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The Northwestern University Knee Orthotic System Part I: The N.u.K.O. Knee Joint

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INTRODUCTION

When an orthosis is applied to the knee, it should, hypothetically allow a full, unrestricted range of motion to occur. Orthotic constraints may be introduced to provide the extra stability required to compensate for soft tissue insufficiency, thereby limiting full range of motion. For example, an orthosis applied to the knee to correct recurvatum should in no way restrict normal flexion, but rather should introduce a constraint force only near extension where the extra stability is required to stop hyperextension.

However, in reality commercially available orthoses fall short of this ideal. One of the major problem areas is that orthotic knee joints used currently follow kinematic or motion pathways which are considerably simpler than those of the natural knee joint, the motion of which is three dimensional in nature. Single axis hinges are most common, although other designs, such as the polycentric, have evolved in an attempt to more closely simulate the complex rolling and sliding which accompanies flexion-extension of the natural joint. The mismatch between the orthotic and natural knee joint motions can cause unwanted constraint forces or binding to occur. Subsequent pistoning of the orthotic components over the lower limb produces restriction of normal range of motion, distal migration of the orthosis, misalignment, and skin pressure discomfort.

The N.u.K.O. knee joint offers some significant advantages over existing orthotic joints, closely mimics the motion of the natural knee, and allows design of more effective knee orthoses.[4] This report describes the proposed orthotic joint, the rationale behind its design, and its advantages.

DESCRIPTION OF THE JOINT

The joint consists of a metal, multicurvature femoral component in the shape of the sagittal profile of the distal femur, and a slotted plastic tibial component with a

