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Leading Opinion

The lexicon of polyethylene wear in artificial joints ☆

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Abstract

The analysis of wear on polyethylene components that have been retrieved after use in patients has provided invaluable understanding of how wear occurs in vivo, and how it may be minimized through improved materials and implant design. The great number of such studies that have been published over the past three decades has lead to an extensive vocabulary to describe the tribology of prosthetic joints. However, these also have led to some confusion, due to the occasional misuse of terms from classical tribology, along with the use of multiple terms to describe the same wear phenomenon, and vice versa.

The author has proposed that our understanding of wear in artificial joints may be enhanced by recognizing that there are four general subject areas: Modes, Mechanisms, Damage and Debris. Wear Mode 1 occurs when the two bearing surfaces are articulating against each other in the manner intended by the implant designer. Mode 2 occurs when a bearing surface articulates against a non-bearing surface. Mode 3 occurs when third-body abrasive particles have become entrapped between the two bearing surfaces, and Mode 4 occurs when two non-bearing surfaces are wearing against each other. The least wear occurs in Mode 1, whereas severe wear typically occurs in Modes 2, 3 and 4.

The classical wear mechanisms that apply to prosthetic joints include adhesion, abrasion and fatigue. These can occur in varying amounts in either of the four wear modes.

As used in the literature for the past three decades, wear "damage" can best be defined as the change surface texture or morphology that is caused by the action of the wear mechanisms. Although a wide variety of terms have been used, an overview of the literature indicates that about eight terms have been sufficient to describe the types of damage that occur on retrieved polyethylene components, i.e., burnishing, abrasion, scratches, plastic deformation, cracks, pits, delamination, and embedded third bodies. The author suggests that, as far as possible, investigators endeavor to limit their descriptions of surface damage to these terms and, importantly, to clearly and consistently distinguish the classical wear mechanisms from the types of damage produced by those mechanisms.

Wear debris refers to the billions of particles, some measuring in nanometers, that are generated by the wear mechanisms, and that initiate biological reactions, such as osteolysis, that may lead to the failure of the implant. As the methods for recovering wear debris from joint fluids and tissues are improved, investigators are using a growing number of terms to describe them. As with the types of damage, it will be important in the coming years to maximize clarity and minimize redundancy of the vocabulary in this important area of research.

Keywords: Polyethylene; Wear; Artificial joints

"*Whenever a new scientific discipline emerges, it not only encompasses the concepts of those subjects on which it is based, but it also has to generate new words that represent the new ideas and new scientific issues and, ultimately, the new products and practices that are developed.*"

Professor David F. Williams; The Williams Dictionary of Biomaterials, 1999.

"*I want to say one word to you. Just one word...... Plastics!*"

"*Just how do you mean that, sir?*"

Mr. McGuire and Benjamin; The Graduate, 1967.

☆ *Note*: Leading Opinions: This paper provides evidence-based scientific opinions on topical and important issues in biomaterials science. They have some features of an invited editorial but are based on scientific facts, and some features of a review paper, without attempting to be comprehensive. These papers have been reviewed for factual, scientific content.

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1. Introduction

The modern era of successful total joint replacement began in the mid-1960s with the introduction of total hip replacements, particularly by McKee and Watson-Farrar [1], which featured a metal-on-metal bearing, and the Charnley [2], featuring a metal-ball-on-polyethylene socket. The clinical success of the latter soon led to the introduction of replacements for other joints using metal-on-polyethylene and, subsequently, ceramic-on-polyethylene bearings, including the knee, ankle, shoulder, elbow and, most recently, spinal discs. Although hip and knee replacements, in particular, have enjoyed great clinical success, degradation and wear of the polyethylene bearing surface has continued to be a concern among biomaterials engineers and clinicians.

During the 1990s, laboratory wear testing using joint simulators demonstrated that increasing the amount of crosslinking in the polyethylene could markedly improve its resistance to the type of wear encountered in a hip prosthesis [3–5], and a number of crosslinked–thermally stabilized polyethylenes were approved for clinical use, initially in hips and subsequently in knees. The longest clinical follow-ups of hip prostheses are now approaching 7 years, and several recent publications have indicated that the rates of wear in vivo are remarkably close to those that were predicted by the hip simulator testing. Fortunately, there also appears to be a corresponding reduction in the incidence and severity of osteolysis induced by polyethylene wear particles [6,7].

