CHAPTER 6

CONCLUSIONS

Using the recently modified wear testing apparatus, three lubricants were tested under high and low loads to determine the effects each combination would have on wear, deformation, and friction in a bovine cartilage on stainless steel system. Several analysis techniques, both quantitative and qualitative, were used to obtain as much information as possible about the amount and nature of cartilage wear in the cartilage on stainless steel system.

The conclusions drawn from this study are discussed below.

1. The lubricant was shown to have an effect on cartilage wear in high-load (65 N) tests. The average wear values obtained for each lubricant were 580 μg of cartilage for saline tests, 330 μg for hyaluronic acid tests, and 270 μg for synovial fluid tests. Lubricant was not shown to be a significant factor for wear in low-load tests.

2. Cartilage wear was shown to be significantly affected by the applied load. High load tests (65 N) produced significantly more wear than low load tests (20 N). The average wear in low-load tests was 67 μg for saline tests, 79 μg for hyaluronic acid tests, and 93 μg for synovial fluid tests. All of these values were significantly less than the corresponding wear values in high-load tests (580 μg, 330 μg, and 270 μg, respectively).

3. Friction was not significantly affected by lubricant, but was, like wear, affected by load. The average friction values for high and low load tests are shown in Tables 4.1 and 4.2, respectively.

4. The total change in vertical displacement of the upper specimen was significantly affected by load, but not by lubricant. The average change in vertical displacement of the specimen was approximately 0.1 mm less for low-load tests.

5. Valuable information about wear mechanisms has been obtained through observation of samples using scanning electron microscopy and histologic sectioning and staining. Early signs of surface delamination were evident, as well as wear marks perpendicular to the direction of sliding; these marks are indicative of another wear mechanism, which could involve surface adhesion.

6. Visible differences in wear were observed in SEM specimens with respect to high and low loads. Both high- and low-load samples showed evidence of plowing wear, while perpendicular markings appeared to dominate the low-load specimen surfaces in hyaluronic acid tests.

7. Preliminary FTIR analysis has shown chemical changes in worn cartilage (see recommendations in Chapter 7).

8. The wear testing apparatus has been fitted with an improved bearing to reduce unwanted motion of the shaft.

9. The procedures for cutting and for testing cartilage specimens (plugs) have been refined and improved for enhanced repeatability.

CHAPTER 7

RECOMMENDATIONS FOR FUTURE RESEARCH

Future testing can benefit from the knowledge and information obtained from this study. Although valuable results have been obtained from this experiment, much work remains to be completed; the interaction of lubricant and surface in the boundary lubrication regime is still not fully understood. La Shaun Berrien, a doctoral student at the Virginia Polytechnic Institute and State University, will continue this work by investigating wear and friction in the cartilage on cartilage system.

Several areas should be explored in the course of future research in this area, some of which are detailed here.

1. The cartilage-on-cartilage system should be tested to determine whether the lubricants used in this study, among others, might have a different effect on wear or friction.

2. FTIR analysis can be used to study possible chemical changes that could occur in the cartilage during sliding. This analysis could be performed on the transferred films on the stainless steel disks, as well as on fresh and worn cartilage and synovial fluid.

3. Further improvements on the biotribological testing device could reduce variations in vertical displacement and friction data.

4. The vertical displacement data, obtained using the LVDT, could be used to learn more about the time-dependent deformation of cartilage under load.

5. Time, or the total number of cycles, can be tested as a variable to measure the wear rate of cartilage under various conditions.

6. More experiments using time and load as variables could provide more information about the protective surface layer discussed by Stachowiak [8].

7. Further characterization and observation of wear particles, using microscopy and particle size analysis, could provide information about the nature of the shapes and size distributions of the particles that are produced during sliding.

8. *In vivo* experiments have already been begun in the College of Veterinary Medicine under the supervision of Dr. Hugo Veit. These experiments can provide vital data for future tests.

9. Dr. Furey has proposed a plan for future testing that will encompass a matrix of testing combinations; healthy and unhealthy (osteoarthritic) cartilage can be tested in conjunction with healthy and unhealthy synovial fluid, as indicated by the chart

below.

