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Quantifying the competing relationship between durability and kinematics of total knee replacements using multiobjective design optimization and validated computational models

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ABSTRACT

Durability and kinematics are two critical factors which must be considered during total knee replacement (TKR) implant design. It is hypothesized, however, that there exists a competing relationship between these two performance measures, such that improvement of one requires sacrifice with respect to the other. No previous studies have used rigorous and systematic methods to quantify this relationship. During this study, multiobjective design optimization (MOO) using the adaptive weighted sum (AWS) method is used to determine a set of Pareto-optimal implant designs considering durability and kinematics simultaneously. Previously validated numerical simulations and a parametric modeller are used in conjunction with the AWS method in order to generate a durability-versus-kinematics Pareto curve. In terms of kinematics, a design optimized for kinematics alone outperformed a design optimized for durability by 61.8%. In terms of durability, the design optimized for durability outperformed the kinematics-optimized design by 70.6%. Considering the entire Pareto curve, a balanced (1:1) trade-off could be obtained when equal weighting was placed on both performance measures; however improvement of one performance measure required greater sacrifices with respect to the other when the weighting was extremized. For the first time, the competing relationship between durability and kinematics was confirmed and quantified using optimization methods. This information can aid future developments in TKR design and can be expanded to other total joint replacement designs.

1. Introduction

Total knee replacement (TKR) success is limited by issues relating to the durability of the ultra-high molecular weight polyethylene (UHMWPE) insert and poor kinematics (Sharkey et al., 2002). In this paper, durability is defined in terms of wear and creep of the UHMWPE bearing insert; in particular wear debris can trigger osteolysis at the bone–implant interface, leading to implant loosening (Revell et al., 1978; Peters et al., 1992; Cadambi et al., 1994; Schmalzried et al., 1997). In terms of kinematics, flexion range of motion and joint constraint are important. If the TKR design prevents the natural femoral rollback motion, the post-operative flexion range of motion will be limited (Luger et al., 1997). Moreover, soft tissues are drastically altered during TKR, and the properties of contemporary biomaterials used for implants require contact geometries different from those of the intact knee. These changes will alter the constraint characteristics of the joint (Luger et al., 1997), which can result in gait adaptation (Andriacchi et al., 1982) and may require revision (Sharkey et al., 2002).

Sathasivam and Walker (1994) performed a parameter study considering UHMWPE contact stresses, joint laxity, and stability. They suggested that moderate sagittal plane conformity and high frontal plane conformity would offer the most favourable characteristics. A weakness of this study is that they did not employ a realistic TKR damage model: only contact stresses were considered. Sathasivam and Walker (1999) later determined the ideal TKR shape considering the conflicting needs of both UHMWPE delamination resistance and kinematics. Their parameter study, however, considered only a small number of TKR geometries (16 designs), and UHMWPE abrasive/adhesive wear was not considered. Dargahi et al. (2003) performed a parameter study to determine the ideal TKR shape considering the same performance measures as Sathasivam and Walker (1994), but only considered sagittal plane geometry. Their study did not determine a single optimum design, and they explained that the definition of optimum design depends on patient specific requirements. None

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of these studies employed a systematic numerical optimization algorithm, such as Sequential Quadratic Programming (SQP). Parameter studies that consider a small number of different designs would not find the optimum implant design.

Multiobjective design optimization determines the best design(s) with respect to two or more performance measures (objective functions) while satisfying any performance or design space limitations (constraints). There is usually a competing relationship between performance measures. In this case we do not have a single optimum design that simultaneously extremizes all performance measures; we instead have multiple optimum designs which form a best trade-off space (or Pareto front). If there are two objective functions, the trade-off space is a curve, and for three objective functions, the Pareto front is a surface. The weighted sum (WS) approach is very widely used for multi-objective optimization. Two major drawbacks are that WS is unable to determine Pareto-optimal solutions within non-convex regions, and the distribution of the solutions is not uniform. More advanced approaches, such as the adaptive weighted sum (AWS) method (Kim and de Weck, 2005, 2006), are known to find solutions on non-convex regions and to provide a better distribution of Pareto curve points (a more accurate description of the relationship between competing objective functions).

During a previous investigation (Willing and Kim, 2009a), single objective design optimization was used to determine the optimum implant geometry that minimizes UHMWPE wear. This work represented the first use of a rigorous and systematic optimization algorithm for TKR shape optimization. The optimum design had large radii of curvature and high conformity in the frontal plane, with smaller radii of curvature and less conformity in the sagittal plane, similar to the conclusion of Sathasivam and Walker (1994).

A later study (Willing and Kim, 2011a) used single objective design optimization to determine the optimum implant geometry considering kinematics (in terms of laxity and flexion range of motion). The optimum TKR design featured high conformity on the medial side and less on the lateral side. This study also included constraints on the maximum allowable UHMWPE damage and fatigue damage score, but did not explicitly include implant durability as an objective function.