It is somewhat more difficult to assess the ongoing clinical performance of a particular polyethylene in a prosthetic knee replacement, primarily due to the difficulty of measuring the amount of wear evident on a radiograph. As in the past, evaluation of the performance of cross-linked polyethylenes in knees and other joints will largely depend on the analysis of damage and wear evident on clinically retrieved implants. In anticipation of this, it is useful to review the methodology that has been applied in the past, particularly with respect to the terminology that has been developed to describe the wear mechanisms and types of damage occurring during in vivo use.

During the past four decades, the dozens of publications that have described the wear phenomena on clinically retrieved polyethylene components have provided valuable insights on the many factors that affected their clinical success or failure. However, some confusion has been generated due to incorrect or inconsistent application of terms from classical tribology to describe and interpret the wear phenomena apparent on the bearing surfaces. With the goal of maximizing the quantity and reliability of the information that may be gained from such studies, the author has previously suggested [4,8,10,46] certain conventions in the methodology and terminology for characterizing polyethylene wear in prosthetic joints. The present paper reviews and expands somewhat on those concepts.

2. Modes, mechanisms, damage and debris

The author has previously proposed [4,8–10] that the general conditions under which a prosthetic joint may function in vivo comprise four distinct "modes," as defined below. In each of these modes, surface damage and wear debris can be generated by one or more of the classical wear "mechanisms," i.e., adhesion, abrasion and fatigue. The author also has proposed that, in the study of wear in joint replacements, it is useful to define "damage" as the visible and microscopic changes in the appearance of the bearing surfaces (i.e., their texture or morphology) that are caused by the wear mechanisms. This distinction is important because, as numerous investigators have noted, a polyethylene component may exhibit substantial surface damage (scratching, pits, etc.) even though very little actual wear (loss of material in the form of debris) has occurred, and vice versa. In fact, the surface damage may have accumulated precisely *because* there has been little removal of material from the bearing surface. Conversely, if the polyethylene is undergoing rapid wear, any scratches or pits that happen to form in the contact zone may soon be polished out, leaving a smooth surface with little damage.

Muratoglu and colleagues ([11]: Optical analysis) demonstrated that it was particularly important to distinguish between damage and wear in the case of crosslinked polyethylene. As shown in Fig. 1, when a highly crosslinked polyethylene acetabular cup that was retrieved after extensive clinical use was heated above the melt temperature of polyethylene, the scratches and dents in the surface disappeared and the texture of the original machine tool tracks was recovered, indicating that very little actual wear had occurred. This distinction will be emphasized again in the discussions that follow.

3. Wear modes

In Mode 1 (Fig. 2), the two bearing surfaces are contacting each other and are moving under load, in the manner intended by the designers. While substantial (even excessive) amounts of wear may occur in Mode 1, this mode is necessary for the prosthesis to function, whereas Modes 2, 3 and 4 represent a malfunctioning prosthesis.

In Mode 2, a bearing surface is wearing against a non-bearing surface. This may occur, for example, if the femoral ball wears completely through the polyethylene acetabular liner and contacts the metal shell, or if the surface of the ball is dragged across the rim of the shell during dislocation. Mode 2 may involve severe wear and rapid failure of the prosthesis.

In Mode 3, the primary bearing surfaces still are articulating with each other, but with abrasive third-body particles interposed (for example, fragments of bone, PMMA, metal or ceramic). This also may increase the rate of wear by orders of magnitude over that in Mode 1.

