Published in final edited form as:

J Biomed Mater Res B Appl Biomater. 2010 August ; 94(2): 312–317. doi:10.1002/jbm.b.31653.

Wear Pattern Observations from TDR Retrievals Using Autoregistration of Voxel Data

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Abstract

Due to their unique geometry, characterization of wear damage in total disc replacement (TDR) is difficult. In the paper, we developed and validated an automated damage calculation technique for explanted TDR components. Eight polyethylene cores implanted from 4.6 to 16.0 years were using cone-beam microCT imaging (SCANCO Medical, Switzerland). The nominal uniform voxel size for the implant under investigation was 18 microns, however with a smaller sample size increased resolutions (10 micron nominal voxel size) could be achieved using the same microCT imaging hardware. Nominal surface data for both sizes of TDR components we examined were obtained from manufacturer's drawings (Link, Germany) and converted to highly discretized triangular meshes. The damage calculation technique utilized an initial alignment phase, followed by a pointwise calculation of the linear damage at each 3D surface point. During the alignment phase, a three-dimensional surface of the undamaged component was automatically aligned with volumetric image data from the damaged component. The alignment algorithm maximized the contact area between undamaged portions of the implant and its nominal surface using an iterative optimization technique. Linear damage at each triangle on the nominal surface was computed by moving along the local normal of the surface both inward and outward direction for a distance much less than the size of the implant. For the retrieved components, the maximum damage occurred away from the central axis of the dome close to the rim. Penetrations of up to 0.8 mm were observed in this region. Lower magnitude penetrations were observed near the pole of the dome. In conclusion, we have developed an analytical method to automatically align and measure three-dimensional surface damage with both high resolution and accuracy on implants with complicated, non-parametric, surface geometry and used this technique to analyze eight implants.

Keywords

wear; polyethylene; spinal implant; total joint replacement; implant retrieval

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Introduction

Multicenter studies of lumbar total disc replacement (TDR) have given short and medium term clinical results that are equivalent to or better than fusion, with low rates of neurologic complications and device failures¹⁻⁵. Due to the novelty of these devices however, long-term results are not currently available⁶. Based on experience with other total joint replacements, it is likely that long-term clinical success will depend substantially upon component wear rates⁷⁻¹¹.

In the absence of long-term clinical wear rate information, wear simulators provide a key source of information regarding the predicted longevity of these components. Unfortunately, there have been wide disparities in reported simulator wear rates for disc arthroplasty components^{12,13}. These disparities have been attributed to differences in simulator wear duty cycles and related path dependent strain hardening. For example, a recent study of polymer on metal components showed that the addition of out of phase “crossing” patterns to the simulator duty cycle induced a 20-fold increase in wear magnitude¹³.

Component retrieval studies can provide a valuable source of validation data for wear simulator studies. Retrieval studies are occasionally criticized because they are predominantly comprised of components obtained from patients where the primary arthroplasty operation has ostensibly “failed”. Nonetheless, as retrieval collections for total disc arthroplasty components continue to grow¹⁴, investigators can obtain clear insights into the clinical performance, as well as the limitations of current component designs. Retrieval studies to date have identified not only changes in TDR component shape due to mechanical deformation (creep), but also clear evidence of adhesive-abrasive wear, and even reported cases of osteolysis^{4,6,14-19}.

Volumetric wear measurements from TDR retrievals and wear simulator studies are commonly performed using the Archimedes principle, and provide a gross metric of device wear resistance, but are limited in that they do not identify regions of the implant that have lost material. Because of this limitation, volumetric techniques fail to give implant designers or physicians any indication of the predominant mode of device use. Volumetric techniques also fail to distinguish component damage induced during the retrieval process from that acquired *in vivo*^{20,21}. Advances have been made in presenting wear “maps” that characterize the spatial variation in wear magnitude for regularly shaped implants such as acetabular liners²². However, these techniques are not readily extensible to components such as those used in total disc arthroplasty, where the implant bearing surface is not defined by geometric primitives.

