Four Bar Linkage Knee Analysis

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INTRODUCTION

Modern prosthetists have a wide selection of prosthetic knees to fulfill many individual specifications. The names "friction," "safety," "lock," "hydraulic," etc. quickly recall particular classes of single axis knees. For these single axis knees, the name (friction, safety, etc.) simply states a unique feature which defines the major mechanical advantage of that class of knees.

Polycentric knees, however, may present the prosthetist with confusion. This confusion results from the fact that the term "polycentric" does not define any specific function. Secondly, these knees require more than a simple knowledge of mechanics to fully understand their functions.

This paper will examine one category of polycentric knees which are known as "four bar linkages." Simple methods for evaluating these knees will be presented. These evaluating methods will enable the prosthetist to determine the major mechanical or cosmetic advantage of most four bar designs. The prosthetist will also learn comparative methods of evaluating the efficiency of a particular four bar design in attaining its specific mechanical or cosmetic goals. This skill is extremely important since each four bar design is unique in its operation. Specifically, each four bar knee has been designed to enhance individual characteristics such as safety, cosmesis, energy conservation and/or swing phase motion.

DEFINITION OF TERMS

1. *Translation* or *translational motion* is the movement of a machine element along a straight line.

2. *Rotation* or *rotational motion* is the movement of one element of a mechanism about a pivot point.

3. *Center of Rotation* is the point about which rotational motion occurs. This may be an actual mechanical pivot point on the mechanism or a purely hypothetical point which may or may not actually be on the mechanism.

4. *Single Axis Knee*—Any knee in which the shin moves in pure rotation about a

constant center of rotation located at the knee bolt.

5. *Polycentric Knee*—Any knee whose design allows the shin to move in a combination of rotational and translational motion. At any given instant of time, this combination can be mechanically described as a purely rotational motion about a constantly changing center or rotation known as the instantaneous center of rotation.

6. *Instantaneous Center of Rotation* (or Instant Center)—The point about which a particular element (shin) may be *assumed* to be moving in pure rotation at any given instant of motion being analyzed. For a single axis knee this will be a constant point at the knee bolt center. For a polycentric knee this will be a theoretical point in the plane of motion (sagittal plane).

7. *Four Bar Linkage Knee*—A specific class of polycentric knees. The knees are characterized by four elements joined at four separate points. The four elements include the thigh, shin and two links. (Note: In actual practice, a single link may be a pair of parallel links acting together. However, for mechanical purposes these pairs are considered as single links.)

Fig. 1A is a typical four bar linkage knee. The thigh is considered as a link or bar joining points B and E. This link is defined $\overline{BE}$. The shin is considered as a link joining points C and D. This link is called $\overline{CD}$. Link BC and ED join the shin to the thigh. Together, all four links join at four points to complete the four bar linkage. Fig. 1B is a kinematic schematic representation of the knee seen in Fig. 1A which shows this typical link arrangement.

STABILITY IN STANCE PHASE OF A FOUR BAR LINKAGE KNEE

Alpha (α) Stability—At this point it is assumed that the reader understands the basic theory of the T.K.A. (Trochanter-Knee-Ankle) line and the accepted T.K.A. alignment method of simple single

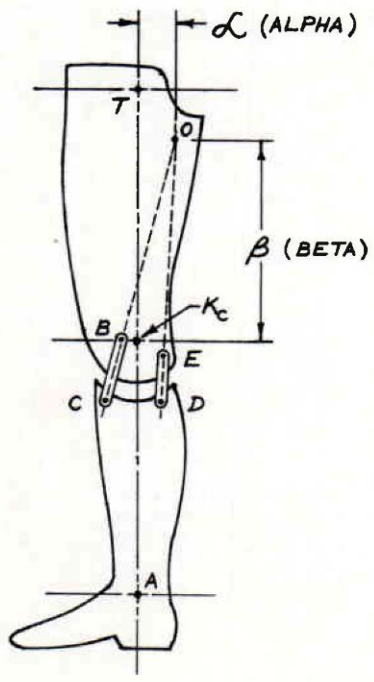

Fig. 1-A.

