A New Concept in Orthotics Joint Design—The Northwestern University Knee Orthosis System

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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, except at appropriate limits of motion where orthotic constraints are intentionally introduced to provide the extra stability required to compensate for soft tissue insufficiency. For example, an orthosis applied to the knee to correct recurvatum should in no way restrict normal flexion, and should introduce a constraint force only near extension where the extra stability is required.

In reality, however, 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, whose motion 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 an unwanted constraint force or binding to occur, with the subsequent pistoning of the orthotic components over the lower limb, producing restriction of the normal range of motion, distal migration and misalignment of the orthosis, and skin pressure discomfort.

Our laboratory has developed an orthotic knee joint which more closely mimics the motion of the natural knee. We believe it offers some significant advantages over existing orthotic joints, and allows design of more effective knee orthoses. This report describes the proposed orthotic joint, the rationale behind its design, its advantages, and evidence of its value. A second report will present a description of a complete knee orthosis using the improved joints.

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 larger, flatter articulating surface approximating the profile of the proximal tibia (Figure 1). 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. In flexion, however, 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. The component curvatures and amount of capture are variable in design, and can be chosen depending upon the patient application. We have chosen a set of curvatures which limits the size of the orthotic joints, yet allows a possible eight millimeters of anterior-posterior displacement to accompany flexion.

Stability is added to the orthotic joint through the presence of inextensible dacron straps which cross the joint (Figure 1). These straps are attached distally to the plastic tibial component, and proximally to a metal ligament attachment plate, which is in turn fastened to the sidebar of the femoral component. The straps simulate the location, orientation, and function of knee ligaments. These "ligament straps" tighten and become lax at different times during the range of motion, yet allow the anterior-posterior rolling and sliding of the femoral component over the tibial component to occur. The number and location of these ligament straps can be varied and is dependent upon the particular mode of stability required. At present, we routinely use three basic ligament strap configurations: an anterior cruciate design, a collateral design, and a posterior cruciate design (Figures 2a, b, c). Note that each joint design has three straps which are located and oriented so as to sequentially tighten at 0°, 45°, and 90° of flexion, respectively.

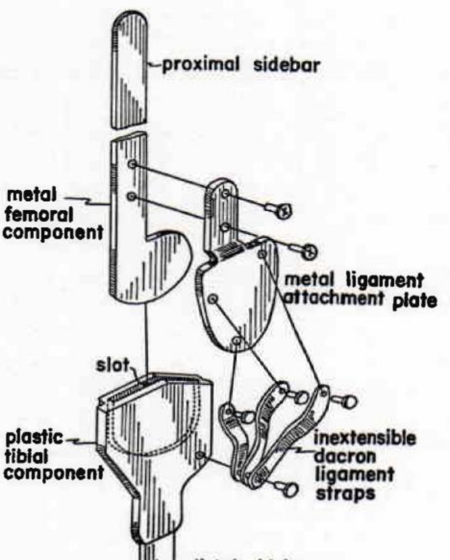

Figure 1: The above sketch shows the components of the proposed orthotic joint design: metal femoral component, slotted plastic tibial component with metal sidebar, metal ligament attachment plate, and three dacron ligament straps (the collateral design in this example).

For example, Figure 3 shows the sequential tightening of the three straps of a posterior cruciate joint. Each one of the straps tightens at a particular flexion angle, while the other two remain lax. Note that when a ligament strap is tight, it has approximately the same line of action or orientation as the natural posterior cruciate ligament. Figure 3 also shows the femoral component rolling and sliding posteriorly with flexion. A computerized mathematical model was used to define potential strap locations. The data generated by the model provides length patterns for all possible strap attachments, predicting where in the flexion range the strap would get tight, and in what direction the subsequent strap force would act.

BIOMECHANICAL DESIGN RATIONALE

Because the surfaces of the anatomical knee articulate without a great deal of capture, the muscles and ligaments (their attachment locations and orientations) must precisely interact with the geometry of the articular surfaces to generate lower limb function yet provide stability. For example, it has been hypothesized by Lewis, et. al. (1983)[3] that knee ligaments have a dual function. The "high-level" function is when ligaments provide stability in a traumatic situation, where the external

Figure 2A: Anterior cruciate joint design.