Radiographic wear measurement techniques are primarily used in measuring *in situ* penetration, and have been shown to be very accurate in laboratory settings for approximating volumetric component wear subsequent to total hip arthroplasty²³. Accuracy is somewhat reduced in actual clinical practice however²⁴⁻²⁷, and extension of these techniques to total disc arthroplasty has not been reported. Shadowgraph and CMM techniques²⁰ are laborious, and are not easily applied to TDR components. Lee, et al.²⁸, used volumetric, CMM, and optical techniques to quantify wear in a metal-on-metal prosthesis.

In the present work, we develop and validate an automated, microCT-based wear calculation technique for generating high-resolution damage maps of explanted TDR components. Since plastic deformation of component bearing surfaces during the “bedding in” period is not differentiated from component wear, the term “damage” is used to define component geometric changes following implantation.

Methods and Materials

Eight retrieved polyethylene cores of a mobile bearing TDR (Charité, Link, Germany) with implantation times ranging from 4.6-16.0 years (mean 9.0 years) were analyzed using the automatic damage calculation technique. Explanted cores were cleaned using soap and a diluted bleach solution and subsequently photographed using a digital camera (Nikon D100 manufactured by Nikon, Inc. of Melville, NY). The radiographic wire marker from each TDR was removed using a precision screwdriver resulting in minimal or no damage. Clinical information for the retrieved TDR cores is presented in Table 1.

Nominal surface data for both sizes of TDR components we examined were obtained from manufacturer's drawings (Link, Germany) and converted to highly discretized triangular surface meshes (approximately 2 million triangles per implant size). Volumetric image data for the damaged components was obtained using cone-beam microCT imaging (MicroCT 80, SCANCO Medical, Switzerland) with a uniform voxel dimension of 18 microns. The volumetric data was thresholded based on X-ray linear attenuation coefficient so that each image voxel could be identified as being either implant or air.

The damage calculation technique was divided into two phases (Figure 1). During the alignment phase, a three-dimensional (3D) surface of the undamaged component was automatically aligned with volumetric image data from the damaged component. Following alignment, component damage was calculated on a highly discretized representation of the component and presented in a quantitative graphical format.

Principal axes and centers of mass for the nominal surface data and the microCT data of each damaged component were computed and aligned to provide a starting point for the alignment algorithm. For severely damaged components, this alignment could be corrected using a graphical user interface^a. The alignment algorithm maximized the contact area between undamaged portions of the implant and its nominal surface using an iterative optimization technique. Linear damage at each triangle on the nominal surface was computed by moving along the local normal of the surface both inward and outward direction for a distance much less than the size of the implant (typically, 0.5% of the longest dimension). This distance was intentionally limited to prevent large implant damage from negatively influencing the accuracy of the alignment. If the surface normal intersected an implant voxel, the (signed) distance from the surface to the implant voxel was defined as damage. Once the damage was assigned to each triangle of the surface, the aggregate damage value was computed for the current implant position. A Nelder-Mead simplex algorithm was then used to minimize the total damage as the function of rotation and translation.

We borrowed several techniques from the field of computer graphics to improve robustness and the speed of calculation. All the transformation matrixes were defined as 4×4 matrixes; and rotations were performed using quaternion techniques to prevent a gimbal lock. A bounding box was used to limit the space that was traversed by the outward normals from the nominal implant surface, thus reducing the computational overhead associated with traversing the entire image space.

Following alignment, quantitative component damage was calculated as described above, but with two significant differences. First, the damage was calculated for each triangle,

^aThe final alignment is insensitive to the starting alignment, although the time required for alignment can be reduced by using a more precise initial orientation.

rather than summed to a single scalar number. Second, the ray-trace distance was increased to sweep through the distance of expected damage, rather than a small sliver.