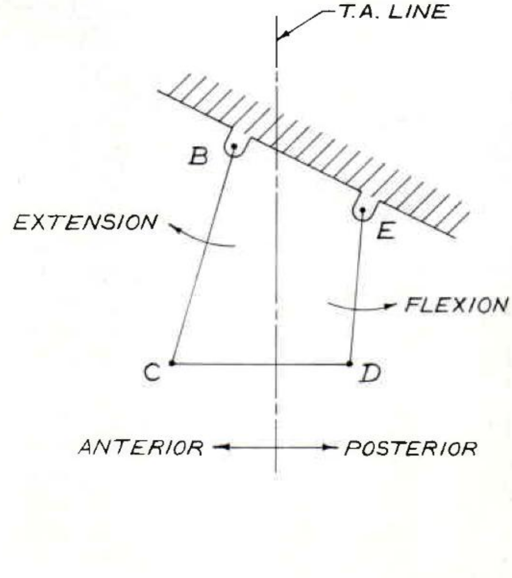

Fig. 1-B.

axis knee mechanisms. In this method the knee is made more stable (safer) by moving the knee center posterior to the T.A. (Trochanter-Ankle) line. Conversely, moving the knee center anterior to the T.A. line decreases weight bearing stability.

Stability of a four bar knee system is also determined by using the T.K.A. theory. The knee center becomes the theoretical "instantaneous center of rotation" in this case. This point must be determined for each position of the knee which is in question.

For static (bench) alignment purposes, the accepted knee position is that of full extension. With the knee fully extended the instantaneous center for rotation is determined by drawing a line through each of the two links joining the shin to the thigh (see Fig. 1A). The instantaneous center of rotation (point O) is the point where these two lines intersect. The stability of the system is determined by noting the position of this instant center in relation to the T.A. line. As in the single axis knee, the center of rotation must be posterior to the T.A. line to be considered as a stable weight bearing system.

At this point the reader's understanding of the "instantaneous center of rotation" and of four bar knee motion may be unclear; this confusion can be eliminated if one understands that a four bar knee is mechanically equivalent to a particular hypothetical single axis knee at any instant of motion being analyzed. This hypothetical knee has its knee bolt located at the instant center of the equivalent four bar knee. Fig.1C gives the single axis equivalent of the four bar knee depicted in Fig. 1A (at the full extension position only). Therefore, the motion and mechanical reaction of the four bar knee in Fig. 1A is precisely identical to that of the single axis knee seen in Fig. 1C at this position of extension. Often it is easier to understand the reaction of the four bar if one visualizes this instantaneous single axis equivalent rather than the actual four bar mechanism.

Since the instant center of a four bar is changing through each position of flexion, the equivalent single axis knee will also be different for each position of flexion. Therefore, care must be taken to analyze the four bar mechanism at the exact angular position which is in question.

A simple method of estimating the instantaneous center of rotation of an actual four bar knee mechanism would be to lay two straightedges along the links and note the point of intersection. A third straightedge could be aligned with the trochanter and ankle center to simulate the T.A. line. Stability of the system is estimated by measuring the distance from the T.A. line to the instant center. For the sake of this discussion, this distance will be defined as "α" (alpha). A positive α value is defined as a knee center which is posterior to the T.A. line. This is a stable or "positive α stability" condition. A negative α value indicates an unstable system with the knee center anterior to the T.A. line.

At this point it is interesting to compare a prosthesis with a single axis knee to the four bar knee prosthesis seen in Fig. 1A. The single axis knee has an $\alpha = 0$ value at

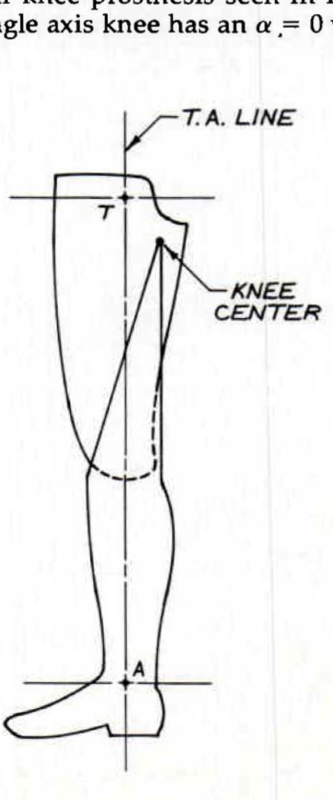

Fig. 1-C.

full extension. As it begins to flex, α becomes negative and progressively more unstable as flexion continues. The special four bar knee in Fig. 1A has a positive α value at full extension. As flexion begins, the value becomes smaller but it remains *positive* for the first few degrees of flexion. Obviously, this knee was designed to have enchanced stance stability and therefore could accurately be called a "four bar safety knee."