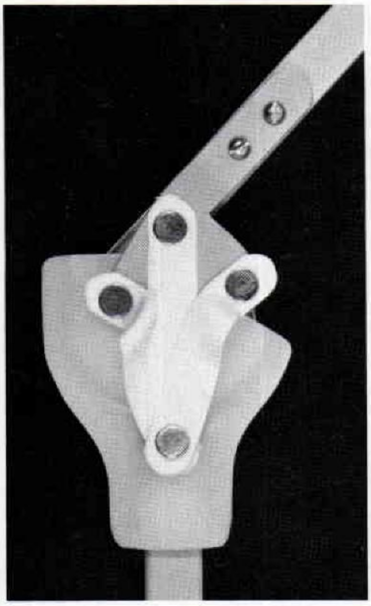

Figure 2B: Collateral joint design.

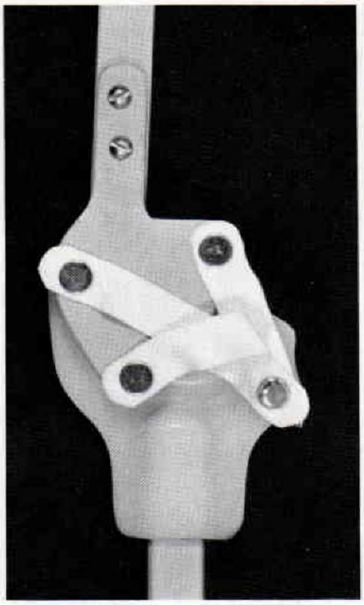

Figure 2C: Posterior cruciate joint design.

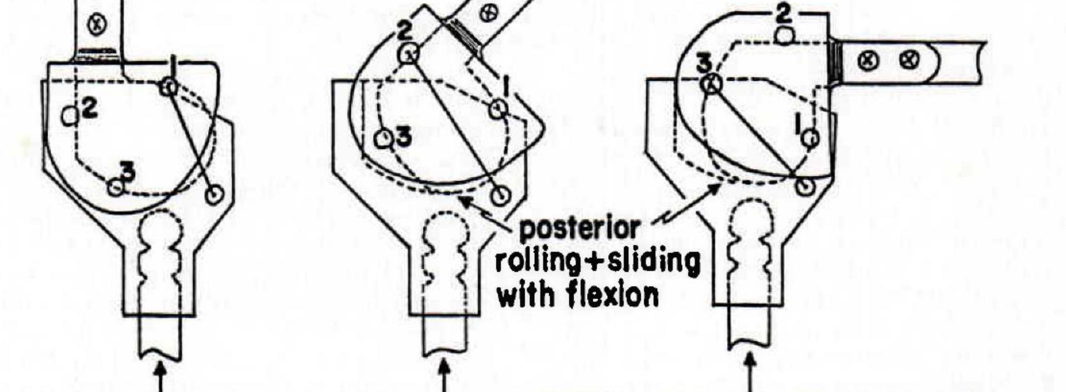

Figure 3: Sketch shows the sequential tightening of the ligament straps of the posterior cruciate joint design, at extension (left), 45 degrees flexion (middle), and 90 degrees flexion (right).

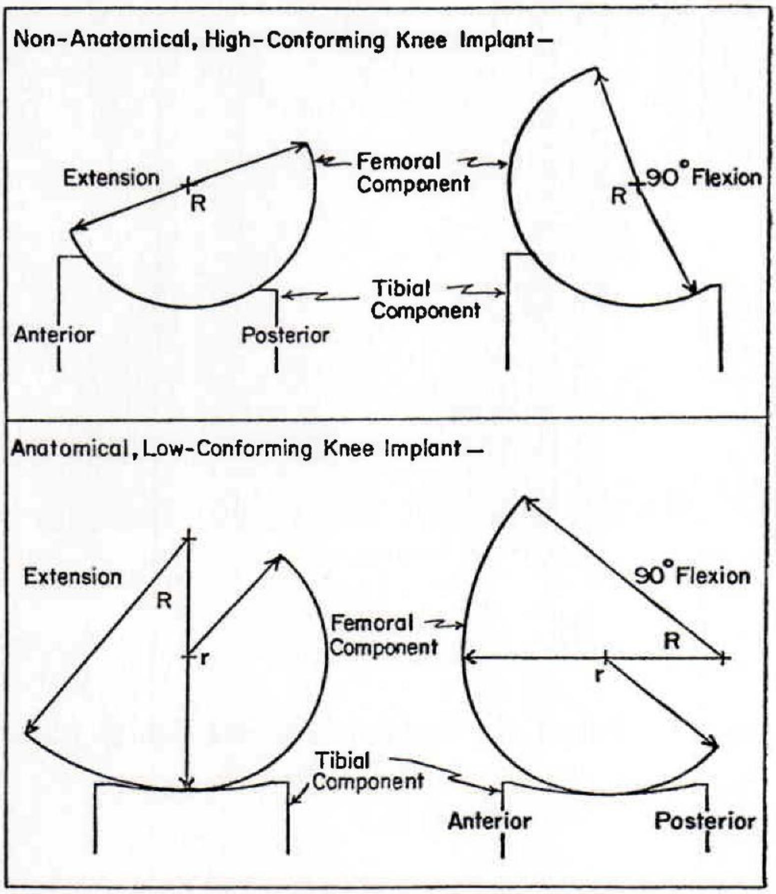

Figure 4: The proposed orthotic joint design is based upon earlier research regarding the interaction of knee ligament mechanics with internal knee prostheses. A sagittal view of the cross sections (radii of curvatures—R,r) of the tibial and femoral components of these implants are shown above.

