Knee Orthoses: Biomechanics[1]

Charles H. Pritham, C.P.O.[2]

Irrespective of etiology, deformities of the knee can be divided into three broad categories: angular (genu valgum, genu varum, genu recurvatum), rotary (internal, external rotation of the tibia relative to the femur), translatory (anterior/posterior subluxation of the tibia relative to the femur). They can be further categorized as either flexible (secondary to flaccid musculature and/or ligamentous and capsular laxity) or fixed (secondary to spastic musculature and/or ligamentous and capsular tightness). For a variety of reasons orthotics has traditionally devoted the majority of its attention to cases of angular deformity and coped with instances of rotary or translatory deformity only secondarily as they arise as complications of angular deformity. For that reason, then, the majority of discussion will focus on this aspect of the situation.

Viewed in the frontal plane (the case is the same in the sagittal plane) with the body aligned so that the weightbearing line coincides exactly with the mechanical axis of the leg (Fig. 1), there is no tendency for the knee to bend into either genu valgum or genu varum. If the weightbearing line deviates to one side, a bending moment or torque is created (Fig. 2) that causes a change in angle (angle of deformity, 0) of the femur relative to the tibia. The bending moment can be quantified by multiplying the deforming force (body weight, W) times the perpendicular distance (x) from the line of action to the center of rotation. As body weight is essentially constant, any increase in angle of deformity will lead to an increase in distance x and an increase in the deforming moment. In real life this tends to create a vicious circle since the deformity is resisted by the capsular and ligamentous elements on the opposite side of the knee. The stress is greatest on those elements farthest away from the center of rotation, as they are best positioned by virtue of their longer lever arm to oppose the deforming force. When the stress becomes intolerable, they yield, and the load falls on elements less strategically placed. As the angle of deformity increases, distance x increases, the deforming moment increases, and a compromised knee is jeopardized further. To correct this situation and prevent further damage, it is necessary to introduce a corrective moment and reduce the angle of deformity.

This corrective moment is created by a three-point pressure system (Fig. 3). For the laws of equilibrium to be satisfied, the forces acting on each side of the structure must be equal, and the clockwise moments acting about the center of rotation must be equal to the counterclockwise moments. The farther forces H and A

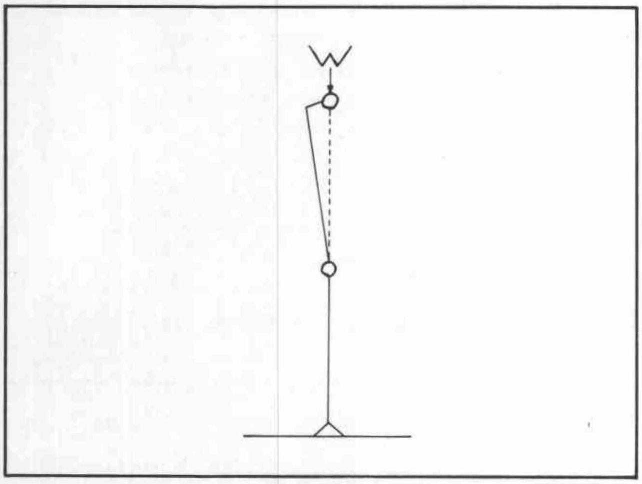

Fig. 1. Lower limb positioned so that weightbearing axis falls through the mechanical axis of the limb.

