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Damage from unintentional metal–metal articulation of CoCrMo, TiAlV, and oxidized zirconium knee replacements following polyethylene insert failure

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ABSTRACT

A small percentage of knee replacements with metal-backed tibial components experience complete polyethylene insert destruction or wear-through during in vivo service, resulting in unintentional articulation of the metal femoral bearing and tibial baseplate. Seven such explanted knee replacement sets were studied to determine the failure events that affected four combinations of unintentionally articulating metals, including both conventional CoCrMo and TiAlV, as well as surface modified oxidized zirconium (OxZr). The surface modified metal experienced local fracture at the surface when in contact with TiAlV and subsequent metal–metal wear of the substrate metal. All unintentional conventional metal–metal couples (CoCrMo–CoCrMo, TiAlV–TiAlV, CoCrMo–TiAlV, and ZrNb (substrate)–TiAlV) experienced adhesive wear processes resulting in material transfer. In mixed-metal pairs, the softer metal transferred to the harder metal (TiAlV transferred to CoCrMo and ZrNb transferred to TiAlV) during adhesion, resulting in gross dimensional change in the softer metal and roughening of the harder metal. While surface modified metals may be advantageous when articulating against polyethylene, in cases of polyethylene insert wear-through, both conventional and surface modified metals result in significant wear damage. The types of wear damage present and the extent of roughening varied across material combinations.

1. Introduction

While knee joint replacement is a highly successful surgical procedure, prosthesis wear is a major limitation contributing to decreased longevity [1,2]. Four common wear modes affecting joint prostheses have been noted [3], with Mode I and Mode II wear most relevant to this study. The most common is Mode I wear at the articular bearing surfaces due to the normal cyclic loading of the knee prosthesis. During progressive knee replacement failure, unintended contact between prosthesis components not intended to articulate (Mode II wear) can produce catastrophic prosthesis damage. Knee prostheses originally intended to articulate only between metal and polyethylene components may eventually articulate between two metal components if the polyethylene insert fails due to wear-through.

Material selection is a key consideration for predicting the longevity and wear performance of knee prostheses. Metal components (i.e. femoral component, tibial tray, and metal-backed patella) are traditionally fabricated from surgical cobalt–chrome (CoCrMo) or titanium alloys (TiAlV) [4]. In addition to their biocompatibility, these materials have the strength and fracture toughness necessary to withstand the high load magnitudes that the knee endures during activities of daily living and elastic moduli that have proven compatible for sustained fixation with human bone [4,5]. The opposing bearing surfaces (i.e. tibial insert and patellar button) are fabricated from ultra-high molecular weight polyethylene (UHMWPE), making use of this polymer's biocompatibility and low modulus to act as a cushion similar to cartilage [4,6]. The wear performance of these metal–UHMWPE bearing couples has demonstrated that CoCrMo may be advantageous over TiAlV as a femoral bearing component due to greater resistance to surface roughening and lower subsequent polyethylene wear [7–9]. In general, polyethylene wear is linked to higher surface roughness in the counterface material, and the ideal metal has a low roughness both in its pristine, as-manufactured state and after in vivo cyclic third body wear [10–13].

Surface-modified metals were introduced to the market in an effort to make use of the scratch-resistant properties of ceramic

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without compromising the fracture toughness of the bulk metallic structure [14]. One such material is oxidized zirconium (OxZr) which consists of a bulk ZrNb alloy substrate and a 5 μm surface-hardened layer of ceramic monoclinic zirconia, achieved by diffusing oxygen into the OxZr surface at an elevated temperature [15]. Unlike coatings that can delaminate under applied mechanical stresses, OxZr has proven resistant to delamination and fracture due to excellent adhesion through the diffusion gradient of oxygen into the metal substrate [15]. This composite material achieves excellent scratch-resistance due to the hardness of the OxZr surface [16] and high fatigue strength due to the fracture toughness of the ZrNb metal alloy substrate [17]. Bearing couples of OxZr and UHMWPE generate less polyethylene debris than bearing couples of other surgical metal alloys [18–20].

It is generally accepted that the type of material (metal, ceramic, polymer, or surface-modified) and the associated mechanical properties influence the way bearing surfaces wear. Literature values of mechanical properties of the surface and substrate of OxZr are compared with those of conventional orthopaedic metals in Table 1. Mode II wear between any combination of these materials in a knee system is expected to have some degree of abrasive wear due to hard particles. In contrast, Mode II wear between any combination of similar or dissimilar metals in the absence of surface modification is expected to result in some degree of adhesive wear, depending on the material properties and surface condition [21]. Since knee replacement mechanics necessitate metal-on-polyethylene systems, the wear consequences from these conventional and surface-modified metals directly articulating in the context of a knee replacement have not been documented as of yet.

