COMPUTER-AIDED PREOPERATIVE PLANNING IN KNEE OSTEOTOMY

Edmund Y.S. Chao, Ph.D.*
Franklin H. Sim, M.D.#

"This paper is dedicated to two of our orthopaedic mentors: Donald B. Kettelkamp and Mark B. Coventry, from whom we have benefited so tremendously in our careers. They taught us the sciences and clinical knowledge related to Knee Osteotomy. We wish to honor these two giants in our field and we shall forever remember them and their profound philosophy, strict discipline and the utmost ethical standards endowed upon us!"

ABSTRACT

It has been demonstrated that osteoarthritis (OA) is activity related and may worsen when joint contact stress becomes excessive due to overloading. Hence, joint **alignment** and **loading** are considered to be the key biomechanical determinants for OA. The initiation of pathologic changes in the knee has been described by the mechanism termed, **"vicious cycle"** in which joint axial malalignment creates excessive stresses to the localized joint cartilage/subchondral bone regions and the surrounding soft tissue which in turn produces more laxity and joint deformity and thus repeats the cyclic degradation mechanism. If this degenerative cycle can be broken with joint alignment surgery such as **osteotomy,** a procedure to realign the knee joint and thus redistribute joint forces applied to each compartment, performed properly and at the appropriate time, the osteoarthritic disease process can be decelerated and even reversed. The main goals of this paper are to emphasize the importance of accurate preoperative planning for osteotomy in order to properly correct joint alignment, and to justify the application of an existing computer program, **OASIS** (Osteotomy Analysis and Simulation Software) using plain radiographs to perform appropriate surgical planning. Normal subjects and knee osteotomy patients were studied to establish a database for the purpose of establishing the utility and efficacy of the presently proposed concept. We wish to rationalize knee osteotomy as a preferred and cost-effective treatment for patients with early symptoms of OA in the knee. This paper presents a new concept of preoperative planning for knee ostetomy based on the underlying etiology of the disease and biomechanical viewpoint with strong emphasis on surgical treatment rationales. The established principles in this paper can be applied to other joints of the body and will help implement preventive measures and other non-surgical means to manage patients with axial malalignment or early degenerative changes.

INTRODUCTION

An estimated 16 million Americans suffer from osteoarthritis (OA), the most common form of joint degeneration and one of the least understood diseases involving musculoskeletal systems. Altman et al.[1] described OA as "a heterogeneous group of conditions that lead to joint symptoms and signs which are associated with defective integrity of articular cartilage, in addition to related changes in the underlying bone and at the joint margins." OA starts with local cartilage damage and becomes more severe and widespread at later stages[41]. The most common radiographic findings are osteophytes and subchondral stiffening or sclerosis[49, 20, 58, 51, 52, 19]. The knee is the most affected peripheral joint in patients with symptomatic OA. Lesions are ten times more prevalent in the knee than in the ankle and almost absent in the wrist[18, 34, 46].

Although OA is proposed to have its etiological causes related to genetic, metabolic and environmental factors, mechanical loading (stresses) and joint angular deformity remain the most intriguing and convincing determinants in certain occupations and physical activities[52, 4, 39, 3]. Other OA pathogenesis indicators such as age, obesity, joint trauma, repetitive loading, etc. are all mechanical-related. The close correlation between OA and biomechanical factors can be easily established at the knee since it is the most heavily loaded joint with a large range of motion but the least stable structure due to its predominant dependence on soft tissue constraints and muscle contraction. Slight axial malalignments can initiate the **"vicious cycle"** as proposed by Coventry[13,14] (Figure 1). This progressive disease process can be described as when a "load increase in one compartment of the knee due to slight axial malalignment causes cartilage degeneration, subchondral bone sclerosis, cyst formation and joint laxity which in turn produces an increased load on the affected side thus causing a cyclic reaction." The introduction of knee joint alignment procedures was intended to interrupt such a degenerative cycle[12, 6, 32, 59, 33, 42, 8, 17].

Unfortunately, knee osteotomy has fallen into disfavor for two main reasons. First, several investigators discov-

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*Orthopaedic Biomechanics Laboratory, Johns Hopkins University, Baltimore, Maryland

#Department of Orthopaedics, Mayo Clinic/Mayo Foundation, Rochester, Minnesota

Corresponding Author: Edmund Y.S. Chao, Ph.D., Orthopaedic Research, Room 225, Ross Building, Johns Hopkins University, 720 Rutland Ave., Baltimore, MD 21205-2196, Fax 410-550-6414; Phone 410-550-6416

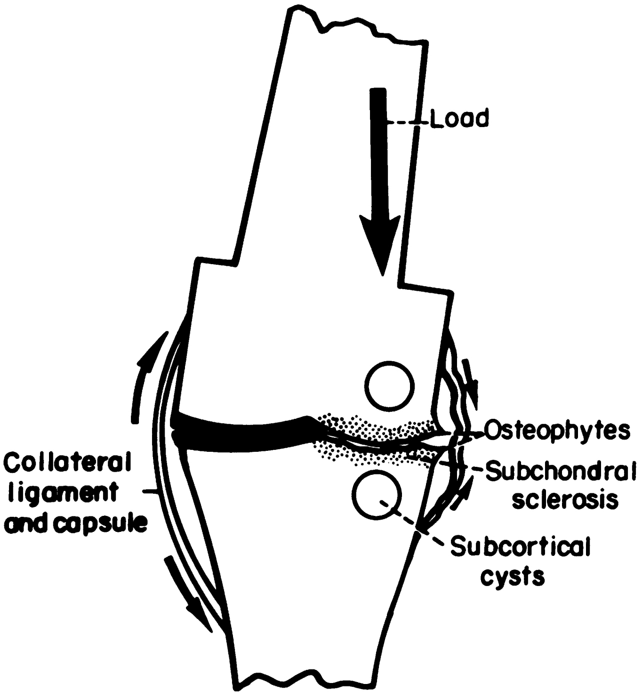


Figure 1 The "vicious cycle" hypothesis relating joint axial alignment and abnormal loading to osteoarthritis in the knee.

ered that knee osteotomy could not maintain long lasting good results and thus is regarded as only a temporary procedure yielding five to seven years of pain-free activity before deformity recurrence[45, 50, 17, 22, 24, 32]. Second, in the recent two decades, prosthetic replacement of the knee by either unicompartmental or total joint arthroplasty has pushed osteotomy aside in favor of the more popular and perhaps easier surgical procedure. The reasons for not obtaining long-term excellent results after knee osteotomy could be due to prognostic factors[48, 50, 60], the uncertainty of which osteotomy procedure to indicate based on specific pathological involvement[54, 61, 47, 27, 35, 43] or the inability to produce adequate overcorrection[16]. While total knee replacement for unicompartmental disease may be over-indicated, unicompartmental knee joint replacement has produced controversial and highly variable results[5, 44, 40, 57, 31, 7]. In addition, prosthetic replacement is certainly more costly and does not leave many options for revision if the surgery is not successful. With today's health care management reform and DRG regulations, more conservative procedures should be considered.

In knee osteotomy, regardless of the type, the issue of overcorrection has created controversial debate[38, 14, 53]. Preoperative planning using biomechanical analysis has a long history of development[10, 37, 28], but these early analytical approaches were tedious and impractical. In addition, no capability was available to visualize the analysis results in the proper selection of the type, location and wedge magnitude of osteotomy correction. Since the osteotomy procedure is designed to correct alignment and to re-distribute joint pressure, careful preoperative planning should be done based on proven biomechanical principles. The publication by Coventry et al.[16] clearly indicated that when osteotomy was performed correctly (proper overcorrection) on carefully selected patients (<30% over the normal weight), excellent results lasted for more than ten years following the initial procedure.

