TRIBOLOGY SERIES, 3

TRIBOLOGY OF NATURAL AND ARTIFICIAL JOINTS

一九八三年十二月五日

TRIBOLOGY SERIES, 3

TRIBOLOGY OF NATURAL AND ARTIFICIAL JOINTS

JOHN H. DUMBLETON

Director, New Product Technology (Europe), Howmedica, Limerick, Ireland

ELSEVIER SCIENTIFIC PUBLISHING COMPANY

AMSTERDAM — OXFORD — NEW YORK 1981

ELSEVIER SCIENTIFIC PUBLISHING COMPANY
335 Jan van Galenstraat
P.O. Box 211, 1000 AE Amsterdam, The Netherlands

Distributors for the United States and Canada:

ELSEVIER/NORTH-HOLLAND INC.
52, Vanderbilt Avenue
New York, N.Y. 10017

Library of Congress Cataloging in Publication Data

Dumbleton, John H
Tribology of natural and artificial joints.

(Tribology series ; v. 3)
Bibliography: p.
Includes index.
1. Artificial joints--Materials. 2. Joints.
3. Tribology. I. Title. II. Series.
RD686.D85 681'.761 80-18875
ISBN 0-444-41898-9

ISBN: 0-444-41898-9 (Vol. 3)
ISBN: 0-444-41677-3 (Series)

Printed in The Netherlands

Contributors

Chapter 2 Professor V. Wright, Department of Rheumatology, University of Leeds, U.K.

Chapter 3 Professor G.R. Higginson and Dr. T. Unsworth, Department of Engineering Science, University of Durham, U.K.

Chapter 10 Professor H.G. Willert and Dr. G. Buchhorn, Orthopaedic Clinic, Göttingen University, West Germany.

and

Dr. M. Semlitsch, Department of Research and Development, Sulzer Bros. Ltd., Wintertur, Switzerland.

Acknowledgement

I would like to thank several people associated with this work. The illustrations were drawn by Leo Murphy and Gerard Slattery and the typing done by Geraldine Considine.

PREFACE

Tribology is the science dealing with the interaction of surfaces in tangential motion. Hence, tribology includes the nature of surfaces, from both a chemical and physical point of view, including topography, the interaction of surfaces under load and the changes in the interaction when tangential motion is introduced. Macroscopically, the interactions are manifested in the phenomena of friction and wear. Modification of the interaction through the interposition of liquid, gaseous or solid films is known as the lubrication process. Hence, from a macroscopic point of view tribology includes lubrication, friction and wear.

Tribology as an entity has only recently grown out of the many different disciplines involved in the study of friction, wear and lubrication. Since earliest times, there have been efforts to reduce the friction necessary for motion and this resulted in the construction of bearings. However, many millions of years before man invented bearings for machines, nature had used bearings to enable articulation to occur between the bones of the skeleton; such articulation is necessary for movement of the skeleton as a whole and for relative motion between skeletal segments required for many activities.

Human joints are one particular example of natural joints and show low wear and exceedingly low friction through efficient lubrication. Disease or accident can impair the function at a joint and this can lead to the necessity for joint replacement. However, it is only in the last twenty years that successful replacement of joints has been carried out and this is one of the triumphs of modern orthopaedics.

Naturally, the tribology of both human joints and prosthetic joints is therefore of interest. However, the interdisciplinary nature of this study must be extended even when compared to the interdisciplinary nature of tribology. This is because natural and prosthetic joints must operate in a body environment. For example, a prosthetic joint must not only give low friction and low wear, but must also be accepted locally by the tissues and produce no long-term systemic response.

Early joint replacements produced many examples of failures due to wear and, in the early stages, it was thought that wear would be the overall determining factor in the performance of an artificial joint. Appropriate materials' selection, however, removed wear as the prime cause of failure, and present day joints, especially at the hip, do not show short-term failure due to wear. However, it is still quite possible that wear is a long-term factor in determining the lifetime of a prosthesis. There are indications that the build-up of wear products in the body can, at some stage, produce an undesirable effect which may necessitate the removal of the device. For newer prostheses, intended to replace joints other than the hip, wear may be a problem. The experience with these joints is generally too short to say, one way or the other, whether this is the case. At the knee, for example, problems due to abrasion of components, have been widely reported. However, wear, per se, was not the prime reason for removal of the device.