	Healthy	Unhealthy
Cartilage	X	X
Synovial Fluid	X	X

As more test results reveal more information about the mechanisms by which healthy and unhealthy systems operate, the differences between healthy and diseased joints will be better understood. This understanding will, in turn, aid researchers in learning more about the specific mechanisms and causes of diseases like osteoarthritis.

REFERENCES

1. Furey, M. J., “Biotribology: Cartilage Lubrication and Wear,” 6th International Congress on Tribology, EUROTRIB ’93, Budapest, Hungary, Aug. 30-Sept 2, 1993.

2. Furey, M. J., “Biotribology: Possible Connections Between Tribology and Osteoarthritis,” Proceedings, 4th International Tribology Conference (AUSTRIB ’94), Dec. 5-8, 1994, Perth, Western Australia, v. 1, pp. 363-368.

3. Furey, M. J., Schroeder, M. O., Hughes, H. L., Owellen, M. C., Berrien, L. J., Veit, H., Gregory, E. M., and Kornegay, E. T., “Biotribology, Synovial Joint Lubrication and Osteoarthritis,” paper accepted for World Tribology Congress, London, 8-12 Sept. 1997.

4. Furey, M. J., Schroeder, M. O., Hughes, H. L., Owellen, M. C., Berrien, L. J., Veit, H., Gregory, E. M., and Kornegay, E. T., “Observations of Subsurface Damage and Cartilage Degradation in ‘in vitro’ Tribological Tests Using Bovine Articular Cartilage,” 21st Symposium of the European Society for Osteoarthrology, Gent, Belgium, Sept. 25-28, 1996, published in *Clinical Rheumatology*, Sept. 1996, v.15, Paper p. 3.2.

5. Furey, M. J., “The Influence of Synovial Fluid Constituents on Cartilage Wear: A Scanning Electron Microscope Study,” Conf. On Joint Destruction, XVIth Symposium of the European Society of Osteoarthrology, Sochi, U.S.S.R., Sept. 28-Oct. 2, 1987.

6. Setton, L. A., Mow, V. C., Muller, F. J., Pita, J. C., and Howell, D. S., “Altered Structure-Function Relationships for Articular Cartilage in Human Osteoarthritis and an Experimental Canine Model,” pp. 27-48, *Joint Destruction in Arthritis and Osteoarthritis*, 1993 by Birkhauser Verlag Basel.

7. Martin, D. F., “Pathomechanics of Knee Osteoarthritis,” *Medicine and Science in Sports and Exercise*, v.26, n.12, pp. 1429-1434, 1994.

8. Marcinko, D. E. and Dollard, M. D., “Physical and Mechanical Properties of Joints (The Pathomechanics of Articular Cartilage Degeneration,” *Journal of Foot Surgery*, v.25, n.1, 1986.

9. Minns, R. J. and Steven, F. S., “The Collagen Fibril Organization in Human Articular Cartilage,” *Journal of Anatomy*, v.123, n.2, pp. 437-457, 1977.

10. Hamerman, D., “Aging and Osteoarthritis: Basic Mechanisms,” *Journal of the American Geriatrics Society*, v. 41, pp. 760-770, 1993.

11. Stachowiak, G. W., Batchelor, A. W., and Griffiths, L. J., "Friction and Wear Changes in Synovial Joints," *Wear*, v.171, pp.135-142, 1994.

12. McCutchen, C. W., "Cartilage is Poroelastic, Not Viscoelastic (Including an Exact Theorem About Strain Energy and Viscous Loss, and an Order of Magnitude Relation for Equilibration Time," *Journal of Biomechanics*, v.15, n.4, pp.325-327, 1982.

13. Swann, D. A,, "Biochemistry of the Vitreous," *Bulletin of the Soc. Belge Ophtal.*, v.223-I, pp. 59-72, 1987.

14. Ghosh, P., Read, R., Armstrong, S., Wilson, D., Marshall, R., and McNair, P., "The Effects of Intraarticular Administration of Hyaluronan in a Model of Early Osteoarthritis in Sheep I. Gait Analysis and Radiological and Morphological Studies," *Seminars in Arthritis and Rheumatism*, v.22, n.6, Suppl. 1 (June), pp. 18-30, 1993.