Motivated by the potential value of computer-aided preoperative planning for knee osteotomy, a special analysis algorithm and computer program were developed by the principal investigator and his associates[25, 29]. This analysis has been applied to a large normal population of different age ranges and genders which demonstrated that osteoarthritis of the knee did not seem to associate with age and gender[28]. However, the age range in this study did not include those in their seventh decade. The same population group will need to be followed longitudinally to rule out age as the key determining factor for OA. This program (Osteotomy Analysis and Simulation Software - "OASIS") was applied to a large patient population with surprisingly good results[55, 56, 21]. Following the optimal correction guidelines, not all varus deformities resulted in upper tibial osteotomy. On the contrary, there were significant numbers of cases that required double osteotomy (upper tibial combined with supracondylar) based on axial alignment, contact pressure distribution and joint line obliquity. Although follow-up is still limited in these cases, the patients and attending surgeons have been extremely satisfied with the outcome following the recommended osteotomy.

The current preoperative analysis is limited to two-dimensional calculation constraints and only based upon the standing radiograph in the AP projection. These limitations pose significant concerns as to the validity of the current analysis scheme and the optimal selection criteria for the final osteotomy procedure. Hence, verification experiments using knee specimens on a simulator should be incorporated. It is also important to assess the biological and biomechanical changes affected by the osteotomy. While these concerns are being investigated in various basic science studies, one must assume that proper unloading of the affected joint can not only bring symptom relief but can also allow the degenerative process caused by biomechanical factors to cease and reverse. In addition, one must also assume that alignment correction performed when the knee is in the neutral extended position will have the same therapeutic effect in all joint flexion positions during activity.

It is clear that joint alignment and pressure (loading) distribution are important determinants affecting osteoarthritis. Knee osteotomy, if performed correctly, can stop and even reverse the "vicious cycle." Proper timing must be taken into consideration in order for surgery to be effective before the joint is irreversibly damaged. These important principles can only be substantiated by following patients with early symptoms of OA that are not severe enough for surgical correction. How to determine the threshold for surgery to maximize the therapeutic effect of osteotomy and whether to use braces or other nonsurgical management to correct high joint compartment load caused by side-thrust during gait[50] are questions that remain unanswered. Hence, this paper offers several significant contributions to the basic understanding of unicompartmental OA in the knee, to the justification of the more conservative and cost-effective procedures on these patients, and finally to the achievement of quality assurance for long-lasting good results to a large patient population.

DEVELOPMENT OF KNEE OSTEOTOMY ANALYSIS PROGRAM —OASIS

In orthopaedic surgical procedures where joint/limb alignment, joint coverage and surface contact pressure distribution are of great importance, accurate modeling and analysis of the involved system based on the patient's 2D (radiographic) imaging data can offer significant information for operative planning to optimize treatment results. Sim et al.[55] and Hanssen and Chao[21] have reported using full-length standing plain radiographs of the lower extremity for the measurement of mechanical axial alignment for preoperative planning of knee osteotomies. Use of the mechanical axis description of alignment is reported to be more reliable than the anatomic description for defining knee joint deformity, especially when other skeletal deformities are present away from the knee joint. These axes provide a more precise description of load transmission through the joint. Hanssen reports using the mechanical axis description of alignment and overlaying a templated wedge using trigonometric principles for angular correction.

In order to accurately determine knee joint pressures and mechanical deformities of candidates for knee osteotomies, a computer software program, OASIS (Osteotomy Analysis and Simulation Software), was developed by the principal investigator when at the Mayo Clinic. The OASIS software is based on the Rigid Body Spring Model (RBSM) technique described by Kawai and Toi[36], An et al.,[2] and Ide et al.[30] When this modeling technique is applied to the human knee, the femur and tibia are represented by rigid

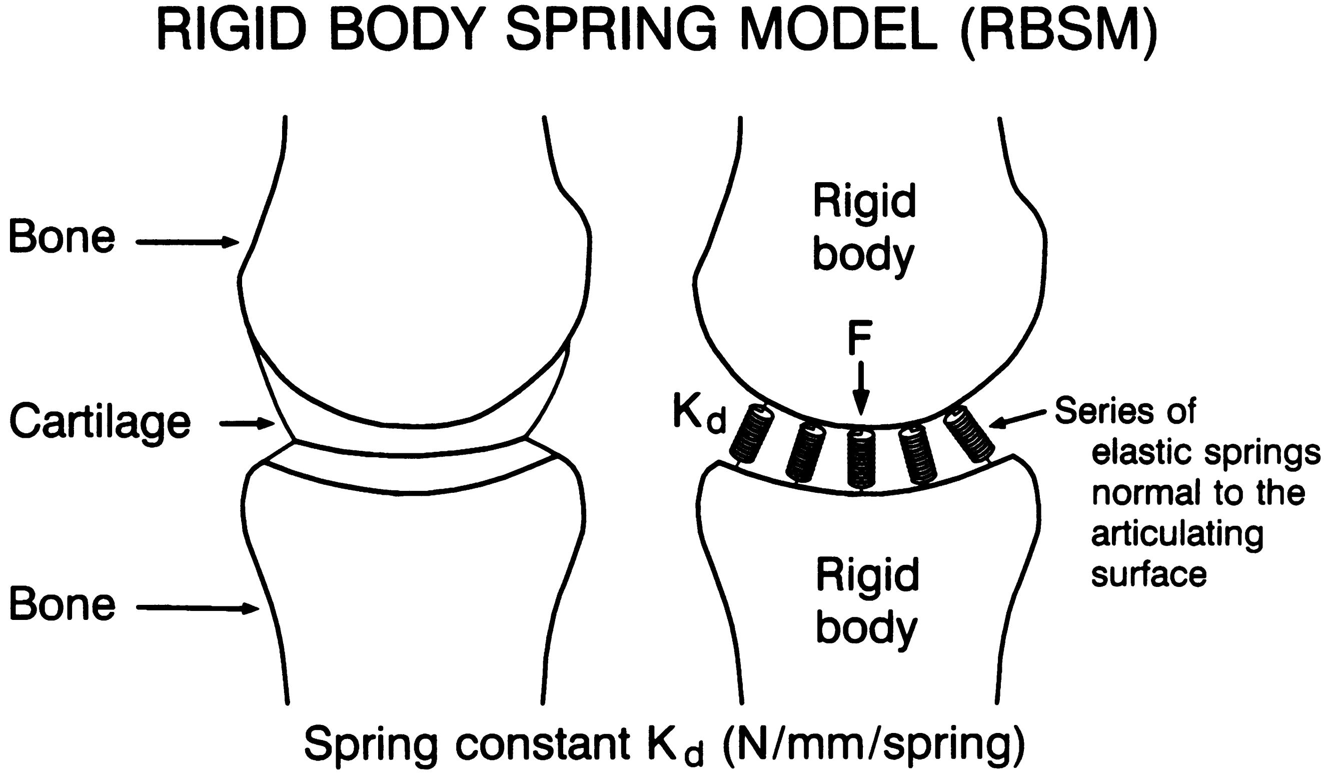


Figure 2 The Rigid Body Spring Model (RBSM) used to obtain contact stress distribution in articulating joints. K_d = cartilage spring stiffness value. The stiffness value for each spring will be designated as K_i.

bodies while articular cartilage and ligaments are modeled as systems of springs between the bodies.

To determine the contact force acting on the femoral condyle, a set of evenly spaced data points are calculated on the tibial contact surface using a cubic polynomial. Cartilage is modeled on the tibial surface as linear compressive springs positioned in the normal direction on the tibial surface (Figure 2). The compressive stresses are obtained by considering the constitutive relationships of the cartilage and assigning a stiffness value for the spring element (k_i) that approximates the properties of the cartilage in that region. The stiffness of the cartilage springs is determined as:

$$k_i = \begin{cases} \dfrac{E(1-\nu)}{(1+\nu)(1-2\nu)} \dfrac{ds_i}{h}, & \Delta u_n > 0 \\ 0, & \Delta u_n \le 0 \end{cases};$$

where E is Young's modulus, v is Poisson's ratio, and h is the thickness of the cartilage. The compressive force applied by each spring is:

$$\vec{f}_i = -k_i \Delta u_n \mathbf{n}_i = -k_i(\Delta z_i \bullet \mathbf{n}_i)\mathbf{n}_i = -k_i(\Delta z_i \bullet (\mathbf{R} \bullet \mathbf{n}_i'))\mathbf{n}_i.$$

The total compressive force on the femur is:

$$\vec{F}_c = \sum_{i=1}^{m} \vec{f}_i = \sum_{i=1}^{m} -k\Delta u_n \mathbf{n}_i = \sum_{i=1}^{m} -k_i(\Delta z_i \bullet (\mathbf{R} \bullet \mathbf{n}_i'))\mathbf{n}_i.$$

The free body diagram used in the RBSM analysis of the lower extremity can be seen in Figure 3. The muscle force directions are determined from the input data. Muscle force components are recalculated at each iteration of the model. The ligament action is specified by their original points on the tibia and insertion points on the femur.