In Mode 4, two non-bearing surfaces are moving against each other under load. Examples of Mode 4 include neck

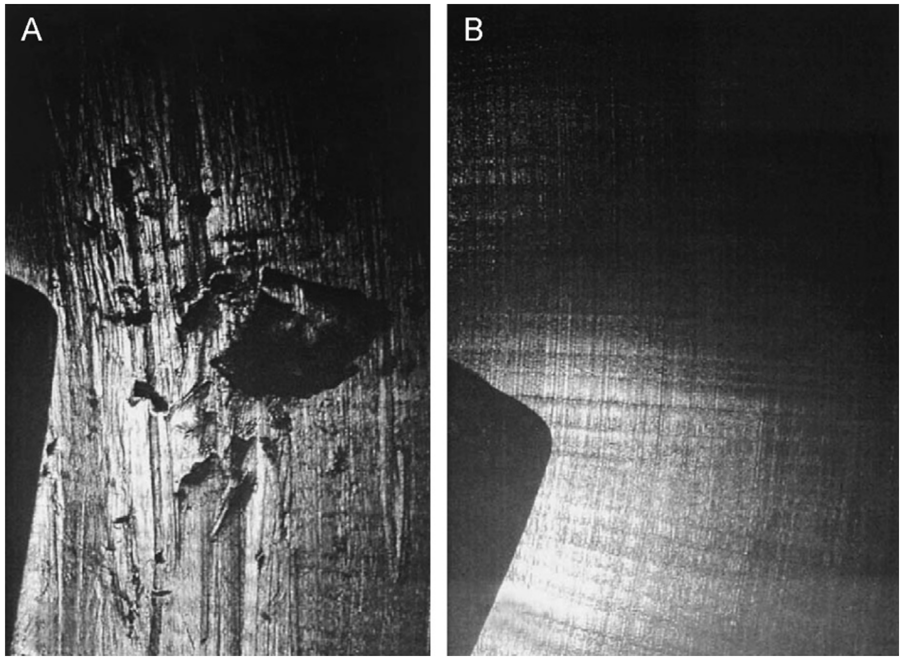

Fig. 1. Micrograph of a tibial plateau of highly crosslinked polyethylene removed from a patient, showing: (A) extensive surface damage (pits, scratches, plastic deformation) that was generated during use in-vivo; (B) smooth original surface that was recovered after the component was heated above the melt temperature of the polyethylene, demonstrating that very little actual wear (removal of material in the form of debris) had occurred [11].