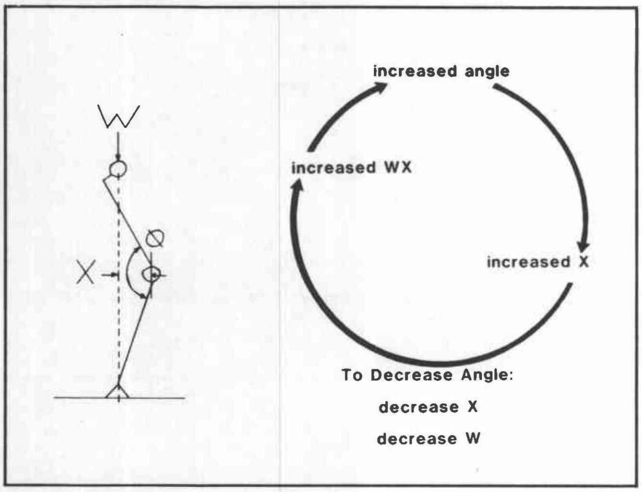

Fig. 2. As the weightbearing axis deviates to one side a bending moment or torque is created.

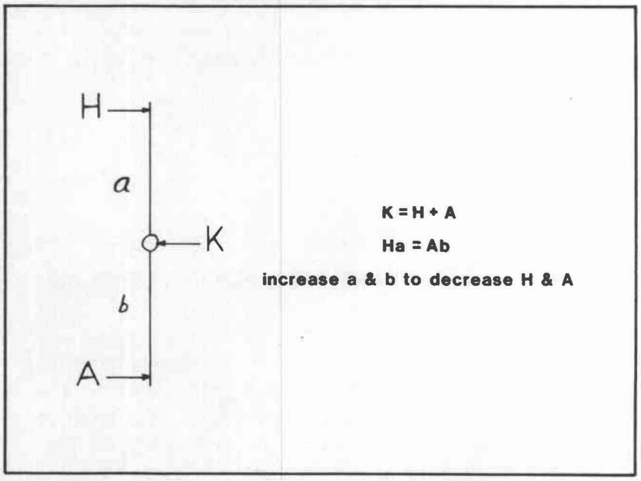

Fig. 3. Three-point pressure system acting about the knee.

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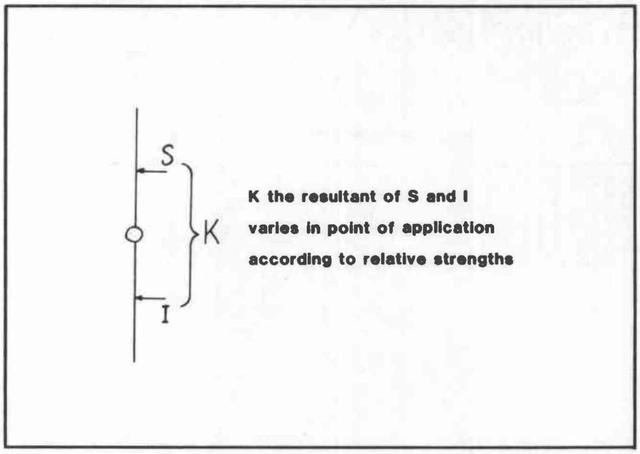
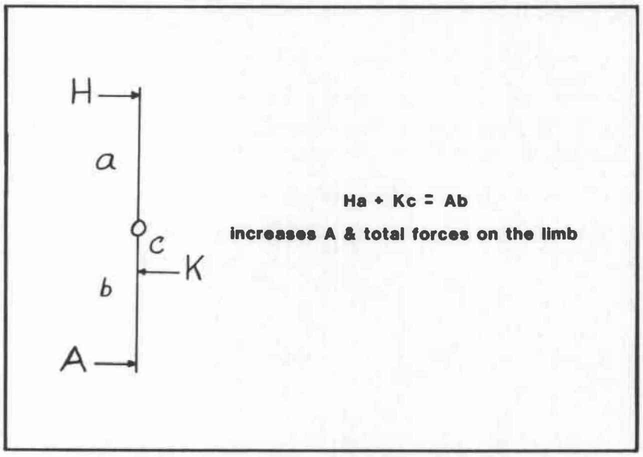
[2] Formerly Director, Prosthetics and Orthotics Laboratory, Rehabilitation Engineering Center, Moss Rehabilitation Hospital, Philadelphia. Presently Branch Manager, Snell's of Louisville.