The final equilibrium equations, a system of six equations with six unknowns, are:

$$\begin{cases} \vec{F}_c + \vec{F}_l + \vec{F}_w = 0; \\ \vec{M}_c + \vec{M}_l + \vec{M}_w = 0. \end{cases}$$

The equilibrium equations satisfy the condition that the sum of all forces and moments due to cartilage compression (Fc), ligament tension (Fl) and body weight (Fw) equal zero. The relative equilibrium positions of the tibia and femur are calculated for given external loads and kinematic constraints. Displacement of the knee center is denoted by U, where:

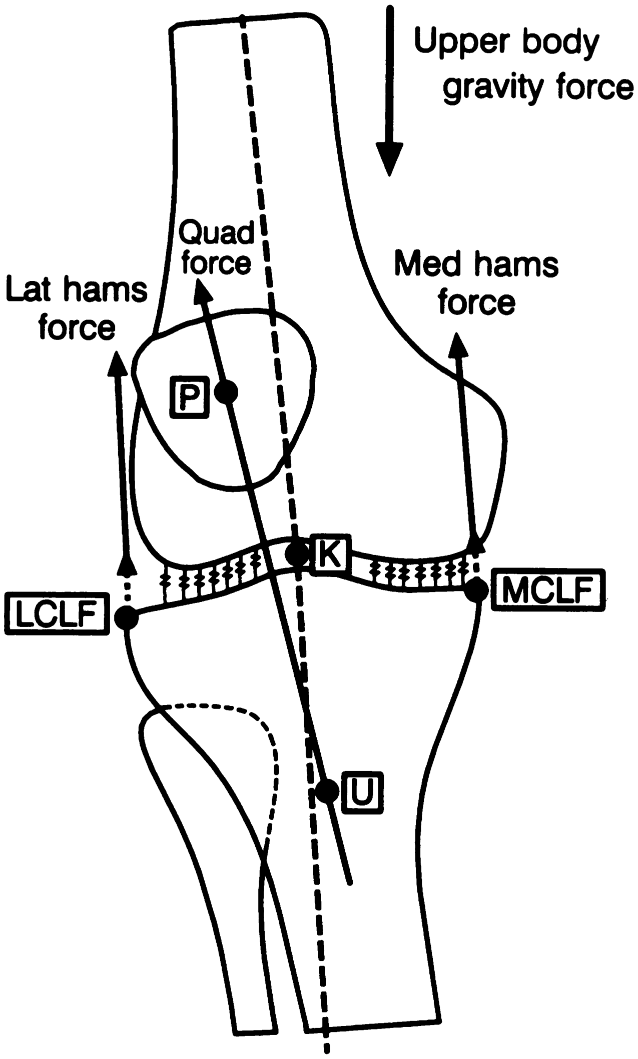


Figure 3 The 2D RBSM model of the knee used in osteotomy preoperative planning. U = patella tendon insertion; K = knee joint center; P = patella center, LCLF = lateral collateral ligament force.

$$\mathbf{U} = (U_x, U_y, \Theta_z)$$

The three displacement unknowns in translation (Ux, Uy) and rotation (θz) can be determined from the three equilibrium equations. An iterative process is used to solve the equilibrium equations. If a cartilage spring is found to be in tension or a ligament spring in compression, its stiffness is subtracted from the equilibrium equation and the process begins again. When there are no inadmissible spring forces, an osteotomy simulation will be com-

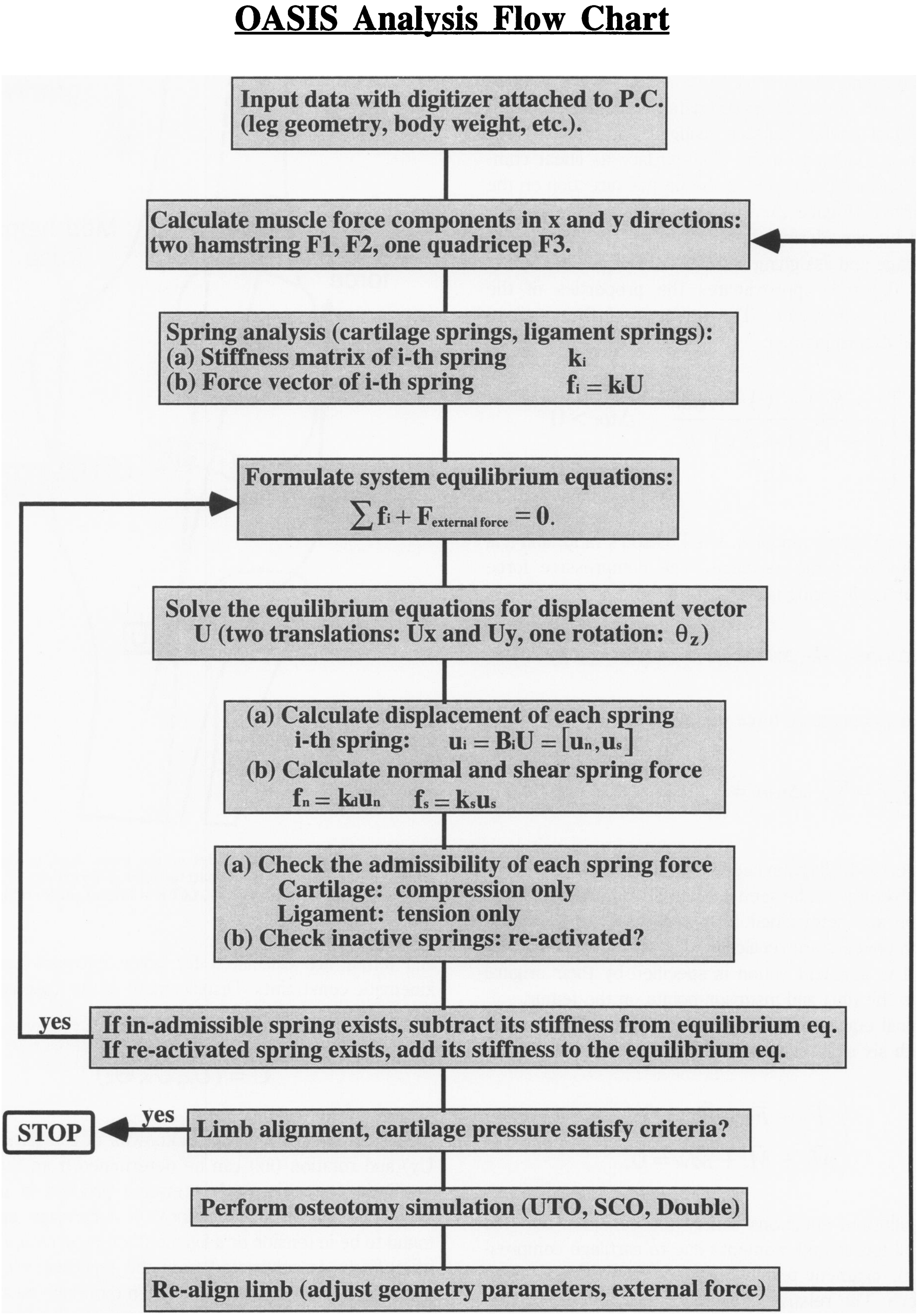


Figure 4 The iterative computational algorithm of the computer program "OASIS."

pleted as illustrated in the flow chart outlining the computational algorithm of the OASIS program (Figure 4).