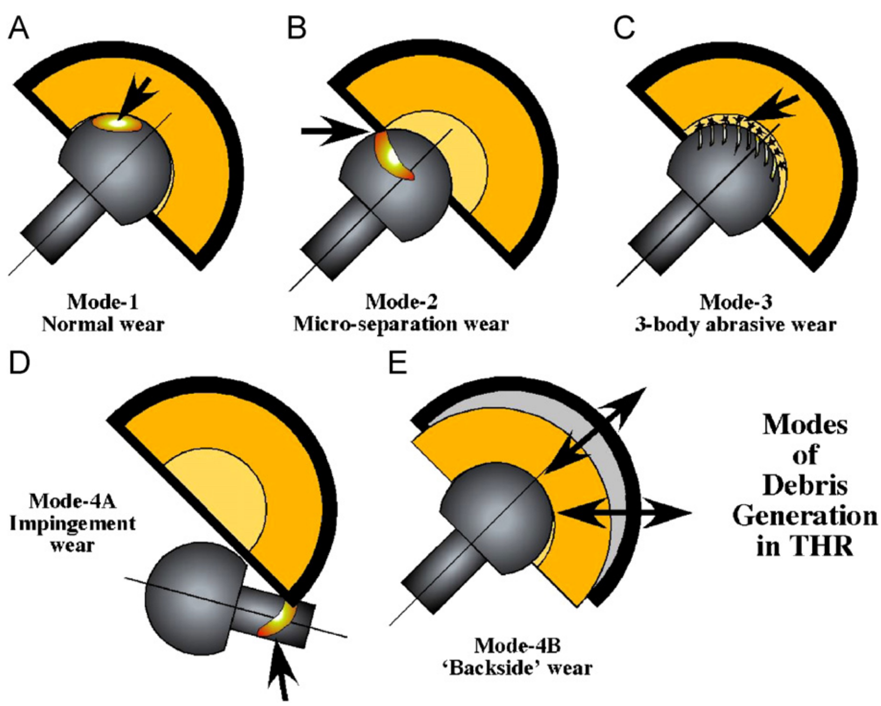

Fig. 2. Schematic illustration of the four wear modes for a total hip prosthesis: (A) in Mode 1, the only the intended bearing surfaces are in contact and undergoing wear; (B) in Mode 2, a bearing surface is wearing against a non-bearing surface, in this example due to subluxation of the ball from the socket; (C) in Mode 3, the wear is occurring between the two primary bearing surfaces, but with third-body abrasive particles interposed; (D) in Mode 4, two wear is occurring between two non-bearing surfaces, examples being (4A) neck–socket impingement and (4B) backside wear between the polyethylene cup and the metal shell. The definitions of these wear modes are applicable to arthroplasties for other joints (knee, ankle, shoulder, elbow, spine, etc.) (Illustration courtesy of Ian C. Clarke, Ph.D).

socket impingement, "backside" wear between an acetabular liner and shell or between a tibial plateau and the underlying plate, fretting between the metal intramedullary stem and the surrounding bone or PMMA mantle, and many others. The debris that are generated in Mode 4 may be sufficient to directly generate a local osteolytic reaction,

Table 1
Mathematical analogs of the four wear modes

Surfaces in contact	Mathematical analog	Mode number
Primary vs. primary	$1 \times 1 = 1$	1
Primary vs. secondary	$1 \times 2 = 2$	2
Primary vs. primary vs. third bodies	$1 \times 1 \times 3 = 3$	3
Secondary vs. Secondary	$2 \times 2 = 4$	4

In the analog of Table 1, a primary bearing surface is assigned the number 1; a secondary, non-bearing surface is assigned a 2, and third-body particles are assigned a 3. Multiplication is the mathematical analog for two or more surfaces in moving contact to cause wear.

and it can migrate to the bearing interface, initiating Mode 3 wear. In a worst case scenario, a prosthesis may be functioning simultaneously in Modes 2, 3 and 4, leading rapidly to clinical failure. Ideally, the goal of the engineer and the surgeon is to design and implant the prosthesis in a manner that minimizes the wear rate in Mode 1, and that avoids Modes 2, 3 and 4 altogether.

Some investigators have questioned the logic of the numbering of the wear modes, suggesting, for example, that third-body abrasion should be Mode 4, since it is the only one that involves more than two surfaces. However, the numbering sequence advocated by the author has the attractive characteristic of being "derivable" from a convenient mathematical analog, as shown in Table 1.

4. Wear mechanisms

Brown and colleagues [15] in their pioneering study, pointed out that wear of polyethylene in a prosthetic joint involves the three fundamental wear mechanisms that were described by Lancaster [39] for polymers in general, i.e., adhesion, abrasion and fatigue, in agreement with Trent and Walker [14]. For purposes of the present discussion, it is important to emphasize that the wear mechanisms are the *processes* that cause *wear* (i.e., the removal of material from the surface of the bearing) and cause *damage* (a change in the texture or appearance of the surface).

The volume of wear that occurs, and the types of damage, depend on the physical scale on which the wear mechanisms are acting. For example, if a single, large third-body particle is dragged across the surface of the polyethylene, a substantial amount of material may be removed (wear), and a large scratch may be generated, easily visible to the eye (damage). In contrast, if abrasive wear of the polyethylene is being caused by millions of microscopic asperities on the surface of the metal (e.g., carbides), then a substantial amount of wear still may occur, but the scratches on the surface of the polyethylene will be too small for the eye to distinguish, such that the surface takes on a highly polished (burnished) appearance. Similar considerations apply to the scale on which adhesive and fatigue wear occur. Again, the presence or absence of visible damage on the surface of the polyethylene component is not necessarily an indication of the volume of wear debris that has been generated.

In very simple terms, adhesive wear can be minimized by using a combination of materials and lubricant such that adhesive bonding between the bearing surfaces is minimized. Although we are not free to choose the lubricant in contact with the surfaces of an artificial joint, fortunately, the proteins present in joint fluids act as boundary lubricants to reduce adhesive wear [40]. Abrasive wear can be minimized by optimal polishing of the bearing surfaces to avoid asperities, and by preventing the formation and entrapment of third body particles. Fatigue wear can be minimized by shaping the bearing surfaces in a manner that minimizes the contact stress (while, of course, allowing the type of motion needed for proper functioning of the joint) and by maximizing the toughness and crack resistance of the materials.