Beta (β) Stability—A second and unique condition affecting knee stability exists with all four bar knee mechanisms. Referring to Fig. 1A, it is noted that the instantaneous center of rotation is superior to the level of the mechanical (or cosmetic) knee center (point K_c). With this prosthetic knee the patient gains a mechanical advantage over a typical single axis knee. This mechanical advantage is gained in *two* ways as a result of raising the instant center.

Fig. 2A is a free body diagram of a typical above knee prosthetic shin shortly after heel strike. The force $\bar{L}$ is the axial component of load applied at the knee bolt by the thigh section. The force $\bar{E}$ is the force applied to extend the knee mechanism. This force is also applied by the thigh at the knee bolt. Forces $\bar{R}_v$ and $\bar{R}_h$ are the vertical and horizontal components of the floor reaction force. To analyze this situation, moments are summed to equal zero about the point "f" to yield the equation:

$$\bar{L}y = \bar{E}h \; (\sum M_f = 0)$$

It is noted that if the knee center is raised, the value of "y" and of $\bar{L}$ will remain unchanged. However, the value of "h" will increase and for the above equation to balance; the value of $\bar{E}$ will proportionately decrease. This simply means that the moment tending to cause knee buckling is reduced and therefore the patient uses less force, $\bar{E}$, to hold the knee in extension.

The second way in which knee stability is increased by raising the knee center is demonstrated in Fig. 2B. This represents a typical above knee prosthetic thigh. Force $\bar{W}$ and $\bar{I}$ are the loads applied to socket by the patient. (note: $\bar{W}$ and $\bar{I}$ are assumed to act on a point along the T.K.A. for this

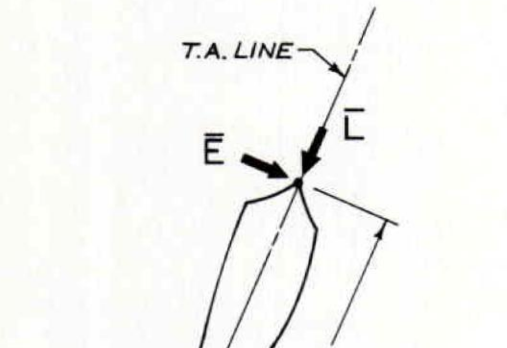

Fig. 2-A.

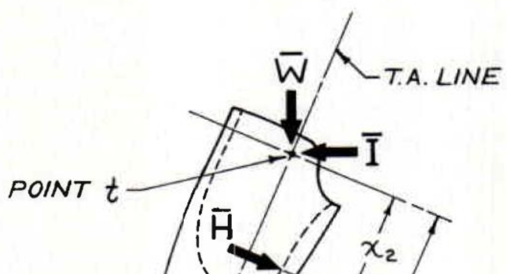

Fig. 2-B.

analysis. $\bar{L}'$ is the axial component of reaction force applied by the shin at the knee bolt ($\bar{L}'' = -\bar{L}$). $\bar{E}''$ is the force applied by the shin tendng to buckle the knee ($\bar{E}'' = -\bar{E}$). $\bar{H}$ is the extension force applied by the residual limb to hold the knee in extension. x_2 is the effective lever arm of the residual limb. To analyze this situation, moments are summed about the point "t" to equal zero:

$$\bar{H}x_2 = \bar{E}'x_1 \ (\Sigma\ M_t = 0)$$

It is noted that if the knee center is raised, the value of x_2 would remain constant. This condition would also decrease the value of $\bar{E}$ (reduce buckling force as seen above) and thus reduce the values of $\bar{E}'$ and $\bar{H}$ proportionately. It is also observed that x_1 would decrease in value creating a second way in which $\bar{H}$ would be proportionately decreased. This second advantage can also be described as increased leverage for the residual limb.