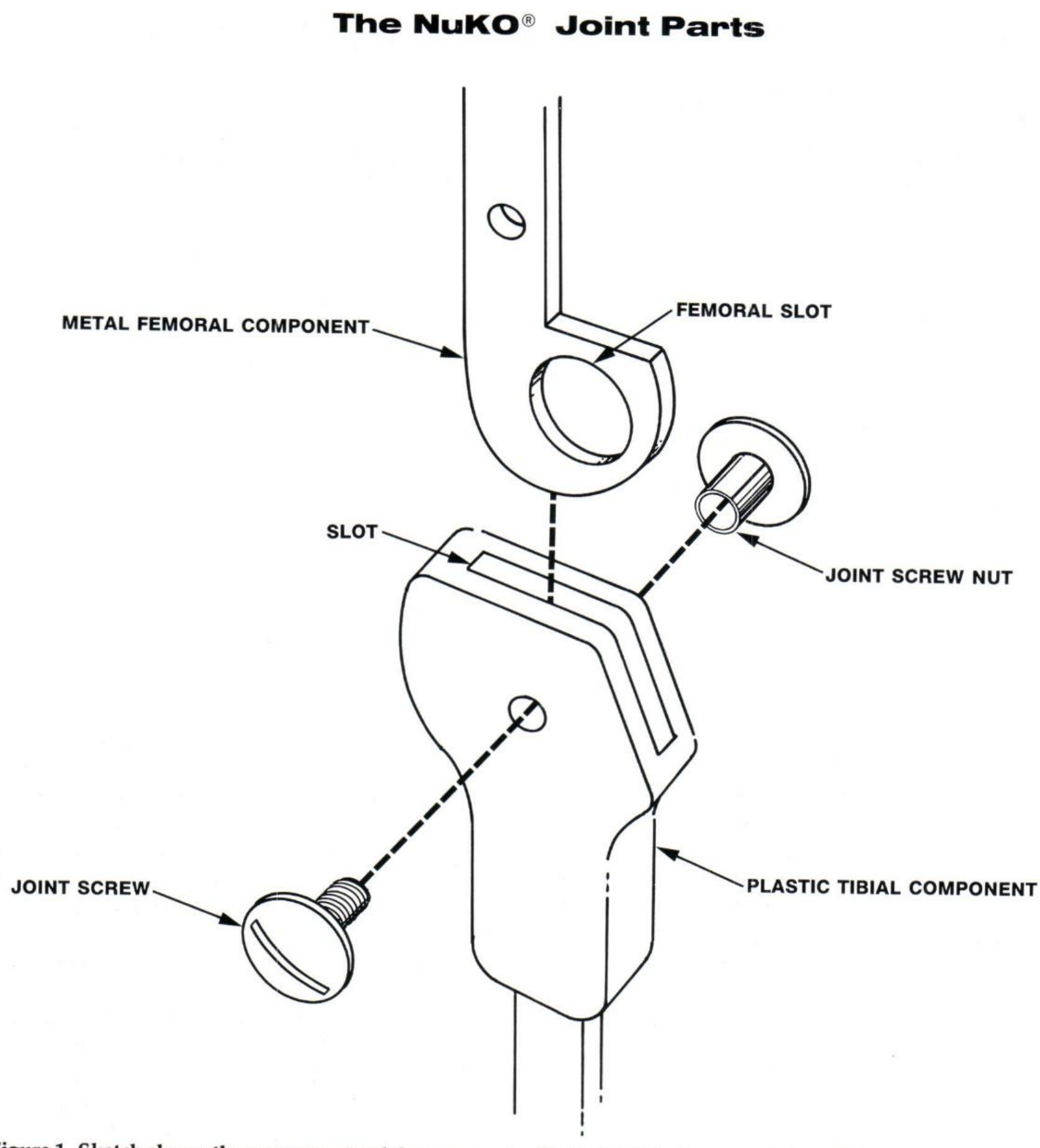

Figure 1. Sketch shows the components of the proposed orthotic joint design: metal slotted femoral component, slotted plastic tibial component with metal sidebar, and joint screw.

larger, flatter articulating surface approximating the profile of the proximal tibia (Figure 1). These incongruencies promote a rolling and sliding of the femoral component within the tibial component cup. The femoral component articulates within the tibial slot so that the surfaces become highly conforming or engaged in extension, preventing anterior-posterior motion, as in the natural joint. However, in flexion, the smaller posterior femoral curvature provides for a low degree of conformity or capture by the tibial curvature, allowing the femoral articulating surface to roll and slide anterior-posteriorly over the tibial component, thereby imitating the natural knee (Figure 2).

Stability is added to the orthotic joint through a specialized "femoral slot and joint screw" mechanism (Figure 1). The slot is formed in the metal femoral head component and captured between the walls of the tibial cup (Figure 3). The specialized mechanism simulates the action and function of the knee ligaments. The "femoral slot and joint screw" mechanism also allows the NU knee joint to tighten and become lax at different times during range of motion activity, yet allow the anterior-posterior rolling and sliding of the femoral component over the tibial component to occur (Figure 2). A computerized mathematical model was used to define "femoral slot and joint screw" placements. The data generated by the model defined the location for proper placement of this mechanism and allows the orthotic knee joint to follow the natural kinematics or motion pathways of the human knee.[4]

BIOMECHANICAL DESIGN RATIONALE

Because the surfaces of the human knee articulate without a great deal of inherent stability, the muscles and ligaments (their attachment locations and orientations) must precisely interact with the geometry of the articular surfaces to produce controlled flexion and extension motions. For example, it has been hypothesized by Lewis, et al.[3] that knee ligaments have a dual function. The "high-level" function occurs when ligaments provide stability in a traumatic situation. In this situation, the

