The Role of Constraint in Contemporary Modular Knee Designs

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The current success of total knee arthroplasty (TKA) as a solution for arthritic problems about the knee is reflected in the increasing number of these procedures. The 1992 annual hospital discharge summaries indicate approximately 160,000 TKAs were performed in the United States for both primary and revision indications.[1] Clinical success of TKA is rooted in a refined appreciation of patient habitus, technical proficiency and implant design. The understanding of this integrated triad has evolved over the past two decades.

The evolution of knee implant design reflects recognition of the principle that implant geometry, acting in concert with surrounding soft tissues, determines the joint stability, range of motion and implant/bone interface forces. Interchangeable plateau geometries associated with modular designs, represent a recent development which permit an optimization of these interactions for a specific patient pathology.

This paper describes a comparative evaluation of the geometrical constraint offered by six primary modular knee systems and describes their clinical applicability.

BACKGROUND

In the early 1970s, Gunston[2,3] introduced the first bicondylar polycentric design for knee resurfacing employing metal and polyethylene articulating components. This arthroplasty was highly dependent on surgical placement and ligamentous support to simulate normal knee motion. Coventry, et al.[4,5] developed a one piece bicompartmental tibial plateau TKA, the Geometric, again using metal and polyethylene as the articulating materials. Both of these prostheses produced good initial clinical results; however, in time, increased implant loosening and other complications were reported.[6-16] These failures were primarily due to poor instrumentation, inadequate use of cement, overly constrained geometry[17] and a lack of appreciation for the nuances of knee mechanics.

The mid-1970s saw the development of total condylar knee designs which are still being used today with good long term clinical results.[18-24] Variations which have been incorporated into the original design concepts include alteration of component materials, metal backing of the tibial plateau and modularity of articular geometries. These changes have been concurrent with an increased understanding of knee joint biomechanics, instrumentation, patient selection, surgical proficiency and cost effectiveness.

MODULARITY IN TOTAL KNEE DESIGN

Restoration of normal knee joint function through surgical reconstruction is dependent upon load sharing between the implant and the surrounding ligaments and other stabilizing soft tissues. Excision, surgical release and

Direction of Tibial Displacement	Flexion Angle	Compressive Joint Force	Physiological Constraint
Anterior	0 degrees	2.3 x BW	1.00 x BW
Posterior	0 degrees	4.0 x BW	2.00 x BW
Medial	30 degrees	4.0 x BW	0.75 x BW
Lateral	0 degrees	4.0 x BW	1.00 x BW
Rotation (±5° int./ext.)	15 degrees	2.6 x BW	100 in-lbs

Table 1. Summary of the loading conditions utilized for anterior, posterior, medial, lateral and rotational stability evaluations. Compressive joint force, in body wieght (BW), derived from Seireg and Arvikar.[26] Physiologic constraint force, in BW, derived from Seireg and Arvikar,[26] and Morrison.[25]

Knee System		Femoral Components	Tibial Tray	Tibial Inserts
7000 Total Knee System		Co Cr Mo	Co Cr Mo	UHMWPE
7000-I	Series I Tibial Insert	65mm A/P	47mm A/P	15mm thick
7000-II	Series II Tibial Insert	69mm M/L	71mm M/L	47mm A/P
Osteonics Corporation, Allendale, NJ				71mm M/L
AMK® Total Knee System		Co Cr Mo	Ti 6Al 4V	UHMWPE
AMK-S	Standard Tibial Insert	63mm A/P	52mm A/P	10mm thick
AMK-C	Constrained Tibial Insert	74mm M/L	75mm M/L	49mm A/P
DePuy®, Warsaw, IN				72mm M/L
AXIOM™ Total Knee System		Co Cr Mo	Co Cr Mo	UHMWPE
AXIOM-S	Standard Tibial Insert	61mm A/P	48mm A/P	10mm thick
AXIOM-C	A/P Curved Tibial Insert	70mm M/L	70mm M/L	48mm A/P
Orthomet, Inc., Minneapolis, MN				70mm M/L
Miller/Galante Total Knee System		Ti 6Al 4V	Ti 6Al 4V	UHMWPE
M/G-F	Flat Tibial Insert	67mm A/P	46mm A/P	8.5 mm thick
M/G-L	A/P Lipped Tibial Insert	76mm M/L	72mm M/L	44mm A/P
Zimmer, Inc., Warsaw, IN				64mm M/L
Natural-Knee® Primary System		Co Cr Mo	Ti 6Al 4V	UHMWPE
NK-C	Congruent Tibial Insert	62mm A/P	53mm A/P	13mm thick
NK-U	Ultra-Congruent Tibial Insert	75mm M/L	79mm M/L	53mm A/P
Intermedics Orthopedics®, Austin, TX				79mm M/L
Performance® Modular Total Knee System		Co Cr Mo	Ti 6Al 4V	UHMWPE
Perf-F	Flat Tibial Insert	60mm A/P	46mm A/P	10mm thick
Perf-C	Curved Tibial Insert	70mm M/L	72mm M/L	46mm A/P
Kirschner Medical Corporation, Timonium, MD				72mm M/L

