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The study of wear behaviors on abducted hip joint prostheses by an alternate finite element approach

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A B S T R A C T

An acetabular cup with larger abduction angles is able to affect the normal function of the cup seriously that may cause early failure of the total hip replacement (THR). Complexity of the finite element (FE) simulation in the wear analysis of the THR is usually concerned with the contact status, the computational effort, and the possible divergence of results, which become more difficult on THRs with larger cup abduction angles. In the study, we propose a FE approach with contact transformation that offers less computational effort. Related procedures, such as Lagrangian Multiplier, partitioned matrix inversion, detection of contact forces, continuity of contact surface, nodal area estimation, etc. are explained in this report. Through the transformed methodology, the computer round-off error is tremendously reduced and the embedded repetitive procedure can be processed precisely and quickly. Here, wear behaviors of THR with various abduction angles are investigated. The most commonly used combination, i.e., metal-on-polyethylene, is adopted in the current study where a cobalt-chromium femoral head is paired with an Ultra High Molecular Weight Polyethylene (UHMWPE) cup. In all illustrations, wear coefficients are estimated by self-averaging strategy with available experimental datum reported elsewhere. The results reveal that the THR with larger abduction angles may produce deeper depth of wear but the volume of wear presents an opposite tendency; these results are comparable with clinical and experimental reports. The current approach can be widely applied easily to fields such as the study of the wear behaviors on ante-version, impingement, and time-dependent behaviors of prostheses etc.

1. Introduction

Debris induced from the surface wear of a polyethylene acetabular cup is a major factor causing implant loosening [1–3]. The decrease of contact area between the cup and the femoral head causes higher stresses [4] and resulting in more polyethylene wear and debris [5–7]. Placement of acetabular cups at large abduction angles has been found as one of the main reasons for early failure of artificial hip joints caused by serious wear on the cup [8]. Therefore, the study of wear behaviors at different cup abduction angles is

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a significant task in the research of biomedical engineering problems.

The wear depth of total hip replacement (THR) is usually estimated with penetration of the femoral head into the cup. Linear wear rate of polyethylene has been associated with osteolysis and subsequent component loosening [3,9]. Acetabular cup loosening due to polyethylene wear is the most frequent reason for long-term revision in THRs [1,2]. The volumetric wear is directly related to the square of the radius of the head, and head size is the most important factor in predicting debris generation [10,11]. In the past decade, wear behaviors of the hip implant and more significant knowledge were obtained through the use of the finite element (FE) method. For example, Maxian et al. [12,13] proposed a sliding distance formula associated with the FE analysis to estimate the polyethylene wear on acetabular cups and the linear wear rate. Teoh et al. [14] extended Maxian's model with the hypothesis of elasto-plasticity. Patil et al. [15] developed a FE model to study the relation between the acetabular abduction angles and linear wear rates. Oki et al. [16] used the FE simulation to verify that the abduction angle of the acetabular component significantly influences the cup loosening. Korhonen et al. [17] showed that the abduction angles can raise mechanical stresses in polyethylene cups. In 2005, Bevill et al. [18] investigated wear of THR with creep models. In Bevill's study, the iterative assessment of wear simulation depended on the initial geometry and the original contact status which yielded incapable results. Moreover, Uddin and Zhang investigated effects of various design parameters on the wear behaviors of acetabular cup, such as head size, clearance, cup thickness, and alternative material combination on the wear of acetabular cup [19]. Later on, the boundary element method (BEM) was adopted to reduce the number of variables on the implant models [20,21]; thus, model reform and arithmetic operation became relatively fast and easy. However, BEM involved with an asymmetric matrix system makes the problems complicated and imprecise [22,23]. In 2010, FE simulations with contact elements were further considered to study wear behaviors of hip implants by Wu et al. [24,25]. Sariali et al. [26] developed a FE model to evaluate the influence of the cup abduction angles on the contact pressures in hip arthroplasty. Queiroz et al. [27] presented a FE procedure to estimate the linear wear rates of acetabular cups in assemblages at various abduction angles. The above studies provided information that larger abduction angles produce higher linear wear rates. Moreover, Hua et al. [28,29] discussed the influences of the cup abduction angles and head lateral micro-separation by contact mechanics on the hip implant and concluded that larger cup abduction angles may raise the von Mises stresses on acetabular cups. Uddin showed that the contact pressures and its corresponding von Mises levels remain quite insensitive to the cup abduction angle [30].

More clinical studies found that the wear behaviors are closely related to the abduction angles. The radiostereometric analysis is aware of the most accurate and precise technique to evaluate polyethylene wear. Udomkiat et al. [6] observed radiographs and suggested that more linear wear and volumetric wear rates were directly related to larger abduction angles. Little et al. [7] used three-dimensional images to explain that larger abduction angles of polyethylene acetabular cup might present higher linear and volumetric wear rates. Wang et al. [31] applied the Dorr method [9] to measure linear wear rate of THRs; they emphasized that the linear wear rates were significantly higher at larger abduction angles. Since clinical studies adopt a mathematical conversion formula reported by Charnley et al. [10] to calculate the volumetric wear, such estimation may not be sufficiently accurate [32]. An alternate process of measurement was designed to understand the volumetric wear of the acetabular cup by Uddin [33]. Moreover, experiments with a simulator were performed by Korduba et al. [34] to evaluate the effects of different abduction angles on volumetric wear rates of polyethylene cups; further results showed that larger cup abduction angles were associated with lower volumetric wear rates. Thus, further studies on the effect of abduction angles to the wear behavior of THRs are significant. Although previous numerical, clinical, or experimental studies on the THRs have given valuable results; factors such as variations of the contact region, the worn geometry, the wear coefficient, and von Mises stresses, among others, were never examined; the avenues of exploration for wear behaviors of THRs are still too numerous.

In general, malposition of the components directly affects the wear behavior on the acetabular cup and further laxity of the joint may cause early failure of the prosthesis. The alignment of the prosthesis in surgery has been evaluated for many years, but the simulation of wear behavior under the effect of implant mal-position in hip joint arthroplasty is seldom discussed [5,7,8]. In practice, the geometry of contact regions between wear components is continuously changed and the wear behavior is related to its historical states. In order to solve such wear problems, a repetitive process is necessary with longer computational time. Such a repetitive process also meets with a large amount of errors from the computer floating point operations; further accumulation of such round-off errors may cause deviation of history-dependent results significantly. Moreover, the wear coefficient plays an important role in the calculation of wear values [35,36]. Wear coefficients are usually derived from specimen tests under existing environment and ranged from 0.02×10^{-6} to $2.5 \times 10^{-6}\,mm^3/N\text{-}m$ for ultra-high molecular weight polyethylene (UHMWPE) against cobalt-chromium (CoCr) material [37–39]. In the FE simulation, selection of wear coefficient from such extensive results is usually controversial. Using adjustment on the wear coefficient to match the experimental results is an inappropriate way. Therefore, we introduce a method of self-average to collect many published results to obtain a reasonable and acceptable wear coefficient for the FE simulations here.

Referring to the above discussions, we propose an easy, fast, and precise FE approach to investigate the abduction angles on the wear of the hip arthroplasty. The alternate FE approach is based on an idea of contact transformation in which most of the computational processes are operated on the contact region that may significantly speed up the repetitive processes and cause fewer round-off errors. An efficient FE model of the implant is constructed and the derivation of wear coefficients is described. Formulations for wears and stresses are discussed in detail next.