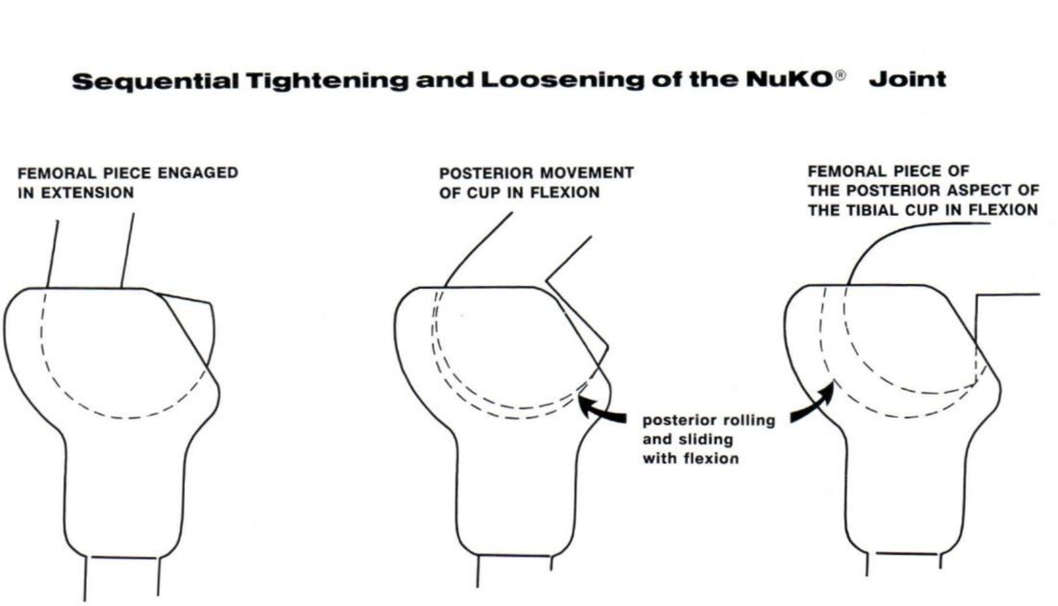

Figure 2. Sketch shows the sequential tightening and loosening of the knee joint at extension (left), 45° (middle), and 90° flexion (right).

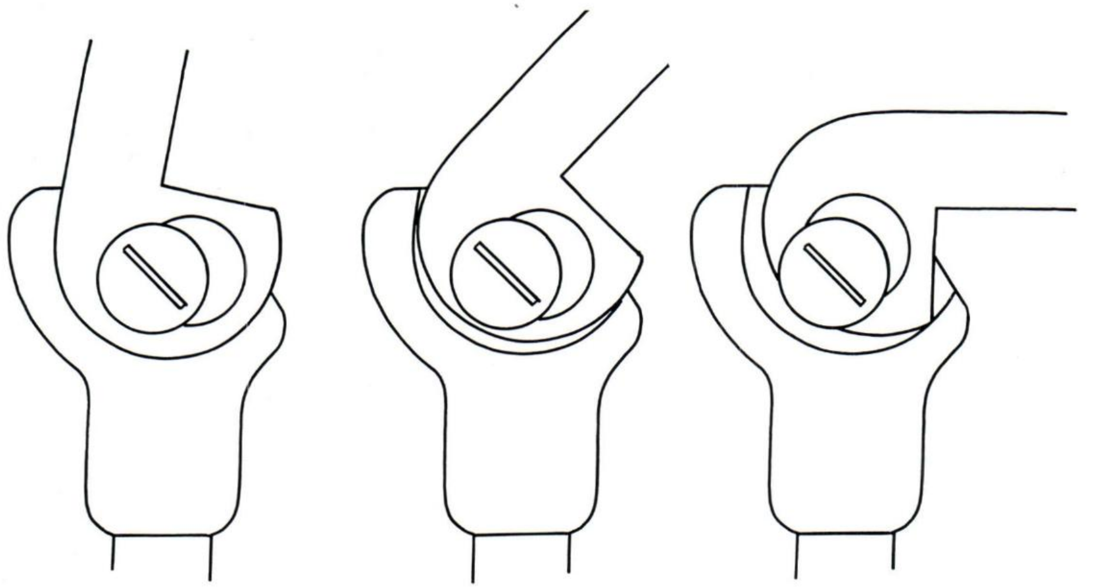

Figure 3-A. Joint at full extension. **Figure 3-B. Joint at 45°.** **Figure 3-C. Joint at 90°.**

external loading rate is too rapid for the muscles to equilibrate. "Low-load" function occurs when ligaments maintain the correct apposition of the articular surfaces during muscle-generated function, providing proper joint lubrication and normal contact forces. This low level function is particularly dependent upon the relationship of the geometry of the articular surfaces and ligaments. As previously mentioned in the introduction, when simplified, artificial joints are placed in (total joint replacements) or around (orthoses) the knee, constraints are generated in the natural joint structures that oppose the motions imposed by the artificial joints. This constraint is recognized externally as pistoning, and internally as, among other things, ligament incompatability.

