} \tag{2}$$

with L is the sliding distance. The next obtained experimental data was the coefficient of friction. It is important for the main input of the explicit dynamic contact mechanic modelling and simulations.



(a) Experiment schematic [12]



(b) CAE model

Figure 1. The bi-axial rocking motion hip simulator model with 32 mm femoral head diameter.

The computation processes adopted the UHMWPE and cp Ti models with material properties obtained from literatures. Modulus of elasticity between the two materials differs much, hence the setup were rigid body for cp Ti and deformable for the softer UHMWPE. Other parameters such as time steps, loads and boundary conditions were carefully set similar to the experimental hip simulator setup of [12]. Computations were then conducted with Abaqus to simulate the dynamics of a biaxial rocking motion hip simulator (Fig 1). A dynamic explicit method were used to take inertial effects into account. The workstation was a four thread 3.9 Ghz CPU and 12 GB random access memory. The numerical results were used as the inputs to compute volumetric wear loss. A custom Python script developed to handle those calculations. On the linear contact pressure wear calculations (Equation 2), linear wear depths must be determined. It is useful for the UHMWPE cup geometry modifications. Geometry update at every 250,000 cycles performed for contact nodes coordinates at the worn area [18]. This repeated process performed until the desired number of cycles achieved. Predicted UHMWPE wear volume is an accumulation of calculated wear at every nodes and time steps. This volumetric wear is usually has a linear trend as experimentally shown by [14] [19, 20, 21]. In the nonlinear contact load model, wear volume was predicted only with the wear parameters at the peak load. There are two reasons for this approach. First, contact area cannot be accumulated from every nodes and every time steps just like the sliding distance on the linear model. Initial attempts in this research to calculate wear volume based on those accumulated contact area found errors up to several hundred percent compared to the experimental data. Second, the nonlinear model was developed by [11] with statistic regression which based on the maximum contact load (W_{max}). Hence, the nonlinear model offers a simple method to predict wear volume without repetitive tasks. There is a limitation to use this method. It is unable to predict the wear depth incrementally.

3. Results and Discussion

Wang et al [11] proposed a new model to calculate the UHMWPE volumetric wear rate per cycle sliding against a hard smooth counter face. The foundation of this model is a postulate that wear is proportional to the frictional work. Other findings by [22] [23] supported the development of the model as described by equation (1). Experimental verification conducted with wear tests of UHMWPE acetabular cup in a BRM hip joint simulator. The simulator provides a cross shear motion as occurred in the human hip joints. Unlike the commonly used Archard model, the data from [11] proved that the wear rate per cycle of UHMWPE is independent of sliding distance. Hence, this model is an update or at least as an alternative for the hip implant biomaterials wear prediction and computation.

Initial work of this study was the model mesh sensitivity analysis. The femoral head model used a 1 mm element size hexahedral mesh. As a rigid body model, it was not subject to mesh variations. Acetabular cup model as the object of wear analysis was tested by element type and element size variations. The tested element types are linear hexahedral (HL) and quadratic tetrahedral (TQ). Element size varied from a 1.5 mm coarse mesh up to 0.3 mm fine mesh. Single bias was applied at all radial direction from the corner close to the contact surfaces. Based on two contact mechanics parameters i.e. maximum contact pressure and maximum von Mises stress, the numerical convergence limit for both hexahedral and tetrahedral elements cannot be found (Fig. 2). The exponential trend of TQ element shows that element size less than 0.5 mm would cause severe computational costs.

