IMPACT-ABSORBING PROPERTIES OF THE HUMAN KNEE

A. HOSHINO, W. A. WALLACE

From Queen's Medical Centre, Nottingham

A biomechanical study has been carried out on 20 cadaveric knees to investigate their load-absorbing mechanism. The impact load was applied using a weight falling onto the transected proximal femur and the force transmitted through the knee was measured at the transected distal tibia using a load transducer.

The peak force transmitted increased as, sequentially, meniscus, articular cartilage and subchondral bone were damaged or removed. The most striking result was found in an implanted knee replacement where the transmitted force reached 180% of that in the intact knee.

The results show that the joint has an impact-absorbing property in each segment and that in the osteoarthritic knee there is less absorption of shock than in the normal knee. The high impact force in an implanted knee suggests that microfractures of the cancellous bone might be expected and may produce loosening.

The role of mechanical factors in the aetiology of osteoarthritis or of loosening of an implanted knee is important. It has been suggested that both osteoarthritis and loosening develop under excessive or repetitive stress. Even if the stress is small in the static condition, it can be expected to become greater if it is applied as an impact loading dynamically.

Impact load applied to the knee when walking, running and jumping will be modified by the visco-elastic properties of the knee and by muscle contraction. In the development and progression of joint degeneration or loosening of an implant it is important to consider the impact-absorbing properties of the joint; these are not yet fully understood.

What is the most important shock-absorber in the knee? Most investigations of the mechanics of the knee have used static loading, not dynamic (Walker 1977; Maquet 1984). Radin et al., in the early 1970s, tested the bovine finger joint using a falling weight and referred to the significance of the peak dynamic force through the joint (Radin, Paul and Lowy 1970; Radin and Paul 1970, 1971). We can find no previous published work involving impact loading on the human knee. The purpose of this study was to investigate the impact-absorbing properties in a biomechanical experiment.

A. Hoshino, MD, Senior Registrar
Department of Orthopaedic Surgery, Tokyo Medical and Dental University, 5–45, Yushima, 1-Chome, Bunkyo-ku, Tokyo, Japan.

W. A. Wallace, FRCS Ed, FRCS Ed(Orth), Professor of Orthopaedic and Accident Surgery
Department of Orthopaedic and Accident Surgery, University Hospital, Queen's Medical Centre, Nottingham NG7 2UH, England.

Requests for reprints should be sent to Dr A. Hoshino.

0301-620X/87/5180 $2.00

MATERIALS AND METHODS

Preparation of the joints. Twenty fresh cadaveric knees were obtained at autopsy. They came from nine males and 11 females aged from 32 to 94 years with an average age of 73.8 years. Each joint was removed by carrying out an osteotomy through the femur 10 cm above the knee, and through the tibia 10 cm below the knee. All the muscles around the joint and the patella were removed, while other soft tissues were preserved.

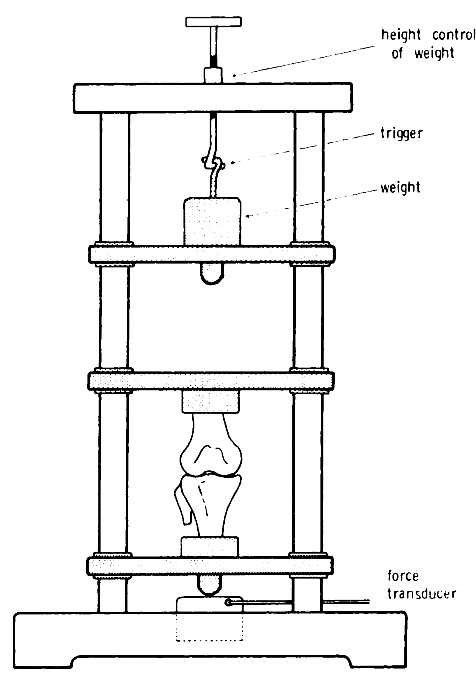

Fig. 1

Specially designed impact-loading jig. The falling weight hits the top of the femur and the transmitted force through the knee is measured by the transducer.

The specimens were stored at $-20°C$ until required, when they were thawed to room temperature before testing. The mechanical influence of refrigeration was investigated in a pilot study and no influence on the pattern of load transmission was found when the same knee was tested "fresh" and again after freezing and thawing. This is also supported by previous work (Sedlin 1965).