To examine this hypothesis, Lew and Lewis[1] performed a study in which cruciate ligament forces were measured during the flexion of specimens containing a low conforming, anatomically shaped knee implant design, as well as high-conforming, non-anatomical implant design (Figure 4). In the non-anatomical implant, which did not allow rolling and sliding to accompany flexion as in the natural joint, the full range of motion was restricted to 60° of flexion, and an abnormally large constraint force was also measured in the posterior cruciate ligament.

The anatomical implant, on the other hand, allowed the rolling and sliding of the natural joint so a full range of flexion was attainable, and cruciate ligament forces approached that of a normal knee. The above findings could be extrapolated to the design of orthotic joint components. The orthotic articular surfaces should have the freedom to reorient themselves as dictated by ligaments and muscles for the full range of the natural joint motions. In this way, unwanted constraints will be minimized, and an unrestricted range of motion can be obtained.

The design of the proposed orthotic joints closely follows this biomechanical principle. The NU orthotic knee joint has articular surfaces that allow five of the six possible components of knee motion, the exception being medial-lateral displacement (Figure 5). Anterior-posterior rolling and sliding of components during flexion-extension are possible, as described earlier. Distraction of component articular surfaces is allowed, which in turn permits

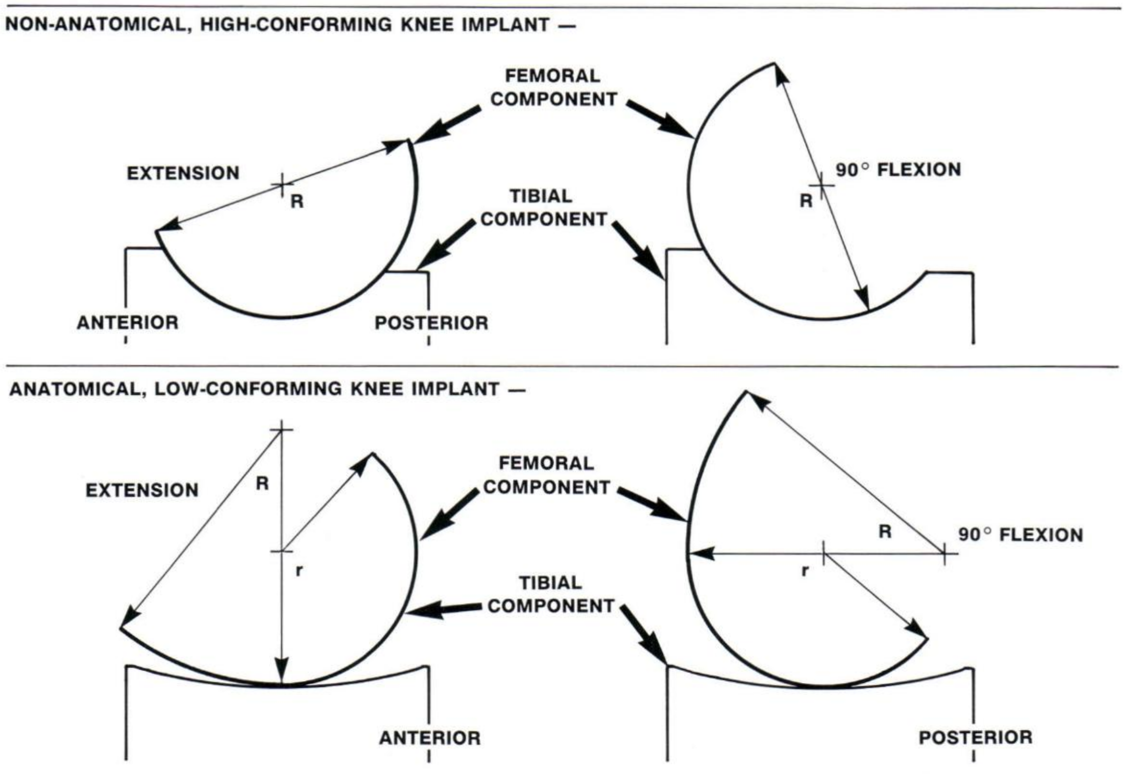

Figure 4. The proposed orthotic joint design is based upon earlier research regarding the interaction of knee ligament mechanics with internal knee prostheses. A sagittal view of the cross sections (radii of curvatures—R,r) of the tibial and femoral components of these implants are shown.

varus/valgus angulations to occur at any flexion angle. Transverse shifts are possible through the anterior/posterior and distractive displacements of the joint components. Thus, the orthotic joint articular surfaces reorient themselves as dictated by the internal knee structures to a greater degree than other commonly used orthotic joints.

Another biomechanical principle considered relates the sequential loading of knee ligaments and various bands of a specific ligament to the geometry and loading conditions of the knee through a wide variety of activities. Lewis, et al.[3] measured ligaments forces in a series of seven specimens, to correlate external joint action and ligament reaction loads. Near full extension, the anterior cruciate was found to be highly loaded during anterior-directed force or anterior drawer, varus, and internal rotation conditions. The posterior cruciate ligament was highly loaded near 90° flexion for posterior-directed forces or a posterior drawer, varus-valgus motions, and internal-external rotation. The medial collateral ligament was highly loaded during internal/external rotation and valgus force, throughout the flexion range. The lateral collateral ligament was highly loaded during varus and internal rotation and throughout the flexion range. During hyperextension, the anterior cruciate and both collateral ligaments were highly loaded. Given the previous argument for anatomically shaped orthotic joint components, the above information is important when designing constraints into