In summary, raising the knee center reduced the knee buckling moment and increases the patients leverage advantage in controlling that moment. With single axis knees these advantages would only be available by sacrificing the cosmetic appearance of bending at the anatomical knee center. This is not the case with a four bar knee mechanism. The four bar knee can give the cosmetic appearance of bending at the proper anatomical height while providing the added stability of a proximal instantaneous knee center. Fig. 1A depicts a typical four bar knee prosthesis and its anatomic (or cosmetic) knee center, $K_c \cdot \beta$ (beta) is the vertical difference between the anatomical knee height and the instantaneous knee center at full extension. The β value (or "β stability") gives a relative value of stability for comparing four bar mechanisms to each other and to single axis knees. β is measured positive if the instantaneous knee center is above the anatomic knee center, and conversely negative if this instant center is lower than the anatomical center.

The simple method outlined previously for determining the instant center will also yield β stability. By determining these values the prosthetist now has a guage for selecting a particular four bar mechanism when "safety" or "stability" are primary concerns. It is interesting to note that both α and β stability are permanently built into a prosthesis and do not require maintenance or adjustment as is typical of single axis safety knees. α and β stability are also independent of any extension aids, hydraulic mechanism, etc.

(WARNING: α and β stability are features of only *certain* four bar mechanisms which were originally designed for stability. Some four bar mechanisms may be designed for cosmetic or swing phase characteristics and therefore may have poor values of α and β stability.)

SHORTENING OF A FOUR BAR KNEE PROSTHESIS DURING SWING PHASE

With the standard single axis knee prosthesis a typical problem encountered is that of foot to floor clearance during swing phase. It is sometimes necessary to

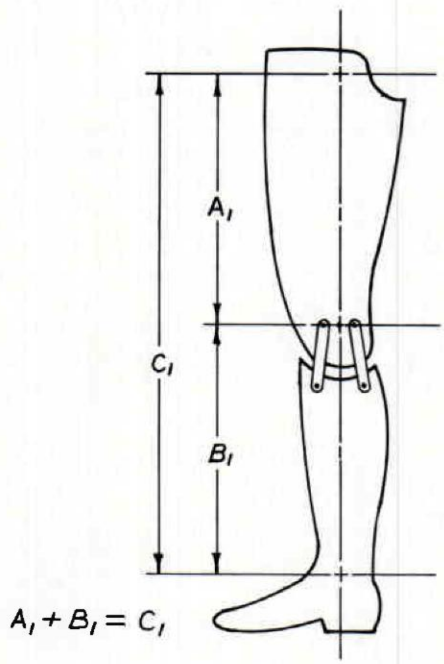

Fig. 3-A.

shorten the prosthesis excessively to provide floor clearance during swing phase. Certain four bar knees, however, actually shorten as they pass from full extension to flexion. This feature allows fabrication of a "full length" prosthesis which automatically "shortens" during swing phase, similar to the actual human knee joint.

Fig. 3A depicts a four bar knee at full extension. The thigh length is "A_1," and the shin length is "B_1." The overall prosthesis length is "C_1" as follows:

$$A_1 + B_1 = C_1$$

In Fig. 3B the mechanism is in the 65° flexion position,* which is generally accepted as the "mid swing" position. The value of $A_2 + B_2$ or C_2 has now decreased and therefore results in additional foot to floor clearance. The amount of overall shortening is defined as the "L" value:

$$L = C_1 - C_2 \text{ (at 65° flexion)}$$

L values for common four bar knee mechanisms are given in Table 1.

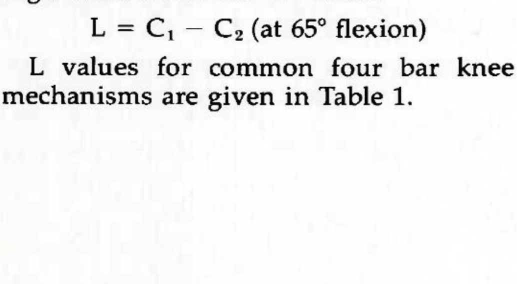

Fig. 3-B.

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ACCELERATION/ DECELERATION OF A FOUR BAR LINKAGE KNEE DURING SWING PHASE

Precise kinematic and dynamic studies of four bar knee units can be extremely complex. Therefore, this paper will not attempt to analyze the complex motion of these mechanisms by any quantitative means. In lieu of a detailed analysis, a general qualitative examination will be presented.