5. Methods for categorizing and interpreting surface damage on polyethylene bearings

Investigators have long recognized the value of close examination of clinically retrieved implants to determine the causes of wear in vivo, and to identify potential methods for minimizing it. Understandably, the need to describe the many different surface features (i.e., types of damage) that are present on the visible and microscopic scales has generated an extensive tribological vocabulary. Unfortunately, different investigators often have used the same term to describe the different types of damage, or different words for the same damage. In addition, some of the terminology has tended to confuse *cause* (wear mechanisms) with *effect* (damage and wear). In their early investigation of polyethylene wear generated in a hip joint simulator, Rose and colleagues [18] commented that, "Research on wear of polyethylene in total joint prostheses has uncovered a bewildering variety of wear mechanisms, sometimes in the same prosthesis." While the present author agrees with the spirit of this statement, it would be more in keeping with the definitions suggested above to say "a bewildering variety of types of damage" (since only a few wear mechanisms were involved).

Table 2 presents a partial list of prior studies of retrieved implants, indicating the specific terms used by the investigators to describe the types of damage observed on the surfaces of the polyethylene bearings. In compiling this table, the author has included several of the early studies of hip prostheses that set the stage for many of the studies to

Table 2
Damage categories for retrieved polyethylene components

Study	Type of implants	Polishing	Burnishing	Scratching	Gouging	Abrasion	Rolls	Folds	Parallel ripples	Creep/cold flow	Surface deformation	Tractive striations
(A) Types of surface damage												
Walker and Gold 1973 [12]	One Charnley cup	X		X		X						
Weightman et al., 1973 [13]	Two Charnely–Mueller cups	X		X	X							
Trent and Walker, 1976 [14]	11 Knee tibial plateaus	X		X		X	X					
Brown et al., 1976 [15]	6 Hip cups					X						
Dowling et al., 1978 [16]	21 Hip cups	X		X					X			
Rostoker et al., 1978 [17]	21 Hips and knees	X		X	X	X		X				
Rose et al., 1979 [18]	8 Hips, 16 knees					X						
Hood et al., 1983 [19]	48 Knees		X	X		X					X	
Landy and Walker, 1988 [20]	90 Knees		X			X				X	X	
Wrona et al., 1994 [21]	Hips and knees		X	X		X				X		
Wasielewski et al., 1994 [22]	55 Knees, conventional and carbon–fiber polyethylene		X							X		
Cornwall et al., 1995 [23]	Knees		X	X		X					X	
Sychterz et al., 1006 [24]	26 Hip cups		X	X		X					X	
White et al., 1996 [25]	29 Knees		X	X		X				X		
Williams et al., 1998 [26]	1635 Knee components		X	X		X				X		
Kurtz et al., 2000 [27]	6 Knees, 3 conventional poly, 3 Hylamer^{TM}		X	X		X				X		
Won et al., 2000 [28]	13 MG-I (1900 poly) and 10 MG II (GUR 415 poly) knees		X	X		X					X	
Harman et al., 2001 [29]	8 Knees		X	X		X				X	X	X
Puloski et al., 2001 [30]	Post stabilized knee posts		X	X		X						
Berzins et al., 2002 [31]	26 MG knees (net molded 1900 w/out stearate) and 43 MG II (extruded-machined 4150 w/stearate)											
Surace et al., 2002 [32]	11 MG I (net molded 1900) and 14 MG II (extruded-machined 415) knees; backside only	X		X		X				X		
Muratoglu et al., 2003 [11]	Knees: 71 conventional and 8 highly crosslinked poly		X	X		X						
Silva et al., 2003 [34]	20 Knees		X	X		X						
Conditt et al., 2004 [36]	124 Knees, 12 designs, backside only		X	X		X					X	
Bradford et al., 2004 [37]	21 Crosslinked acetabular cups, 2 non-crosslinked cups		X	X		X					X	
Kurtz et al., 2007 [38]	21 Charité III spinal discs		X	X		X					X	

(B) Types of surface damage (con't)

