Key Points

- The biomechanics of total hip replacement are affected by design factors, surgical technique, component placement and orientation.
- Abrasive wear, adhesive wear, and surface fatigue are the most relevant in total joint polyethylene wear.

The function of a total hip replacement is dependent upon the implant design and materials, wear and performance characteristics, short and long-term stability, surgical technique and component placement and alignment. Although the surgeon only directly controls the surgical technique, component placement and alignment, an understanding of the biomechanical performance of total hip replacement is necessary to maximize longevity and optimize function by restoring normal biomechanics and kinematics to the hip.

Center of Rotation

The center of rotation of the hip joint is the geometrical center of the femoral head. Careful preoperative planning and intraoperative execution should ensure that, after total hip replacement, the center of rotation is restored to its pre-disease position. Utilization of modern, highly modular hip prostheses allows selection of appropriate neck length to re-establish femoral offset and soft tissue tension, once the center of rotation has been established. In the dysplastic patient, it is common for the center of rotation to be displaced dorsally. Restoration of the hip center to the center of the true acetabulum during arthroplasty confers both anatomical and biomechanical advantages (Sariali 2008). The best acetabular bone stock is generally found in the true acetabulum, thus positioning the acetabular component within the true acetabulum optimizes dorsal coverage and medialization of the component. Returning the center of rotation to the true acetabulum in these cases also increases the lever arm for the abductor muscles, restoring biomechanics (Sariali 2008). “High hip center” and cup lateralization have both been implicated in early failure in people (Sariali 2008, Stans 1998).

Version

The complementary retroversion of the acetabular component, and anteversion of the neck of the femoral component should reflect normal patient anatomy, thus restoring range of motion to normal or near normal levels prior to impingement. Relative, or absolute anteversion of the cup for instance potentially leads to impingement in external rotation, predisposing to cranio-dorsal luxation. Similarly, excessive cup retroversion may lead to impingement during hip flexion. While stem anteversion improves range of motion, it reduces femoral offset.

Offset

Cup position, cup size and center of rotation, femoral head size, stem size, neck length, stem version, and stem position within the medullary canal all influence offset, which is defined as the distance between the center of the femoral head and the center of the medullary canal, or anatomic axis of the femur. Medialization or lateralization of the acetabular component alters the offset by changing the center of the femoral head. Although offset can be corrected by
making a reciprocal adjustment to the neck length, an incorrect center of rotation will remain. Reduced offset results in abductor muscle dysfunction owing to a diminished lever arm. Therefore, the abductor muscles must generate a larger force to balance body weight. The increased force creates a larger joint reaction force and increases wear (Sariali 2008). In addition, reduced offset results in soft tissue laxity that predisposes to luxation. Subluxation during the stance or swing phase also likely results in increased wear by causing microseparation edge loading (Stewart 2001).

**Bearing Diameter**

In order for dislocation to occur, the femoral head has to displace within the cup. The distance required for luxation to occur is referred to as the jumping distance; the translation of the center of the femoral head that precedes luxation. The jumping distance increases proportionally as the diameter of the femoral head increases, and is inversely related to angle of lateral opening, i.e. as the angle of lateral opening increases, jumping distance decreases. Bearing diameter also affects wear rate, since sliding distance increases as diameter increases. Therefore, selection of femoral head diameter must take resistance to luxation and wear into consideration. The jumping distance is also related to the geometry of the cup, and if the design is not a complete hemisphere, the jumping distance is reduced.

**Bearing Type**

Bearings can be broadly divided into hard-on-soft (e.g. metal or ceramic on polyethylene) and hard-on-hard (e.g. ceramic on ceramic, metal on metal and ceramic on metal). Hard-on-soft bearings operate with boundary lubrication (also known as border lubrication), a condition in which a complete fluid film does not develop between apposing surfaces. Thus, there is momentary dry contact between wear surface high points or asperities; in this case, friction and wear are significant, and wear is proportional to sliding distance; a function of bearing diameter. Hard-on-hard bearings operate with mixed lubrication, a mixture of characteristics between boundary, or thin film, and fluid-film lubrication, in which there is complete separation of elements by fluid. Mixed lubrication can lead to lower wear, thus hard-on-hard bearings are ideal for use in larger bearings, since these lubrication mechanisms may improve with higher sliding velocities (Fisher 2006).

**Femoral Head Materials**

The metallic alloys that have been used with the UHMWPE bearing surfaces are stainless steel, cobalt-chromium alloy, and titanium alloy. Laboratory and clinical studies in man have shown that wear rates of UHMWPE coupled with either stainless steel or cobalt-chromium are comparable (Manley and Dumbleton, 2006). Historically, cobalt-chromium was chosen over the 316L stainless steel available at the time because the cobalt-chromium alloy was more resistant to corrosion. Newer more corrosion resistant stainless steel alloys are now available, and the use of these newer alloys is increasing. Titanium alloys are more vulnerable to abrasion than cobalt-based alloys; therefore, they are not commonly used as bearings in people. Hardening of the surface of titanium alloy heads using techniques such as gas nitriding, solution nitriding, or ion implantation may improve performance, but wear can still occur if the hardened layer is penetrated (Manley and Dumbleton, 2006).
In man, cast or forged cobalt-chromium alloy predominates as the choice of femoral head material for articulation against UHMWPE. For this reason, the wear of cobalt-chromium alloy against UHMWPE bearing combination is the standard against which all other bearing combinations are measured (Barrack 2004).