K the resultant of S and I varies in point of application according to relative strengths

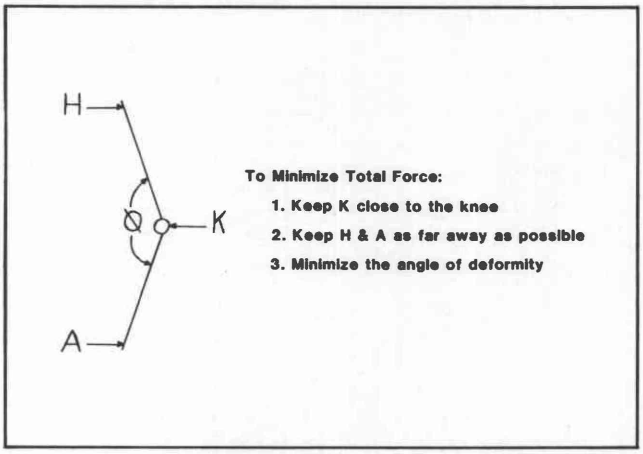
Fig. 4. Force K acting as two sub-forces, S and I.



$Ha + Kc = Ab$

increases A & total forces on the limb

Fig. 5. As force K moves away from the knee the total force on the limb increases.



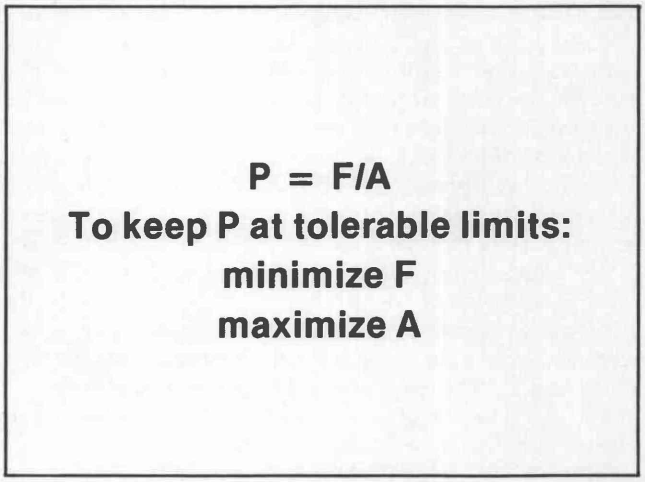
To Minimize Total Force:

1. Keep K close to the knee
2. Keep H & A as far away as possible
3. Minimize the angle of deformity

Fig. 6. A summarization of criteria necessary to minimize the force on the limb.

are from the center of rotation, the smaller they can be, due to increased lengths of their lever arms a and b. Force K can seldom be applied directly at the center of rotation (Fig. 4), as the anatomical structures vary in their ability to tolerate the pressure. It may very well prove necessary to locate force K some distance from the knee and apply it as two sub-elements, S and I. K would be equal to the sum of the two and vary in point of application according to their relative strength. As K moves away from the center of rotation (Fig. 5), it increases the bending moment acting in one direction or another, and if the laws of equilibrium are to be satisfied, the opposing moment will have to increase in magnitude, leading to an increase in total force on the limb. Figure 6 summarizes the discussion thus far. It should be noted that any orthosis fabricated to satisfy these conditions must be strong enough to do so without yielding or bending as the old pattern of the vicious circle (Fig. 2) will assert itself. Yet another factor to be taken into account is the familiar relationship of pressure, force, and area (Fig. 7). The need to satisfy these conditions and thus reduce the total force exerted must be, of course, balanced with the desire not to encumber adjacent joints, and to keep the orthosis as cool and light as possible.