Table 2. Total knee systems utilized in this evaluation.

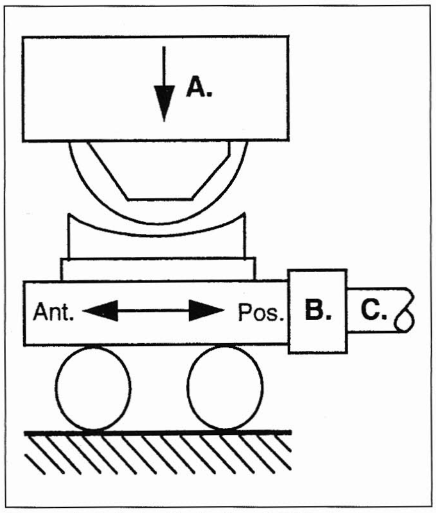

Figure 1: Anterior-Posterior stability test assembly. A.) Compressive joint force. B.) Load cell. C.) Linear shear actuator.

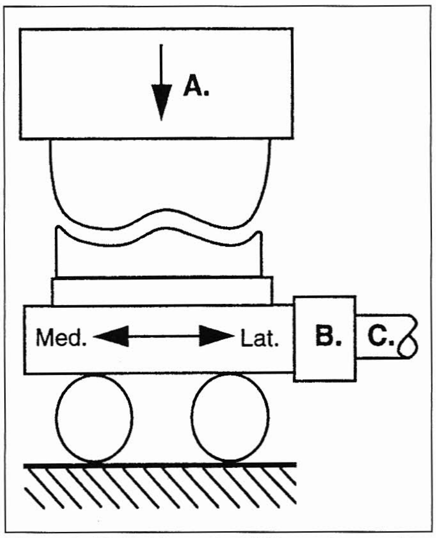

Figure 2: Medial-Lateral stability test assembly. A.) Compressive joint force. B.) Load cell. C.) Linear shear actuator.

continuous pathological weakening of ligamentous structures requires an increased dependency upon the implant system for stability, which must be provided by geometrical interaction between the femoral and tibial components.

Implant modularity defines an ability to select different tibial plateau geometries for a specific femoral component and tibial tray design, extending the clinical application of these devices. It allows the use of single set instrumentation, contributing to technical proficiency and clinical outcome. Further, the economic considerations of stocking multiple knee systems is currently viewed as a prohibitive hospital practice. The availability of modular knee systems represents a continuing design evolution which attempts to address a spectrum of knee pathologies within a single system.

MATERIALS AND METHODS

Stability is achieved in non-hinged, total knee replacements through geometric variation of the condylar surfaces. The intrinsic stability of an implant system is defined as the capacity of the implant to limit rotational, anterior-posterior, and medial-lateral displacements to within normal ranges. In the absence of gross material deformation, intrinsic stability due to geometric variation may be described in terms of the shear force which acts orthogonal to the compressive contact loads between the femoral and tibial components.

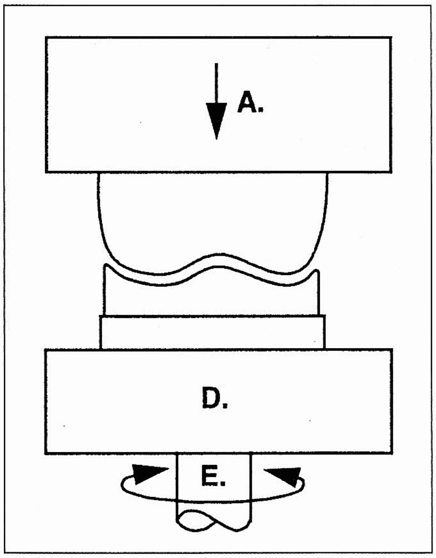

Figure 3: Rotational stability test assembly. A.) Compressive joint force. D.) Torque cell. E.) Torsional actuator.