Basic single axis knees with mechanical friction and spring assisted extension are essentially "linear" in their response during swing phase. The term "linear" applies a "constant" or "constant rate of change" of some property of the system. The mechanical friction is constant regardless of knee position or velocity. The spring assisted extension assist constantly increases (approximately) as knee flexion increases. The extension assist is also independent of knee velocity. Both of these features are adjustable to allow "tuning" or the swing phase characteristics of "heel rise" at "toe off" and impact at full extension.

Often it is impossible to suit a particular patient's gait pattern by tuning a basic single axis knee. Adjustment of friction or extension may cure one problem only to create another. Although both heel rise and terminal impact may finally be adjusted to prosthetic tolerances, the result may be a system that requires excessive effort by the patient. In this case, the patient often insists that the system be adjusted to suit his requirements for ease of flexion at the sacrifice of smooth operation.

Four bar knees are nonlinear in their operation. As the position of the shin changes, acceleration (deceleration) vary relative to position. This variance can be nonlinear depending on the design of the four bar mechanism. Therefore, it is possible to design a knee with motion characteristics similar to normal human knee motion. For example, certain four bar knee designs have built-in terminal deceleration which requires no use of mechanical friction or other devices.

To understand the acceleration-deceleration of a four bar mechanism the shin can be compared to the pendulum of a pendulum clock. By lowering the weight on the pendulum, the effective pendulum moment arm is lengthened. This adjustment slows the pendulum movement. Raising the weight conversely increases the speed of the pendulum. In the four bar knee the "pendulum moment arm" is increased as the instant center moves proximally during flexion. This action slows the shin movement and causes the deceleration phenomenon. Conversely, as the instant center moves distally, the shin accelerates.

As stated above, the precise quantitative analysis of a four bar motion is very difficult. However, the prosthetist can observe the operation of these knees and then make certain qualitative judgments regarding the swing phase characteristics of a particular mechanism. Terminal deceleration and response time (from "toe off" to full extension) are two characteristics which are very easy to observe. These observations can be made by either manually swinging the knee mechanism or by actual testing on a patient.

It should be noted that hydraulic and pneumatic knee mechanisms are also considered "nonlinear" in their operation. However, this nonlinearlity is not the same as that of a four bar mechanism. Hydraulic and pneumatic knees respond nonlinearily to different *velocities of operation*. This is not the case with four bar mechanisms. Four bar mechanisms are nonlinear with respect to shin position; not velocity. If a four bar mechanism is desired which automatically adjusts to varied gait speed, that mechanism must incorporate a hydraulic or pneumatic unit.

ADVANTAGES OF A FOUR BAR KNEE IN THE SITTING POSITION

General case—A sitting advantage of a four bar knee is the effective shortening of the shin as it passes into flexion. This feature was noted above as a swimg phase benefit of a four bar prosthesis which simulated the motion of the actual human knee joint. This advantage also gives the unilateral above knee amputee the visual appearance of legs with matching knee heights when sitting.

For tall amputees, an excessively long shin can cause clearance problems when sitting at desks or tables. In addition, when sitting on low chairs the tall amputee is forced into an uncomfortable position of excessive hip flexion. The four bar knee reduce both of these problems by the shortening action of the shin when sitting.

The "L" value was defined above at 65° knee flexion to provide a comparative method of analyzing shortening of a prosthesis. If the same calculation is made at 90° of knee flexion, the value obatined would be the effective shortening of the prosthetic shin when sitting. This value is defined as the "S" value. S values for common four bar knees are listed in Table 1.

$$S = C_1 - C_2 \text{ (at } 90° \text{ flexion)}$$

(see Fig. 3A and 3B)

Special Case-Knee Disarticulation—Conventional single axis knees present a particular cosmetic problem when fitting long above knee or knee disarticulation amputations. With these amputations, it is impossible to fabricate a prosthesis with a knee center at the anatomical height unless outside joints are used. However, outside joints have no friction adjustment, are not durable, and increase knee width. The distal end of the socket can only be placed wihin ½ to 2¼ inches proximal (depending on the particular knee mechanism) to the knee bolt center when a conventional above knee joint is used. In the case of knee disarticulation this could require lowering the prosthetic knee center approximately 2 to 4 inches below the anatomical (cosmetic) knee center, resulting in an excessively long thigh and short shin components. This condition is cosmetically unsightly when sitting and causes clearance difficulties when sitting in confined areas such as the rear seat of small automobiles.

