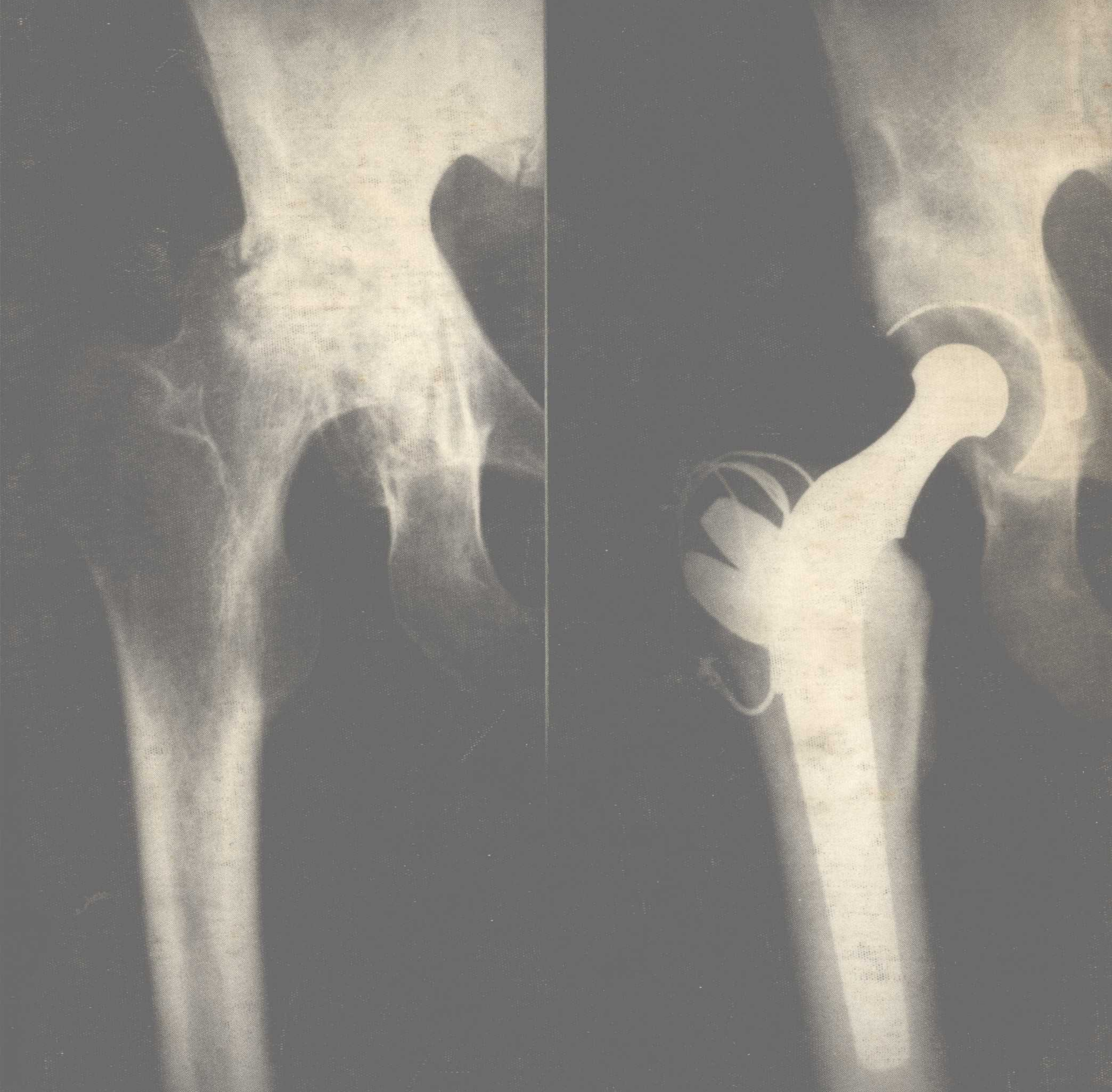
John Charnley

Low Friction Arthroplasty of the Hip

Theory and Practice



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Theory and Practice

With 440 Figures, 205 in Colour

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To my wife Jill

and to the

Members of the Low Friction Society

all of whom have been personally associated with some part of this work during their period of Residency at Wrightington.

Preface

The theme of this work is the application of the engineering theory of frictional torque to total hip replacement.

The author adhered tenaciously to this theory, involving the use of a small-diameter femoral head, throughout the epoch when the large-diameter, metal-to-metal design dominated the field. During that considerable period general satisfaction with the early results rendered criticisms of the large-diameter head unwelcome. There was a formidable array of counter-criticism: the small head would pierce a film of synovial fluid; the small head would wear the socket too rapidly; the small head would always have a high risk of dislocation; detachment of the trochanter, to achieve precise orientation for the small head, was unacceptable.

But all these objections have now been largely overcome. Lubrication of high molecular weight polyethylene (HMWP) on metal is now accepted as being mainly by the boundary regime with thick fluid films playing no part. We now know that HMWP can indeed tolerate the very high stresses imposed by the small head and in tribological theory there may even be some advantage in high stress. Dislocation is now known not to be an automatic sequel to the small head.