Knee System	Anterior [lbf]	Posterior [lbf]	Medial [lbf]	Lateral [lbf]	Rotation [in-lbf]
7000-I	127	283	410	>600	34
7000-II	135	425	403	>600	49
AMK-S	25	183	200	447	24
AMK-C	137	268	222	437	168
AXIOM-S	52	170	105	253	24
AXIOM-C	82	240	133	307	29
M/G-F	88	183	333	283	32
M/G-L	127	260	420	443	46
NK-C	192	300	320	>600	59
NK-U	160	543	303	>600	88
Perf-F	30	360	253	573	23
Perf-C	217	358	400	>600	64

Table 3: Average maximum constraints measured for anterior, posterior, medial, lateral and rotational stability evaluations of three tibial inserts (n=3).

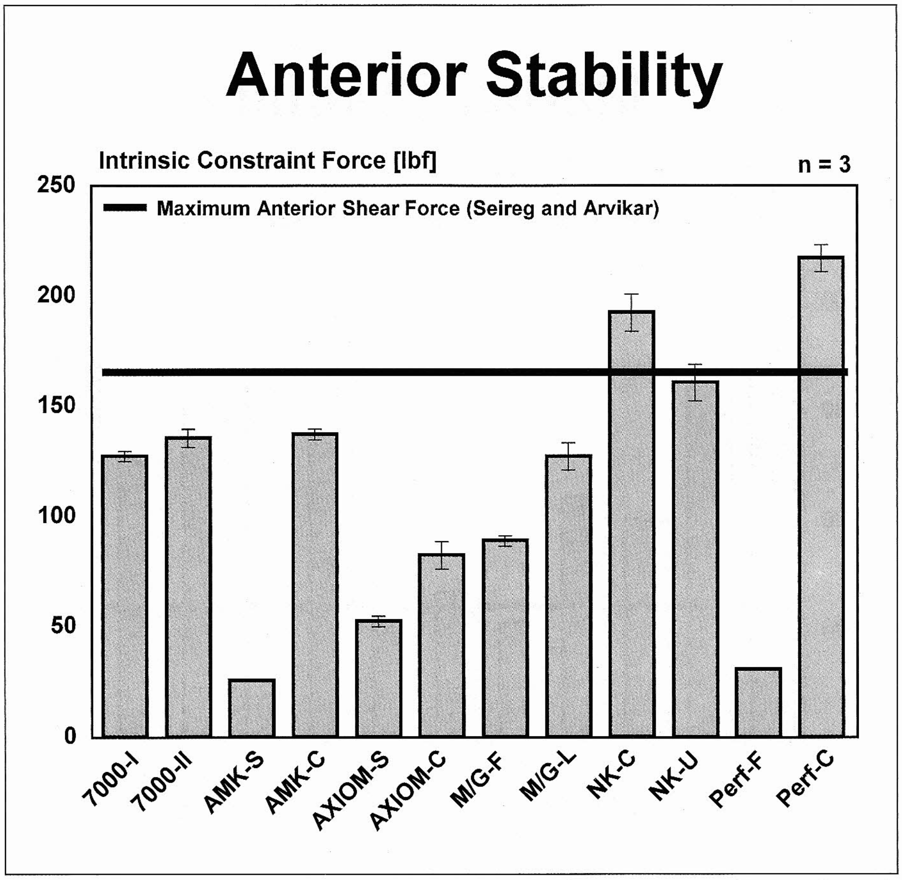

Figure 4: Average, maximum anterior constraint force measured for each insert. Error bars indicate ±1 standard deviation. The loading conditions for this direction were 0° extension and 2.3 x BW (375 lbf) compressive load.