The condition of the articular cartilage was evaluated macroscopically. The extent of tibiofemoral osteoarthritis was graded thus: 0, normal; 1, slight articular fibrillation; 2, cartilaginous erosions; 3, deep ulceration or eburnated bone.

Testing equipment (Fig. 1). The distal end of the tibia was fixed vertically and the proximal femur was positioned in extension in its natural valgus angle. The specimen was mounted on moving frames using screws and acrylic resin cement. These moving frames were connected to the support posts through linear bearings which reduced friction to a minimum. Thus the joint could move in a vertical direction only, with minimal friction. The lower moving frame was placed onto a piezo-electric transducer (Kistler type 9021) bolted to the bottom plate.

The falling weight was also mounted through linear bearings to the support posts. The weight and the falling distance were adjustable; in this series a 1.8 kg weight was used and a 10 cm height. These values were identified from a pilot study which showed that this artificial load produced a similar trace on a force plate to that obtained from a normal person descending one step onto a force plate.

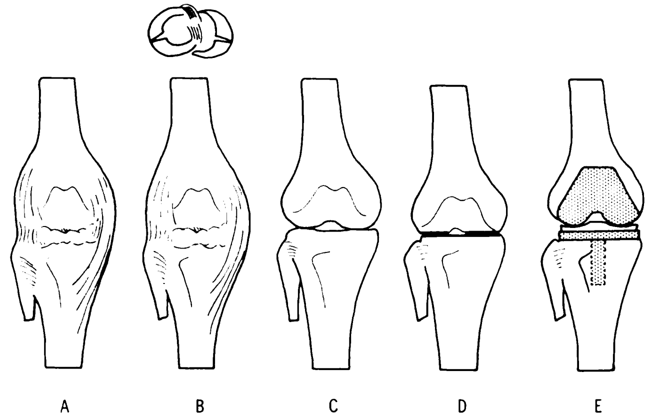

Fig. 2

The stages of the experiment: A – intact knee; B – radial cut of both lateral and medial menisci; C – menisci and soft tissues removed; D – articular cartilage and subchondral bone removed; E – conventional total knee replacement (TKR).

When the falling weight hits the top of the femur through the upper moving frame the transmitted force goes to the lower moving frame through the knee and hits the top of the transducer. This transducer has a high natural frequency (100 kHz) which reduces mechanical resonance. The transducer was connected to an amplifier (Kistler type 5007) which included a low-pass filter (2.2 kHz) and then to a digital storage oscilloscope from which the force–time waveform of the impact force was recorded.

Testing. The transmitted impact force applied through the joint was first measured through the intact knee with