KNEE JOINT AXIAL ALIGNMENT AND PRESSURE DISTRIBUTION

One hundred and twenty normal subjects of different gender and age ranges were studied for their knee joint alignment and 2D contact pressure distribution using the analysis program OASIS[28]. The tibiofemoral angle was consistent within the entire normal population studied (1.2° ± 2.2° varus). There was no significant difference between male and female subjects or different age groups ($p > 0.05$). In measuring the femoral anatomic valgus, the selection of the anatomic axis of the femur was important since the proximal femoral, distal femoral, and the overall femoral anatomic axes were different. Based on the distal anatomic axis, the femoral anatomic valgus for the entire population studies was 4.2° ± 1.7°. When the proximal femoral anatomic axis was used, the femoral anatomic valgus became 5.8° ± 1.9°, as opposed to 4.9° ± 0.7° when the overall femoral anatomic axis was used. Gender and age did not cause any significant differences.

The patellofemoral Q angle was 5.8° ± 6.7° for the entire group, and there was no gender-related difference. However, the patellotibial Q angle was significantly larger in the female subjects (9.9° ± 4.9°) than in the male subjects (6.8° ± 5.9°; $p<0.05$), while age did not produce any significant variation. The anatomic Q angle (Q_A) was also significantly greater ($p<0.05$) in the female subjects (18.8° ± 4.6°) compared to the male subjects (15.6° ± 3.5°). The knee joint obliquity angle (e) was 1.0° ± 1.5° varus (tilting medially) for the male subjects, which was significantly different from the female subjects (0.1° ± 1.7° valgus, $p<0.05$). Again, age did not produce any significant difference in this parameter.

The normal contact force distribution on the medial plateau was 75% ± 12% of the total knee joint force under simulated one-legged standing. There was no statistical difference between gender and age groups tested. The resultant force passing through the knee articular surface was mainly perpendicular to the joint line (94.3% body weight) with only a minor shear component (0.9% body weight) pointing medially. Only the lateral collateral ligament carried minute tension in all the normal subjects studied.

The plateau pressure was normalized against the subject's body weight and expressed as a percentage of body weight per millimeter. The maximum pressure on the plateau was higher in female subjects (4.0 ± 1.3% body weight/mm) than in the male subjects (3.5 ± 1.0% body weight/mm), and this difference was statistically significant ($p < 0.05$). However age did not change plateau pressure distribution. A parametric analysis was performed to correlate plateau force distribution with tibiofemoral angle, G location, joint cartilage thickness and knee joint muscle contraction. Changing the tibiofemoral angle and its effect on plateau force distribution can be used to study the pathomechanics of genu varum or valgum associated with joint malalignment. In order to establish such a relationship, the tibiofemoral angles of all the normal subjects studied were correlated with their medial plateau contact forces expressed as a percentage of the total knee joint force. The medial plateau force distribution had a negative linear relationship with the tibiofemoral angle ($R = 0.824$; $p <0.001$; Figure 5). A positive tibiofemoral angle represents a varus axial alignment while a negative value stands for a valgus alignment. This diagram also illustrates the scattering of the tibiofemoral angle and medial plateau contact force among the normal population studied.

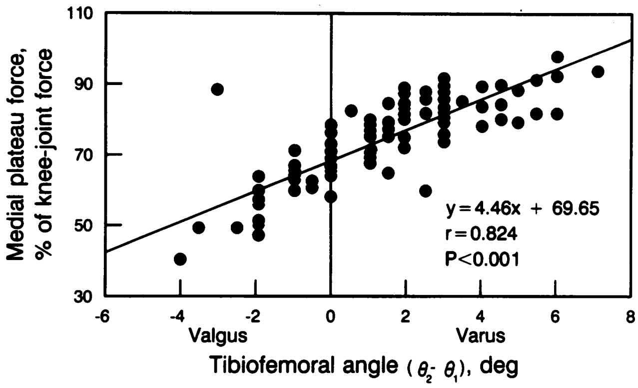


Figure 5 Correlation of medial plateau force and tibiofemoral angle in the normal population studied.

Variation of G location was achieved by changing IR from -1 (through the opposite hip joint center) to 2 (laterally to distance of "C" from H; Figure 6). Different values of IR can be used to simulate a varus or valgus moment applied to the knee in the frontal plane during gait. When G is lateral to K ($IR > 0.8$), there will be a valgus moment (abduction moment) applied through the knee joint. On the other hand, when G is medial to K ($IR < 0.8$), there will be a varus moment (abduction moment or lateral thrust) applied to the knee joint. Such variation significantly affects the plateau force distribution (Figure 7). The selection of $IR = 0.8$ (approximating the one legged standing posture) as the demarcation point between valgus and varus moments was based on the values obtained from the normal population groups. When IR approaches 2, medial contact force approaches 0 with the medial collateral ligament in tension in order to maintain knee joint equilibrium. When IR becomes less than 0.3, all knee joint force will be borne by the medial plateau with the lateral ligament in strong tension.

The effect of cartilage thickness on plateau force distribution and joint peak pressure magnitude was insignificant based on the present model and its analytical assumption. Increasing quadriceps and hamstring contractions caused

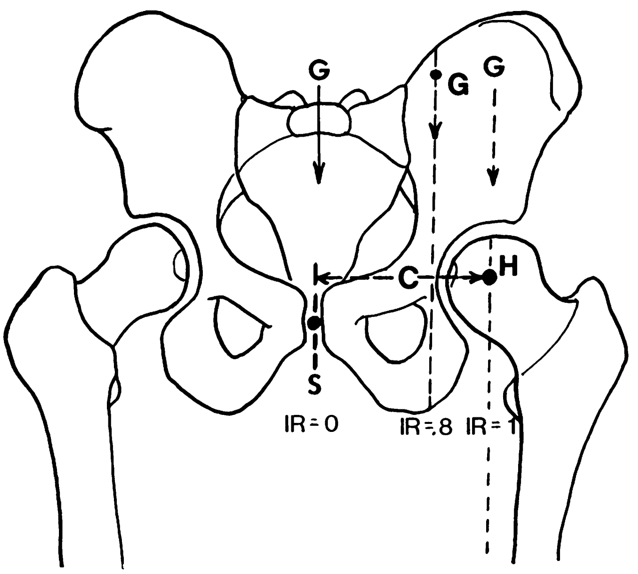


Figure 6 Effect of upper body gravity (G) during gait on knee joint contact force distribution. IR = interval ratio. IR = 1, gravity passing through the hip center, H; IR = 0, gravity passing through the pubic symphysis, S.

joint peak pressure to increase proportionally, but the relative plateau contact force distribution was not affected. Hence, the association of age with knee alignment deformity and early OA was not established. However, this study covered wider age ranges and no longitudinal follow-up was performed.

COMPUTER-AIDED PREOPERATIVE PLANNING

Traditionally, the axial alignment of the limb has been determined by measuring the femoral-tibial (anatomic) angle from standing radiographs and then judging the amount of correction required to normalize, or to overcorrect. The normal anatomic axis measured five degrees of valgus[38]. The mechanical axis normally averages 1.2 degrees varus and is more reliable than the anatomic axis when defining lower limb alignment[28]. This is particularly true when there are femoral or tibial deformities away from the knee joint that contribute to the limb malalignment. The same standing radiograph has been used to estimate osteotomy wedge length based on the assumption that the arc of the wedge is approximately 1 mm per degree of the angular correction. The use of such a simplified and erroneous method to estimate osteotomy wedge size is totally unacceptable. This is one of the faulty procedural steps in previous knee osteotomy preoperative planning which was responsible for the unsuccessful outcomes.