load occurs too rapidly for the muscles to equilibrate. The "low-load" function is when ligaments keep the correct apposition of the articular surfaces during muscle-generated function, providing for 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 as they oppose the motions imposed by the artificial joints. This constraint is recognized externally as pistoning, and internally as, among other things, ligament incompatability.

As an example of the above, Lew and Lewis (1982)[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 a 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 about 60 degrees of flexion, and abnormally large constraint forces appeared in the posterior cruciate ligament. The anatomical implant, on the other hand, allowed the rolling and sliding of the natural joint, so that a full range of flexion was attainable, and cruciate ligament forces approached that of a normal knee. The above findings can be extended to the design of orthotic joint components. The orthotic articular surfaces should have the freedom to reorient themselves as dictated by the internal ligaments (or muscles, for that matter) for as many of the components of natural joint motion as possible. 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. Depending upon the constraints introduced to the orthotic joints and complete knee orthosis (because of the patient's particular condition), the proposed orthotic, articular surfaces can potentially allow five of the six possible components of knee motion, the exception being medial-lateral displacement (refer to 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 varus-valgus rotations to occur at any flexion angle. Transverse rotations 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. Given any particular soft tissue insufficiency, specific ligament strap constraints can be added to restrain any of the above affected motion components, so that the joints allow a full range of knee motion to occur. The only exception is for points in the motion where extra stability is required to compensate for the soft tissue instability present. The validity of this design concept will be demonstrated by a mechanical evaluation, a description of which follows in the next section of this report.

Another biomechanical principle to be considered is that the geometry of the natural knee ligaments is such that they become loaded during a wide range of external joint load conditions. Lewis, et. al. (1983)[3] measured ligament forces in a series of seven specimens, with the purpose of cataloging external load conditions (applied to the tibia) which loaded particular ligaments.

The anterior cruciate was found to be highly loaded during several load conditions near extension (anterior-directed force or anterior drawer, varus, and internal rotation). The posterior cruciate ligament was highly loaded for various external load directions near 90 degrees flexion (posterior-directed force or posterior drawer, varus-valgus, and internal-external rotation). The medial collateral ligament was highly loaded during internal-external rotation and valgus, throughout the flexion range. The lateral collateral ligament was highly loaded during varus and internal rotation, throughout the flexion range. The anterior cruciate and both collateral ligaments were highly loaded during hyperextension. Given the previous argument for anatomically shaped orthotic joint components, the above information is important when designing constraints into the orthotic joints (such as "ligament straps") or the complete orthosis, to provide stability for specific ligament insufficiencies.

The orthotic ligament straps are oriented and located in relation to the orthotic articular surfaces so as to function similar to the natural knee ligaments. The straps sequentially tighten within the flexion range, such that their lines of action (when taut) can assist in the restraint of the array of external load conditions described above. The ligament straps, in conjunction with changes to the orthotic interface (to be described in a later report), provide stability to the anatomically shaped orthotic joint surfaces, and can be tailored to handle specific ligament insufficiencies.