Another way to tackle the problem is to use a weightbearing brim (Fig.8). This, of course, reduces the deforming force and thus the deforming moment. What is not so apparent is that it might very well change the length of the lever arm x and reduce the bending mo-



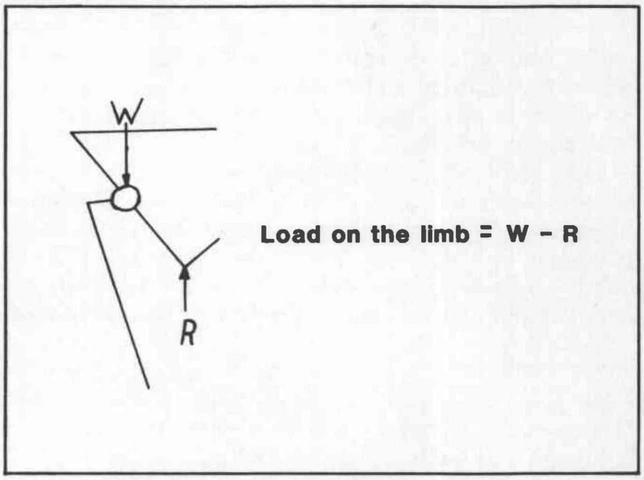
$P = F/A$

To keep P at tolerable limits:

minimize F

maximize A

Fig. 7. The relationship of pressure to force and area.



Load on the limb = W - R

Fig. 8. Use of a weightbearing brim creates a proximally acting force, R, that counteracts weight, W.

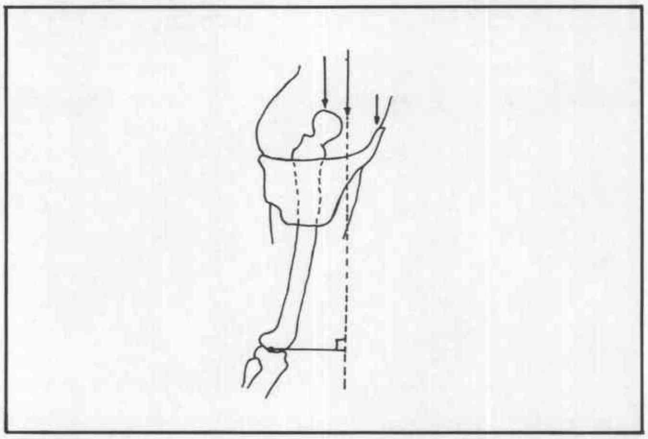


Fig. 9. Forces applied to the higher anterior wall of a quadrilateral brim tend to move the weightbearing axis anterior to the head of the femur, and the knee center.

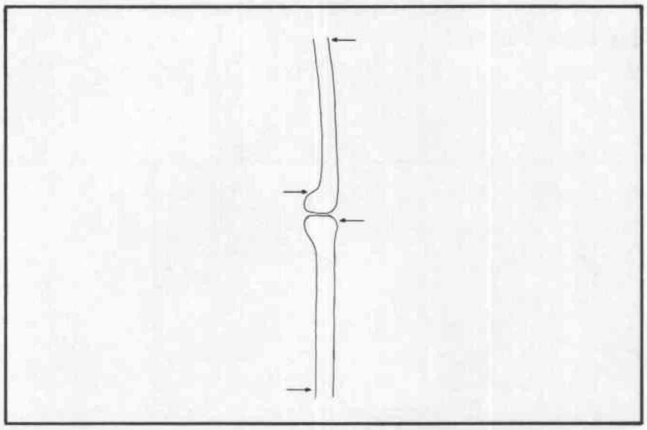


Fig. 10. Use of force couples acting on the femur and tibia to prevent anterior subluxation of the tibia relative to the femur. The force system would be reversed in an instance of posterior subluxation. A system of force couples is subject to the same sort of analysis and criteria as a three-point pressure system.

ment. If some of the body weight is borne medially on an ischial seat, it would tend to shift the line of action of the body weight medial to its usual course through the head of the femur. This phenomenon is at work when a KAFO with a quadrilateral brim is used in cases of gluteus medium lurch. It might very well have implications in cases of genu varum and genu valgum. In the sagittal plane (Fig. 9), a similar situation is identified in the UCLA Functional Long Leg Brace (Ref. 2). Moving the line of action of the weight line anterior by virtue of the load on the Scarpa's Triangle, a knee extension moment is generated. Knee extension is further aided by the intimate fit of the quadrilaterial brim and a firm fit of the foot in the shoe which produces a distractive effect on the leg, straightening it, as would pulling on opposite ends of a rope.