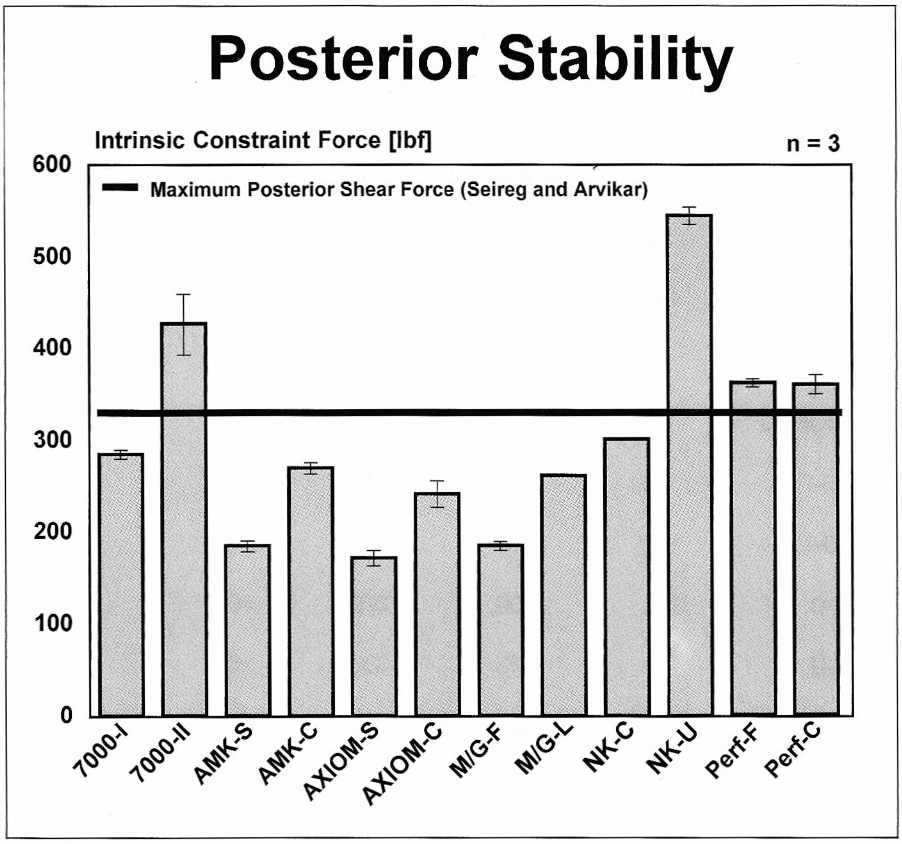

Figure 5: Average, maximum posterior constraint force measured for each insert. Error bars indicate ±1 standard deviation. The loading conditions for this direction were 0° extension and 4.0 x BW (650 lbf) compressive load.

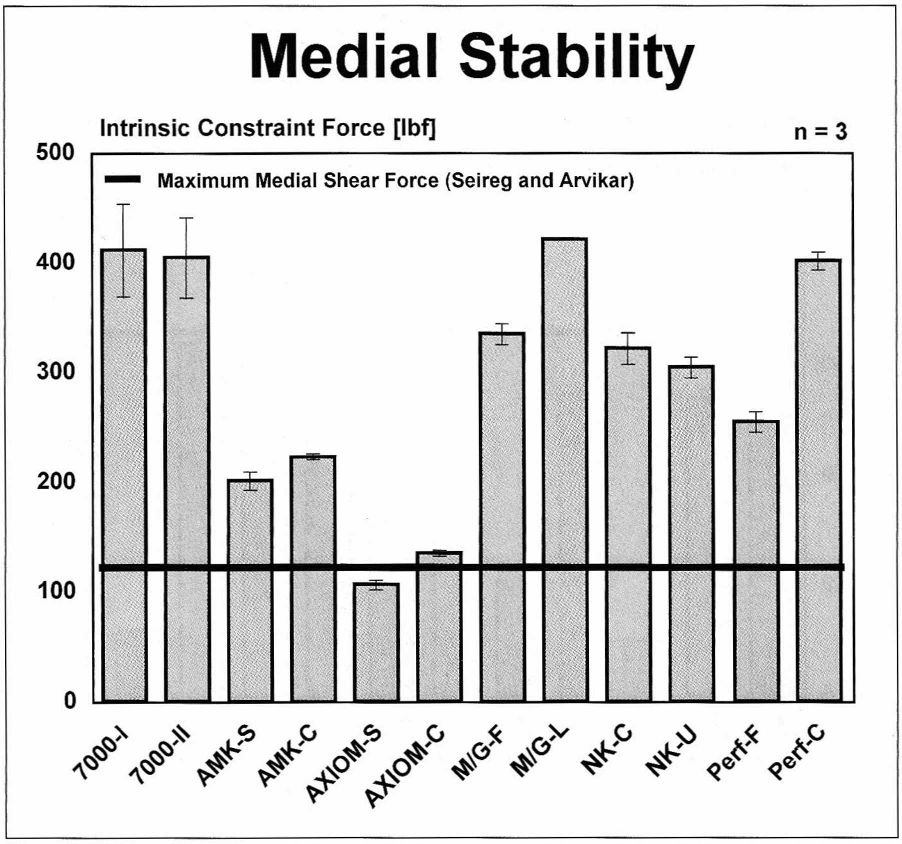

Figure 6: Average, maximum medial constraint force measured for each insert. Error bars indicate ±1 standard deviation. The loading conditions for this direction were 30° flexion and 4.0 x BW (650 lbf) compressive load.