The damage calculation code was implemented in MATLAB version 2008a on SUSE Linux with 2.6.5-7.97-smp kernel on a dual-processor AMD Opteron(tm) Processor (Opteron 246) machine with 16GB RAM and a similarly configured MacPro system. The actual damage calculation was performed using a compiled MEX function to conserve memory as well as to decrease computation time. The code was highly vectorized to allow for a parallel (SMP) implementation. Typical computation with a 1.5 million triangle nominal surface and a 3 gigabyte microCT image data set was 10 to 15 minutes.

Results

For all of the retrieved implants, the maximum damage was found to occur away from the central axis of the dome close to the rim (Figure 2). Penetrations of up to 0.8 mm were observed in this region. Lower magnitude penetrations (up to 0.4 mm) were observed near the pole of the dome. We observed that the dominant penetration pattern was similar on opposing bearing surfaces (superior/inferior) of most of the implants. The wear magnitudes however, were distinct on opposing bearing surfaces.

Two methods were used to validate the algorithm. The first method compared the point-wise measurements at the pole of the dome using a calibrated micrometer (0.001 mm accuracy) to the results from the algorithms. The mean damage measured at the dome using the micrometer was 0.34 mm (range: 0.22 - 0.55 mm). The mean damage measured at the dome using the algorithm was 0.27 mm (range: 0.10 - 0.48 mm). A summary of these measurements can be found in Table 2.

The second validation technique measured damage that was inflicted on an unimplanted Charité core using a microtome. The core was initially scanned without any damage to it with the exception of minimal damage caused by radiographic wire marker removal. The initial scan was used to generate a highly discretized triangular surface representation (~ 2 million triangles) of the component. Material was then removed from the dome using the microtome at approximately 50 and 350 microns (as measured using the calibrated micrometer). MicroCT scans were taken between each slicing increment and evaluated using the algorithm (Figure 3). Additionally, the algorithm was performed using the voxel data from the unimplanted and the surface representation from the voxel data of the same unimplanted core (Figure 3). When adjusted for area, the mean damage measured on this component was -0.027 ± 0.017 mm (95% Confidence Interval: -0.05 to -0.005).

Discussion

We have developed an analytical method to automatically align and measure three-dimensional surface damage with both high resolution and accuracy on implants with complicated, non-parametric surface geometry and used this technique to analyze 8 implants with varying degrees of freedom. This method has multiple advantages over prior techniques. The alignment is performed using only the undamaged portions of the implant surfaces and thus the results are unaffected by even very large missing sections of the implant. Since this technique works with non-parametric surfaces, it allows a user to use complicated CAD drawings as a nominal surface. The algorithm is completely automatic and removes user bias from the analysis. Additionally, the implementation of the code is highly scalable and can make use of a multiple processor machine. These advantages allow for several applications of this analysis method such as comparing wear simulator wear patterns to retrieved component wear patterns^{7,29-31}, validation of finite element analysis

techniques for predicting component wear^{32,33}, and characterization of manufacturing tolerances. Additionally, the technique provides synthesis of high-resolution microCT data into an easily understandable component damage map. MicroCT imaging allows very accurate evaluation of polymer core implants, however the image measurement algorithm presented in the current work is not limited to this modality alone. Any volumetric dataset such as MRI, ultrasound, or voxel representation of surface measurements (e.g., white light interferometry), allowing a broad class of other implants can be analyzed.

The principal drawback of this technique, which it shares with other surface-based wear assessment techniques, is its inability to distinguish between different damage mechanisms; there is no ability to distinguish a material that is worn from a material that is displaced due to creep or by surgical tools during explantation. Some of this can be ameliorated by further analysis of the damage; plastic deformation (creep) should keep the volume of the implant constant, while the wear should decrease the total volume of the material. Recent studies have attempted to separate creep from wear using results from finite element simulations³³. Another limitation is that if the implant is severely damaged such that only a small part of the original surface is intact, the alignment procedure will produce a best fit solution rather than the solution which accurately aligns the surface to the implant. In simulations where two-third of the component was removed (by deleting the voxels from the data set), the final alignment was still successfully obtained once the starting alignment (prior to iterative optimization) was overridden based on visual inspection. The detailed exploration of maximum aligned damage was not performed, however. The smallest amount of measurable damage is dictated both by the voxel size and by the systematic error during scans such as temperature stability, (etc.). Voxel size in our microCT is limited to 10 μm . Other researchers have reported systematic error with similar MicroCT configurations of approximately 3 mm³³⁴.