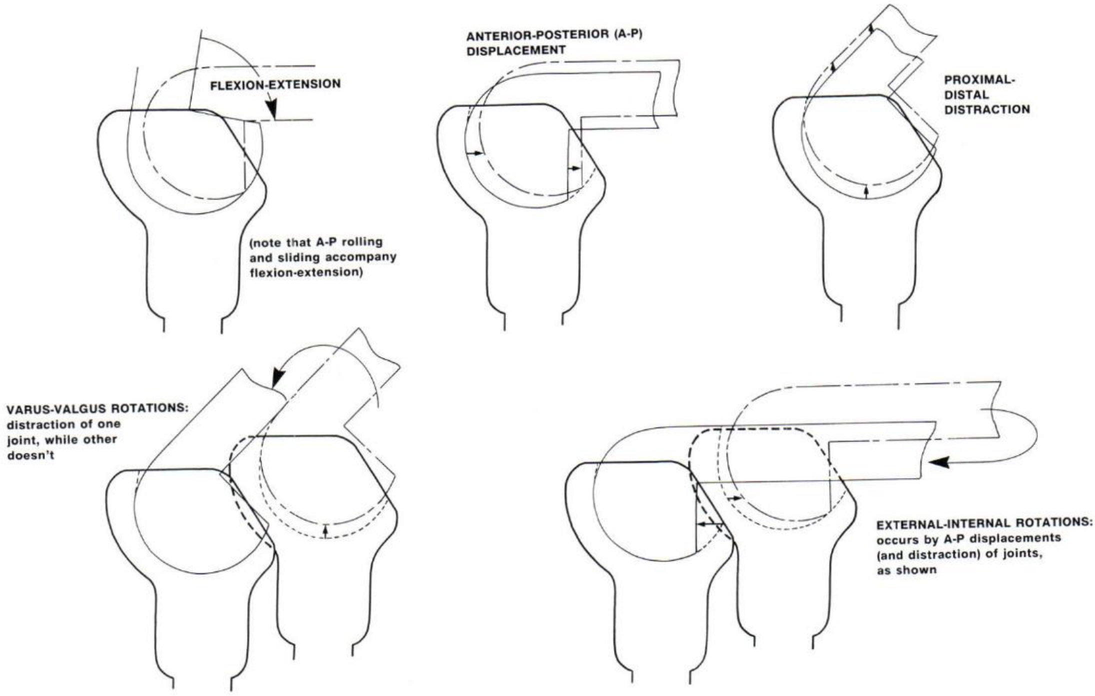

Figure 5. Sketch shows how the various components of knee joint motion can occur with the proposed orthotic joint design. Medial-lateral displacement is the only motion not allowed.

the orthotic joints or the complete orthosis to provide stability for specific ligament insufficiencies.

The orthotic "femoral slot and joint screw" mechanism is oriented and located in relation to the orthotic articular surfaces so as to function similar to the natural knee ligaments. The mechanism allows sequential tightening and loosening of the orthotic knee joint. When the orthotic joint is in extension, no anterior-posterior motion is allowed. As the knee joint begins to flex, anterior-posterior displacement is permitted along with rolling and sliding. Human ligaments also sequentially tighten and loosen about the knee joint and allow both anterior-posterior motion with rolling and sliding. The mechanism provides stability to the anatomically shaped orthotic joint surfaces, and allow the NU knee joint to work on a non-fixed asis of rotation.

MECHANICAL VERIFICATION OF THE DESIGN

The authors have previously reported a procedure for comparing the efficacy of orthotic knee joints, based upon their tendency to produce pistoning.[2] Pistoning transducers were designed, which were incorporated into the sidebars of various orthotic joint designs. As a subject wearing an evaluation orthosis performed functional activities, the transucers on the medial and lateral orthotic joint sidebars would directly measure the resulting pistoning constraint forces generated between the simplified orthotic joint motion and the complex natural joint motion. This procedure was used to compare the pistoning tendency of the proposed anatomically shaped orthotic joints with three commonly used, commercially available orthotic joint designs: single axis hinges, posterior offset hinges, and polycentric hinges. Resultant pistoning constraint forces were measured during loaded and unloaded flexion, level walking, rising from a chair, and stair climbing activities.

The combined results over all the activities are presented in Figure 6 for each joint design. The mean and standard deviation of the combined resultant pistoning forces are given below the bar graphs, and the normalized mean forces are plotted. The data suggests that the proposed orthotic joints, because of their semi-constrained, anatomically shaped design, generated an average of 76% less pistoning constraint than the commercially available joint designs.[4] Also note that there is no statistical significance in the differences among the pistoning forces of the other three commercially available joint designs.

SUMMARY

An improved orthotic knee joint system has been designed, based upon biomechanical principles associated with knee motion and ligament mechanics. The orthotic joint articular surfaces are anatomically shaped and semiconstrained to approximate natural knee motion, particularly the anterior-posterior rolling and sliding which accompanies knee flexion and extension. Stability is added to the orthotic joint system through a "femoral slot and joint screw" configuration. The pre-