A dynamic testing system has been developed to assess the intrinsic performance characteristics of non-hinged knee replacement systems. An evaluation of contemporary knee designs was carried out on a modified materials testing machine for anterior, posterior, medial, lateral and rotational stability under a spectrum of compressive loads consistent with those reported during normal gait.[25,26] Compressive loads and flexion angles were chosen to represent those points in the gait cycle where maximum shear forces act (Table 1). For a 60 year old 5'8" male subject, an average body weight of 163 lbf was determined from actuarial tables and used in this study.[27] The six primary modular total knee systems evaluated are summarized in Table 2.

Anterior-Posterior and Medial-Lateral Shear Testing

The tibial and femoral components of each system were embedded in poly-methyl-methacrylate, (PMMA), and mounted in a testing apparatus designed for a Model 1115 Instron Testing Machine, (Instron Corp., Canton, Massachusetts) (Figure 1,2).

The respective shearing displacements were then applied to three inserts of each design at a loading rate of 5.0 inches per minute until implant subluxation. Anterior, posterior, medial and lateral subluxation were defined as a dislocation of the tibial component relative to a stationary femoral component. The shear forces required to induce subluxation provide a measure of the maximum ability of the device to constrain displacement in the test direction. The average, maximum constraint forces produced by displacement in these directions are reported (Table 3).

Rotational Testing

The components of each system were embedded in PMMA, mounted in the testing apparatus in 15° flexion and loaded to 430 lbf compression (Figure 3). This simulates the gait force and position at which maximum rotatory torque is generated in the normal knee. The system was then rotated about the central axis to ±7.5o at 3.2° per second and the torque versus angular displacement recorded on the Instron's integral X-Y plotter. The results reported reflect a 5° internal and external angular displacement about a neutral axis in the axial plane (Table 3).

EVALUATION

A description of the mechanical forces which normally act across the knee joint is necessary for interpretation of data obtained during testing. Over the normal walking cycle gravitational, ligamentous, and muscular forces acting together with inertial and ground reaction effects produce significant compressive, shearing, and rotatory forces at the knee joint. Knee stability has been determined to be directly related to joint contact force.[28, 29] Although these forces have not been measured directly *in vivo*, several investigators have approximated values using kinematic, electromyographic and mathematical analyses.[25,26]

An analysis describing compressive, anterior-posterior and medial-lateral forces across the knee joint has been developed by Seireg and Arvikar.[26] These findings describe the maximum forces generated at the knee joint during walking. In the normal knee, these forces are resisted by joint congruity and stabilizing soft tissue structures. Under compressive load the maximum anterior, posterior, medial and lateral shear forces approach 1.0, 2.0, 0.75 and 1.0 times body weight, respectively, during the gait cycle. This physiologic data is utilized in interpreting the test values obtained.

Anterior instability is not a frequently reported clinical problem in total knee replacement. The constraint measured for the majority of the designs demonstrated a minimal requirement for soft tissue support to counter the anterior shear forces reported by Seireg and Arvikar[26] (Figure 4). The AMK Standard and Performance Flat tibial bearing inserts require soft tissue participation to balance the shear forces and prevent anterior subluxation. In contrast, the Natural-Knee Congruent and Performance Curved tibial bearing inserts have considerable intrinsic stability and may avoid anterior subluxation even in the absence of soft tissue support.

At 0° extension, all of the tibial plateau designs evaluated demonstrate a minimal requirement for the involvement of posterior stabilizing soft tissues (Figure 5). Therefore, the presence of a competent PCL to assist the prevention of posterior subluxation may not be required in these designs. Four of the plateau designs, those exceeding the maximum normal posterior shear force, demonstrated sufficient intrinsic stabili-