In addition to the mechanical alignment, the effects of soft tissue tension, obliquity of the joint line, and gravity shift of the upper body all affect the tibiofemoral plateau pressure distribution and ultimately the correct location and magnitude of an intended osteotomy. These factors are difficult to assess with visual inspection and manual planning. For these reasons, the software program OASIS was developed to provide a comprehensive preoperative assessment of the factors that guide the surgeon's final determination of the location, magnitude, and type of knee osteotomy most appropriate for the individual patient[28, 56]. On the full length anteroposterior weight bearing radiograph, the joint centers, mechanical and anatomic tibiofemoral axes, patella center, joint contour outline, muscle and ligament insertion points, and joint articular surface contact areas are identified and manually digitized on a translucent, background-lighted electrostatic digitizer. With this analytical model, the muscles, ligaments, and cartilage are represented by a series of linear springs while the bony structures are assumed to be rigid bodies (Figure 7).

Simulation analysis input data include body weight, muscle contraction, ligament and cartilage stiffness properties, and the upper body gravity location. Osteotomy simulation parameters for the magnitude and location of the osteotomy wedge can then be performed interactively with immediate tabulation and graphical display of the simulation session. A printout of the upper tibial closing wedge valgus osteotomy at its usual location is provided to the surgeon (Figure 8). Alternative options of an opening wedge, barrel-vault (also known as the dome) osteotomy at any level of the femur or tibia can also be simulated and made available for the surgeon. The output of the software "OASIS" includes the tibiofemoral angle based on the mechanical and anatomic axes, percent of force passing through the medial plateau, peak plateau pressure, joint shear force, collateral ligament tension, joint line obliquity in degrees from a horizontal line, joint loading axis (a line connecting the hip and ankle joint centers), location in reference to tibial plateau width, and the lower extremity length change. The size of the osteotomy angle, as measured along the bone surface, is also provided to the

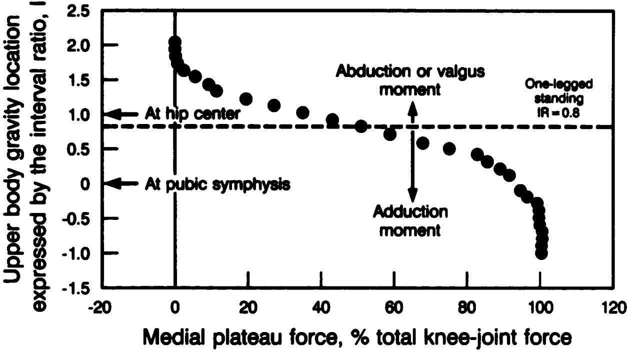
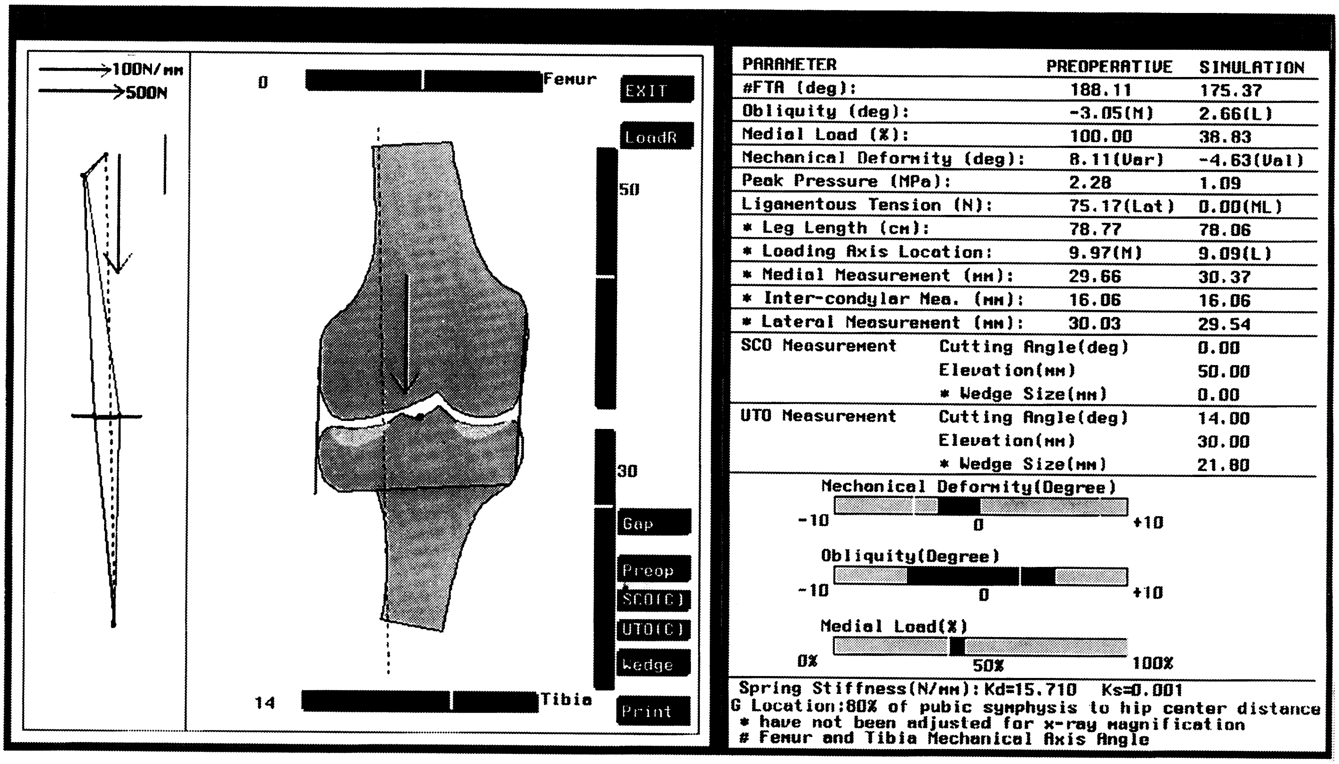


Figure 7 Effect of upper body loading location on the medial plateau force distribution as a means of stimulating walking effects on knee joint loading in the AP plane.