There remains only the trochanter. Dissatisfaction with reattachment has been the cause of the many years of delay in writing this book. A method which satisfies the author has at last been found. This is important because it is now possible to view Chap. 21 (Biomechanics) for its practical application in attempting to reduce stress in total hips. It is quite possible that from this quarter will come the next phase of development, which is to prolong the survival of total hips in young patients, and to eliminate fatigue fractures in heavy men, by reducing stress, and doing so by engineering design.

Wrightington, September 1978

John Charnley

Acknowledgements

It is a pleasure to acknowledge help from colleagues who have not been named in the text; and especially pupils whose papers, published from Wrightington, have had to be excluded because not cogent to this work. There are a number of such papers to be found in *Clinical Orthopaedics and Related Research*, and my practice has been to add my name as the last of the authors for the purpose of aiding retrieval. I owe a debt of gratitude to Dr. Marshall Urist, Editor-in-Chief of *C.O.R.R.*, who has done so much to make that journal a true scientific archive; the publication of our papers from Wrightington in *C.O.R.R.* has been a vital encouragement to us over the years.

I am indebted to Mr. K.L. Barnes, F.R.C.S., Surgeon Superintendent of Wrightington Hospital, for casting a shrewd eye over the manuscript. Also, if in the course of time hydroxychloroquine should justify our hopes as a prophylactic agent against fatal pulmonary embolism, it is interesting to put on record that this potential in relation to total hip replacement was first spotted by Barnes, by clinical judgement, on a remarkably small series of patients and prompted the full-scale trials reported here. In a separate trial group, at King Edward VII Hospital, Midhurst, I am specially grateful to Dr. P.J. Doyle for his careful recording of data in relation to the prophylaxis of pulmonary embolism.

Mrs. A. Proffitt, Nursing Officer, Wrightington Hospital, and Sister Pring of King Edward VII Hospital, Midhurst, have kindly prepared for me the lists of instruments used in Chap. 14. I am greatly indebted to Mrs. Rosamunde Cock, M.C.S.P., Superintendent Physiotherapist, King Edward VII Hospital, for her most important help and advice in writing the chapter on post-operative rehabilitation.

Dr. Heinz Götze has taken the responsible step (for a publishing house so dedicated to perfection as Springer-Verlag) of permitting my own drawings to be used to illustrate the steps of the operation, (professionally 'touched up' where necessary) in order not to lose those surgeon's details which professional artists sometimes can miss. For this, and for the beautiful art work of his staff, I am very grateful.

I am also indebted to: Mr. Peter Kilshaw of the Department of Medical Illustration, Ribbleton Hospital; Mrs. E.M. Stringfellow for histological preparations; Mrs. S. Houghton and Mrs. D. Moss for work on many aspects of the clerical records; Mr. Ken Marsh and Mr. Frank Brown for the development of instruments and other researches in the Bioengineering Laboratory; Mr. Frank Dandy, Senior Laboratory Technician, for the immense amount of bacteriological work he carried out over a period of 10 years in the development of clean air operating; and above all Miss Margaret Green who has cheerfully undertaken the vast amount of typing and re-typing which was involved, at the same time pursuing her onerous clerical duties as my personal secretary.

In Britain it is not considered good form to acknowledge commercial undertakings in too glowing terms, even though the work would not have been possible without their collaboration; therefore I must satisfy myself merely by mentioning them by name: Messrs. Chas. F. Thackray Ltd. of Leeds; Codmann & Shurtleff Inc. of Randolph, Massachusetts, U.S.A.; Howorth Air Engineering of Farnworth; C.M.W. Laboratories of Blackpool.

Contents

Introduction

Many varieties of total hip replacement can give good results in the hands of surgeons who do not specialise in this field of surgery; but papers on complications, delivered to surgical societies even currently in 1978, make one wonder how consistently good are the good results in small groups of experience. The failure of most surgeons to stick to one type of operation, or to one surgical exposure, also implies underlying discontent.

The challenge comes when patients between 45 and 50 years of age are to be considered for the operation, because then every advance in technical detail must be used if there is to be a reasonable chance of 20 and more years of trouble-free activity. It is not in a young patient's interest for a surgeon to count on a successful 'revision' should mechanical failure ensue earlier than was expected. The best time to use acrylic cement is the first time; this is when the gritty surface of fresh cancellous bone can best accept cement. For this reason the author restricts this book to the primary intervention, in order to emphasize that only by performing easy operations very well shall we avoid an appalling accumulation of untreatable failures in the next two decades.

The longest duration of follow-up after this operation, in patients still alive and still successful, is 15 years. It is therefore a serious responsibility to extrapolate to another 50% for follow-up, and for age at operation to patients 10 years younger from the start. Therefore for vigorous patients of 45 years of age and over, it is emphasized that total hip replacement can be justified only when all the technical advances evolved during the last 5 years are adopted, some of which are described for the first time in this text.

Strictly speaking the procedure described in this book should not be regarded as a surgical operation at all. It should be seen as an exercise in practical mechanical engineering. Seen in this way the rate of mechanical failure ought to be as low as after any well-tried engineering routine. Practical engineering fortunately is easier than surgery, because in the traditional attitude to surgery the quality of a surgeon is revealed in the way he adapts himself to unforeseen difficulties in the course of an operation. But in practical engineering every job is first of all reduced to the same set of elements, by being 'taken to pieces', and the new components are then inserted without impediment and every time in exactly the same way. Therefore there should be no unforeseen difficulties. The fact that reassembly might take as long as the rest of the procedure is no matter if by this means we might some day aspire in hip surgery to a mechanical success rate of 99%.