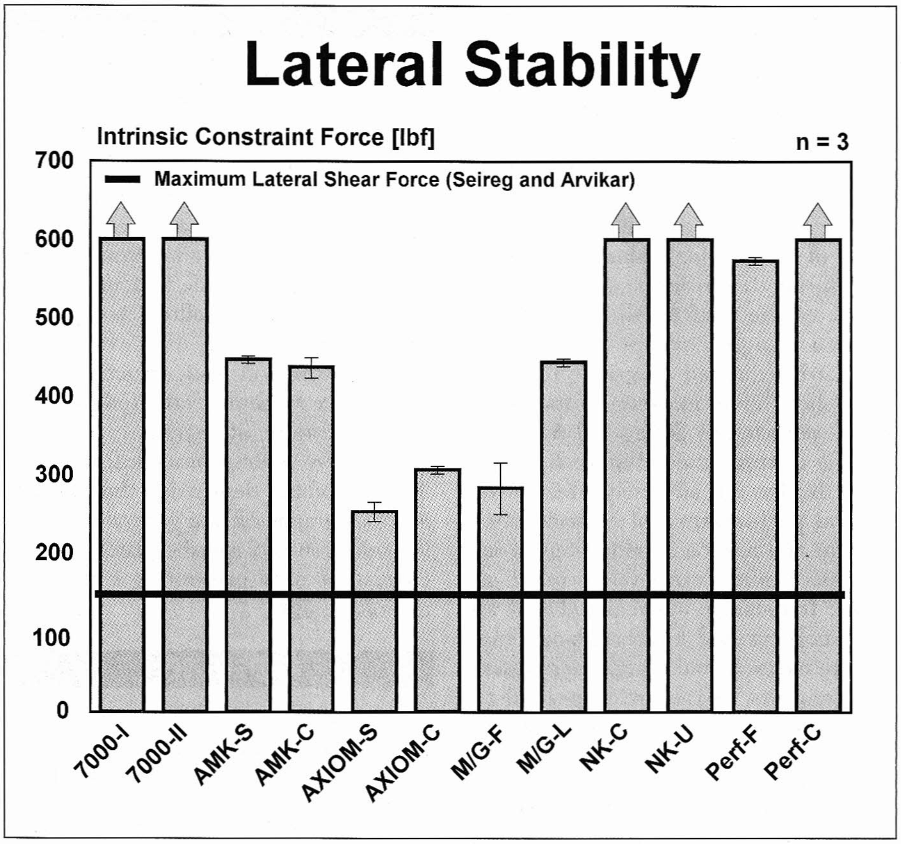

Figure 7: Average, maximum lateral constraint force measured for each insert. Error bars indicate ±1 standard deviation. The loading conditions for this direction were 0° extension and 4.0 x BW (650 lbf) compressive load.