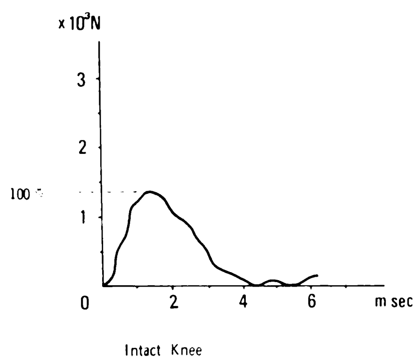

Fig. 3

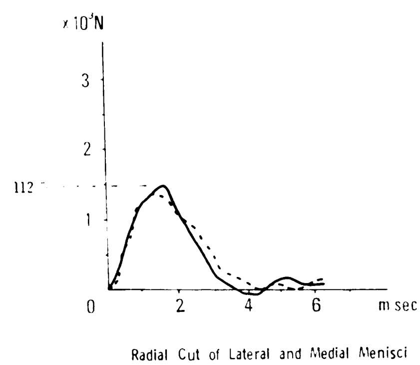

Fig. 4

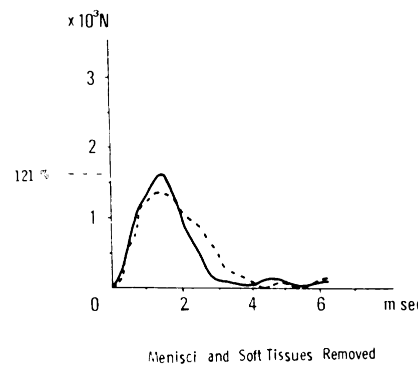

Fig. 5

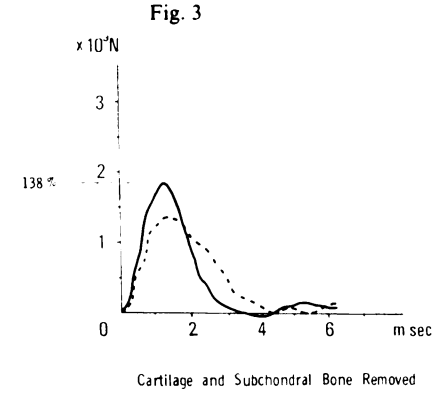

Fig. 6

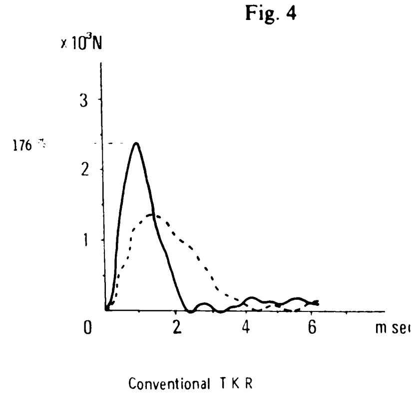

Fig. 7

Force–time waveform of the impact force as the tissues were progressively damaged or removed. Broken lines show the intact knee for comparison.

all the soft tissues attached (Fig. 2A). The lateral and medial menisci were then cut radially and vertically and the transmitted impact force was measured again (Fig. 2B). Next the menisci and all the soft tissues were removed and the force again measured (Fig. 2C). In the following stage the articular cartilage and subchondral bone were removed minimally (as when carrying out a condylar knee replacement); the cut surfaces were then brought in contact and the impact force was measured (Fig. 2D). Finally, a total condylar type of knee prosthesis with a metal-backed tibial component was implanted with cement (Fig. 2E). This model was selected because it is a popular prosthesis which has had good long-term results (Insall et al. 1983).

At each stage the measurement was repeated several times. The joint was kept moist during the experiment.

RESULTS

A 1.8 kg weight dropped from a 10 cm height gave an extremely high peak impact force transmitted through the knee but this varied in each joint because of the size of the knee, its age and condition. In the intact joints the peak impact forces were from 1130 to 2720 newtons (mean 1598 newtons) and they increased as each segment of the knee was damaged or removed. In the implanted knees the peak impact force reached from 1940 to 3820 newtons (mean 2820 newtons).

A knee from a 55-year-old woman with no osteoarthritis illustrates the waveform at each stage (Figs 3 to 7). The peak impact force was 1360 newtons (100%) in the intact knee (Fig. 3) and increased to 1520 newtons (111.8%) after the lateral and medial menisci were cut radially (Fig. 4). It reached 1640 newtons (120.6%) after the menisci and all the soft tissues had been removed (Fig. 5), increasing to 1870 newtons (137.5%) on removal of articular cartilage and subchondral bone (Fig. 6) and finally in the implanted knee replacement (Fig. 7) it was 2390 newtons (175.5%). This tendency was seen in every joint regardless of its condition. The summarised results are given in Figure 8, where each percentage is based on the peak value obtained from the original intact condition. These results were highly significant ($p < 0.0005$) using Student's paired *t*-test.

A comparison of the results from the normal knee (Grade 0) and the osteoarthritic knee (Grade 1, 2, or 3) was carried out at the stage of removal of the articular cartilage and subchondral bone (Fig. 9). At this stage (after Stage D) any abnormalities of the joint surfaces had been removed. The peak impact force increased to 152% in the normal knee but only to 124% in the osteoarthritic knee ($p < 0.001$). This can be interpreted retrospectively as showing that in normal knees 52% of load transmission is absorbed by the healthy knee but in the osteoarthritic knee only 24% of the load transmission is absorbed by the degenerate joint.

DISCUSSION

One of the mechanical characteristics of the human joint is its visco-elasticity (Walker 1977). Elasticity is a property in which the relationship between the force and the time is linear while viscosity does not have this linear relationship. Elasticity may be measured under static