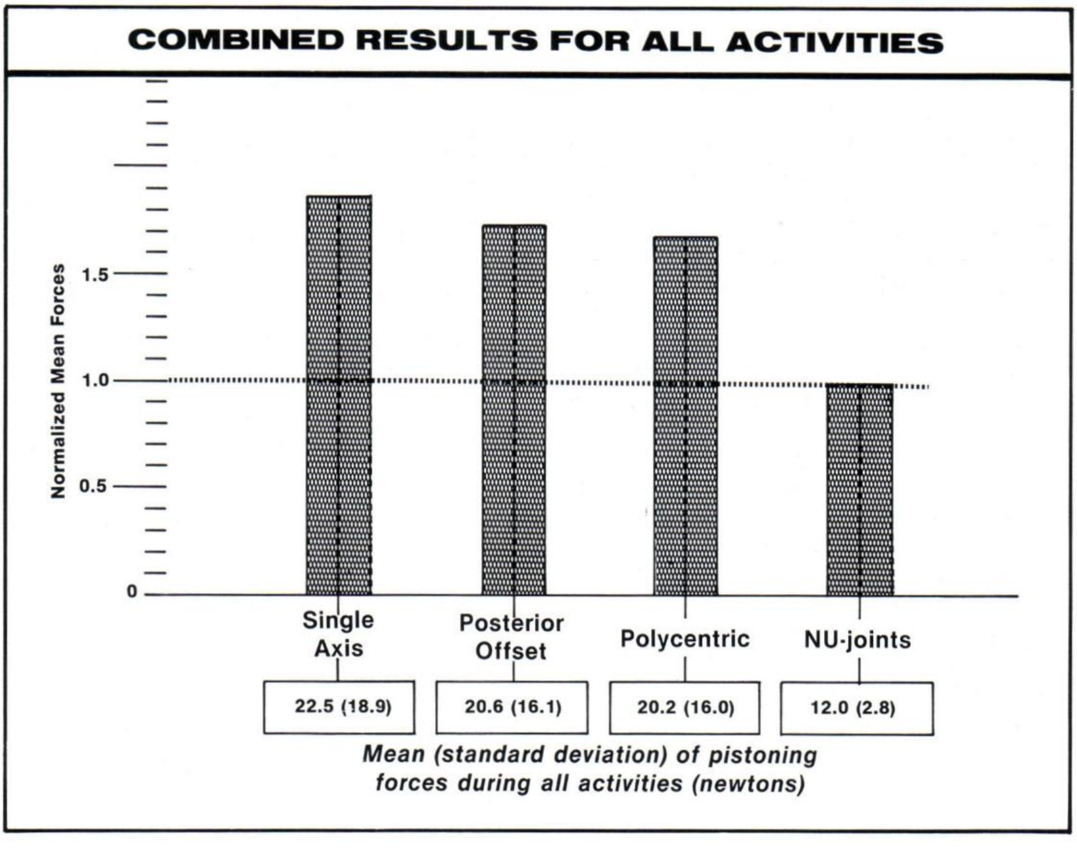

Figure 6. Sketch is a summary of the resultant pistoning constraint forces for a combination of all the test activities for each joint design. The means and standard deviations of the resultant pistoning forces are presented, as well as the normalized mean resultant pistoning forces over the four joint designs.

cise location and orientation of this mechanism was determined by a mathematical model.

The functional result of this design concept shows the orthotic joint motion more closely matches the motion pathways of the natural knee. An exception is noted at particular points in the range of motion when extra stability is added to the orthosis design to compensate for soft tissue insufficiency. This improvement was demonstrated in a mechanical evaluation, where the proposed orthotic joints generated an average of 76% less pistoning constraint force than other currently popular joint designs. Thus, the improved design more closely matches natural knee motion, decreasing the effects of binding, motion restriction, and discomfort, often associated with pistoning.

The degree of suspension or fixation of a knee orthosis effects, and in most instances limits, the motion pathways allowed by the associated orthotic joints. Since the motion of most currently available orthotic joints does not match natural knee kinematics, a tightly fitted interface will magnify the pistoning constraint. This situation would be particularly harmful, for example, if an orthosis was intended to protect surgically reconstructed knee ligaments. In this case, the pistoning constraint may cause stretching of the healing tissue. On the other hand, if the interface components do not intimately secure the orthosis to the lower limb, the device would also not provide the necessary stability to the joint. Thus, improvements to the interface suspension are limited by orthotic joint kinematics. In the case of the proposed orthotic joints, it was demonstrated that the motion mismatch and resultant pistoning were reduced, thereby setting the stage so that improvements to the orthotic interface can be realized.

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