What are the wear mechanisms and what controls them?

The primary materials used in bearing surfaces of total joint replacements include ultra-high molecular weight polyethylene, cobalt alloys, titanium alloys, stainless steel alloys, alumina, and zirconia. In general, the relationship between the properties of these materials and the in vivo wear performance of joint replacement components has been difficult to establish because so little is known about how these properties (and numerous potentially confounding patient, surgeon, and design-related factors) affect wear mechanisms.1-4

Modes of Wear

Wear occurs in four modes,5-7 depending on location (Fig. 1). Mode 1 is the only wear mode associated with joint articulation; modes 2, 3, and 4 occur at other nonintentional articulations as a function of prosthesis materials, design, and implementation parameters.

Mode 1 is an articulation between intended bearing surfaces. Examples include the femoral head and the acetabular cup of a total hip replacement, and the femoral condyle and the tibial plateau of a total knee replacement. Examples of mode 2, an articulation between a primary bearing surface and

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*Figure 1* Modes of wear in orthopaedic joints.
a surface that was never intended to be a bearing surface, are the femoral
head and the metal back of an acetabular cup (eg, through a worn
polyethylene acetabular liner) and the femoral condyle and the metal back-
ing of a patellar component (eg, through a worn patellar button). Mode 3
is an articulation between intentional bearing surfaces in the presence of third-
body components; examples include the femoral head and the acetabular
cup in the presence of polymethylmethacrylate cement debris, metallic
debris, hydroxyapatite particles, bone particles, or ceramic debris. One
example of mode 4, an articulation between two nonbearing secondary sur-
faces, is backside wear caused by motion between the back of a polyethylene
insert and the metallic tray of a total knee tibial component; another exam-
ple is fretting wear between the trunion and cone of a modular femoral com-
ponent of a total hip replacement.

**Mechanisms of Wear**

Wear can occur through five major mechanisms—adhesion, abrasion, third
body, fatigue, and corrosion. Adhesive wear occurs when the atomic forces
occuring between the materials in two surfaces under relative load are
stronger than the inherent material properties of either surface. For example,
when there is relative motion between two surfaces, bonding of asperities
occurs. Continued motion of the surfaces requires breaking the bond junc-
tions. Each time a bond junction is broken, a wear particle is created, usual-
ly from the weaker material (Fig. 2). In orthopaedic joint replacements,
adhesive wear usually occurs when small portions of the polyethylene sur-
face adhere to the opposing metal bearing surface. The removal of polyethy-
lene results in pits and voids so small that they may not be evident on visu-
al inspection of the articulating surface.

The adhesive wear performance of both acetabular hip and tibial knee
components has been related to the plastic flow behavior of polyethylene. In
acetabular components, for example, the generation of submicron wear par-
ticles has been associated with local accumulation of plastic strain under
multiaxial loading conditions until a critical or ultimate strain is reached.9-11
Wear particles are released from the articulating surface following the accu-
mulation of this critical plastic strain. Indeed, a plasticity-induced damage
layer has been shown to develop at the articulating surface during hip simu-
lator wear testing of both conventional and cross-linked polyethylene acetab-
ular components.12 The layer is associated with permanent reorientation of
crystalline lamellae in the polyethylene morphology (Fig. 3).13

Abrasive wear occurs between surfaces of different relative hardness. In
an abrasive wear mechanism, microroughened regions and small asperities
on the harder surface locally plow through the softer surface (Fig. 4). Abrasive wear results in the softer material being removed from the track
traced by the asperity during the motion of the harder surface.

Third-body wear is a form of abrasive wear that occurs when hard parti-
cles become embedded in a soft surface (Fig. 5). Examples of third bodies
include metallic or bone particles embedded in a polyethylene bearing sur-
face. The particle acts much like the asperity of a harder material in abrasive
wear, removing material in its path. Hard third-body particles such as bone
cement can produce damage to both the polyethylene articulating surface
and the metallic alloy femoral bearing counterface. \(^{14}\)

The extent of abrasive wear of polyethylene, metallics, and ceramics has
been shown to be a function of the surface roughness of the metallic or
ceramic counterface and the presence or absence of hard third-body parti-
cles. \(^{14,15}\) In one in vitro hip simulator study, simulation of a roughened
femoral head increased the amount of wear damage to the polyethylene,
even in an elevated cross-linked polyethylene (although the overall wear rate
was still dramatically lower than for conventional polyethylene articulating
against a well-polished metallic counterface). \(^{15}\) In other studies, isolated
scratches more dramatically increased the wear rate than generalized roughness of the metallic counterface and could also change the wear performance ranking of various polyethylene formulations. Thus the magnitude of the effect of surface roughness of the metallic counterface on overall wear rate remains controversial.