Thus, the state of knowledge as regards wear and joint replacement is that wear is not the prime cause of short-term failure but may well be the long-term limiting factor. It is certainly essential to carry out wear testing whenever there is a change in materials or in processing, to ensure that no untoward effects occur. Furthermore, wear testing must be done on presently used materials to determine whether there is any long-term possibility of failure.

In writing this book, the aim was to summarise the state-of-the-art as regards wear and joint replacement. Hence, the first task is to give a survey of the causes of failure of prostheses. In this way, the importance and standing of wear among the many other causes of failure, becomes evident. Friction, lubrication and wear in natural joints is also considered, since this provides a baseline against which to judge the performance of artificial joints. A history of artificial joints is not given although the evolution of such joints is of interest when one considers the present-day state of joint replacement. Reference to early attempts at joint replacement are widely scattered but the evolution of joint prosthesis design from about 1960 can be gathered from the orthopaedic literature. Wear testing, both in the laboratory on wear machines and on joint simulators, is extensively described, as this is the main way in which new materials are evaluated before use in the body. The role of statistical analysis of wear experiments has been emphasised as the tendency in wear evaluations of materials for joint replacement has been to base conclusions on too few wear measurements. Statistical significance is rarely evaluated. A discussion on in vivo methods of wear measurement and the role of wear debris in prosthesis acceptability is also given, as is a description of the examination of removed components. Lastly, there is a discussion of the steps required before the introduction of a new material for joint prosthesis use.

Many papers have been published in the area of wear of prostheses and prosthetic materials. It is not the aim of this survey to report all of these publications in detail, but rather to give an over-view of the whole subject, along with some conclusions. Sufficient references are given for the interested reader to go further into the literature, so that personal conclusions may be drawn. It is fair to say that the literature on wear of joint materials is conflicting and that there is a great deal of work necessary in order to rectify this situation. It is hoped that this book will in some small fashion assist this process.

It is recognised that many scientists and engineers intending to go into the field of joints and joint replacement are hindered by the fact that much of the terminology is of a medical nature. There are, however, several excellent books which will help the researcher to become acquainted with the basic terminology and methods, and a list of these is given. It is highly recommended that workers in the fields of materials and engineering make contact with an orthopaedic surgeon for discussions before embarking on an ambitious course of friction and wear testing. This interaction is far more fruitful if the worker has some knowledge of the medical problems and can converse using medical terminology.

REFERENCES

1 W.F. White, "Language of the Health Sciences," John Wiley & Sons, New York, 1977.
2 G.L. Smith and P.E. Davis, "Medical Terminology: A Programmed Text," John Wiley & Sons, New York, 1976.
3 A. Osol (Ed.), "Blakiston's Pocket Medical Directory," McGraw-Hill Book Company, New York, 1973.
4 R. Warwick and P.L. Williams (Eds.), "Gray's Anatomy" Longman Ltd., Edinburgh, 1973.
5 C.T. Blauvelt and F.R.T. Nelson, "A Manual of Orthopaedic Terminology," The C.V. Mosby Company, Saint Louis, 1977.
6 F.R. Schneider, "Handbook for the Orthopaedic Assistant," The C.V. Mosby Company, Saint Louis, 1972.
7 C.J.E. Anthony and N.J. Kolthoff, "Textbook of Anatomy and Physiology," The C.V. Mosby Company, Saint Louis, 1971.