15. Keller, W. G., Aron, D. N., Rowland, G. N., Odend'hal, S., and Brown, J., "The Effect of Trans-Stifle External Skeletal Fixation and Hyaluronic Acid Therapy on Articular Cartilage in the Dog," *Veterinary Surgery*, v.23, pp. 119-128, 1994.

16. Furey, M. J., "Joint Lubrication," Chapter 23, pp. 333-351, *Biomedical Engineering Handbook*, 1995 by CRC Press, Inc.

17. Yao, J. Q. and Unsworth, A., "Asperity Lubrication in Human Joints," *Proceedings of the Institution of Mechanical Engineers*, v.207, pp. 245-254, 1993.

18. Hlavacek, M., "The Role of Synovial Fluid Filtration by Cartilage in Lubrication of Synovial Joints – IV. Squeeze-Film Lubrication: The Central Film Thickness for Normal and Inflammatory Synovial Fluids for Axial Symmetry Under High Loading Conditions," *Journal of Biomechanics*, v.28, n.10, pp. 1199-1205, 1995.

19. Mow, V. C., Ateshian, G. A., and Spilker, R. L., "Biomechanics of Diarthroidal Joints: A Review of Twenty Years of Progress," *Transactions of the ASME*, v. 115, pp. 460-467, 1993.

20. Unsworth, A., "Tribology of Human and Artificial Joints," *Proceedings of the Institution of Mechanical Engineers*, v.205, pp. 163-172, 1991.

21. Bergman and Loxley, *Anal. Chem.* 35: 1961 – 1965, 1963.

22. Lipshitz, H. and Glimcher, M. J., "'In Vitro' Studies of Wear of Articular Cartilage, II. Characteristics of the Wear of Articular Cartilage When Worn Against Stainless Steel Plates Having Characterized Surfaces," *Wear*, v.52, pp. 297-337, 1979.

23. Schroeder, M. O., "Biotribology: Articular Cartilage Friction, Wear, and Lubrication," M.S. thesis, Mechanical Engineering, Virginia Polytechnic Institute and

State University, Blacksburg, VA, July, 1995.

24. Clarke, I. C., "In Vivo and In Vitro Comparative Studies of Animal Articular Surfaces," *Annals of Biomedical Engineering*, v.3, pp. 100-110, 1975.

25. Clark, J. M., "Variation of Collagen Fiber Alignment in a Joint Surface: A Scanning Electron Microscope Study of the Tibial Plateau in Dog, Rabbit, and Man," *Journal of Orthopaedic Research*, v.9, pp.246-257, 1991.

26. Chai Ben-fu and Tang Xue-ming, "Ultrastructural Study of Hip Joint Osteoarthritis," *Chinese Medical Journal*, v.103, n.4, pp. 290-294, 1990.

27. Pellegrini, V. D., Smith, R. L., and Ku, C. W., "Pathobiology of Articular Cartilage in Trapeziometacarpal Osteoarthritis. II. Surface Ultrastructure by Scanning Electron Microscopy," *Journal of Hand Surgery*, v.19A, pp. 79-85, 1994.

28. Howell, D. S. and Altman, R. D., "Cartilage Repair and Conservation in Osteoarthritis: A Brief Review of Some Experimental Approaches to Chondroprotection," *Osteoarthritis*, v.19, n.3, pp. 713-724, August, 1993.

29. Sokoloff, L., "Osteoarthritis as a Remodeling Process," *Journal of Rheumatology*, v.14, Suppl. 14, pp. 7-10, 1987.

30. Brandt, K. D., "Compensation and Decompensation of Articular Cartilage in Osteoarthritis," Paper, Conference on Inflammation '93, Vienna, Austria, October 12th, 1993.

31. Burkhardt, B. M., "Development and Design of a Test Device for Cartilage Wear Studies," M.S. thesis, Mechanical Engineering, Virginia Polytechnic Institute and State University, Blacksburg, VA, December, 1988.

32. Saikko, V., "Wear and Friction Properties of Prosthetic Joint Materials Evaluated on a Reciprocating Pin-On-Flat Apparatus," *Wear*, v.166 (1993), pp. 169-178.

33. Brittberg, M., "Treatment of Deep Cartilage Defects in the Knee with Autologous Chondrocyte Transplantation," *The New England Journal of Medicine*, v.331, n.14, Oct. 6, 1994, pp. 889-895.