Table 1
Mechanical properties of materials in this study from the literature [16,17,22–26].

Material	Rockwell hardness *A*	Fracture toughness K_{Ic} (MPa m$^{1/2}$)
OxZr surface (monoclinic ZrO_2)	35–40	2.6
OxZr substrate (Zr–2.5Nb)	10–15	15–75
Ti–6Al–4V	15–20	54–91
Co–28Cr–6Mo	18–25	75

The purpose of this study is to determine the material failure events that occur in vivo when orthopaedic implant metals (conventional and surface-modified) unintentionally articulate due to worn-through polyethylene. Visual, topographic and chemical surface analysis techniques are applied to explanted knee replacements that experienced such failure (Fig. 1) in order to characterize damage modes and compare different material combinations. It is hypothesized that lower hardness or lower fracture toughness in mixed-material pairs plays a critical role in the type of damage occurring on bearing surfaces exposed to Mode II wear in vivo.

2. Materials and methods

Databases inclusive of 399 explanted knee prostheses archived in two established, institutional review board approved implant retrieval programs were queried to identify explants meeting the following inclusion criteria: (i) consist of a metal-backed tibial component design with a modular fixed-bearing polyethylene tibial insert; (ii) exhibit complete wear-through of the tibial polyethylene insert and Mode II wear resulting in unintended articulation between the metal femoral component and tibial baseplate; and (iii) availability of all major prosthesis components for analysis, including the femoral component, tibial baseplate, tibial polyethylene insert. This search yielded 26 explanted knee prostheses designed to replace only one condylar surface

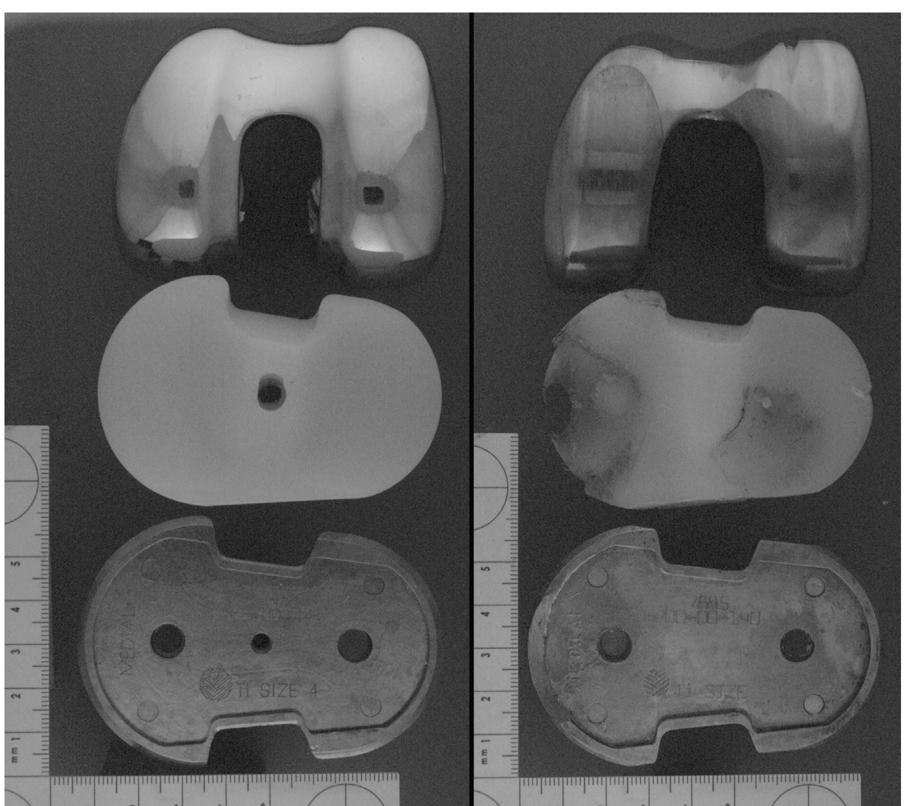

Fig. 1. Metal femoral component, polyethylene fixed-bearing insert, and metal tibial baseplate in explanted knee replacements: explanted set which experienced only Mode I polyethylene wear (left) and explanted set which experienced Mode II metal–metal wear through worn polyethylene (right).