Undoubtedly some who glance through these pages will be dismayed by what might appear to be the complexity of the operation, to judge from the number of steps needed to describe it and by the considerable armamentarium. But when an operative technique can be broken down into precise steps, each of which can be illustrated and facilitated by a special tool, the only difficulty facing the surgeon is to remember the sequence of the many easy steps. Keeping familiar with the sequence of the steps is the main problem, rather than their mere performance, and this is enormously helped by being able to perform three or four of these operations per week. This is the aspect of specialization which 'pays off' in the end-product.

Surgeons who are diffident about embarking on new and apparently complicated procedures can take heart in the knowledge that mechanical aptitude is a cerebral process. Aptitude which resides only in the fingers is a dangerous talent, though some hours of instruction at a fitter's bench can work wonders in boosting any postgraduate's self-confidence. This is an important aspect of the post-graduate training programme at Wrightington.

Finally the author thinks it important that he should state his belief that **in the case of osteoarthrosis** some type of artifical replacement of the hip is here to stay and that it could make a surgical specialty in itself. This might not apply to total replacement of the knee, and research into the pathology of rheumatoid arthritis may some day make joint replacement in that condition unnecessary. But in degenerative osteoarthrosis of the hip, total replacement must not be viewed as one of many passing phases in the evolution of surgery to be displaced in time by preventive measures. For the overwhelming majority of patients with osteoarthrosis of the hip, total replacement will always be the treatment of choice. It is most unlikely than anything will ever compete with it for speed of recovery and quality of the early result. Osteoarthrosis of the hip probably has its origin in a racial gene, as indicated in the remarkable differences in distribution throughout the world. There cannot therefore exist any prophylactic treatment for that strange, idiopathic condition of the hip correctly called **osteoarthrosis**.

Chapter 1

Low Friction Principle

The term low friction arthroplasty (or more correctly low frictional torque arthroplasty) was coined to emphasize the small diameter of the prosthetic head (22 mm) essential to the underlying theory. Low friction arthroplasty (LFA) is characterised even more particularly by the combination of a small prosthetic femoral head with a socket of maximum external diameter. Consequently the socket has maximum wall thickness.

The theory of low frictional torque arthroplasty is summarized in Fig. 1.1 reproduced from the Lancet 1961 under the title 'Arthroplasty of the hip—a new operation'. [1]

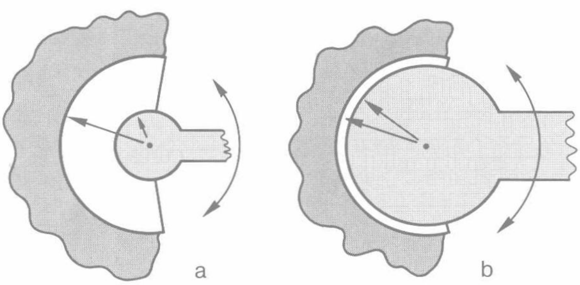

Fig. 1.1 a, b. Original illustration of the low friction torque principle applied to hip arthroplasty. **a** Thick socket-small femoral head: difference in radii favours socket remaining stationary; **b** not so with only slight difference in radii

Lubrication of Animal and Artificial Joints

The author's approach to total hip replacement from the point of view of lubrication started as a result of a chance encounter with a patient who had a Judet femoral head replacement for osteoarthrosis 1 or 2 years previously and whose hip in certain positions emitted an audible squeak. Enquiries established that colleagues had also had similar experiences. In the X-rays the stem of the prosthesis was seen to be lying in a grossly enlarged track in the femur, and this suggested that under load high friction between the head and the arthrosic socket was resisting movement and that the movement was now taking place between the loose stem and the femur.

This incident served to emphasize the ignorance of basic principles of lubrication, as applied to artificial animal joints, which existed at that time. The mere fact that a polished sphere of a plastics material, or of metal, felt 'slippery' when wetted with tissue fluids and handled in surgical rubber gloves, was no proof that this slippery behaviour would persist in an arthrosic acetabulum under heavy loads.

Lubrication of Animal Joints

At that time the universally accepted theory of lubrication in animal joints gave a dominant role to the action of synovial fluid. Maconnaill (1950) [2] was impressed by the incongruity existing between joint surfaces in the range of movement used when moving under load, compared with what he called the 'close-packed' situation adopted by some joints, as part of a muscle-sparing mechanism, when 'standing at ease'. Maconnaill saw in the incongruity of joint surfaces Nature adopting the principle of hydrodynamic lubrication, demonstrated par excellence in the Michel bearing, where convergent wedges of fluid generate pressure under the action of rotation and separate the surfaces moving under load.

Applied to animal joints however this concept was not convincing, because slow motion, and especially slow oscillating motion, is not ideally suited to the persistence of full-thickness fluid films between sliding surfaces.