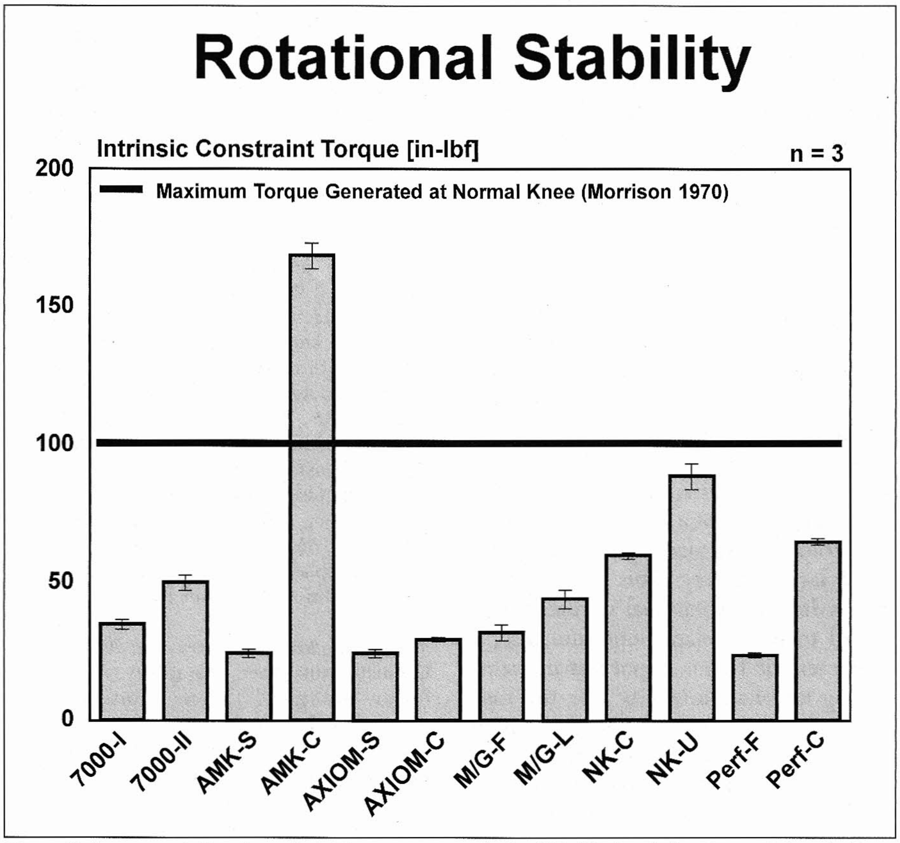

Figure 8: Average rotational constraint torque measured at ±5° int./ext. rotation for each insert. Error bars indicate ±1 standard deviation. The loading conditions for this direction were 15° flexion and 2.6 x BW (430 lbf) compressive load.

ty to not require any posterior stabilizing soft tissue to prevent subluxation. However, because posterior instability is not strictly limited to walking, careful consideration of the constraint provided by the implant and soft tissues during other activities is essential.

The medial-lateral constraint offered by all of the systems evaluated is mainly attributed to the intercondylar eminence of the insert. All of the tibial plateau designs, except the AXIOM Standard, exhibited a capacity to withstand shear forces in excess of the maximums reported by Seireg and Arvikar[26] for the normal knee (Figure 6,7). To date, this has not adversely affected the clinical performance of existing knee systems and may be advantageous in situations of minor varus-valgus malalignment. It must be appreciated that all semi-constrained knee replacements require balanced and functional collateral ligaments which are expected to reduce medial-lateral shear forces acting on the tibial plateau during gait.

During normal walking, rotation about the long axis of the tibia is characterized by alternating internal and external angular displacement approximating a total of 13°.[30] Knee rotation occurs primarily during the last few degrees of extension, limited by osseous joint anatomy and the surrounding musculo-ligamentous complex. Morrison[25] has estimated torques at the knee during normal walking to approach 100 in-lbf, and beyond, dependent upon body weight. This value is used as a baseline to compare rotational constraint of the implant systems.

Rotation in the axial plane is a primary requirement of normal gait. The constraint torque measured for these designs implies that soft tissue participation, particularly balanced collateral ligaments, are required to achieve knee stability. In general, soft tissue involvement should be encouraged in order to decrease the dependency on intrinsic rotational constraints afforded by the condylar geometry. This load sharing will reduce the rotational stresses transferred to the implant-bone interface, a characteristic that is important in maintaining interface integrity. For the case of the AMK Constrained insert, which exceeds the torque estimated by Morrison,[25] soft tissue participation is likely to be minimal. Higher stresses will then be transferred to the implant/bone interface increasing the potential for fixation failure.

CONCLUSION

The inclusion of tibial plateau modularity within a specific knee design extends the range of intrinsic mechanical stability offered by a system. Clinical features of soft tissue inadequacy and bony pathology for a given patient determine the contribution implant geometry must provide to achieve knee stability. Modularity allows component selection to maximize the involvement of the existing soft tissue structures.

The six systems evaluated demonstrate a range of intrinsic stability afforded by their geometrical profiles. These stabilities depicted in the comparison bar graphs offer a general guide to the selection of a specific plateau design consistent with presenting soft tissue pathology. STI