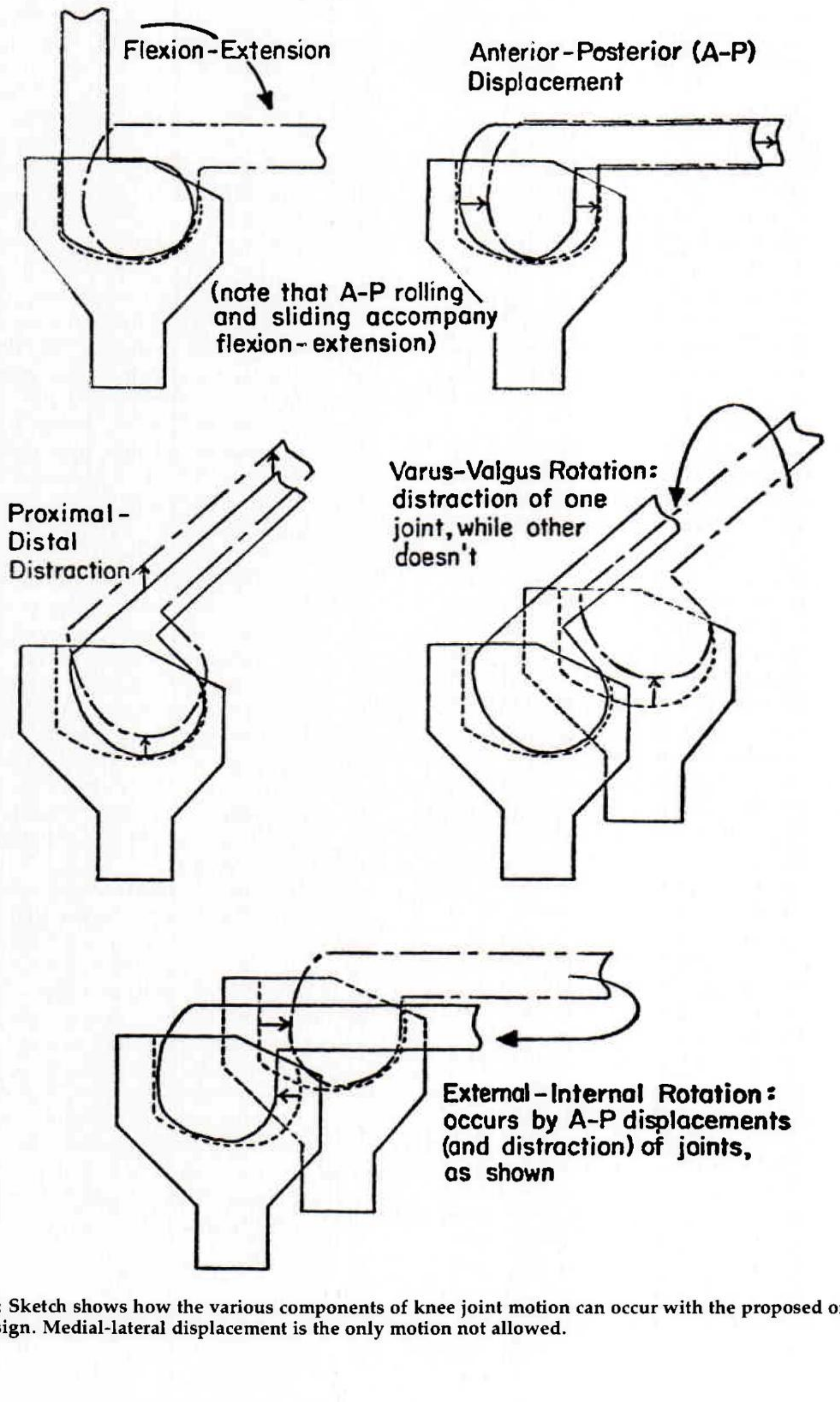

Figure 5: Sketch shows how the various components of knee joint motion can occur with the proposed orthotic joint design. Medial-lateral displacement is the only motion not allowed.

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 (refer to Lew, et. al. 1982[2] for details). Pistoning transducers were designed, which were capable of being interchangeably incorporated into the sidebars of various orthotic joint designs. As a subject wearing an evaluation orthosis performed functional activities, the transducers on the medial and lateral orthotic joint sidebars would directly measure the resulting pistoning constraint forces generated by the conflict 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 (the collateral design) with three commonly used, commercially available orthotic joint designs: single axis hinges, posterior offset hinges, and polycentric hinges. The resultant pistoning constraint forces were measured as a subject performed loaded and unloaded flexion, level walking, getting in/out of a chair, and climbing up/down a step.

Figure 6 presents the combined results over all the activities, for each joint design, the mean and standard deviation of the combined resultant pistoning forces, and the normalized mean forces. The data suggests that the proposed orthotic joints, because of their semi-constrained, anatomically shaped design, generated an average of 76 percent less pistoning constraint than the commercially available joint designs ($p \leq .01$). Also note that there is no statistical significance in the differences among the pistoning forces of the three commercially available joint designs.