Up to that time the only experimental work which had been published on the lubrication of animal joints was that of E. Shirley Jones (1936)[(3)], and of a number of experiments the one of greatest interest was that in which he made a freshly amputated human finger joint function as the pivot of a pendulum. This was an elegant experiment because it explored the resistance to movement of a loaded joint with the surfaces sliding at different speeds. This is because of the well-known fact of a pendulum that the time for each swing is the same whether the amplitude be large or small; therefore at the start of the experiment the speed of sliding will be high when the amplitude is great and will get progressively less as the amplitude decays. In his experiments with the amputated finger joint Jones found that when plotted against time the decrement of each swing behaved in an exponential fashion, which meant that frictional resistance was disproportionately high at high speeds of sliding. This was consistent with the viscous behaviour of a fluid and from this it was concluded that lubrication of the finger joint must incorporate a hydrodynamic mechanism (Fig. 1.2).

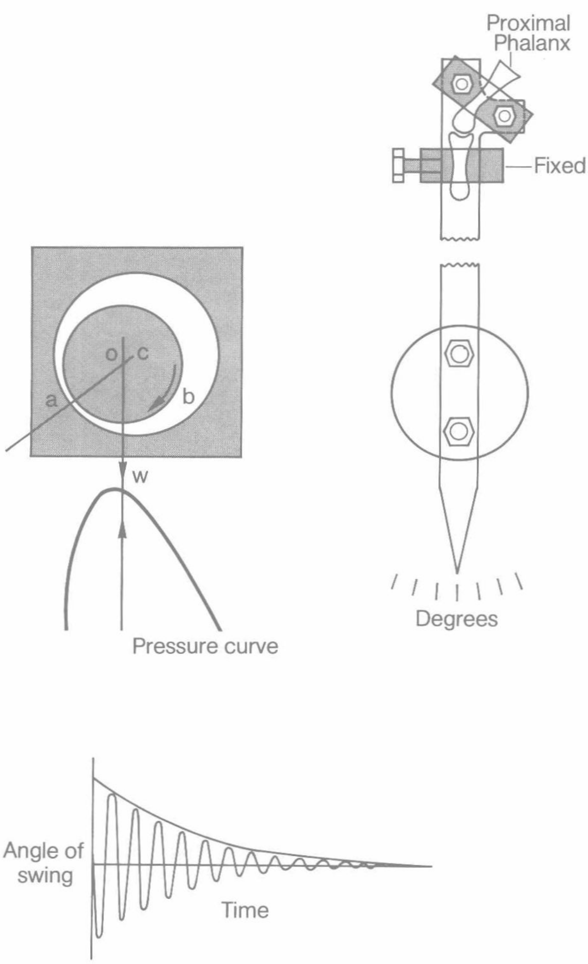

Fig. 1.2. Original experiment of E. Shirley Jones reproduced from his paper

The regime of lubrication which is the diametric opposite of hydrodynamic lubrication is known as 'boundary' lubrication. This mode of lubrication is equivalent to the sliding of dry surfaces which possess intrinsically slippery qualities; the extreme examples being graphite or molybdenum sulphide or polytetrafluorethylene. Also in this category is the lubricating action of substances which react chemically with the sliding surfaces and thereafter function as molecular films too thin to show viscosity in accordance with the laws of fluid mechanics. A good example of this is the lubricating action of fatty acids such as the oleic, stearic, palmitic acids, etc., which form soaps in combination with the metal surfaces of plain bearings. The intriguing feature of this mode of lubrication is that though extremely thin, as a result of being bound chemically to the sliding surfaces, the lubricating films are more resistant to rupture than thick films of grease or oil unable to make a chemical bond with the sliding surfaces. In these latter cases a film of oil or grease would be able to remain intact only as a result of the (relatively small) molecular forces acting between the molecules of the oil itself.

The boundary mode of lubrication seemed to the author ideally suited to the lubrication of slow-moving, heavily loaded animal joints and especially since these were exposed to oscillating motion and capable of remaining stationary under load for several seconds without exhibiting 'stiction' at the moment of resuming movement. It seemed possible that Jones had made an error in choosing a finger joint for the pivot of his pendulum because a finger joint is unstable in the absence of the collateral ligaments and to retain the ligaments would offer greater resistance at large amplitudes of swing than at small ones; this could explain an exponential pattern of decay of amplitude without postulating a viscous fluid mechanism.

The author repeated the pendulum experiment, this time choosing a human ankle joint (Fig. 1.3).

