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Double Short Flexure Type Orthotic Ankle Joints

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Abstract

The Habilitation Technology Laboratory at Gillette Children's Hospital has developed two designs for durable "short" double-flexure type ankle joints. Flexure elements, singly and in multiples, have been used for centuries to create hinges. Some of the earliest hinges were of animal hides and used for doors and lids. In recent decades, long (flexure length-to-thickness ratios greater than 5-to-1) plastic flexures have been used as a bridge between thigh, calf and foot sections of fracture orthoses. Those designs were unstable when subjected to varus, valgus, torsional or longitudinal loading, and, because of that, gave a poor impression of the potential value of flexure designs in orthotics. At Gillette, we have been developing and using short (flexure effective length-to-thickness ratios less than 2-to-1) double-flexure orthotic joints since 1976. The short flexure design solves the structural instability problems but magnifies fatigue durability problems. We have designed a testing apparatus which simultaneously subjects four ankle-foot orthoses to service cycle repetitions. This has helped to determine more quickly and objectively which designs and materials are more durable. The double-flexure design approach retains the weight and cosmetic advantages of plastic orthoses while providing several advantages over the posterior leaf design. The flexures can be located for full congruency at anatomic and orthotic joint axes. The desired ankle range-of-motion is almost totally free of resistance, and the degree of motion restraint can be easily and precisely controlled. Gillette has provided several thousand ankle-foot and knee-ankle-foot orthoses utilizing these ankle joints. Utilization has been in a wide variety of diagnoses among adults as well as children.

Introduction

The weight, cosmesis and foot control advantages of polypropylene ankle-foot orthoses (AFOs) long ago made them a clear and appropriate favorite, in most cases, over the style of AFO which incorporates metal bars, joints and stirrups. One of the few disadvantages of the polypropylene AFOs has been that those designs have not provided all of the motion control characteristics of metal joints at the ankle. The standard posterior-leaf type AFO utilizes a single, long-flexure linkage between the foot section and calf section. That flexure has a buckling bias due to its curved cross section. It buckles to allow dorsiflexion much more easily than it buckles to allow plantarflexion. This is a characteristic we desire. However, as we narrow the posterior leaf to allow easier dorsiflexion, the plantarflexion stop becomes less definite. This "softness" of the plantarflexion stop may be beneficial in some circumstances. However, the point at which motion is stopped often will creep to greater plantarflexion angles with use over time.

The moderate resistance of the posterior leaf during dorsiflexion is no problem during near-normal gait, since body weight is more than sufficient to power dorsiflexion between mid-stance and heel-off without significant effort by the client. However, that dorsiflexion resistance is sufficient to cause problems and fatigue in non-weight bearing activities. An example is the operation of the accelerator of a motor vehicle where it is necessary to vary and hold the ankle through a range of dorsiflexion angles.

Finally, the axis of flexion of the posterior leaf is located well posterior to the anatomical ankle axis. This causes pistoning of the orthosis on the calf of the leg as the ankle flexes. This is a problem for more active clients.

Of course, many orthotists have devised ways to overcome some of these shortcomings. Medial and lateral diagonal straps have been used to create a more definite plantarflexion stop. We, and others[1,5] have devised various types of rotating joint/plastic hybrids which retain the metal ankle joint features, but at a significant weight compromise of fabrication complexity.

Flexure Joint Design Fundamentals

The concept of using multiple flexures to achieve a hinge action is not new. Some of the earliest of such inventions were the use of pieces of animal hides to create hinges for doors and lids. In modern times, short plastic hinge designs have been commonly used for cabinet doors and tool box lids. "Long" flexures (flexure length-to-thickness ratios greater than 4 to 1) were introduced to the orthotic field in the '70s as fracture orthosis joint components. Those designs have fared well only when use was temporary and when torsional, compression and sheer loadings were minimal. The "long" flexures tend to be unstable when subjected to those loadings.

Watanabe, *et al.*, presented a multitude of plastic flexure designs in their 1982 article.[6] They included inventive variations for intrinsically limiting range-of-motion. Those designs were of the "long" flexure type and subject to the problems cited above.

The performance of any flexure subjected to a combination of axial, sheer and bending loads is strongly dependent on the material choice, the proportioning, and the dimensioning of the design. This paper will not go into detail regarding the engineering of flex members but there are a few fundamentals which should be presented to help orthotists better understand these useful devices. Some of these fundamentals are intuitive, such as: If other dimensions are held constant, increasing the length of a flexure will increase its tendency to bend, twist and buckle when subjected to shear, torsional and compressive loads; however, shorter flexures will build up greater stresses when bent through a given flexion angle.

Some other flexure engineering fundamentals are *not* so intuitively obvious. As a flexure is repeatedly bent through its angular range-of-motion, the bending and unbending (or reverse bending) stresses subject the flexure to "fatigue." If the peak values of the fatigue stresses are great enough, a fatigue crack will be nucleated and will grow until the flexure fails. When this happens, intuition may tell us we can make the flexure stronger by making the cross-sectional area more robust. This is not true. For a given flexure material, length and angular range-of-motion, peak bending fatigue stresses are proportional to the thickness (cross-section dimension in the direction of motion) of the flexure.[4] So, we can actually reduce the peak bending fatigue stresses, increase the flexure's resistance to fatigue damage, and increase its service life by *reducing* the thickness of the flexure. In fact, we have seen many cases where, in a polypropylene flexure, a fatigue crack progressed to the point where it reduced the effective thickness (and, therefore, also reduced peak bending fatigue stresses) to below a critical value and further fatigue damage was virtually halted. Of course, thickness cannot be reduced too much or the cross-sectional area will not be great enough to withstand torsional, sheer and tension stresses.