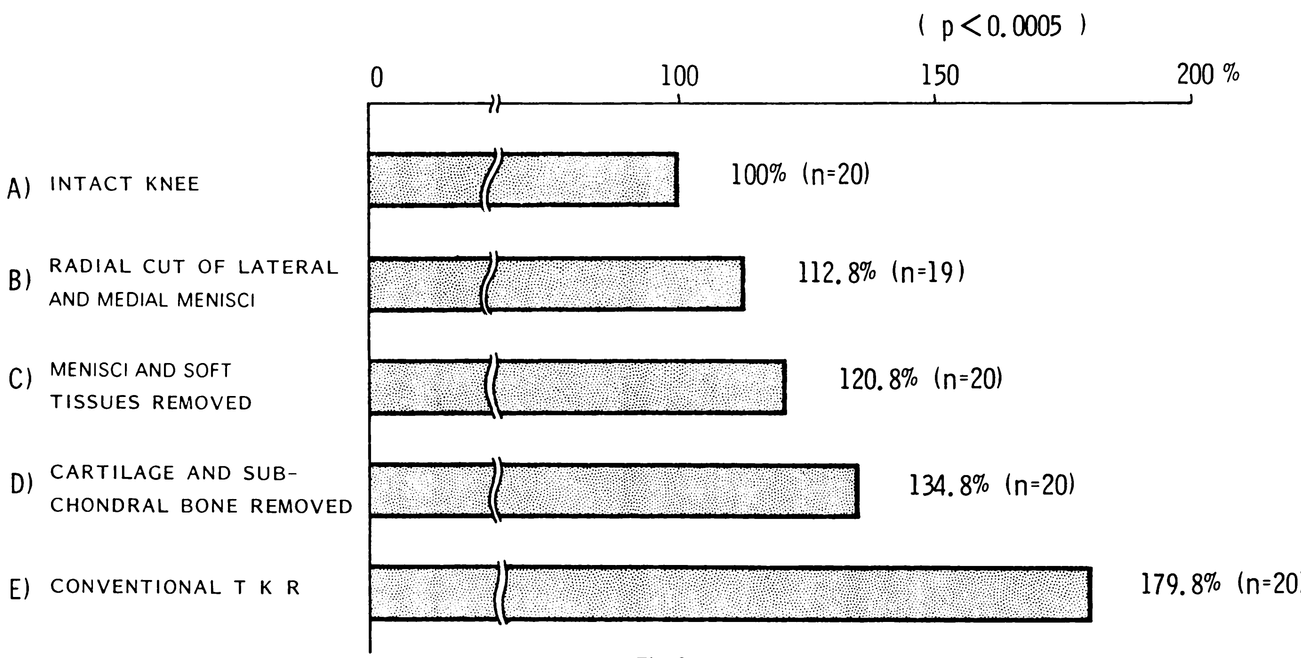

Fig. 8

Overall results of the mean peak impact force at each stage.

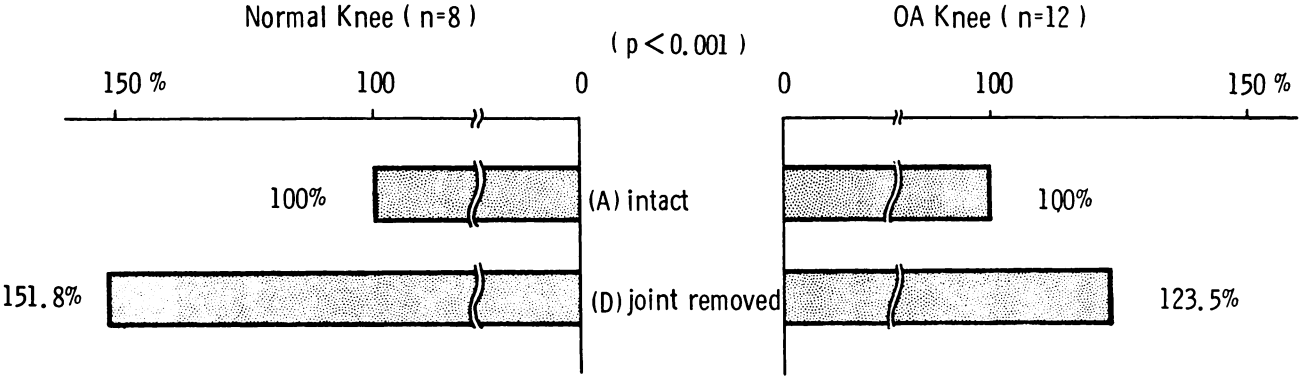

Fig. 9

The mean peak impact force of the normal knee compared with the osteoarthritic knee.

force but viscosity can only be studied using a dynamic force which is in fact the more common physiological loading during daily activity.