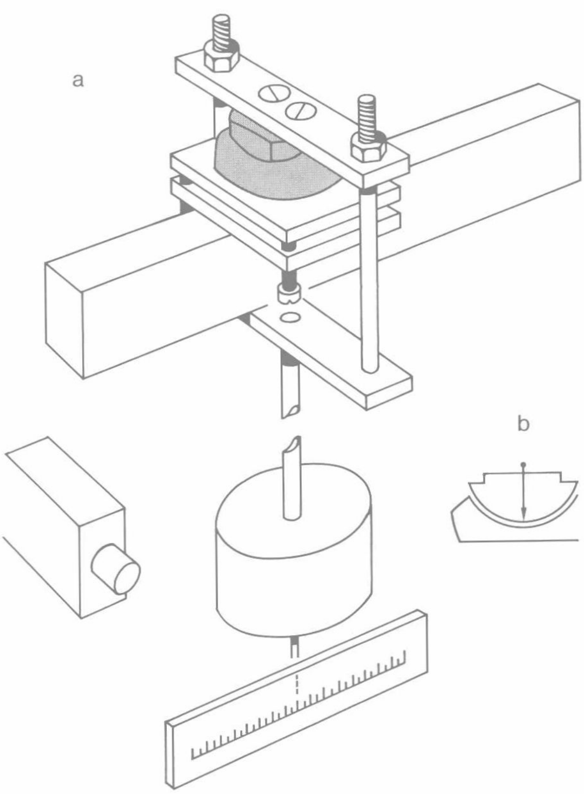

Fig. 1.3. Pendulum experiment using human ankle-joint

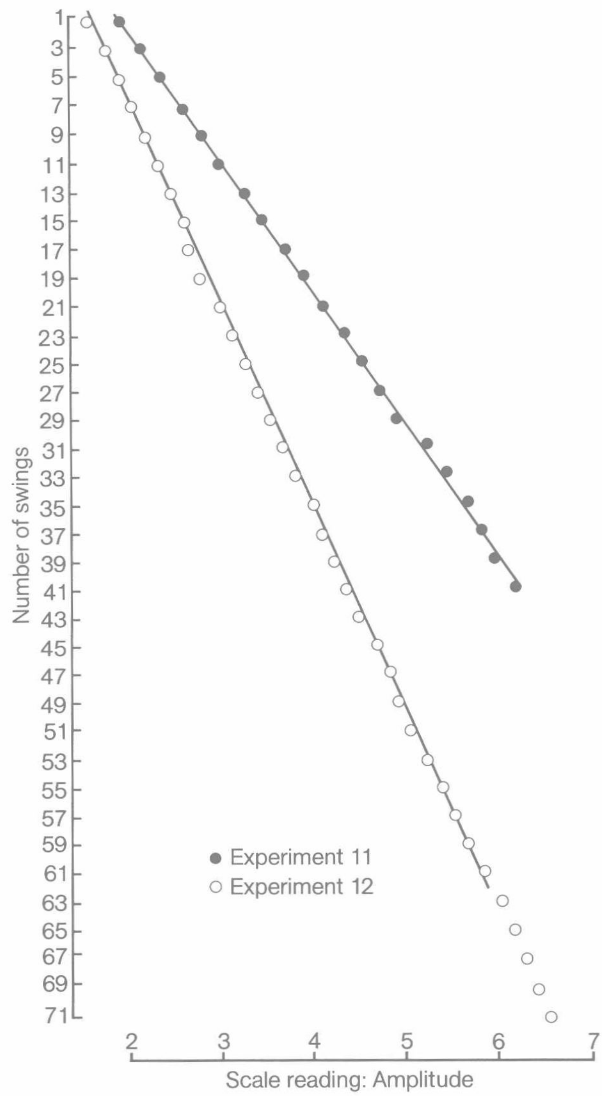

Fig. 1.4. Graphs of decay of amplitude with number of swings. Increase in number of swings when visible synovial fluid was not wiped away with dry cloth (Expt. 12 compared with Expt. 11) did not change straight line performance

Because of the deep curvature of the components of the ankle joint this biological pivot was self-locating in the absence of collateral ligaments. In these experiments the decay of amplitude followed a straight line (Fig. 1.4) indicating that the coefficient of friction in the joint remained the same despite changes in the rate of sliding. This is a recognised feature of boundary friction within certain fairly wide limits of speed. It was interesting also to note that the straight-line behaviour of the decrement of amplitude was not greatly changed whether the ankle joint was visibly wetted with synovial fluid or had been wiped clean of visible liquid with a dry cloth. This suggested that a smear of lubricant was as effective as a large volume, a state of affairs more in accordance with the theory of boundary lubrication than hydrodynamic lubrication.

Against the theory of boundary lubrication as the sole explanation of lubrication in animal joints is often advanced the fact that the coefficient of friction of an animal joint is so astonishingly low (in the region of 0.01 or even less) and in ordinary engineering practice most examples of boundary lubrication have coefficients of friction in the region of 0.10 or higher.

However, it is still possible that the last word has not yet been said on the ultimate nature of lubrication in animal joints and, as is commonly the case in matters of lubrication, a mixed regime of fluid film and boundary lubrication probably exists, with Nature having discovered a unique means of making a mixed regime.

Synovial Fluid as a Lubricant

In the designing of a total joint replacement the practical importance of the foregoing remarks is that when these experiments were extended to the substances likely to be used in the construction of artificial joints [before the introduction of high molecular weight polyethylene (HMWP)] it was found that synovial fluid was incapable of acting as a lubricant. Thus a chrome-cobalt surface sliding on chrome-cobalt; stainless steel sliding on bare bone; and Perspex (Lucite or polymethylmethacrylate) sliding on bare bone; when lubricated with bovine synovial fluid all presented coefficients of friction in the region of 0.5 and squeaked under load. On the other hand stainless steel sliding on normal articular cartilage was well lubricated with synovial fluid (coefficient of friction in region of 0.05) and this combination therefore was not greatly inferior to articular cartilage sliding on articular cartilage (Fig. 1.5).