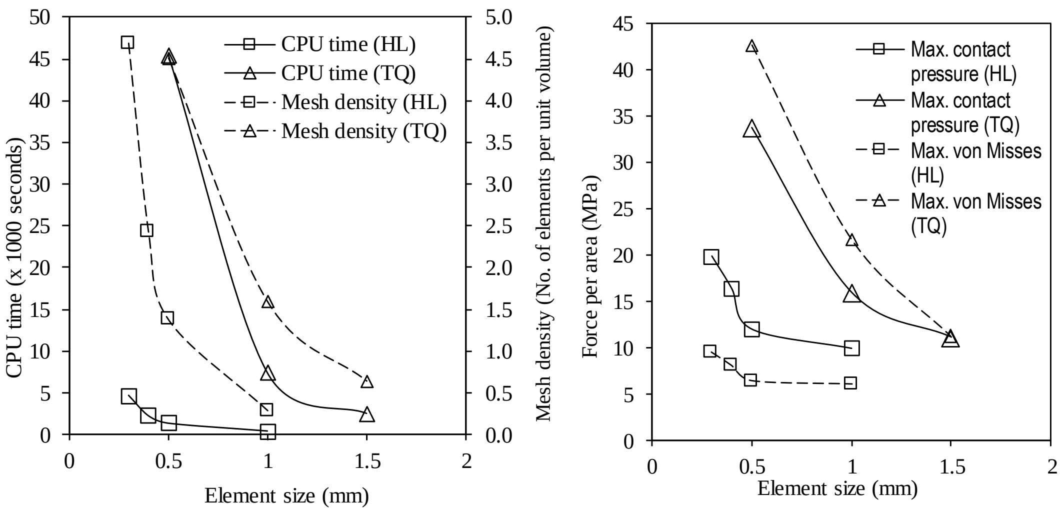


Figure 2. CPU time and mesh density (left), maximum contact pressure and maximum von Mises stress (right) as the function of element size.

Evaluation of the results taken from various mesh variations was continued with the gait load cycle (Fig. 3). Three models with 0.5 mm and 0.3 mm hexahedral and 0.5 mm tetrahedral elements were selected to be compared with applied load (Fig. 4). All element types show a similar trend, meshes must be smaller to obtain calculated load closer to the applied load. Hexahedral element perform better with curves closer to the Paul physiological load than the tetrahedral. The drawback of hexahedral element is the need to use finer element to approach the 1.96 kN maximum load. In this case is 0.5 mm or lower (Fig. 4(a)) while the tetrahedral can do the same with the 1 mm element size (Fig. 4(b)). Because equation (1) depends on both maximum load and contact area, this calculated load assessments cannot yet concluded the suitable mesh to accurately predict UHMWPE acetabular cup wear volume.

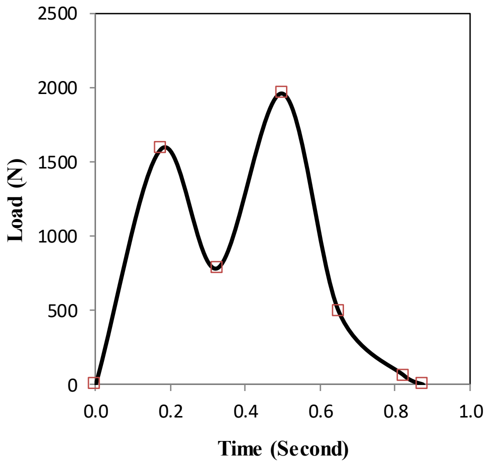
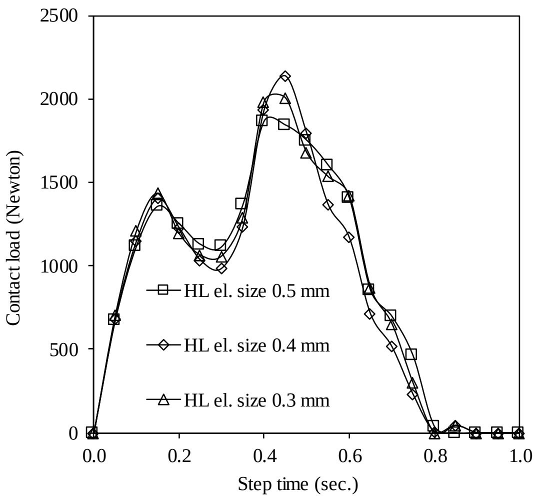
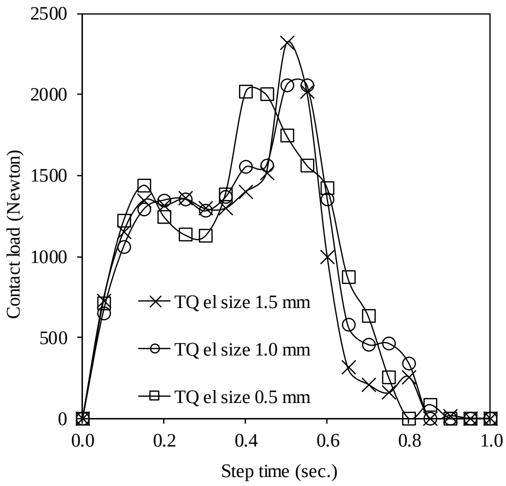


Figure 3. Load for the CAE model based on the Paul physiological load [12].



(a) Contact load by HL elements.



(b) Contact load by TQ elements.

Figure 4. Calculated load at the surface of UHMWPE acetabular cup.