With certain four bar knee designs it is possible to place the distal end of the socket

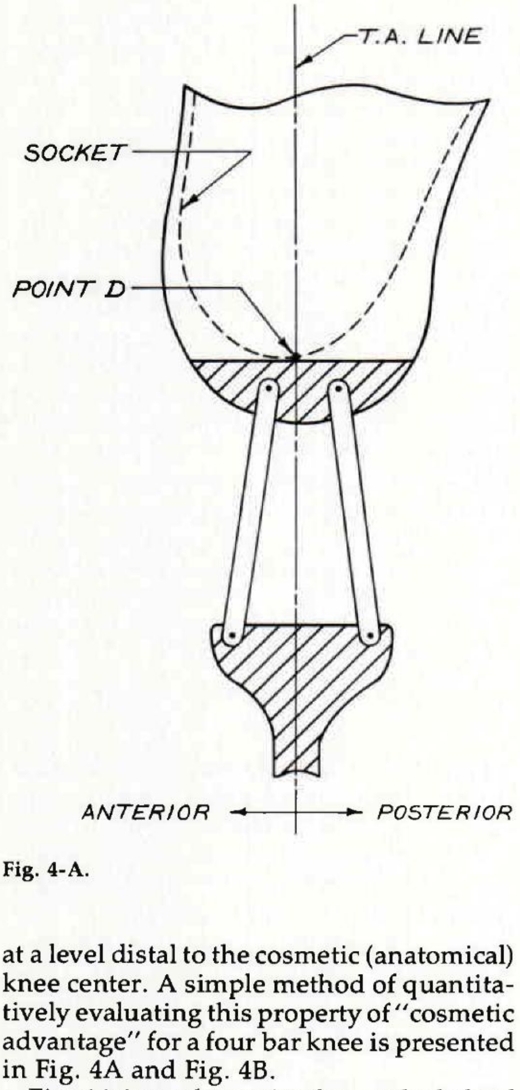

Fig. 4-A.

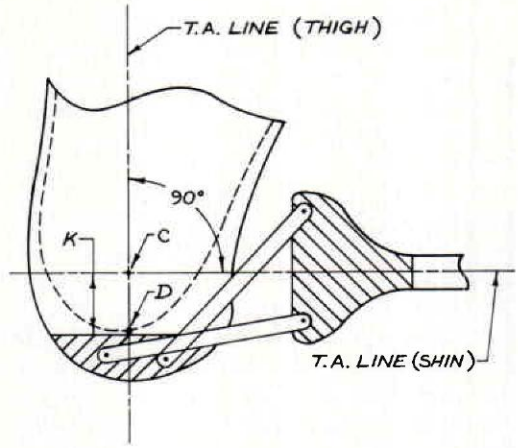

Fig. 4-B.

at a level distal to the cosmetic (anatomical) knee center. A simple method of quantitatively evaluating this property of "cosmetic advantage" for a four bar knee is presented in Fig. 4A and Fig. 4B.

Fig. 4A is a schematic of an endoskeletal four bar knee mechanism that has been designed to have the aforementioned "cosmetic advantage." The point D is the most distal position at which the socket can possibly be placed along the T.A. line. With the knee mechanism fully extended, the T.A. line is noted on both the shin and thigh. The point D is also noted. The knee mechanism is then flexed 90° as seen in Fig. 4B. The point at which the shin T.A. line and the thigh T.A. line intersected is noted and defined as point "C." Finally, the distance from point C to point D is measured and this value is defined as "K" or the "K factor." If the point D is distal to the point C, the K factor is positive. If the converse is true, the K factor is negative. A positive K factor indicates a "cosmetic advantage" over single axis systems (Note: C is the "Cosmetic Knee Center").

All single axis knee shin units have negative K factor values ranging approximately from minus ½ to minus 2½ inches. Outside joints, however, have a positive K factor value that can be as large as necessary.

Table #1 lists K factors for the most common four bar linkage knees. Those knees with a positive K factor would give the best cosmetic knee center for knee disarticulation amputations. Those knees with negative K factors would tend to be undesirable cosmetically for knee disarticulation amputations.

Positive K factors and L values are not the only property affecting true cosmetic analysis of a four bar knee. Each mechanism must be judged by the individual prosthetist to determine the ease of finishing or the general appearance of the finished prosthesis. Certain four bar mechanisms may have positive K factors but may be difficult to finish-fabricate with an acceptable cosmetic appearance.