These observations therefore seemed to indicate that synovial fluid was a specific lubricant for articular cartilage and for nothing else. The specificity of a lubricant for the material of a surface is characteristic of boundary lubrication because it involves that quality known as 'oiliness'. This does not apply in hydrodynamic lubrication where oiliness in a lubricant is unnecessary: water or air can be used to lubricate hydrodynamically, provided that the geometry of the rotating surfaces, the area of the surfaces, the load to be carried and the speed of rotation are all known.

From these considerations the author decided in 1958 that the only chance of success in lubricating an artificial animal joint would be by using surfaces which were intrinsically slippery on each other; in other words, self-lubricating irrespective of whether tissue fluid were present or not. This led to trials of polytetrafluorethylene (Teflon, PTFE), with spectacular early results. Unfortunately the poor wearing properties of pure PTFE, and the disastrous complications with PTFE 'filled' with material designed to enhance wear resistance, ended in PTFE being abandoned in 1961, after some 300 total hip operations had been performed with a number of different mechanical modifications. The PTFE era taught a number of very important lessons which might still have warnings for future development in this field and for this reason a brief review of selected experiences is cogent.

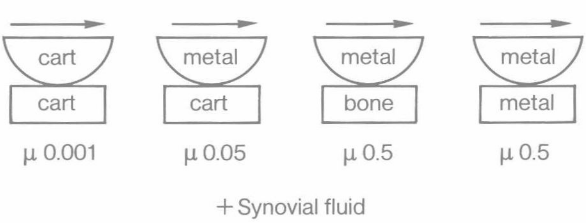

Fig. 1.5. Typical coefficients of friction with different pairs of substances in hip arthroplasty

a) Particle Size and Tissue Reaction

It is now well known that PTFE in the hip joint produced voluminous masses of amorphous caseous material. This presumably is the proteinaceous material resulting from vast numbers of dead foreign-body giant cells. Particle size might be very important in the production of granulomatous material because PTFE particles were very large (often 300 μm) and their large size could prevent transport away from the site of production. The high rate of production of PTFE particles (rapidity of wear) in addition to the large size of the particles, might have been responsible for defeating the available transport system for removing the particles and the caseous debris. Therefore slow production (high wear resistance) and small size of abraded particles might be important features in reducing local accumulations of caseous material even if the production of wear particles may never be avoided.

Therefore it would seem possible, if wear has to be accepted as inevitable, that the ideal implant will produce very small particles. The factors which control the size of abraded particles of HMWP as yet are unknown but the particles produced in the (LFA) hip in the author's experience seem to be smaller than those produced in knee arthroplasties. This might suggest that the high loading of a small-diameter ball can prevent 'third body' abrasion, perhaps by burnishing the particles into the surface, perhaps by the tendency of the small-diameter head to 'bore' into the plastic and remain close fitting, rather than combining elements of rolling and sliding encouraged by the large-diameter spherical surfaces of the knee.

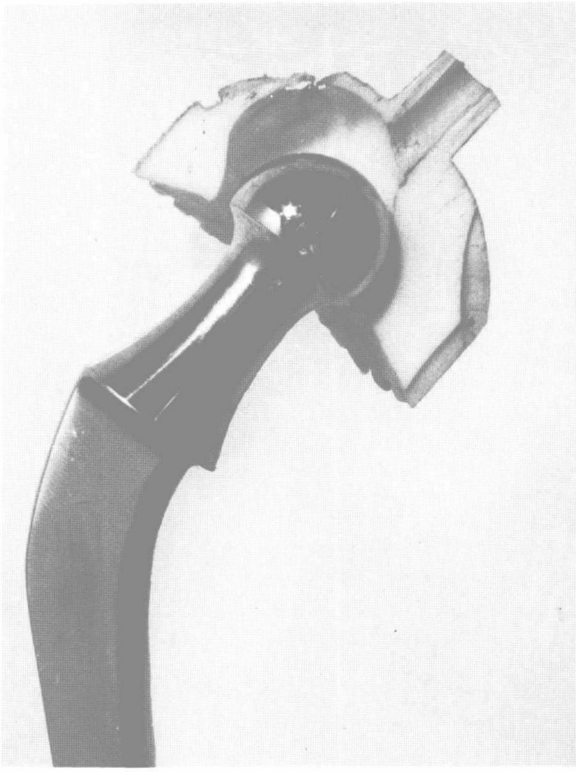

Fig. 1.6. Total wear-out of Teflon socket after 3 years. Note vertical direction of wear track

b) Direction of Socket Wear

The rapidity of wear of Teflon hip sockets enabled the direction of wear to be recognised in periods as short as 2 or 3 years (Fig. 1.6). When wear is very slight, as with HMWP, it is difficult to be sure of the precise direction of wear.