Polyethylene

UHMWPE is manufactured from powder that is converted into solid form by ram extrusion of rods, or compression molding of blocks. The component is then machined from the solid UHMWPE. Sometimes a near net shape component is molded from powder prior to final machining. The final step in the manufacturing process is sterilization, which can be performed by ethylene oxide, gas-plasma, or gamma irradiation in air. Sterilization of UHMWPE by gamma radiation introduces cross-linking of the polyethylene molecules from the interaction of the free radicals formed during irradiation. Laboratory and clinical studies in man have demonstrated improved wear resistance of gamma sterilized UHMWPE compared with UHMWPE sterilized by nonionizing means (ethylene oxide or gas-plasma) (Manley and Dumbleton 2006). Sterilization by gamma radiation in air creates the potential for oxidation of UHMWPE, because of the existence of free radicals that are not cross-linked. Oxidation reduced the mechanical properties of these components. For this reason, some manufacturers have changed the sterilization process to gamma irradiation in an inert atmosphere such as nitrogen, argon, or vacuum; the lack of oxygen in these environments prevents initiation of the oxidative process (Manley and Dumbleton 2006).

Since cross-linking was shown to reduce UHMWPE wear, it was theorized that increasing cross-linking further would result in an even more wear-resistant UHMWPE. Highly cross-linked UHMWPE can be produced by using higher doses of radiation followed by or combined with heat to enhance the cross-linking process and the removal of free radicals. Among the many variables that can be manipulated in the production of highly cross-linked UHMWPE, the key variables are radiation dose and the temperature of heating (Manley and Dumbleton 2006). Manufacturers of UHMWPE components for people have introduced different highly cross-linked polyethylenes by different choices in the radiation dose, and heating temperature. These efforts have been largely successful, and studies on highly cross-linked UHMWPE liners have consistently showed lower femoral head penetration and an 87% lower risk of osteolysis (Kurtz 2011). However, cases of in vivo oxidation at the rim and rim delamination in annealed polyethylene, and rim fracture in remelted polyethylene have provided motivation for ongoing research on the long-term stability and mechanical performance of this first generation of highly cross-linked UHMWPE (Kurtz 2011).

Wear

Wear is defined as the progressive loss of substance from the operating surface of a body occurring as a result of relative motion at the surface (Jin 2006). The moving contact between a metal head and ultra-high molecular weight polyethylene (UHMWPE) bearing surface is the first point of load transfer in total hip replacement. This moving contact between these two apposing surfaces generates wear debris that result in the cytokine mediated osteolysis and bone resorption that has been implicated as the primary long-term failure mode in total joint replacement.

Five types of wear have been described. Adhesive wear is the transfer of material from one surface to another during relative motion by the process of solid phase welding. Abrasive wear is the displacement of materials by hard particles. Adhesive wear and fatigue wear may
work together, with the surface asperities of the two surfaces momentarily sticking together, causing shear stresses that, over time, lead to eventual fatigue of the asperity (Stewart 2010). Erosive wear is the loss of material from a solid surface due to relative motion in contact with a fluid that contains particles. Corrosive wear is a process in which chemical or electrochemical reactions with the environment dominates, such as oxidative wear (Jin 2006).

Not all wear debris are generated from the bearing surfaces. Wear debris can be produced from any modular junction at which there is relative motion between the components, for example, backside wear between the inside of the metallic outer shell and the outside of the inner polyethylene liner in a metal backed acetabular component. Unintended contact, such as impingement of the femoral neck on the acetabular component will generate debris. These wear mechanisms apply equally to both hard-on-soft (e.g. metal or ceramic on polyethylene) and hard-on-hard (e.g. ceramic on ceramic, metal on metal and ceramic on metal) bearing surfaces.

Of the five types of wear, abrasive wear, adhesive wear, and surface fatigue are the most relevant in total joint polyethylene wear. It should be noted that the various wear types might occur simultaneously or sequentially. For example, wear particles produced as a result of adhesive wear, can then act as third bodies causing abrasive wear (Jin 2006). Once particles come between adjacent bearing surfaces, the amount of wear debris generated through abrasive wear depends on the hardness of the material, the magnitude of the contact force, and the sliding distance. Sliding distance is related to the diameter of the femoral head. For a given range of motion, a small femoral head will have a shorter sliding distance than a large femoral head, thus, the small femoral head will generate less wear in abrasion and fatigue. Mechanical factors affecting surface fatigue include material hardness, material fatigue resistance, contact stress magnitude, and the amount of cycling between tensile and compressive sub-surface stresses. The magnitude of both contact and sub-surface stresses depends on joint reaction forces, surface friction, material stiffness, the thickness of surface materials, and the conformity of bearing surfaces (Hollister 1995).

In summary, there are three laws of wear that should be considered in the context of total joint replacement.

1. Wear volume increases as the normal load increases.
2. Wear increases as the sliding distance increases.
3. Wear decreases as the hardness of the softer sliding component increases.

An understanding of the biomechanics of total hip replacement allows the surgeon to make logical choices in implant selection. In addition, critical evaluation of surgical technique, component placement, and alignment, in light of the implications of implant biomechanics are necessary to optimizing functional outcome for patients.
References