CONTENTS

CHAPTER 1

A SURVEY OF JOINT REPLACEMENT FAILURES AND THE ROLE OF WEAR

I. INTRODUCTION

Human joints have evolved over several million years to provide the basis for movement by allowing bones to articulate on one another. Joints allow a combination of stability and mobility, the proportions of which vary, depending on the position and function of the joint. The hip joint, for example, provides stability due to the ball-and-socket configuration while, at the same time, allowing a moderate range of motion. On the other hand, the knee provides a wide range of motion at the expense of stability; the configurations of the distal femoral and proximal tibial surfaces does not give a contact with intrinsic stability and stabilisation is provided by an array of ligaments which span the joint acting as braces and by the joint capsule itself. Joints allow motions about one, two or three axes depending on the joint; usually one motion will predominate but to neglect the others is to forget the true function of the joint and may obscure the true pattern of motion.

Besides motion and stability, joints may be classed as weight bearing or non-weight bearing. The weight bearing joints are the joints at the hip, knee (tibio-femoral joint especially) and ankle. However, the joints of the upper extremities are certainly load bearing even if non-weight bearing and can be shown to be subject to quite high loads under certain conditions.

The tribological behaviour of human joints is superb. The lubrication regime results in the ability of the joint to operate under a wide range of conditions ranging from high loads at low speeds to low loads at higher speeds and with the ability to go from a rest position to sliding motion under the most severe conditions without damage to the joint. The excellence of the lubrication is reflected in the low friction coefficient which typically lies in the range 0.003-0.015. Wear in joints is minimal under normal circumstances and the cartilaginous surfaces last an entire lifetime of 70 years or more.

Joint function may, however, be compromised by trauma, disease or by abnormal usage. Accidents may damage the cartilage and since hyaline cartilage can only regenerate as fibrocartilage, a structure having poor wear resistance, irreparable damage to the joint function may ensue. Diseases such as arthritis may also result in degenerative changes and loss of joint function. The compromise of function at one joint may lead to abnormal loading at a neighbouring joint and eventually to deterioration of function at that joint also. In short, a combination of biological, chemical and mechanical changes results in loss of function, the ability of the joint to move freely, and in the development of pain. Pain may in fact be the dominating factor which determines the extent to which the joint will be used; lack of usage in itself will lead to degenerative joint changes whether this lack of use is due to pain avoidance or actual mechanical damage.

Whatever the causes, and in many instances the causes are not well understood, the result is pain and loss of mobility leading to perhaps permanent deformity around the affected joint. Many different treatments are available to be employed at various stages in joint deterioration. No one treatment is wholly satisfactory.

Treatments range from the relief of pain using analgesics, through the suppression of inflammatory responses using steriods, both systemically and by local injection into the joint, to actual intervention or joint arthroplasty. Arthrodesis, essentially the elimination of the joint, carries a high success rate at the metacarpophalangeal joint, knee and ankle; there is relief of pain at the sacrifice of motion since the joint is stiff. Synovectomy has good results in rheumatoid arthritis if carried out at an early stage in the disease. Osteotomy provides relief of pain in osteoarthritis by cutting across the bone distal to the arthritic joint and allowing it to reunite in a slightly different position; the prognosis for movement range is not as predictable as the relief of pain. Arthroplasty implies the creation of a new joint and in present usage means the employment of an implant or joint prosthesis so that one or both of the joint surfaces is replaced. Usually a total joint prosthesis is employed and the earliest use was at the hip where dramatic reduction in pain and the speedy restoration of mobility was achieved. Since the operation was first widely used some 20 years ago, over one million total hip prostheses have been implanted. Total joint prostheses have also been used at the knee, ankle, shoulder, elbow, wrist, thumb and finger joints. This usage is of more recent origin and the results are not as outstanding as at the hip. Due to the success of total joint replacement the pendulum has swung away from the alternative treatments; research into the causes, treatment and prevention of arthritis and related diseases is still going on but the complexities of the origins of arthritic diseases do not hold hope for an early solution although pharmaceutical work has resulted in the appearance of more effective pain relief and anti-inflammatory agents to ameliorate some of the effects of disease.

II. JOINT PROSTHESES

The object of total joint replacement is the relief of pain and the restoration of joint mobility. The configuration of the device depends upon the joint to be replaced and the function to be reproduced. Typically one component is of plastic, usually ultra high molecular weight polyethylene (UHMWPE), while the other is of a metallic alloy such as cast cobalt-chromium-molybdenum alloy or 316L stainless steel; other alloys such as MP35N, titanium and titanium alloy (Ti-4Al-4V) have been used. This metal/plastic materials combination has developed from the all-metal joint prostheses first employed.