**Fatigue wear** occurs when surface and subsurface cyclic shear stresses or strains in the softer material of an articulation exceed the fatigue limit for that material. Because polyethylene is the weaker of the two materials in a bearing couple, fatigue wear damage to the polyethylene component dominates. Under these repeated or cyclic loading conditions, subsurface delamination and cracking can occur, eventually leading to the release of polyethylene particles (Fig. 6). Fatigue damage can range from small areas of pitting not apparent on visual inspection to macroscopic pits several millimeters in diameter to large areas of delamination that can encompass an entire tibial plateau.

Fatigue fracture mechanisms in tibial components have been directly related to the plastic flow parameters of polyethylene, such as yield stress and ultimate stress. The performance of polyethylene components has also been associated with the presence of microscopic voids (so-called unconsolidated defects). Thus, the plastic flow behavior and the presence of defects are believed to affect the clinical wear damage performance of polyethylene components. Implant retrieval analyses suggest that patient weight, activity level, and length of time of implantation are associated with the severity of surface damage of components. Therefore, polyethylene fatigue fracture mechanisms have been suggested to contribute to certain forms (eg, pitting and delamination) of polyethylene surface damage.

Damage modes such as accelerated fatigue wear, radial rim cracking, cup fracture, and delamination have been associated, at least in part, with oxidative degradation of the polyethylene. In support of these reports, experimental studies demonstrated a significant decrease in fatigue and fracture resistance following oxidative degradation. Delamination is probably not exclusively a consequence of subsurface oxidation, however. Research by Blunn and associates supports the notion that damage to polyethylene tibial components is also dependent on joint kinematics. Delamination damage was observed on a flat polyethylene surface when a metal indenter had been sliding against it, but not for static loading or pure indenter rolling. Furthermore, the oxidative state and the quality of the polyethylene do not necessarily correlate with clinical wear performance. In a study of 92 retrieved Charnley acetabular components, no relationship was found between the radiographic wear rate measured while the components were implanted and either semiquantitative polyethylene measures (eg, the presence of a subsurface white band or the percentage area of unconsolidated particles) or changes in polyethylene density (an indirect measure of oxidative degradation).

**Corrosive wear** is an indirect wear mechanism. A form of third-body wear, the liberated corrosive debris acts as an abrasive third body. Corrosive wear can also be considered an accelerating mechanism for corrosion itself, because the motion of an articulation can remove corrosive products and the
protective passive layer sooner than interfaces with no relative motion. Liberation of corrosive products exposes a greater surface (with less protection against corrosion) to further corrosion, and hence accelerates the removal of even more material.

Adhesive, abrasive, and fatigue wear generally occur in both polyethylene acetabular hip and tibial knee components, although the relative contributions of each of these wear mechanisms differ in the two types of joints. Adhesive and abrasive wear generally dominate in polyethylene acetabular hip components, whereas fatigue wear is also an important wear mechanism in polyethylene tibial knee components. The forms of wear damage arising from the wear mechanisms described above include scratching, burnishing, abrasion, pitting, delamination, and embedded metallic or acrylic debris.21

Multiaxial Loading and Modeling Efforts

Efforts to understand the wear mechanisms and improve wear resistance of polyethylene have focused on the development of improved numerical models to predict the effect of load, geometry, and material properties on the stress and strain distributions occurring on and within joint replacement components. Early models incorporated loading only (monotonic behavior) without considering unloading, and were based on bilinear elastic or elastic-plastic approximations of the stress-strain behavior of polyethylene.31-38 However, investigations of the unloading behavior and permanent plastic deformations in polyethylene have shown that classical plasticity theory greatly overpredicts the permanent strains on unloading. In fact, simulating cyclic loading in polyethylene components using conventional plasticity theory may lead to exaggerated predictions of residual strains and stresses.39 Accordingly, modeling the cyclic loading behavior of polyethylene components may be more clinically relevant than modeling only monotonic behavior. The nonlinear behavior of polyethylene (eg, simultaneous recoverable and irrecoverable deformations on loading and unloading) also increases the importance of correctly simulating the kinematics of loading. Also, constitutive relationships for polyethylene should incorporate a continuous description of material response as the material transitions from linear viscoelastic to nonlinear viscoelastic to viscoplastic behavior.40 The development of such constitutive models for conventional and cross-linked polyethylenes is currently an area of active research.39,41,42