The next evaluation is to check whether the calculated contact pressures are appropriate or not (Fig. 5 (a)). The Paul physiological load used by [12] has a maximum pressure approximately 15 MPa applied to the hip implant specimens. Due to the dynamic of the system which rotate at one Hz and the friction between the two materials, calculated pressure magnitudes could differ from the load. Finer meshes with smaller element size tend have higher calculated contact pressures. Data from the 0.5 mm tetrahedral element has very high unrealistic contact pressures compared to the contact load. The tetrahedral element has another drawback, its computational cost is higher than the hexahedral. This is why the tests of tetrahedral elements were stopped at 0.5 mm element size (Fig. 2). The closer curves to the load were obtained from the 0.3 mm and 0.5 mm hexahedral elements. The next numerical outputs related to contact pressure is the calculated von Mises stress (Fig. 5(b)). Similar trends with contact pressure were found. Tetrahedral element predicted too high stress magnitudes, more than 40 MPa. This result is unrealistic. Wear of the polymer could be catastrophic. The fatigue failure limit of typical UHMWPE is 32 MPa. From these checks, it can be concluded that the tetrahedral element is not suitable for this wear modelling and computation.

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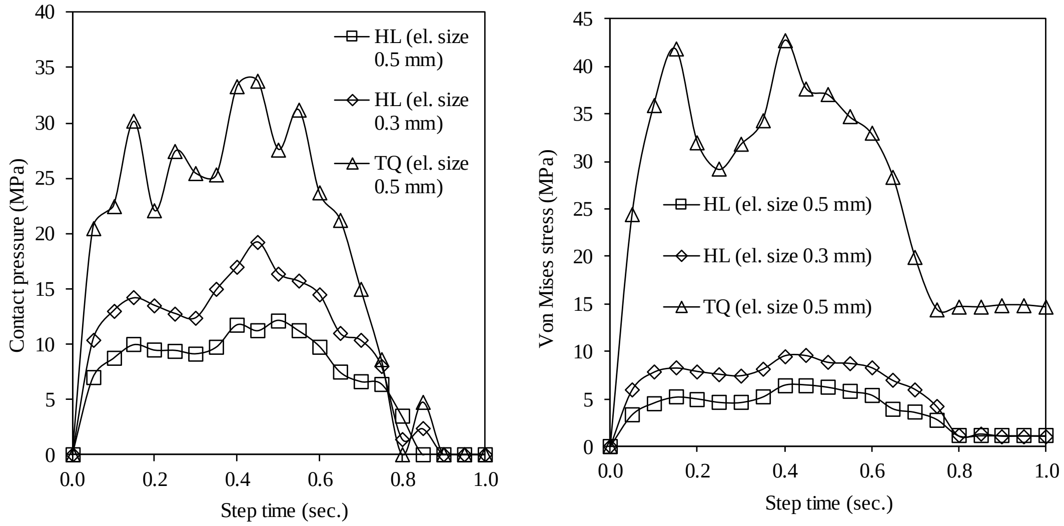

(a) Calculated contact pressures. (b) Computed von Mises stress.

Figure 5. Predicted UHMWPE cup contact pressures and von Mises stresses.

The von Mises curves of all fine hexahedral meshes show low stress values below the elastic plastic limit of UHMWPE. These are indications that the polymer material is safe and strong enough to withstand the physiological load.

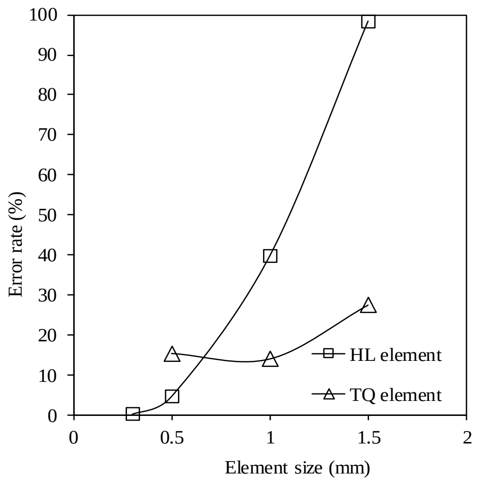

Figure 6. Errors at various element type and size.

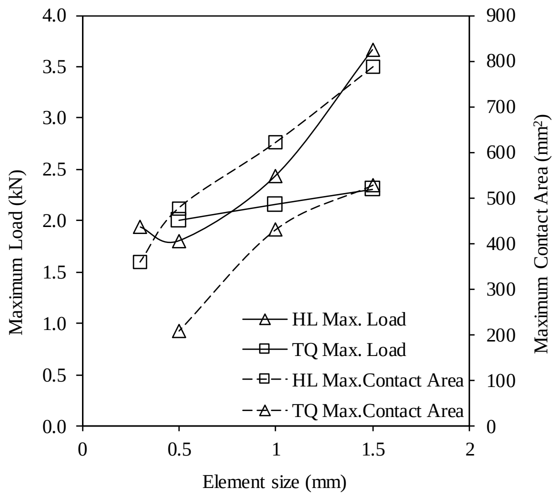

Figure 7. Maximum load and contact area at various element types.