Besides the relief of pain and the restoration of mobility, a joint prosthesis must have low friction and low wear. There are, also, other criteria to be satisfied such as resistance to mechanical failure and resistance to loosening. The materials and implant must not cause tissue irritation or rejection. And the performance of the implant is important not only in the short term but also over the many years that the device is expected to function.

The number of total joint replacements carried out is extremely large and so it is imperative that joint replacement prostheses be as reliable as possible otherwise large numbers of patients will be adversely affected; replacement of a joint prosthesis is usually much more difficult than the original operation to replace the natural joint and typically takes twice the length of time. Statistics on joint replacement are not readily available. However, a recent study in the United States gives some insight into the numbers involved (ref. 1). Table 1 gives the estimated number of total joint replacements at the hip, knee and other locations carried out in the years 1972 to 1976.

TABLE 1
Estimated number of total joint replacements in the United States in the years 1972-1976.

Joint	1976	1975	1974	1973	1972
Hip	80,000	80,000	77,500	75,000	55,000
Knee	40,000	32,500	20,000	10,000	4,000
Other	10,000	8,500	6,500	3,800	2,500

The number of total hip implantations has leveled off at 80,000 per year while the number of knee prostheses implanted is still increasing and in 1976 was 40,000. The number of other joints implanted (ankle, elbow, shoulder and so on) is far lower but is increasing (note that the replacement of joints in the hand can easily lead to eight prostheses being used for one hand of one patient since all the joints are more or less affected). It is estimated that, if very reliable joint prostheses were available, the number of total joint replacements would be 89,600 at the hip, 52,800 at the knee and 33,900 at other locations based on the 1976 figures. These statistics show the growth potential for joint replacement at the other joints but even so the number of joint replacements at any one joint position would never approach the numbers used for the hip and knee. This is partly due to the lower involvement of the other joints in disease and to the availability of effective, alternative treatments to joint replacement. It must also be remembered that the ratio between hip and knee replacements is different in the United States than elsewhere. In Europe, rather fewer knee prostheses are implanted compared to total hip prostheses. A ratio of three hips to one knee implantation is generally accepted. However, whatever the precise numbers are, it is clear that a large number of total joint implantations are carried out each year throughout the world with most implantations being done at the hip with the knee second highest in a ratio 2:1 or 3:1. Replacements at the other joints are being carried out but the numbers are uncertain. A conference on joint replacement in the upper limb reported clinical experiences in the "tens of patients" (ref. 2), indicating the short time of experience and possibly the smaller patient population. The subject is further complicated by the large number of designs available for prostheses to replace a given joint. For example, it is estimated that over 400 designs of knee prosthesis are, or have been, available. Although, of course, the number of original design concepts is limited and so only a few different types of knee joint are really available, nonetheless, the task of gathering implantation statistics on all these available designs is a daunting prospect only somewhat alleviated by the knowledge that by far the largest part of the market will be taken by less than ten of the available designs. A similar situation holds for joint prostheses for other joint locations although the numbers of alternative designs are not as large as for the knee. Incidentally, the existence of so many designs indicates that no one design is satisfactory in all respects and this is understandable bearing in mind the wide range of clinical conditions and surgeon preferences encountered.

III. JOINT PROSTHESIS PERFORMANCE

There are different ways in which the performance of a joint prosthesis may be judged. From the point of view of the patient, relief of pain is of paramount importance with restoration of movement initially a secondary consideration but a requirement which must be met especially since the removal of pain will encourage the patient to undertake activities hitherto abandoned. Obviously of importance is the continued functioning of the artificial joint. The surgeon is naturally also interested in the performance of the prosthesis but the point of view is somewhat different from that of the patient. The patient may be disappointed in the performance of a particular prosthesis whereas, the surgeon, recognising the technical limitations and perhaps in cases of severe degenerative disease knowing the limited objectives, is quite satisfied with the result. On the other hand, the