Another limiting factor we have found with the use of this code has been in accurately specifying the surface of an as-implanted component. The CAD file of the component has a quantifiable deviation from the actual machined shape of the device before it is implanted into the patient. Thus the measured damage is actually a sum of *in vivo* damage and manufacturing variation. The magnitude of this deviation is bounded by the manufacturing tolerances, and can be partially ameliorated by microCT scanning an identical (virgin) component that has been manufactured using the same processes. The virgin component microCT scan can then be used to generate the unworn reference surface for comparison.

The present work provides the means to compile a library of surface damage topologies observed in retrieved TDA components. When correlated with clinical observations, such a library can provide device designers, manufacturers, and clinicians with valuable insights into the effects of sizing, positioning, and material selection on the actual topology of damage. Material choice³⁵⁻³⁸, device geometric design³⁹⁻⁴¹, surgical placement⁴² has been correlated to wear rates in other joint arthroplasty components, and it is anticipated that it will also affect wear in TDR components. Limited information is now available regarding the long-term, *in vivo* wear performance of total disc replacements. However, similar to other orthopedic implants, wear in total disc replacements is expected to be a critical factor in implant longevity. Because of the complicated motions experienced by these devices, evaluation of not only wear volume, but also wear patterns will be critical in understanding device performance and in developing next generation total disc replacements.

Acknowledgments

Supported in part by NIH Grant R01 AR47904.