The frequency with which the direction of wear was vertically upwards, or even upwards and laterally, made Elson and Charnley (1968)[(4)] recommend that in designing total hip replacements we should not count on the joint force being advantageously inclined at 10° medially but we should assume that the joint force acts as though it were directed vertically. This emphasizes, among many other matters, the importance of designing the hip socket to be totally enclosed inside the acetabulum.

c) Fillers to Enhance Wear Resistance

PTFE filled with glass fibre, or with a synthetic proprietary substance (Fluorosint-Polypenco) showed enhanced wear resistance by a factor of 20 when lubricated with water in the laboratory. The surfaces of the plastics specimens also became highly polished in these laboratory experiments and the stainless steel counterface also remained in a high state of polish. In the human body however this type of filled PTFE behaved very badly. PTFE filled with glass fibre even after 1 year in the body developed a 'pasty' surface which could be scraped away with a blunt instrument. Fluorosint wore in the body just as rapidly as ordinary PTFE but the result was even worse, because the filler acted abrasively and lapped metal from the prosthetic head. The sockets retained a matt surface and never acquired the glazed surface that they did in the laboratory.

Ultra-High Molecular Weight Polyethylene

The introduction of HMWP by the author in 1962 as a material for socket surfaces in joint replacement necessitated a change of emphasis in lubrication theory as applied to artificial joints. The unique low coefficient of friction of PTFE could no longer be deployed and emphasis now had to be turned towards materials offering high resistance to wear and producing therefore a minimum of abraded detritus.

The coefficient of friction of HMWP is at least five times higher than that of PTFE, but its wear resistance in laboratory tests is 500–1000 times better. The very high wear resistance of HMWP now made acceptable the very high stresses on the plastics material produced by the small-diameter femoral head inseparable from concepts of low frictional torque. It thus became feasible to compensate for increased frictional resistance by designing for low frictional torque.

In this change of policy two unpredicted factors came to light which helped to offset the inferior coefficient of friction of HMWP compared with Teflon. In the first place HMWP is one of the plastics materials whose coefficient of friction becomes less under high stress; in the second place HMWP proved to be capable of a modest degree of boundary lubrication by synovial fluid. This latter property therefore made it an exception to the author's statement in the early stages of this work that there were no substances available for joint replacement which could avail themselves of synovial fluid as a lubricant.

Pendulum Comparator

A method of attempting to compare the frictional torque of different designs of total hip implant is the pendulum 'comparator' illustrated in Fig. 1.7. This device, developed by the author at Wrightington, is not intended to measure absolute values of friction but merely to make broad, even qualitative, comparisons of the frictional torque offered by different designs of total hip replacement when compared against a 22-mm-diameter stainless steel sphere in a socket of HMWP. Like all methods of measuring frictional resistance these tests are prone to erratic behaviour and it is impossible to make fine distinctions over the middle range of observed results; but for its main purpose, which is to reveal extremes of behaviour, it is valid.

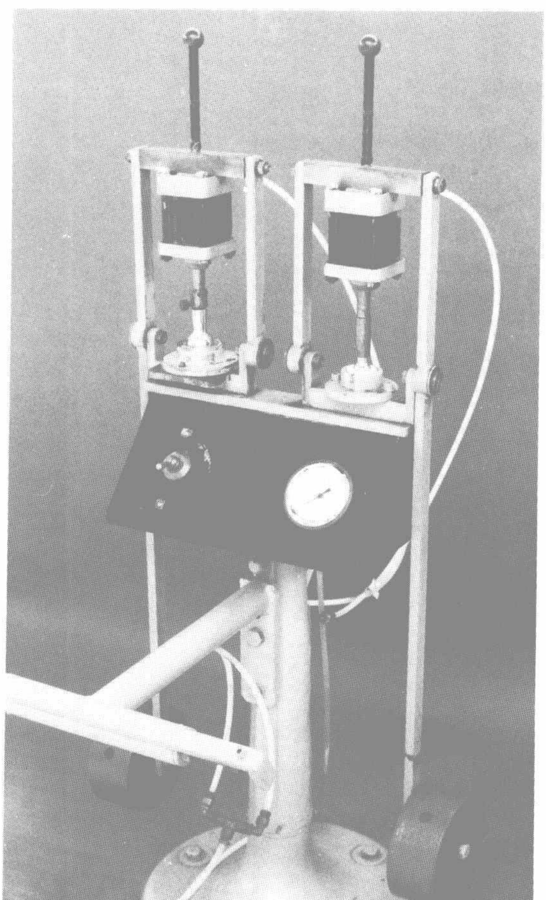

Fig. 1.7. Pendulum comparator

The device consists of two separate pendulum systems each with a heavy metal bob of identical weight and swinging on ball bearings. Each pendulum carries a cylinder and piston connected by a flexible tube to a compressed air source to deliver a force of about 200 lb (90 kg) at each piston rod. The femoral head component of the device to be tested must be cut from its stem and attached, by brazing, to a stub to fit the piston rod.

The sockets to be tested are mounted in metal holders using acrylic cement (Fig. 1.8). The point corresponding to the centre of the hemispherical cavity of the socket must be at a prescribed distance above the base plate on which the holder lies. This distance is the height of the horizontal axis passing through the ball bearings of the pendulum. The metal mounts taking the hip sockets locate on three pins on the base of the comparator.

The comparison is made by drawing both pendula to their maximum amplitude where they are held by a trigger. The bobs are released simultaneously without applying load to the hip implants to be compared. The number of swings is counted until the pendula start to be out of phase but of course are still swinging vigorously (this will usually be about 8–10 half-cycles). This demonstrates that in the unloaded state there is no gross difference between the two sides. The bobs are again brought back to the starting triggers and air pressure is applied to the two implants to be compared. The bobs are released and the number of half-cycles on each side are counted until each pendulum stops.