Another important concentration of current research is on improved understanding of the more clinically relevant multiaxial large deformation
behavior of polyethylene in predicting component performance, including
surface damage. The small punch or miniaturized disk bend test has been
proposed to characterize the equibiaxial tensile mechanical behavior of
polyethylene using specimens measuring 0.5 mm in thickness.43-45
Previously, indirect measures of the mechanical behavior of polyethylene,
such as density, had been used to examine the relationship between mechan-
cal performance and clinical wear performance of polyethylene.34,46 A
unique feature of the small punch test methodology is that it allows for the
direct measurement of mechanical behavior from retrieved components that
have dissimilar physical, chemical, and mechanical properties due to oxida-
tive degradation, plasticity-induced alterations, or design-specified material
property gradients. Results from these studies suggest that clinical wear per-
formance may be predicted from the measured large deformation equibiax-
ial behavior of polyethylene.45

Relevance

Prevention of each of the wear mechanisms in each of the wear modes
requires different materials and design considerations in the development of
strategies for their avoidance. Design criteria should provide the best overall
combination of materials, bearings, and surface finishes and treatments,
derived from knowledge of existing strategies to protect against each of the
wear mechanisms.

There is a notably better understanding today of the factors that influence
adhesive, abrasive, and fatigue wear mechanisms in polyethylene joint com-
ponents. However, the introduction of new polyethylene materials have still
relied heavily on empirical in vitro hip simulator screening studies for
acetabular hip components. With regard to polyethylene tibial knee replace-
ment components, there is even less guidance on methods to predict the clin-
ical performance of new polyethylene materials with respect to wear damage.
Nevertheless, elevated cross-linked polyethylenes have been introduced into
clinical practice not only for conventional acetabular hip components but
also for more highly stressed, relatively thin (5-mm) acetabular hip compo-
nents that articulate against a femoral head with a relatively large (38-mm)
diameter. Cross-linked polyethylenes are also being considered for more
highly stressed applications, such as those occurring in the less conforming
articulating surface geometries in total knee replacements.47 In all cases,
these new materials (and designs) are being introduced into clinical practice
without a fundamental understanding of the mechanical behavior of the
material under the complex multiaxial loading conditions that these compo-
nents undergo.

Future Directions for Research

Future research should include study of wear occurring at sites and in modes
other than mode 1. Prevention of wear during intentional mode 1 articula-
tion has received the most research attention, because wear is expected to
occur at this site. However, unintentional mode 2, 3, and 4 articulations can also generate substantial wear. To fully address the issue of wear prevention, protection against wear mechanisms at unintended articulations must also be considered in future implant designs.

More accurate prediction of stress and strain distributions of polyethylene joint components using the finite element method is needed to ensure that joint replacement designs will benefit from the improved wear resistance of cross-linked polyethylenes (or other possible future material formulations) without sacrificing other important aspects of mechanical performance such as fatigue and fracture resistance. To this end, there is a need for a better understanding of the multiaxial mechanical behavior of conventional and cross-linked polyethylenes. In addition, constitutive relationships that capture the viscoelastic and viscoplastic characteristics of polyethylene need to be developed and implemented in time-dependent finite element analysis methodologies to improve prediction of the stress and strain distributions in polyethylene joint components.

Another important direction for future research is evaluation of the dynamic and time-dependent properties of implant materials and their articulations. Dynamic properties have received little attention, yet the materials are exposed to dynamic loading conditions. Material creep and relaxation during periods of relative inactivity (eg, during sleep) may influence accumulated stresses and could contribute to some of the discrepancies between in vitro wear simulations and in vivo results. More accurate predictions of the location and severity of permanent deformation to polyethylene components under in vivo loading conditions should help investigators develop better design paradigms to enhance long-term performance of joint replacements prior to their clinical introduction.

References


Material and Design Considerations