References

1. Blumenthal S, McAfee PC, Guyer RD, Hochschuler SH, Geisler FH, Holt RT, Garcia R Jr, Regan JJ, Ohnmeiss DD. A prospective, randomized, multicenter Food and Drug Administration investigational device exemptions study of lumbar total disc replacement with the CHARITE artificial disc versus lumbar fusion: part I: evaluation of clinical outcomes. *Spine (Phila Pa 1976)*. 2005; 30(14):1565–75. discussion E387-91. [PubMed: 16025024]
2. Guyer RD, McAfee PC, Banco RJ, Bitan FD, Cappuccino A, Geisler FH, Hochschuler SH, Holt RT, Jenis LG, Majd ME. Prospective, randomized, multicenter Food and Drug Administration investigational device exemption study of lumbar total disc replacement with the CHARITE artificial disc versus lumbar fusion: five-year follow-up. *Spine J*. 2009; 9(5):374–86. others. [PubMed: 18805066]
3. McAfee PC, Cunningham B, Holsapple G, Adams K, Blumenthal S, Guyer RD, Dmietriev A, Maxwell JH, Regan JJ, Isaza J. A prospective, randomized, multicenter Food and Drug Administration investigational device exemption study of lumbar total disc replacement with the CHARITE artificial disc versus lumbar fusion: part II: evaluation of radiographic outcomes and correlation of surgical technique accuracy with clinical outcomes. *Spine (Phila Pa 1976)*. 2005; 30(14):1576–83. discussion E388-90. [PubMed: 16025025]
4. McAfee PC, Geisler FH, Saiedy SS, Moore SV, Regan JJ, Guyer RD, Blumenthal SL, Fedder IL, Tortolani PJ, Cunningham B. Revisability of the CHARITE Artificial Disc Replacement. *Spine*. 2006; 31(11):1217–1226. [PubMed: 16688035]
5. Delamarter RB, Bae HW, Pradhan BB. Clinical results of ProDisc-II lumbar total disc replacement: report from the United States clinical trial. *Orthop Clin North Am*. 2005; 36(3):301–13. [PubMed: 15950690]
6. Punt IM, Visser VM, van Rhijn LW, Kurtz SM, Antonis J, Schurink GW, van Ooij A. Complications and reoperations of the SB Charite lumbar disc prosthesis: experience in 75 patients. *Eur Spine J*. 2008; 17(1):36–43. [PubMed: 17929065]
7. Anderson PA, Rouleau JP, Toth JM, Riew KD. A comparison of simulator-tested and -retrieved cervical disc prostheses. Invited submission from the Joint Section Meeting on Disorders of the Spine and Peripheral Nerves, March 2004. *J Neurosurg Spine*. 2004; 1(2):202–10. [PubMed: 15347007]
8. Kop AM, Swarts E. Quantification of polyethylene degradation in mobile bearing knees: A retrieval analysis of the Anterior-Posterior-Glide (APG) and Rotating Platform (RP) Low Contact Stress (LCS) knee. *Acta Orthop*. 2007; 78(3):364–70. [PubMed: 17611851]
9. Jacobs JJ, Hallab NJ, Urban RM, Wimmer MA. Wear particles. *J Bone Joint Surg Am*. 2006; 88(Suppl 2):99–102. [PubMed: 16595453]
10. Hallab NJ, Cunningham BW, Jacobs JJ. Spinal implant debris-induced osteolysis. *Spine*. 2003; 28(20S):S125–38. [PubMed: 14560184]
11. Kostuik JP. Complications and surgical revision for failed disc arthroplasty. *Spine J*. 2004; 4(6 Suppl):289S–291S. [PubMed: 15541678]
12. Kurtz SM, Patwardhan A, MacDonald D, Ciccarelli L, van Ooij A, Lorenz M, Zindrick M, O'Leary P, Isaza J, Ross R. What is the correlation of in vivo wear and damage patterns with in vitro TDR motion response? *Spine (Phila Pa 1976)*. 2008; 33(5):481–9. [PubMed: 18317190]
13. Grupp, TM.; Yue, JJ.; Garcia, R.; Schwiesau, J.; Fritz, B.; Blömer, W. Biotribology of total disc arthroplasty prostheses - Wear simulation according to ISO and ASTM documents. Berlin, Germany: May 1-4. 2007 p. PA-WE07
14. Kurtz SM, van Ooij A, Ross R, de Waal Malefijt J, Peloza J, Ciccarelli L, Villarraga ML. Polyethylene wear and rim fracture in total disc arthroplasty. *Spine J*. 2007; 7(1):12–21. [PubMed: 17197327]
15. van Ooij A, Kurtz SM, Stessels F, Noten H, van Rhijn L. Polyethylene wear debris and long-term clinical failure of the Charite disc prosthesis: a study of 4 patients. *Spine*. 2007; 32(2):223–9. [PubMed: 17224818]
16. Pitzen T, Kettler A, Drumm J, Nabhan A, Steudel WI, Claes L, Wilke HJ. Cervical spine disc prosthesis: radiographic, biomechanical and morphological post mortal findings 12 weeks after implantation. A retrieval example. *Eur Spine J*. 2007