As biomechanical studies on the knee have advanced the significance of the mechanical factors in the aetiology of osteoarthritis (Maquet and Pelzer 1977) or of loosening of the implanted knee (Werner, Foster and Murray 1978) have become obvious. Unfortunately most studies in the past have investigated the elastic character; viscosity, which we believe is more important, has been ignored because it is difficult to measure.

This study was an experiment in vitro and the knee was positioned in extension. This closely parallels the moment of heel-strike which will give the biggest impact force to the knee, but we accept that in normal use the knee is slightly flexed. As we have investigated both visco-elasticity and load transmission the results simulate the more common loading pattern which occurs in daily activities. On the other hand, this study does not allow investigation of the additional effects of muscular contraction; we are therefore carrying out further research on this in vivo.

A static weight of 1.8 kg resting on the knee produces a force of only 17.6 newtons. If this weight falls from a height of 10 cm it gives 90 times this force (mean 1598 newtons) which is transmitted through the intact joint; inevitably this force is greater if the knee has lost its impact-absorbing (or shock-absorbing) properties. In vivo, when descending a flight of stairs the knee is loaded by the weight of the body (70 kg) which, at each step down, drops the height of the step (10 to 15 cm).

Not many papers have described the impact-absorbing properties of joints, but those by Radin et al. in the early 1970s reported systematic studies in vitro using bovine finger joints (Radin et al. 1970; Radin and Paul 1970, 1971): they found impact-absorbing properties in bone (subchondral, cancellous and cortical bone) and in periarticular soft tissues, but not in articular cartilage. Later they presented a hypothesis for osteoarthritis indicating that degeneration of cartilage is associated with and follows relative stiffening of the underlying bony subchondral bed. This was supported by experiments in vivo using rabbits and pigs (Simon et al. 1972; Radin et al. 1973; 1978). We are attracted by this hypothesis but it remains unproven.

Serink, Nachemson and Hansson (1977) reported different results from a similar experiment and several arguments have arisen as a result. They removed the articular cartilage alone to evaluate its properties. However, the articular cartilage and the subchondral bone are strongly connected to each other and make a shell structure over the end of the bone. It is our view that impact-absorbing properties should be studied only when the articular cartilage and the subchondral bone remain together as a composite material.

Several interesting features emerged from our study. A radial and vertical cut of a meniscus, which is an "experimental" meniscal injury, resulted in the impact force increasing to 113%; removal of a meniscus, which is an "experimental" total meniscectomy, gave an even higher impact force of 121%. Past biomechanical studies done under static loading have shown that the menisci act in force transmission (Walker and Erkman 1975) and stress distribution (Bourne et al. 1984), but the impact-absorbing property of the meniscus has not previously been proven although it seems to be obvious. Our results have proved that the menisci do act as shock-absorbers regardless of their condition ($p<0.0005$). In fact, this was found even when some of them were severely damaged and associated with osteoarthritis. Therefore total meniscectomy, even for a degenerate meniscus, will expose the knee to more severe mechanical stresses. This is supported by clinical studies of degenerative changes after meniscal injury or meniscectomy (Jackson 1968; Johnson et al. 1974) as initially suggested by Fairbank (1948).

Impact-absorbing properties of the articular cartilage and subchondral bone are also evident from this study ($p<0.0005$) although the mechanical properties of each individual knee may vary slightly depending on the presence and extent of osteoarthritis. Soft articular cartilage combined with hard subchondral bone forms a thin structure at the joint surface but it may act like the shell of an egg to absorb the impact force. On the other hand our comparison between the normal knee and the osteoarthritic knee highlights the initial hardness of the osteoarthritic knee ($p < 0.001$) which is seen radiologically as sclerosis. This study shows that osteoarthritis is a condition associated with less shock absorption than the normal knee. Thus a vicious circle occurs; the impact force produces microfractures of the subchondral bone which will result in a stiff sclerotic change after fracture healing, which makes the impact force even higher.

From the implanted knee replacement a further interesting feature was found. If a conventional knee prosthesis which consists of metal (chrome–cobalt–molybdenum alloy) and hard plastic (ultra high molecular weight polyethylene) is implanted using cement this makes the joint even more stiff.