REFERENCES

1. National Centers for Disease Control and Prevention, National Center for Health Services, Annual National Hospital Discharge Summaries, 1992.
2. Gunston FH: Polycentric knee arthroplasty: Prosthetic simulation of normal knee movement. J Bone Joint Surg 53-B(2):272-277, 1971.
3. Gunston FH: Polycentric knee arthroplasty. Prosthetic simulation of normal knee movement: interim report. Clin Orthop Rel Res 94:128-135, 1973.
4. Coventry MB, Finerman GAM, Riley LH, Turner RH, Upshaw JE: A new geometric* knee for total knee arthroplasty. Clin Orthop Rel Res 83:157-162, 1972.
5. Coventry MB, Upshaw JE, Riley LH, Finerman GAM, Turner RH: Geometric total knee arthroplasty. I. Conception, design, indications and surgical technic. Clin Orthop Rel Res 94:171-176, 1973.
6. Bryan RS, Peterson LFA, Combs JJ Jr.: Polycentric knee arthroplasty. A review of 84 patients with more than one year follow-up. Clin Orthop Rel Res 94:136-139, 1973.
7. Bryan RS, Peterson LFA, Combs JJ Jr.: Polycentric knee arthroplasty. A preliminary report of postoperative complications in 450 knees. Clin Orthop Rel Res 94:148-152, 1973.
8. Coventry MB, Upshaw JE, Riley LH, Finerman GAM, Turner RH: Geometric total knee arthroplasty. II. Patient data and complications. Clin Orthop Rel Res 94:177-184, 1973.
9. Skolnick MD, Coventry MB, Ilstrup DM: Geometric total knee arthroplasty. A two-year follow-up study. J Bone Joint Surg 58-A(6):749-753, 1976.
10. Shoji H, D'Ambrosia RD, Lipscomb PR: Failed polycentric total knee prostheses. J Bone Joint Surg 58-A(6):773-777, 1976.
11. Gunston FH, MacKenzie RI: Complications of polycentric knee arthroplasty. Clin Orthop Rel Res 120:11-17, 1976.
12. Skolnick MD, Bryan RS, Peterson LFA, Combs JJ, Ilstrup DM: Polycentric total knee arthroplasty. A two-year follow-up study*. J Bone Joint Surg 58-A(6):743-748, 1976.
13. Bryan RS, Peterson LFA: Polycentric total knee arthroplasty: a prognostic assessment. Clin Orthop Rel Res 145:23-28, 1979.
14. Lewallen DG, Bryan RS, Peterson LFA: Polycentric total knee arthroplasty. A ten-year follow-up study. J Bone Joint Surg 66-A(8):1211-1218, 1984.
15. Torisu T, Morita H: Roentographic evaluation of geometric total knee arthroplasty with a six-year average follow-up period. Clin Orthop Rel Res 202:125-134, 1986.
16. Rand JA, Coventry MB: Ten-year evaluation of geometric total knee arthroplasty. Clin Orthop Rel Res 232:168-173, 1988.
17. Black JD, Matejczyk MB, Greenwald AS, Wilde AH: Rotational characteristics of non-hinged total knee replacements. Trans Orthop Res Soc 2:56, 1977.
18. Laskin RS: Modular total knee-replacement arthroplasty. A review of eighty-nine patients. J Bone Joint Surg 58-A(6):766-773, 1976.
19. Insall J, Scott WN, Ranawat CS: The total condylar knee prosthesis. J Bone Joint Surg 61-A(2):173-180, 1979.
20. Scott RD, Volatile TB: Twelve years' experience with posterior cruciate-retaining total knee arthroplasty. Clin Orthop Rel Res 205:100-107, 1986.
21. Ranawat CS, Boachie-Adjei O: Survivorship analysis and results of total condylar knee arthroplasty: Eight- to 11-year follow-up period. Clin Orthop Rel Res 226:6-13, 1988.
22. Windsor RE, Scuderi GR, Moran MC, Insall JN: Mechanisms of failure of the femoral and tibial components in total knee arthroplasty. Clin Orthop Rel Res 248:15-20, 1989.
23. Vince KG, Insall JN, Kelly MA: The total condylar prosthesis: 10- to 12-year results of a cemented knee replacement. J Bone Joint Surg 71-B(5):793-797, 1989.
24. Thomas BJ, Cracchiolo A III, Lee YF, Chow GH, Navarro R, Dorey F: Total knee arthroplasty in rheumatoid arthritis. Clin Orthop Rel Res 265:129-136, 1991.
25. Morrison JB: The mechanics of the knee joint in relation to normal walking. J Biomech 3:51-61, 1970.
26. Seireg A, Arvikar RJ: The prediction of the muscular load sharing and joint forces in the lower extremities during walking. J Biomech 8:89-102, 1975.
27. Scientific Tables. Diem K, Lentner C (eds.), Ciba-Geigy Limited, Switzerland, p. 711, 1973.
28. Black JD, Greenwald AS: Medial-lateral and anterior-posterior stability of non-hinged total knee replacements. Trans Orthop Res Soc 4:96, 1979.
29. Greenwald AD, Black JD, Matejczyk MB : Total knee replacement. In: The American Academy of Orthopaedic Surgeons Instructional Course Lectures, Murray DG (ed.), C.V. Mosby Company, St. Louis, MO, 30:301-312, 1981.
30. Kettlekamp DB, Johnson RJ, Smidt GL, Chao EYS, Walker M: An electrogoniometric study of the knee motion in the normal gait. J Bone Joint Surg 52-A:775-790, 1970.