17. Fraser RD, Ross ER, Lowery GL, Freeman BJ, Dolan M. AcroFlex design and results. *Spine J*. 2004; 4(6 Suppl):245S–251S. [PubMed: 15541673]
18. Hallab N, Link HD, McAfee PC. Biomaterial optimization in total disc arthroplasty. *Spine*. 2003; 28(20):S139–52. [PubMed: 14560185]
19. Pimenta L, Diaz RC, Guerrero LG. Charite lumbar artificial disc retrieval: use of a lateral minimally invasive technique. Technical note. *J Neurosurg Spine*. 2006; 5(6):556–61. [PubMed: 17176025]
20. Chuter GS, Cloke DJ, Mahomed A, Partington PF, Green SM. Wear analysis of failed acetabular polyethylene: a comparison of analytical methods. *J Bone Joint Surg Br*. 2007; 89(2):273–9. [PubMed: 17322451]
21. Schmalzried TP, Callaghan JJ. Wear in total hip and knee replacements. *J Bone Joint Surg Am*. 1999; 81(1):115–36. [PubMed: 9973062]
22. Bowden AE, Kurtz SM, Edidin AA. Validation of a micro-CT technique for measuring volumetric wear in retrieved acetabular liners. *J Biomed Mater Res B Appl Biomater*. 2005; 75(1):205–9. [PubMed: 16037962]
23. Hui AJ, McCalden RW, Martell JM, MacDonald SJ, Bourne RB, Rorabeck CH. Validation of two and three-dimensional radiographic techniques for measuring polyethylene wear after total hip arthroplasty. *J Bone Joint Surg Am*. 2003; 85-A(3):505–11. [PubMed: 12637439]
24. Wan Z, Boutary M, Dorr LD. Precision and limitation of measuring two-dimensional wear on clinical radiographs. *Clin Orthop Relat Res*. 2006; 449:267–74. [PubMed: 16702911]
25. Barrack RL, Lavernia C, Szuszczewicz ES, Sawhney J. Radiographic wear measurements in a cementless metal-backed modular cobalt-chromium acetabular component. *J Arthroplasty*. 2001; 16(7):820–8. [PubMed: 11607896]
26. Gallo J, Havranek V, Cechova I, Zapletalova J. Wear measurement of retrieved polyethylene ABG 1 cups by universal-type measuring microscope and X-ray methods. *Biomed Pap Med Fac Univ Palacky Olomouc Czech Repub*. 2006; 150(2):321–6. [PubMed: 17426800]
27. Ebramzadeh E, Sangiorgio SN, Lattuada F, Kang JS, Chiesa R, McKellop HA, Dorr LD. Accuracy of measurement of polyethylene wear with use of radiographs of total hip replacements. *J Bone Joint Surg Am*. 2003; 85(12):2378–84. [PubMed: 14668508]
28. Lee JL, Billi F, Sangiorgio SN, McGarry W, Krueger DJ, Miller PT, McKellop H, Ebramzadeh E. Wear of an Experimental Metal-on-Metal Artificial Disc for the Lumbar Spine. *Spine*. 2008; 33(6):597–606. [PubMed: 18344852]
29. Serhan HA, Dooris AP, Parsons ML, Ares PJ, Gabriel SM. In vitro wear assessment of the Charite Artificial Disc according to ASTM recommendations. *Spine*. 2006; 31(17):1900–10. [PubMed: 16924206]
30. Saikko V. Effect of contact pressure on wear and friction of ultra-high molecular weight polyethylene in multidirectional sliding. *Proc Inst Mech Eng [H]*. 2006; 220(7):723–31.
31. O'Leary P, Nicolakis M, Lorenz MA, Voronov LI, Zindrick MR, Ghanayem A, Havey RM, Carandang G, Sartori M, Gaitanis IN. Response of Charite total disc replacement under physiologic loads: prosthesis component motion patterns. *Spine J*. 2005; 5(6):590–9. others. [PubMed: 16291097]
32. Baudriller H, Chabrand P, Moukoko D. Modeling UHMWPE wear debris generation. *J Biomed Mater Res B Appl Biomater*. 2007; 80(2):479–85. [PubMed: 16862559]
33. Bevill SL, Bevill GR, Penmetsa JR, Petrella AJ, Rullkoetter PJ. Finite element simulation of early creep and wear in total hip arthroplasty. *J Biomech*. 2005; 38(12):2365–74. [PubMed: 16214484]
34. Vicars R, Fisher J, Hall RM. The accuracy and precision of a micro computer tomography volumetric measurement technique for the analysis of in-vitro tested total disc replacements. *Proc Inst Mech Eng H*. 2009; 223(3):383–8. [PubMed: 19405443]
35. Maher SA, Furman BD, Babalola OM, Cottrell JM, Wright TM. Effect of crosslinking, remelting, and aging on UHMWPE damage in a linear experimental wear model. *J Orthop Res*. 2007; 25(7):849–57. [PubMed: 17415754]
36. Oskouian RJ, Whitehill R, Samii A, Shaffrey ME, Johnson JP, Shaffrey CI. The future of spinal arthroplasty: a biomaterial perspective. *Neurosurg Focus*. 2004; 17(3):E2. [PubMed: 15636558]