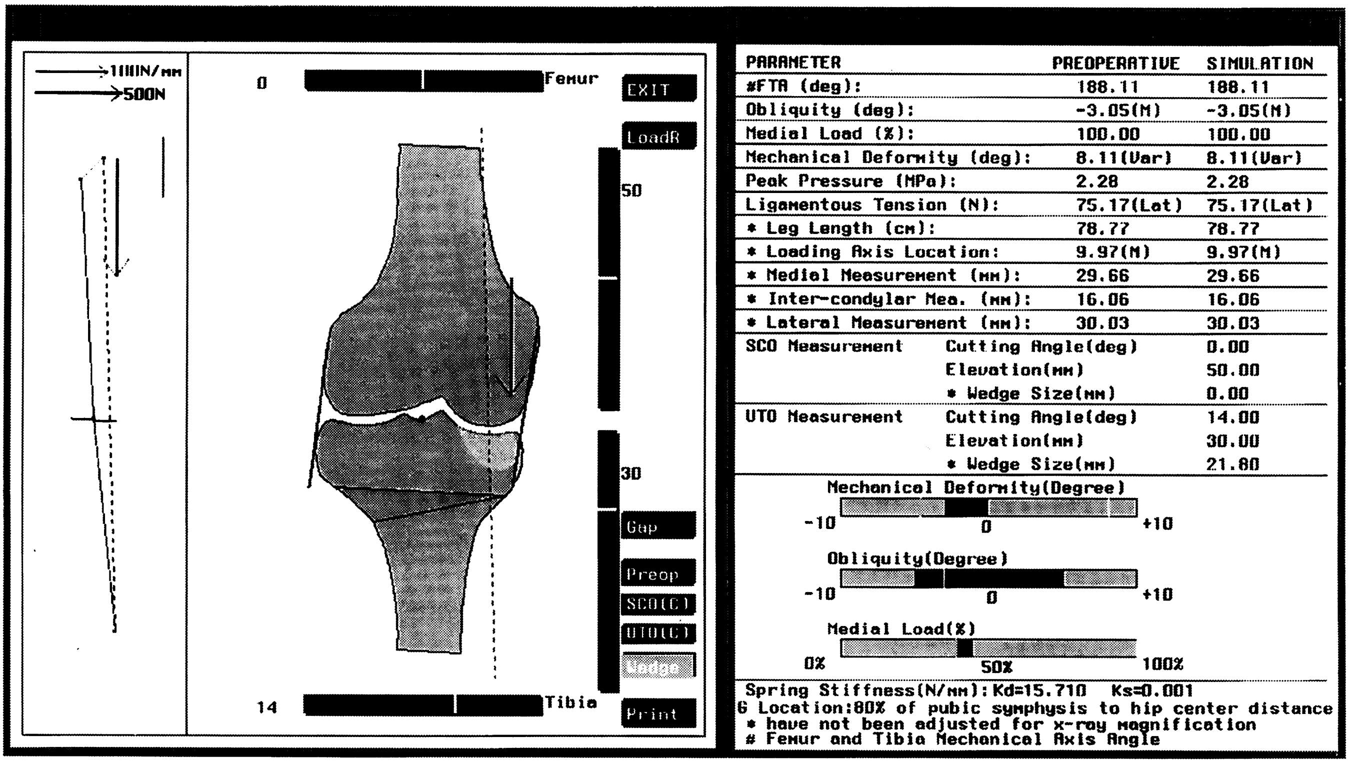


PARAMETER		PREOPERATIVE	SIMULATION
#FTA (deg):		188.11	175.37
Obliquity (deg):		-3.05(M)	2.66(L)
Medial Load (%):		100.00	38.83
Mechanical Deformity (deg):		8.11(Var)	-4.63(Val)
Peak Pressure (MPa):		2.28	1.09
Ligamentous Tension (N):		75.17(Lat)	0.00(ML)
* Leg Length (cm):		78.77	78.06
* Loading Axis Location:		9.97(M)	9.09(L)
* Medial Measurement (mm):		29.66	30.37
* Inter-condylar Mea. (mm):		16.06	16.06
* Lateral Measurement (mm):		30.03	29.54
SCO Measurement	Cutting Angle(deg)		0.00
	Elevation(mm)		50.00
	* Wedge Size(mm)		0.00
UTO Measurement	Cutting Angle(deg)		14.00
	Elevation(mm)		30.00
	* Wedge Size(mm)		21.80

Spring Stiffness(N/mm): Kd=15.710 Ks=0.001
G Location:80% of pubic symphysis to hip center distance
* have not been adjusted for x-ray magnification
# Femur and Tibia Mechanical Axis Angle

Figure 8 An example case of a man with 8.11° varus deformity in his right knee. All critical information on the preoperative planning analysis is included.

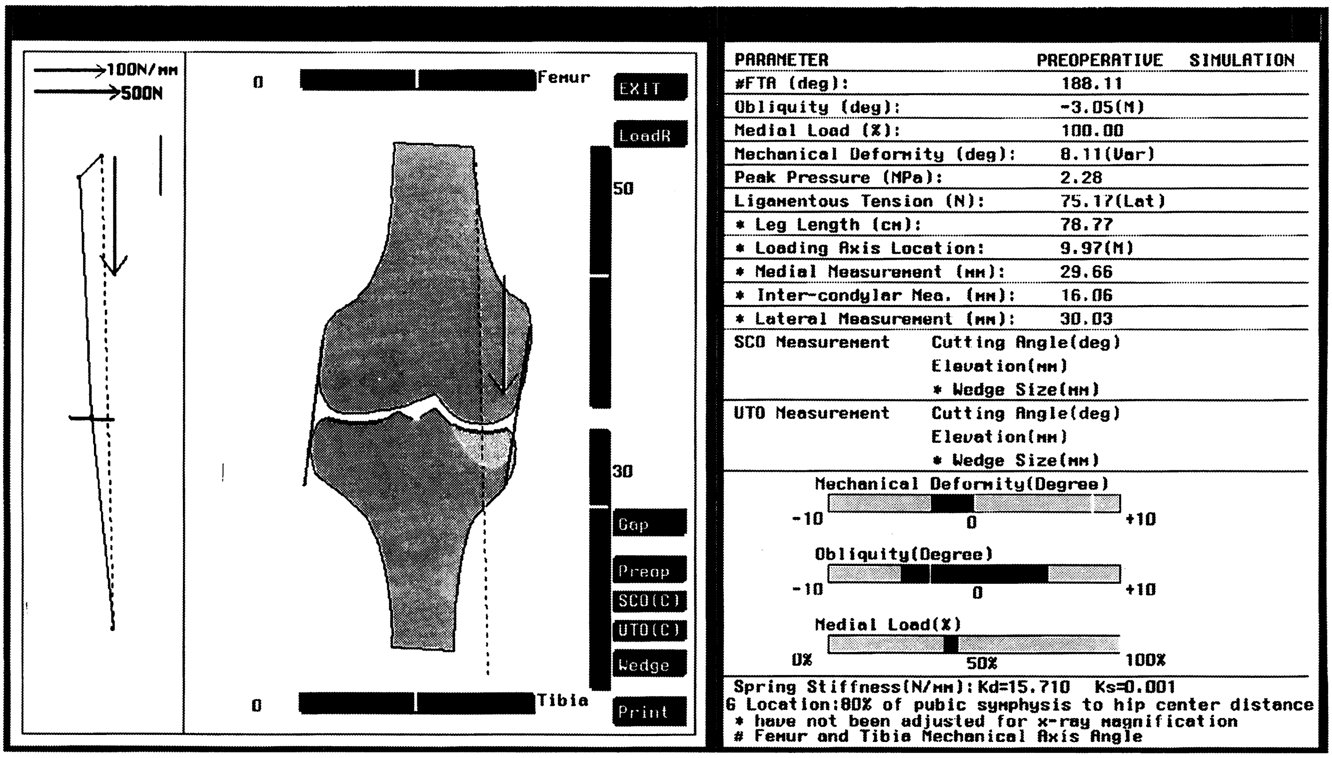
A. Preoperative conditions



PARAMETER		PREOPERATIVE	SIMULATION
#FTA (deg):		188.11	188.11
Obliquity (deg):		-3.05(M)	-3.05(M)
Medial Load (%):		100.00	100.00
Mechanical Deformity (deg):		8.11(Var)	8.11(Var)
Peak Pressure (MPa):		2.28	2.28
Ligamentous Tension (N):		75.17(Lat)	75.17(Lat)
* Leg Length (cm):		78.77	78.77
* Loading Axis Location:		9.97(M)	9.97(M)
* Medial Measurement (mm):		29.66	29.66
* Inter-condylar Mea. (mm):		16.06	16.06
* Lateral Measurement (mm):		30.03	30.03
SCO Measurement	Cutting Angle(deg)		0.00
	Elevation(mm)		50.00
	* Wedge Size(mm)		0.00
UTO Measurement	Cutting Angle(deg)		14.00
	Elevation(mm)		30.00
	* Wedge Size(mm)		21.80

Spring Stiffness(N/mm): Kd=15.710 Ks=0.001
G Location:80% of pubic symphysis to hip center distance
* have not been adjusted for x-ray magnification
# Femur and Tibia Mechanical Axis Angle

B. Simulated postoperative results with a 14° wedge at the upper tibial region



PARAMETER	PREOPERATIVE	SIMULATION
#FTA (deg):	188.11	
Obliquity (deg):	-3.05(M)	
Medial Load (%):	100.00	
Mechanical Deformity (deg):	8.11(Var)	
Peak Pressure (MPa):	2.28	
Ligamentous Tension (N):	75.17(Lat)	
* Leg Length (cm):	78.77	
* Loading Axis Location:	9.97(M)	
* Medial Measurement (mm):	29.66	
* Inter-condylar Mea. (mm):	16.06	
* Lateral Measurement (mm):	30.03	
SCO Measurement Cutting Angle(deg)		
Elevation(mm)		
* Wedge Size(mm)		
UTO Measurement Cutting Angle(deg)		
Elevation(mm)		
* Wedge Size(mm)		

Spring Stiffness(N/mm): Kd=15.710 Ks=0.001
G Location:80% of pubic symphysis to hip center distance
* have not been adjusted for x-ray magnification
# Femur and Tibia Mechanical Axis Angle

C. Wedge size and location simulation

surgeon. In addition, a joint gap in either compartment of the knee can be closed to compensate for weight-bearing effects causing the joint to open in severely deformed knees. It should be realized that this method is a static, two-dimensional analysis that assumes that an improved redistribution of joint forces in the standing position will be beneficial to the patient during dynamic knee performance. Experimental and analytical studies have been performed to validate this model[29]. Large numbers of normal and clinical case studies have been investigated to evaluate the efficacy of this program[28]. The value of this method of preoperative planning on the final clinical outcome of patients undergoing osteotomy is being prospectively studied.