Study	Smears and pulls	Wrinkles	Cracks	Pitting	Indentations	Craters	Flaking	Spalling	Delamination	Wear through	Embedded third bodies
Walker and Gold 1973 [12]			X	X	X						X
Weightman et al., 1973 [13]			X								

Table 2 (*continued*)

(B) Types of surface damage (con't)

Study	Smears and pulls	Wrinkles	Cracks	Pitting	Indentations	Craters	Flaking	Spalling	Delamination	Wear through	Embedded third bodies
Trent and Walker, 1976 [14]			X	X	X	X					X
Brown et al., 1976 [15]			X								
Dowling et al., 1978 [16]	X	X	X	X			X	X			
Rostoker et al., 1978 [17]			X	X	X	X					X
Rose et al., 1979 [18]			X			X			X		X
Hood et al., 1983 [19]				X					X		X
Landy and Walker, 1988 [20]	X								X		X
Wrona et al., 1994 [21]			X	X					X	X	
Wasielewski et al., 1994 [22]				X					X		X
Cornwall et al., 1995 [23]				X					X		X
Sychterz et al., 1006 [24]				X							X
White et al., 1996 [25]				X					X		
Williams et al., 1998 [26]			X	X					X	X	
Kurtz et al., 2000 [27]				X					X		
Won et al., 2000 [28]				X					X		X
Harman et al., 2001 [29]				X					X		
Puloski et al., 2001 [30]				X					X		X
Berzins et al., 2002 [31]				X					X		
Surace et al., 2002 [32]			X	X					X		X
Muratoglu et al., 2003A [33]				X					X		X
Silva et al., 2003 [34]				X					X		
Conditt JBJS 2004 [35,36]				X					X		X
Bradford et al., 2004 [37]				X							X
Kurtz et al., 2007 [38]			X								X

follow. The more recent studies primarily involve knee prostheses, in which damage assessment has become a key investigative tool. The list is intended to be illustrative and informative, but clearly is not comprehensive.

One of the first studies to characterize wear in retrieved polyethylene components was that of Weightman and colleagues [13], who described "polishing" in the main contact areas that they attributed to "plastic flow" of the polyethylene (i.e., rather than wear). They also observed large "scratches," occasionally with "cracks" perpendicular to the scratches, which they attributed to "brittle fracture wear." If correct, brittle fracture wear could be considered a fourth wear mechanism acting on the polyethylene (that is, if the cracks were generated on a single pass, rather than by a fatigue mechanism). However, based on the subsequent body of literature, it is the author's opinion that these "cracks" likely were remnants of the tool tracks generated during the original machining of the components.

Trent and Walker [14] described the morphology of the bearing surfaces on eleven retrieved tibial components. While this study drew valuable attention to the complexity of the wear events occurring in vivo, the terminology employed was a mixture of causes (mechanisms), including "two and three body abrasion," "entrapped cement fragments" "penetration and gouging," and effects (damage), including "scoring," "smearing and stretching of the surface," "shreds of plastic on the surface," "roll formation," "cracking," "pitting" and "large dents or craters." In some cases, the terminology was ambiguous. For example, "cracking" may refer to a wear mechanism (fatigue) or the type of damage it produces (cracks).

Brown and colleagues [15] presented detailed definitions of the adhesion, abrasion and fatigue wear mechanisms, and made a clear and consistent distinction between the mechanisms and the types of surface damage that they generated. In contrast to many other studies in which several wear mechanisms were thought to be active, Brown and colleagues attributed all of the surface damage evident on six acetabular cups (retrieved after one to five years of clinical use) only to adhesive wear. They also measured substantial amounts of oxidative degradation in the polyethylene cups and, with what can now be seen as amazing foresight, predicted that "the evidence of oxidation could imply that the fatigue wear component is about to play an important role."

In a study of 21 acetabular cups removed post-mortem, Dowling and colleagues [16] noted that the superior main contact zone, which they referred to as the "high wear area," was "smooth and well polished," whereas the inferior "low wear area" retained the original machine tool tracks, although these had been partially worn down. They observed gross damage consistent with fatigue wear ("pitting and flaking," "long cracks" and "spalling") and, using transmission electron microscopy, adhesive wear ("fans, or long thin smears") and abrasive wear ("ploughing or scratching"). Importantly, their observations demonstrated that substantial wear of the polyethylene could produce a visibly polished surface, but very high magnification revealed "ripples" (of unknown cause) and "bald patches" attributed to flaking (fatigue wear).