37. Taksali S, Grauer JN, Vaccaro AR. Material considerations for intervertebral disc replacement implants. *Spine J.* 2004; 4(6 Suppl):231S–238S. [PubMed: 15541671]
38. Collier MB, Engh CA Jr, McAuley JP, Engh GA. Factors associated with the loss of thickness of polyethylene tibial bearings after knee arthroplasty. *J Bone Joint Surg Am.* 2007; 89(6):1306–14. [PubMed: 17545435]
39. Shuff C, An HS. Artificial disc replacement: the new solution for discogenic low back pain? *Am J Orthop.* 2005; 34(1):8–12. [PubMed: 15707133]
40. Hopkins AR, Hansen UN, Amis AA, Knight L, Taylor M, Levy O, Copeland SA. Wear in the prosthetic shoulder: association with design parameters. *J Biomech Eng.* 2007; 129(2):223–30. [PubMed: 17408327]
41. Lundberg HJ, Pedersen DR, Baer TE, Muste M, Callaghan JJ, Brown TD. Effects of implant design parameters on fluid convection, potentiating third-body debris ingress into the bearing surface during THA impingement/subluxation. *J Biomech.* 2007; 40(8):1676–85. [PubMed: 17400230]
42. Kligman M, Furman BD, Padgett DE, Wright TM. Impingement contributes to backside wear and screw-metallic shell fretting in modular acetabular cups. *J Arthroplasty.* 2007; 22(2):258–64. [PubMed: 17275644]

Figure 1. Flow chart illustrating the methodology for obtaining a damage map of a total disc replacement.

Figure 2.

Damage maps and microphotographs of both sides of the eight explanted Charite polyethylene cores. The top row is a photograph of one side of the eight explanted polyethylene cores while the bottom row is a photograph of the opposite side of the cores. The second row is the wear map calculated by the algorithm that corresponds to the top row, while the third row is the wear map that corresponds with the bottom row. MAA-### and SAL-### are the implant identifiers assigned by the Drexel University Implant Research Center.

Figure 3. Validation damage maps from an unworn surface automatically registered to itself (top) and a component with approximately 300 microns of damage inflicted on it using a microtome (bottom).

Table 1

Clinical information for retrieved TDRs.

Implant Identifier	Age at Implantation	Gender	Primary Diagnosis	Level	Implant Fixation Method	Year of Index Surgery	Year of Removal Surgery	Endplate Size	Implantation Time (years)
Maa013	33	F	Disc degeneration	L3/L4	Noncoated	1992	2005	2	12.7
Maa 015	44	M	Disc degeneration	L4/L5	Noncoated	1989	2005	2	16.0
Maa 017	46	F	Disc degeneration after HNP operation	L5/S1	Noncoated	1999	2005	3	6.5
Maa 018	33	F	Disc degeneration	L4/L5	Noncoated	1995	2006	3	10.6
Sal 003	45	M	Disc degeneration	L5/S1	Noncoated	1997	2006	3	8.3
Maa 022	47	F	Disc degeneration	L4/L5	Coated	2001	2006	3	5.3
Maa 023	45	F	Disc degeneration	L5/S1	Coated	2001	2006	3	4.6
Sal 004	44	M	Disc degeneration	L4/L5	Noncoated	1998	2006	3	7.8

Table 2

Summary of dome penetration validation study results.

Implant Identifier	MicroCT Dome Penetration (mm)	Micrometer Dome Penetration (mm)
Maa013	0.31	0.36
Maa015	0.56	0.55
Maa017	0.31	0.34
Maa018	0.32	0.33
Sal003	0.42	0.43
Maa022	0.14	0.22
Maa023	0.19	0.23
Sal004	0.23	0.23