Wear volume calculation based on equation (1) conducted on the UHMWPE acetabular cup model. The dynamic modelling needed two parameters, coefficient of friction and wear factor. Those two have to be obtained experimentally. The pin on disc wear tests delivered a coefficient of friction data equal to 0.2. Wear factors were also obtained from the tests after a million cycles. The values are K_1 = 4.02 x 10^{-8} $mm^{(5/3)}$ $N^{-(2/3)}$ for 2 MPa and K_1 = 8.02 x 10^{-8} $mm^{(5/3)}$ $N^{-(2/3)}$ for 3 MPa contact pressures. Wear calculation with the K_1 (2 MPa) constant values were not adequate. Experimental validation with volumetric wear data from [12] at 90.7 mm^3 per one million cycles found errors up to 51% (hexahedral) and 58.45% (tetrahedral). The next was the wear calculations with K_1 (3 MPa) as shown in Fig. 6. Initially the error is high on coarse meshes

(1.5 and 1 mm) but then drop drastically. At the 0.5 mm element size, acceptable error was found 4.31%. The lowest value is 0.53% obtained from the 0.3 mm element size. Meanwhile, the tetrahedral offers lower error rate with coarse element size but it cannot drop to the acceptable lower rate.

This result demonstrated that polymer wear volume can be predicted with a nonlinear contact load and contact area equation [11] and a constant wear factor (K_1). This method is relatively fast and easier but recently limited only to the wear volume. The use of Archard linear contact pressure equation is much complicated. It must be optimized with a series of wear factor data at various contact pressure ($K_2=f(P)$) as discussed by [8]. In the new model, two main calculated contact mechanics parameters needed, the maximum load and contact area. These parameters are dependent to the element size (Fig 7). Various size should be tested until the maximum load is close to the experimental, in this case equal to 1.96 kN according to [12]. Plotted curves between the maximum loads and contacts area could reveal the contact mechanic situations (Fig 8). Based on those contact areas and the acetabular cup radius, displacements (h) can be geometrically calculated. The results were plotted as a function of load (W) as shown in Fig 9. The power relations $y = ax^b$ have b exponents higher than the parabolic frictionless Hertzian exponent of 1.5 [24]. These metal on polymer contacts were less stiff than Hertzian contact.

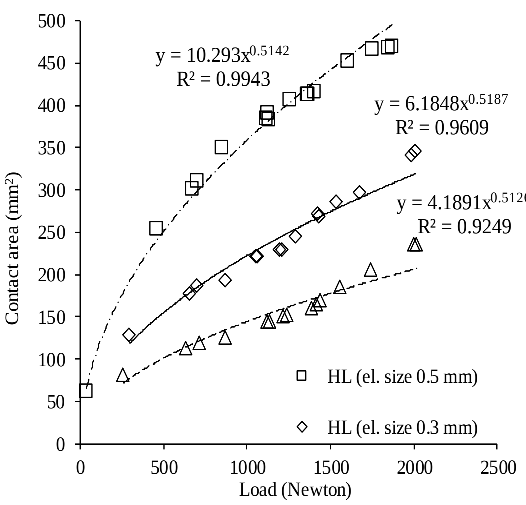

Figure 8. Load and contact area relation.

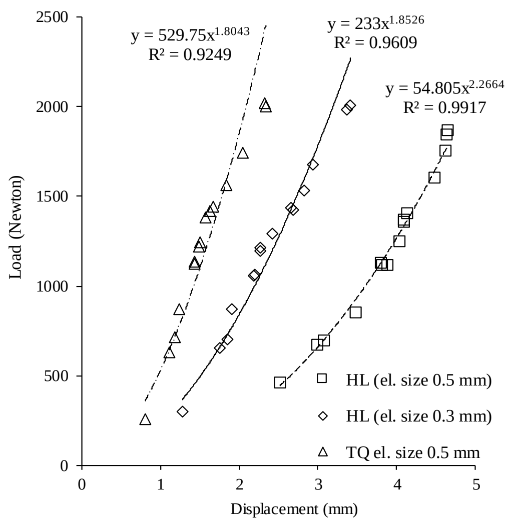

Figure 9. Load and displacement relation.

4. Conclusions

Wear volume prediction for hip implants made from a metal on polymer biomaterial pair of cp Ti and UHMWPE can utilize a nonlinear contact pressure model. The process is fast and simple. Tests conducted on the 32 mm hip implant models show that the hexahedral element is suitable for the contact mechanics calculations. Minimal error was found 0.53% with 0.3 mm element size validated with experimental data.

5. Acknowledgements

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