Modern prosthetic design, whether with or without cement, attempts to simulate anatomical joint movement (Hungerford and Kenna 1983) and to prevent stress concentration in the prosthesis/bone interface (Lewis, Askew and Jaycox 1982; Hoshino 1984). The high impact forces which result from hard artificial materials may cause damage to the cancellous bone around the prosthesis and may produce long-term loosening. The results suggest that the ideal prosthesis should have a similar visco-elasticity to the human joint.

This study does not completely characterise the impact-absorbing properties of the human knee, as the mechanical role of muscle contraction in vivo is still unknown. It does, however, provide some clues to the aetiology of osteoarthritis and loosening of the implanted knee and it may be useful in improving future prosthetic design and materials.

We would like to thank Professor R. E. Cotton, Department of Pathology, City Hospital, Nottingham, for helping with the materials and Mr T. McDonald for his technical advice. The Tokyo Medical and Dental University supported Dr Hoshino during his research fellowship year.

REFERENCES

Bourne RB, Finlay JB, Papadopoulos P, Andreae P. The effect of medial meniscectomy on strain distribution in the proximal part of the tibia. *J Bone Joint Surg [Am]* 1984;66-A:1431–7.

Fairbank TJ. Knee joint changes after meniscectomy. *J Bone Joint Surg [Br]* 1948;30-B:664–70.

Hoshino A. Mechanical analysis of the tibial component design in knee prostheses. *Ochanomizu Med J* 1984;32:43–53 (in Japanese).

Hungerford DS, Kenna RV. Preliminary experience with a total knee prosthesis with porous coating used without cement. *Clin Orthop* 1983;176:95–107.

Insall JN, Hood RW, Flawn LB, Sullivan DJ. The total condylar knee prosthesis in gonarthrosis: a five to nine-year follow-up of the first one hundred consecutive replacements. *J Bone Joint Surg [Am]* 1983;65-A:619–28.

Jackson JP. Degenerative changes in the knee after meniscectomy. *Br Med J* 1968;ii:525–7.

Johnson RJ, Kettelkamp DB, Clark W, Leaverton P. Factors affecting late results after meniscectomy. *J Bone Joint Surg [Am]* 1974;56-A:719–29.

Lewis JL, Askew MJ, Jaycox DP. A comparative evaluation of tibial component designs of total knee protheses. *J Bone Joint Surg [Am]* 1982;64-A:129–35.

Maquet PGJ. *Biomechanics of the knee: with application to the pathogenesis and the surgical treatment of osteoarthritis.* 2nd. Berlin etc: Springer-Verlag, 1984.

Maquet PG, Pelzer GA. Evolution of the maximum stress in osteoarthritis of the knee. *J Biomech* 1977;10:107–17.

Radin EL, Paul IL. Does cartilage compliance reduce skeletal impact loads? The relative force-attenuating properties of articular cartilage, synovial fluid, periarticular soft tissues and bone. *Arthritis Rheum* 1970;13:139–44.

Radin EL, Paul IL. Importance of bone in sparing articular cartilage from impact. *Clin Orthop* 1971;78:342–44.

Radin EL, Paul IL, Lowy M. A comparison of the dynamic force transmitting properties of subchondral bone and articular cartilage. *J Bone Joint Surg [Am]* 1970;52-A:444–56.

Radin EL, Parker HG, Pugh JW, et al. Response of joints to impact loading. 3. Relationship between trabecular microfractures and cartilage degeneration. *J Biomech* 1973;6:51–7.

Radin EL, Ehrlich MG, Chernack R, Abernethy P, Paul IL, Rose RM. Effect of repetitive impulsive loading on the knee joints of rabbits. *Clin Orthop* 1978;131:288–93.

Sedlin ED. A rheologic model for cortical bone: a study of the physical properties of human femoral samples. *Acta Orthop Scand* 1965; Suppl 83:20–2.

Serink MT, Nachemson A, Hansson G. The effect of impact loading on rabbit knee joints. *Acta Orthop Scand* 1977;48:250–62.

Simon SR, Radin EL, Paul IL, et al. The response of joints to impact loading. II. In vivo behaviour of subchondral bone. *J Biomech* 1972;5:267–72.

Walker PS. *Human joints and their artificial replacements.* Springfield: Charles C Thomas, 1977.

Walker PS, Erkman MJ. The role of the menisci in force transmission across the knee. *Clin Orthop* 1975;109:184–92.

Werner F. Foster D, Murray DG. The influence of design on the transmission of torque across knee prostheses. *J Bone Surg [Am]* 1978;60-A:342–8.