Implant durability and kinematics are both important factors for the design of TKR, but no previous studies simultaneously considered these design criteria using a systematic optimization algorithm. Hence it is not known if and which kind of relationship or trade-off exists between durability and kinematics. Furthermore, none of the optimization studies that considered UHMWPE damage included the effects of crossing motion at the contact surface, which is known to affect wear rates (Wang et al., 1997; Willing and Kim, 2009b).

We hypothesize that a competing relationship exists between the durability and kinematics performance of cruciate retaining fixed bearing TKR. Furthermore, we propose that this relationship can be described using a Pareto curve. The objective of this study was to determine the Pareto curve relating implant durability and kinematics performance using multiobjective design optimization in conjunction with high-fidelity UHMWPE wear and kinematics models. The limitations of previous studies were addressed by (a) using a systematic optimization algorithm (the SQP method), (b) using an experimentally validated UHMWPE wear model which considers crossing motions, and (c) using the AWS methods to define a Pareto curve which quantifies the relationship between durability and kinematics.

2. Method

A numerical simulation framework was developed in order to calculate the durability and kinematics performance for any candidate TKR design, which combined a TKR parametric modeller with UHMWPE damage and kinematics simulations.

2.1. Parametric modeller

Custom HyperWorks v7 (Altair Engineering Inc., Troy, MI) scripts were written which allow 14 design variables to control the shapes of the femoral component and UHMWPE insert of a numerical model of a TKR (Willing and Kim, 2011a), as shown in Figs. 1 and 2. By changing 14 design variables, we can represent an extremely wide range of different designs. The design variables could only be modified within finite ranges (Table 1), which were implemented in order to prevent model generation and simulation failures related to extreme design perturbations.

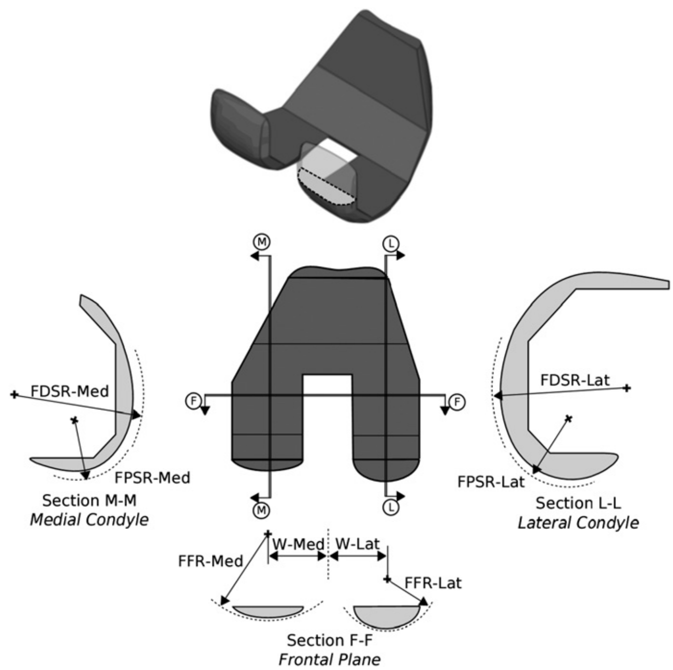

Fig. 1. Femoral component parametric model controlled by design variables. -Med and -Lat denote medial and lateral parameters, respectively.

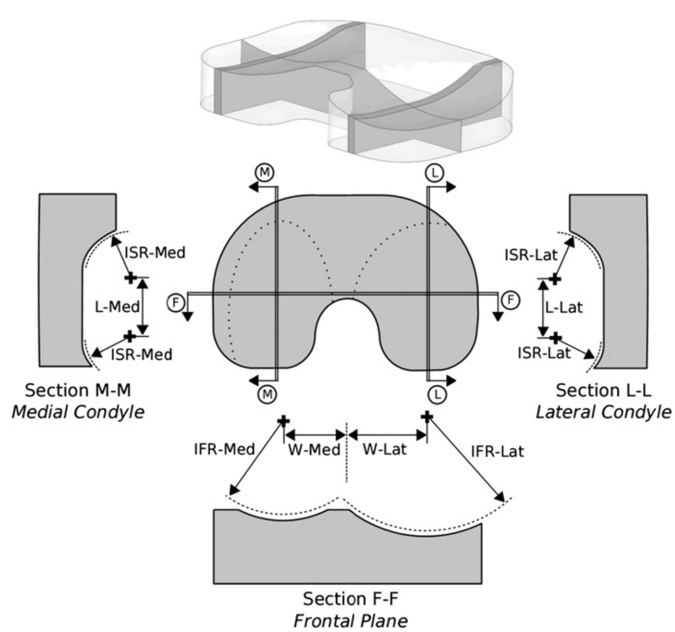

Fig. 2. UHMWPE insert component parametric model controlled by design variables. -Med and -Lat denote medial and lateral parameters, respectively.