DISCUSSION

In summary, an improved orthotic knee joint system has been designed, based

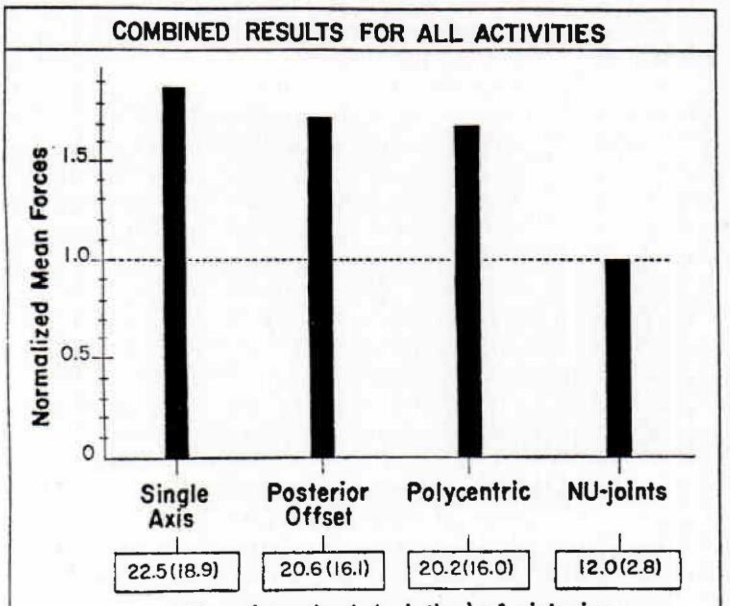

Figure 6: At left is a summary of the resultant pistoning constraint forces for a combination of all the test activities for each joint design. The means and standard deviations of the resultant pistoning forces are presented, as well as the normalized mean resultant pistoning forces over the four joint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

upon biomechanical principles associated with knee motion and ligament mechanics. The orthotic joint articular surfaces are anatomically shaped and semi-constrained, so as to allow a close approximation of the components of 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 various configurations of inextensible dacron straps crossing the joints. The precise location and orientation of these ligament straps is determined by a mathematical model.

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

Another advantage of the anatomical orthotic joints is their high degree of variability; that is, various joint parameters can be tailored to address specific soft tissue problems. Many variations of soft tissue instability exist, due to the involvement of individual or combinations of knee ligaments and/or capsular structures, each with its own instability direction. Many of the current, commercially available orthotic joints cannot be modified to handle specific ligament problems, as one design is used regardless of the type of soft tissue insufficiency present.

The following are some of the potential variations of the basic proposed orthotic joint designs. The mathematical model can be easily adapted to compute locations of ligament straps which tighten at other flexion angles of interest (besides the 0°, 45°, and 90° straps of the basic design).

It is also possible to design various hybrid strap configurations by combining one or more ligament straps from the cruciate and/or collateral joint designs. For example, an individual presenting with an antero-medial rotatory instability resulting from an anterior cruciate and medial collateral ligament deficit may require a hybrid combination of the anterior cruciate and collateral strap configurations.

Other variables are the curvatures of the articulating surfaces of the orthotic joints. For example, given a person with a total knee replacement requiring orthotic treatment, the orthotic joint component curvatures and strapping configuration can be tailored to match the geometry of the internal implant. Application of the orthotic joint designs to specific clinical situations will be described by several case studies presented in a later report.

The degree of suspension or fixation of a knee orthosis to the lower limb is intimately related to the motion pathways allowed by the associated orthotic joints. Since the motion of most currently available orthotic joints does not match natural knee kinematics closely enough, a tightly fitting interface will just magnify the pistoning constraint. This situation would be particularly harmful, for example, if an orthosis was intended to protect surgically reconstructed knee ligaments, since the pistoning constraint may cause stretching of the healing tissue. On the other hand, if the interface components were not tightly fitting to relieve the effects of the pistoning constraint, the orthosis would not provide the necessary stability to the joint. Thus, improvements to the interface suspension are limited by orthotic joint kinematics.

However, 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. This also will be dealt with in great detail in a later report.

In a subsequent report, the inclusion of the improved orthotic joints in a completed knee orthosis will be described. Some of the topics included will be the biomechanics of knee orthotic suspension, suspension improvements contained in the Northwestern orthosis system, fabrication details, and a group of case studies showing the adaption of the orthosis system to specific knee ligament problems.

NOTES

[1]Lew, W.D. and Lewis, J.L., "The Effect of Knee Prosthesis Geometry on Cruciate Ligament Mechanics During Flexion," *Journal of Bone and Joint Surgery*, Vol. 64-A, 1982, pp. 734-739.

[2]Lew, W.D., Patrnchak, C.M., Lewis, J.L., and Schmidt, J., "A Comparison of Pistoning Forces in Orthotic Knee Joints," *Orthotics and Prosthetics*, 36, 1982, pp. 85-95.

[3]Lewis, J.L., Lew, W.D., Shybut, G.T., Jasty, M., and Hill, J.A., "Biomechanical Function of Knee Ligaments," in press, to appear as a chapter in a book entitled *Sports Medicine of the Knee*, published by the C.V. Mosby Company.

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