In their landmark study of 21 polyethylene components from hips and knees, Rostoker and colleagues [17] defined seven "modes" of "surface change or disturbance" (i.e., damage), including "wear polishing," "scratches and gouges," "folds," "pits, indentations and craters," "abrasion or shredding," "cracks" and "embedded bone cement". However, they stated that they "have not seen any indication of what must be unambiguously interpreted as a crack". In some cases, what appeared to be cracks may have been "a crevice produced by a fold". The authors also emphasized that it was not always possible to determine which wear mechanism was responsible for a given type of damage, for example, whether a pit was caused by material removal (fatigue wear) or simply by plastic deformation, without producing wear debris.

Using a similar approach, Hood and colleagues [19] examined the tibial plateaus and patellar components of 48 retrieved knees and categorized the damage into seven "modes of surface degradation." As indicated in Table 2, these corresponded to the categories of Rostoker and colleagues [17] with the exceptions that "burnishing" replaced "polishing," "scratches" replaced "scratches and gouges," "pits" and "delaminations" replaced "pits, indentations and craters" and "cracks" were omitted. In addition, Hood and colleagues compiled an overall "damage score" for each component that took into account the location and percent area occupied by each type of damage (graded from zero to 3). Positive correlations were found between the damage score and the patient's weight, as well as the duration of use.

The study by Hood and colleagues was the first to implement a quantitative scheme for assessing the extent of surface damage. This technique has been adapted by many subsequent investigators (Table 2), and has provided valuable information on the factors affecting the clinical function of the implants, recently including highly cross-linked acetabular cups [37] and spinal disc arthroplastices [38]. An important limitation of this approach, however, is that, as noted above, a high damage score does not necessarily indicate that a large amount of wear has occurred. In fact, the opposite may be true, and it is the volume of wear debris released to the tissues that determines the incidence and severity of the foreign body reaction, particularly osteolysis [9,41,42]. The importance of this distinction was recently emphasized by Puloski and colleagues [30], who stated, "An important concept that must be kept in mind when one attempts to quantify the wear of polyethylene is the difficulty in distinguishing wear, in which material is lost, from plastic deformation (creep or cold flow), in which the polymer is distorted in shape without loss of material. This can be especially difficult when an attempt is made to differentiate adhesive wear seen as burnishing, but it is easier when one is trying to identify fatigue damage such as delamination and pitting." Unfortunately, Puloski and colleagues went on to state, "Although the use of the term wear to describe all forms of surface and subsurface deformation may be semantically imprecise, we will continue to use it in this study, acknowledging that the damage can occur without the subsequent generation of debris." The same approach was taken by Sychterz and colleagues [24].

In the present author's opinion, it would be less likely to mislead the readership if investigators maintained the distinction between the total dimensional change and actual wear. For example, "total penetration" and "thinning" may be used to refer to the loss in thickness of polyethylene acetabular cups and tibial plateaus, respectively, without implying that this was due solely to wear, rather than plastic deformation.

6. Wear debris

As noted above, in the context of the proposed lexicon, the amount of wear refers to the volume of wear debris that has been removed from the prosthesis, and deposited into the adjacent tissues. An extensive body of literature has demonstrated that, in the case of polyethylene, these particles may include a variety of shapes (e.g., beads, granules, fibrils, flakes and others), with sizes ranging from several millimeters down to the nanometer scale [43–45]. The techniques for extracting these particles from the joint fluids and tissues, for categorizing their morphology, and for characterizing their relative bio-reactivity are undergoing rapid evolution, and any attempt at this time to compile a comprehensive and useful lexicon would be "shooting at a moving target." In the meantime, the essential message is that, barring gross mechanical failure of a polyethylene component, the successful long-term clinical performance depends primarily on minimizing the volume of wear debris released to the tissues, and only indirectly on the type and amount of damage that accumulates on the surfaces of the component.

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