TABLE 1 (VALUES IN CENTIMETERS)						
FOUR BAR KNEE		$\alpha_{0°}$	$\beta_{0°}$	$K_{0°}$	$L_{65°}$	$S_{90°}$
OTTO BOCK-HABERMAN 3R20 (WITH 4R41 ATTACHMENT)	LEAST STABLE	0.3	10.2	-3.6	1.5	1.4
	MOST STABLE	6.7	18.3	-3.3	0.8	0.6
OTTO BOCK 3R21 FOR KNEE DISARTICULATION		-0.3	4.5	1.4	3.7	4.5
ORTHOPEDIC HOSPITAL IN COPENHAGEN (O.H.C.) BY UNITED STATES MANUFACTURING CO. (5M100)		3.0	9.3	1.2	2.5	2.7
UNITED STATES MANUFACTURING COMPANY'S SMALL POLYCENTRIC KNEE DISARTICULATION (5M-105)		-0.2	10.5	-3.4	0.7	-0.1
HOSMER 4-BAR POLYCENTRIC KNEE (70507) (EXOSKELETAL)		2.6	-0.2	0.0	1.4	2.4
POLYCADANCE AK-4		NOT AVAILABLE AT TIME OF PRINTING				
TEH-LIN TK-4000 (ALL TEH-LIN FOUR BARS ARE IDENTICAL)		10.4	30.0	-4.0	0.9	0.5
POLYMATIC (EXOSKELETAL)		5.5	29.8	-?	2.3	2.4

Table #1 was composed using methods which are graphical. Therefore the values derived are subject to a wider margin of error than purely calculated values. Manufacturers should be consulted for more precise data.

The values tabulated were measured using the methods described above. The T.A. line was *assumed* to be a line passing through the foot bolt and the center of the pylon or shin unit. This assumption was made simply to provide a uniform method of evaluating and comparing four bar knee designs. This T.A. line should not necessarily be used for alignment purposes. For this purpose the manufacturer's instructions should be strictly followed.

The Polymatic and Polycadance knees are not in production at this time but are included to show the uniqueness of each four bar design.

Certain knees can be tilted in the sagittal plane. This feature allows some adjustment of α and β values by moving the instant center relative to the T.A. line. The values tabulated in Table #1 were measured with all knees in the vertical position (no tilt).

The Otto Bock 3R20 knee has an adjustable extension stop which adjusts all of the values listed. Therefore the least stable and most stable positions are listed to show the full range of adjustment.

ENERGY CONSUMPTION WITH FOUR BAR KNEE MECHANISMS

The amputee consumes energy during ambulation through muscular activity. This muscular activity develops the forces necessary for ambulation. It is the goal of the prosthetist to eliminate unproductive forces and minimize the productive forces required of the patient. This results in a proportional decrease in the energy loss of the patient during ambulation.

It was shown above that α and β stability reduce the force required from the patient to maintain extension during the early part of stance phase. This force reduction results in a directly proportional energy savings and therefore, α and β give a relative means of evaluating this energy loss.

It was noted that the four bar knee prosthesis can shorten as it passes from extension to flexion. This feature eliminates energy losses due to gait defects such as "hip hiking," "vaulting," "circumducting," etc. This feature also eliminates the need for excessive shortening of the prosthesis. The amount of prosthetic shortening causes a directly proportional energy loss. Moving the patient's mass center up and down during each full cycle of gait is the source of this loss. Therefore, the L value gives a relative means of analyzing the reduction of this particular energy loss.

The special acceleration-deceleration properties of certain four bar mechanisms also contribute to energy savings. The efficient operation afforded by these knees reduces the need for mechanical friction. Since mechanical friction is an energy consuming phenomenon, this furnished an additional means of energy conservation for certain four bar knees.

Finally, the acceleration and deceleration of a four bar knee are relative to knee position. In effect, these properties are perfectly timed controls occuring only at the position at which they are required. The precision and efficiency thus provided can also serve as a source of energy savings.

CONCLUSION

Four bar knee mechanisms can provide the prosthetist with a selection of knee characteristics which were previously unavailable with a single axis knees. The prosthetist should, through simple analysis of any four bar mechanism, be able to define the unique qualities or advantages of that knee mechanism. With this skill the prosthetist can confidently select a four bar knee to meet the specific needs of an individual prosthetic patient.

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