Subluxation of the tibia (such as might occur due to the pull of the quadriceps secondarily to ligamentous laxity in cases of genu valgum in arthritis, a situation described by Smith, et al., in reference 2), can be combatted by separate force couples acting on the femur and the tibia (Fig. 10). This is a feature of the University of Michigan Arthritic Knee Brace.

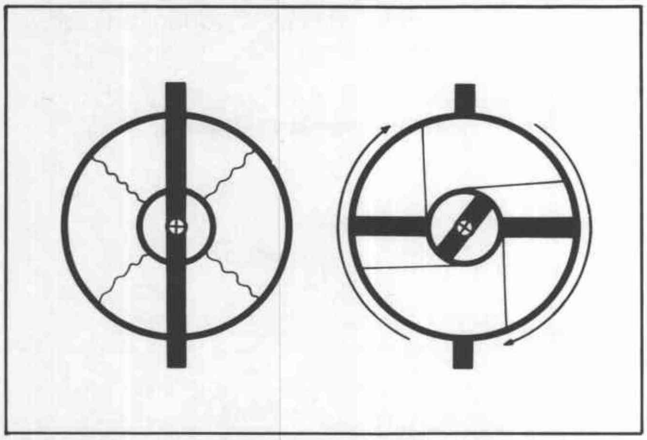


Fig. 11. Schematic cross-section of a limb, on the left, with the skin (outer circle) connected to the bone (middle circle) by soft tissue (radiating rippling lines) and acting about the center of rotation (innermost circle). The broad vertical line is for reference. As rotary forces (arrows) are applied, on the right, the force is transmitted from the skin to the bone by the soft tissue. As slack in the soft tissue must be taken up it becomes apparent that the bone moves less than the skin.

In the absence of direct action on the skeleton, control of rotation is more problematical. As the proximal portion of the shin is triangular, considerable rotational control can be achieved as in the PTB prosthesis, the spiral ankle-foot orthosis (AFO), and the hemi-spiral AFO. Purchase about the condyles of the femur and the patella can be achieved, but is compromised by the necessity for unencumbered knee flexion. It is, of course, possible to use a quadrilateral brim to gain a purchase on the proximal structures, but any prosthetist will be glad to regale his orthotist companion with tales or rotary instability in above-knee prostheses. The last alternative is a frictional coupling between the soft tissue and broad elastic straps as in the Lenox Hill Derotation Orthosis (Fig. 11). As considerable slack must be taken up in the soft tissues, 20 degrees of motion at the surface may result in only 10 degrees of motion of the femur about its axis. Moreover, the efficacy of even the best such measures is called into question considering the magnitude of the bending moment generated by the action of the center of gravity about the long axis of the leg and comparing it with the moments that can be induced about the same axis by the maximum tolerable force acting at the surface of the leg.

In conclusion, some of the biomechanical factors involved in the function of knee orthoses are reviewed. Due consideration of these factors, the anatomical structures involved, and the intended purpose of the orthosis at the time of prescription should inevitably lead to a more functional orthosis.

References:

1. *Final Report, Functional Long Leg Brace Research.* University of California, Los Angeles. Prosthetics/Orthotics Education Program, March 30, 1971.
2. Edwin M. Smith, M.D., Robert C. Juvinall, M.S.M.E., Edward B. Correll, M.S.M.E., and Victor J. Nyboer, M.D., "Bracing the Unstable Arthritic Knee," *Archives of Physical Medicine and Rehabilitation,* Vol. 51, No. 1, Jan. 1970, pp. 22-28, and 36.