APPLICATION OF OASIS TO KNEE OSTEOTOMY PATIENTS

The 2D models for the knee were constructed using normal subjects' and patient' plain radiographs in standing posture. Static force analyses were performed based on estimated muscle/tendon contractions and measured external loading. The RBSM was used to predict joint pressure distribution by assuming that bones are rigid bodies and that joint cartilage constitutes a series of elastic springs.

Using a normal database, the analysis software ("OASIS" Osteotomy Analysis and Simulation Software) was expanded for osteotomy preoperative planning. An osteotomy affects the leg alignment, muscle force direction, muscle length and weight bearing areas of joints. These are all biomechanical factors which play an important role in preoperative planning to improve long term osteotomy results[11]. However, it is impossible to quantify the effects of osteotomy on all of these biomechanical factors using conventional methods, such as cutting and pasting sections traced from radiographs by hand. This practical and easy to use computer program is capable of analyzing each patient's preoperative condition and interactively generating the optimal surgical procedure[21].

This software has been used to provide clinical service in over 375 cases analyzed by the principal investigator. It is important to note that intrinsic pathomechanical changes in articular cartilage depend upon local stress levels rather than global joint loading. The stress within the joint cartilage is not only determined by the magnitude and direction of the contact force but also by the size and shape of the articular surface. Therefore, it is essential to estimate the pressure distribution on the joint and the peak values before and after the osteotomy simulation; this is accomplished using the RBSM technique. With this software, bone geometry and loading conditions can be changed according to the osteotomy procedure. The calculated pressure distribution is then displayed in three dimensions super-imposed on the geometry of the articular surface. In many cases, such analysis has proved to be helpful. Example cases are used to demonstrate the potential utility of such software (Figure 9). The computer-aided osteotomy type and wedge angle location are also available in the general output of the program.

In an unpublished study to determine the significant factors which indicate whether an osteotomy candidate should receive an upper tibial osteotomy (UTO) or a supracondylar osteotomy (SCO), 266 knees with unicompartmental osteoarthritis and varus deformity were analyzed using OASIS. The optimal criteria used to select osteotomy type and wedge angle were: 1) medial plateau force, 40 ± 2% of the total knee joint force, 2) joint obliquity $\leq \pm 3°$, and 3) minimal collateral ligament tension. The type of osteotomy selected based on the optimal criteria was correlated with key parameters (FTA - femorotibial angle based on mechanical axis, joint peak pressure, plateau line obliquity, ligament tension and joint loading axis location) using unpaired t-tests and ANOVA. There was a significant correlation between the pre-operative joint obliquity and the type of osteotomy (UTO/SCO) that provided acceptable results[11]. UTO was most suitable for mean pre-operative joint obliquity of 1.9° (medial tilt) and a mean FTA of 5.9° varus. SCO was necessary for mean pre-operative joint obliquity of 2.7° (lateral tilt) and a mean FTA of 7.5° varus. Cases requiring a double osteotomy were those having an average preoperative FTA of 11.3° varus. In this study, it was concluded that use of the FTA (mechanical or anatomical axis) and lower extremity loading axis alone cannot satisfactorily predict optimal results since they do not correlate with joint obliquity, the key determining factor based on the current analysis.

DISCUSSION

One goal of reconstructive surgery in orthopaedics is to realign the appendicular skeleton so that the related joints can transmit physiologic pressures without causing high contact stress induced osteoarthritis. In the hip, femoral head coverage has a significant effect on cartilage degeneration and joint dislocation, especially among patients with developmental dysplasia of the hips. Proximal femoral and/or pelvic osteotomies have demonstrated excellent clinical results, alleviating pain and mobility limitations in affected patients. Unicompartmental joint disease of the knee is a common condition among middle aged men and women. It also affects a large population in Asia due to their style of activities of daily living. Joint deformity and pain often prevent these otherwise healthy individuals from enjoying life and being productive. Performing limb/joint alignment surgery redistributes knee joint stress between the diseased and the unaffected compartment to allow normal functional use of the knee. Knowing how to perform such procedures and determining the appropriate angular corrections are key factors for successful treatment outcome. Longevity of excellent clinical results also correlates closely with the site and amount of surgical correction. Hence, a careful preoperative planning guide for this type of procedure saves surgeons' time by providing various surgical options and potentially improving postoperative results.

The biomechanical justification of knee osteotomy is that it will realign the lower extremity weight bearing axis and unload the affected tibial plateau thus relieving the compartment pressure. Pain may be relieved thereby allowing functional recovery in patients with unicompartmental arthritic involvement. However, in the preoperative preparation of the procedure, the magnitude, type and location of the osteotomy to be performed are often difficult to determine as each patient may have a different deformity with widely varying pathologic involvement. It has been well demonstrated that even a small amount of angular change in knee alignment can drastically alter joint pressure distribution, which may negate the therapeutic effect of such a reconstruction procedure. In addition, the effects of soft tissue tension, joint line obliquity and upper body gravity shift on knee plateau pressure distribution may also influence the long term result of osteotomy. Thus, manual planning and visual inspection on preoperative radiographs can be inadequate. In addition, key information such as joint load distribution, joint pressure, joint line obliquity, etc., will not be available. For these reasons, an Osteotomy Analysis Simulation Software (OASIS) program was developed to provide comprehensive presurgical planning of knee osteotomy, so as to provide all rational options for surgeons.

An analytical model is derived based on the AP standing radiograph of the patient's lower extremities, covering the hip and ankle joints. The joint centers, mechanical and anatomical axes of the femur and tibia, patella center, joint contour outline, muscle and ligament insertion points, and joint articular surface contact area are manually digitized on a translucent, background-lighted electrostatic digitizer. In this model, muscle, ligaments, and joint cartilage are represented by a series of linear springs, while the bone segments are assumed to be rigid bodies. Body weight, muscle contraction, ligament and cartilage stiffness properties, and the upper body gravity location are the input data for the simulation analysis. The entire digitizing procedure and model analysis takes approximately 40-60 minutes.

The computer program is interactive with graphic display and tabulation of analysis results for any simulated osteotomy. Input parameters and osteotomy wedge angle and location are introduced using a mouse or a keyboard guided by clear menu instructions on the monitor screen.