The tests are performed with bovine synovial fluid as a lubricant. It is important that the implants should be freshly washed in soapy water which is then eliminated by an adequate period under a running tap. Thereafter care should be taken not to get grease from the fingers on to the test surfaces.

The apparatus can be criticised as being unphysiological in that a constant load is maintained on the to and the fro half-cycles. It is not possible to design otherwise because slight errors of centring, inevitable when parts of the instrument deflect under the load, could produce serious errors if the load were applied repeatedly in one direction and removed in the other. By maintaining a constant load the errors caused by the load assisting the swing in one direction are neutralised by the load impeding the swing in the other direction.

Another criticism is that the state of any fluid film which might exist must be best at the start and that any contribution of fluid lubrication must decline throughout a test. Against this it is main-

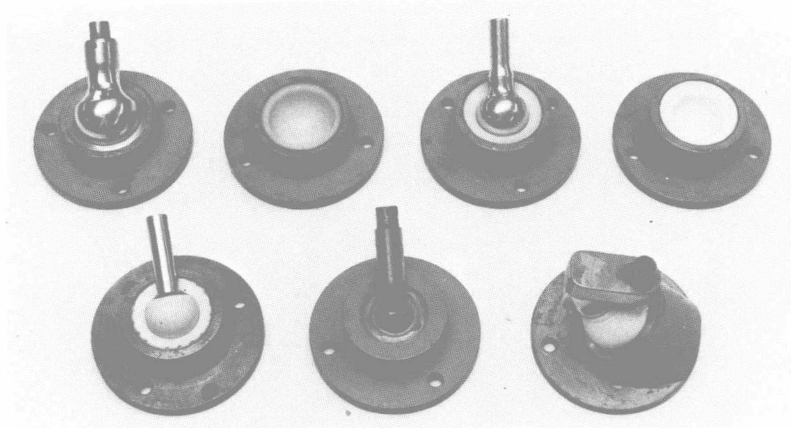

Fig. 1.8. Sockets mounted in holders to locate centre of rotation as near as possible to axis of the pendulum comparator

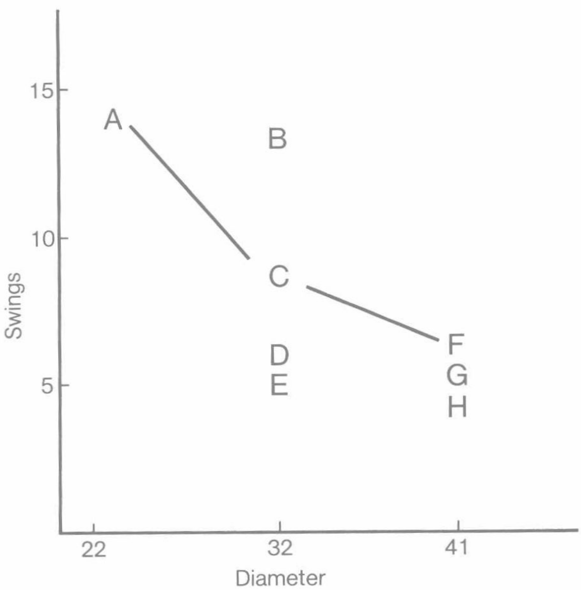

Fig. 1.9. *A, C, F,* represent different diameters of metal (stainless steel) ball on HMWP. The number of swings to stopping decreases as diameter increases: the opposite of what would be expected with fluid lubrication. Load 250 lb in all cases
D, polyester socket with 32-mm diameter chrome-cobalt head
E, ceramic (Al_3O_3) head 31-mm diamter on socket of same ceramic (Boutin)
B, ceramic (Biolox) head on HWMP socket
G, trunnion design (Weber) 42-mm polyester sphere
H, McKee–Farrar 41-mm chrome-cobalt head on socket of same

tained that, whatever may be the mechanism of lubrication, the comparison starts with all the joints being offered the same circumstances and the test reveals how different artificial joints react under these same starting conditions.

An important feature of the design is that the plane in which the ball oscillates is not unlike that during the weight-bearing phase of walking in the human body: the axis of rotation of the ball is at an angle to the central axis of the socket. To rotate the ball on the same axis as that of the socket would incur great variations in frictional torque depending on the fit of the ball in the socket: a large socket would give point contact with the head in the depth of the socket and therefore a very low frictional moment; a too-small socket would cause a 'cone-clutch' effect with binding of the head at the rim of the socket with very high frictional torque. An annular zone of contact halfway down the socket (as was recommended for the McKee-Farrar metal-to-metal implant) would give intermediate frictional torque. By oscillating in a plane perpendicular to the central axis of the socket, sensitivity to errors of fit of the ball in the socket is minimised because the length of the friction moment arm is the radius of the ball and is therefore constant.

Some typical results, the averages of many tests, all using lubrication with synovial fluid, are shown in Fig. 1.9. Points of special interest are as follows:

1. Metal/HMWP

The relationship between the number of swings and the diameter of the metal ball is well demonstrated in the sequence A (22 mm) – C (32 mm) – F (41 mm). If an important element of fluid-film lubrication were to be present one would expect that spheres with large diameters would make more swings than those with small diameters under