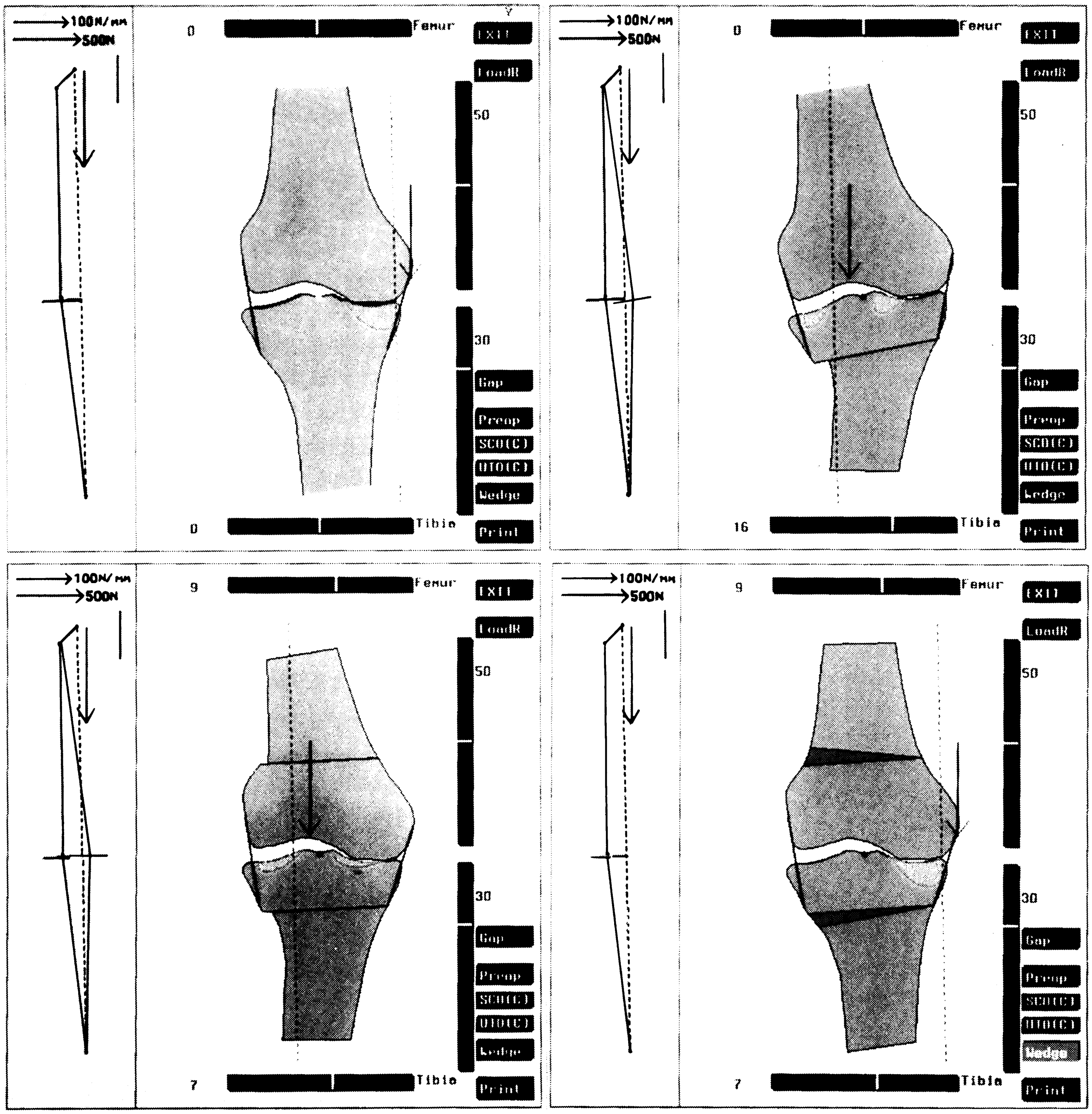


Figure 9 A difficult bilateral double osteotomy case of a man with large varus deformity in both knees.

Figure 9A. Computer-aided preoperative planning on his right knee showing single upper tibial osteotomy will be inadequate to correct the alignment and joint pressure distribution when compared to the double osteotomy;

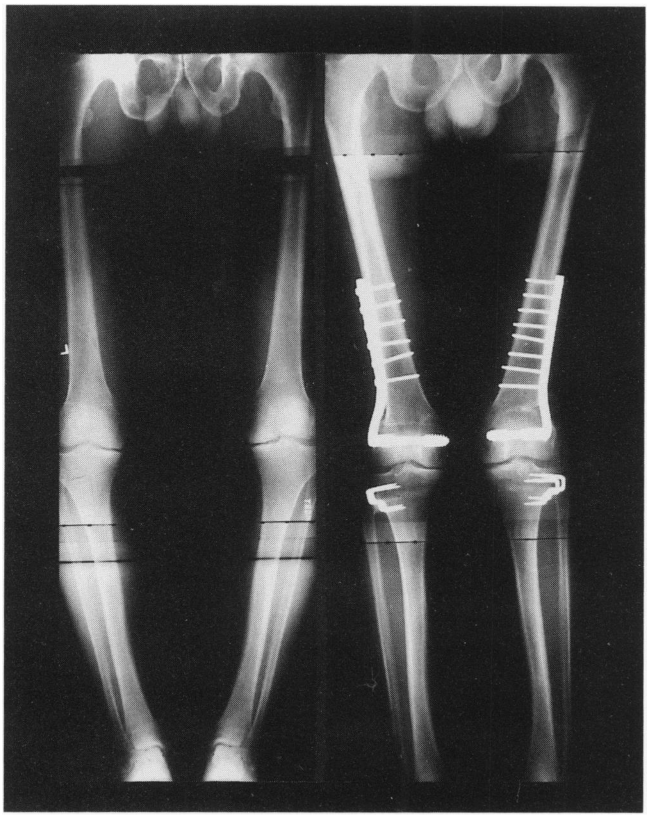


Figure 9B. The pre and postoperative radiographs of this patient.

Upper tibial and supracondylar osteotomies at the usual level of proximal tibia and distal femur are routinely provided, while additional options of closed-wedge, open-wedge or dome/barrier type of osteotomy at any level of the long bones can be easily performed. The output of the program includes tibiofemoral angle based on both mechanical and anatomic axes of the femur and tibia, percent of joint force passing through the medial plateau, peak joint pressure, joint shear force, collateral ligament tension, joint line obliquity analysis, joint loading axis (the line joining the hip and ankle center), location in reference to tibial plateau width, and the lower extremity length change. The osteotomy size measured along the bone surface is also provided based on the estimated x-ray magnification using proper markers on the radiograph. These truly provide unprecedented information required to achieve reliable and relevant preoperative planning in knee osteotomy as the surgeon is not limited to the specific type of osteotomy.

Large normal data base and clinical case follow-up analyses are being conducted to study the efficacy of this program. Experimental and analytical studies should also be performed in order to validate the model. The true value of this simulation program must await the clinical and functional results of prospective studies conducted in different institutions involving large patient populations. Thus far, the program has saved an enormous amount of time in providing preoperative planning while the information provided to the surgeons has been utilized with great enthusiasm. It is important to realize that the current analysis is static, two-dimensional, and based on the fundamental assumption that improved joint force redistribution under standing posture will carry its therapeutic effect to the dynamic performance of the knee. Without this assumption, the current analysis is invalid. From a practical point of view, such an assumption is essential as with all reconstructive procedures in orthopaedics. Finally, various indicators have been suggested to predict the outcome of knee osteotomy[50]. Unfortunately, these indicators cannot be used to obtain the optimal osteotomy wedge. Therefore, the true utility of such indicators is questionable. However, they may provide unique value in assessing the functional outcome of these patients before and after the reconstructive surgery.

SUMMARY

We believe the osteotomy should play a major role in the knee surgeon's armamentarium. Long term satisfactory results can be obtained in well-selected patients with unicompartmental degenerative arthritis of the knee associated with malalignment. The success of this procedure is highly dependent on selection of the patient with appropriate surgical indications. Surgical technique must be precise and based on accurate preoperative planning. Knee osteotomy, regardless of its type and location, performed with modern technological tools, should provide satisfactory long term clinical results in the majority of patients. If the osteotomy is properly performed with careful planning, the patient can expect a relatively uncomplicated conversion to a prosthetic replacement when increasing knee symptoms require further surgical intervention. Based on the unique pathomechanics involving osteoarthritis and the success demonstrated in recent studies, knee osteotomy has met original expectations and continues to be a viable option. In severely deformed knees, a single osteotomy at high tibial or femoral supracondylar regions may not be able to correct the alignment and maintain proper joint line obliquity. A complex dual osteotomy may be necessary to achieve proper knee alignment and provide the essential requirements for appropriate pressure redistribution in the knee joint. A computer-aided preoperative planning software package like "OASIS" can help to produce surprisingly positive clinical results for these different reconstructive procedures. Long term prospective follow-up studies of patients are required to validate the effectiveness of this preoperative planning scheme and are now in progress. When such methods are properly established, the surgeon should be even more confident in performing osteotomies about the knee for the treatment of unicompartmental knee degenerative disease. This allowed definitive treatment for patients with early osteoarthritis in the knee. Such procedures should be considered first before other more aggressive joint replacement procedures are performed.

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