"Gillette" Double Flexure Joint Designs

At the Habilitation Technology Laboratories of Gillette Children's Hospital, we have been developing and using "short" flexure (flexure length-to-thickness ratios of 2-to-1 or less) ankle joint designs since 1976 (**Figure 1**).[2,3] We have also occasionally used them for orthotic knee, elbow and wrist joints (**Figures 2** and **3**). Our work has yielded two designs which we routinely use in our practice. In one design the flexures are integral parts of the polypropylene shell (**Figure 4**). The other design utilizes pre-molded polyurethane flexure units (**Figures 5a** and **5b**). Both of these designs provide the following characteristics:

1. Allow precise and adjustable control of ankle position and motion;
2. Exert minimal resistance throughout the prescribed range-of-motion;
3. Allow the orthotist to align the orthotic axis of rotation congruent with the anatomical ankle axis, and;
4. Accomplish this without significant weight or cosmetic sacrifices.

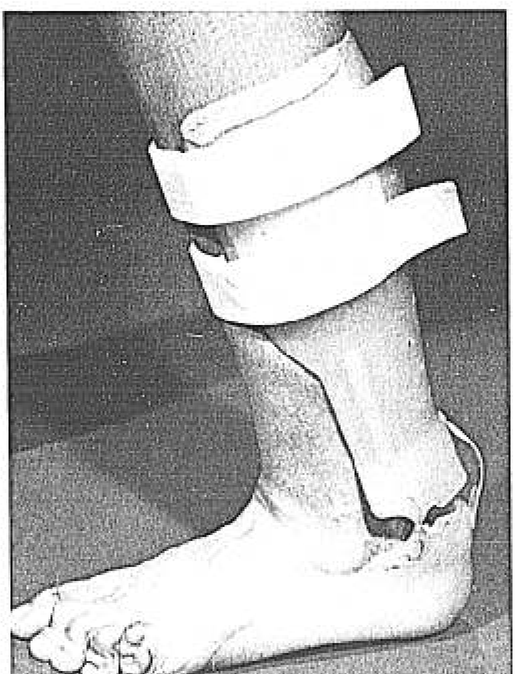


Figure 1. This polypropylene shell type ankle-foot-orthosis was fabricated in 1976 for a teenage boy. The polypropylene flexures are formed from the shell material.

Polypropylene is a very interesting material for use in flex members because it seems to have the ability to realign polymer chains to resist fatigue damage. Also, procedures such as cold deformation can be used in the fabrication of polypropylene flexures to create some preferential micro-structure alignment. The polypropylene flexure design we have developed involves both material removal and crushing (cold deformation) steps to form the two in-line flexures into the ankle-foot orthosis shell.

Figures 6 through **8** help to explain the fabrication procedure. When the plaster model is covered with the hot, flexible 5 mm thick polypropylene (monopolymer), extra

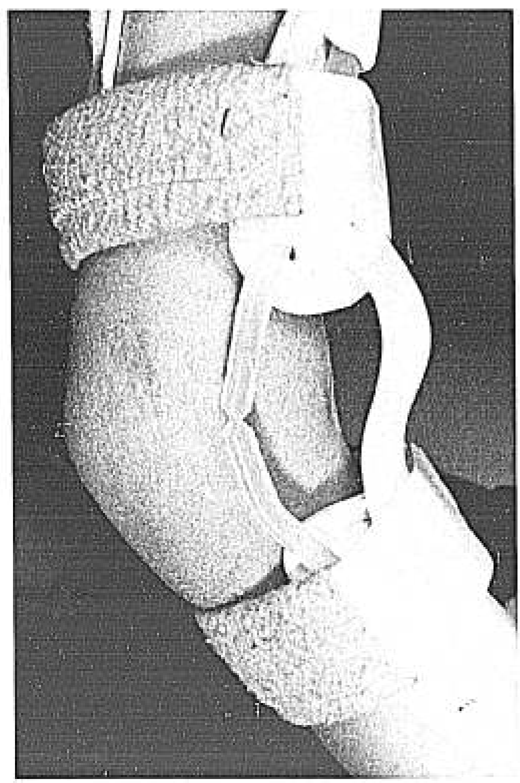


Figure 2. Short polypropylene flexures are excellent for wrist and elbow applications. They work well, especially in pediatric applications, to save weight and lessen bulk. The flexure visible in this photo and a similar one on the medial side were fabricated in minutes from scrap pieces of polypropylene.

small pieces of polypropylene (5 mm thick and heated along with the large sheet) are added to increase the shell thickness at important locations; one in the area of each malleolus where the flexures will be formed, and a third in the area of the Achilles tendon directly posterior of the malleoli. The surfaces of the polypropylene must be wiped clean with a solvent before heating. The polypropylene should be removed from the oven very soon after it becomes transparent. If the polypropylene is too hot when removed from the oven, paraffin molecules will have migrated to, or formed at, the surface and the small pieces will not bond to the main shell. After the polypropylene shell has cooled, it is removed from the plaster model and the desired location of the medial and lateral flexures is determined and marked. A 6.5 mm diameter drill hole is used to create the posterior surface of the flexures. The anterior surface is formed with a hand-held power tool with a small rotating cutter. **Figure 7** shows the desired dimensions. A special long-nosed cylindrical-jaw clamping tool is then used (**Figures 8a, 8b,** and **8c**) to cold form the flexures to the desired thickness (3 mm) and in alignment with each other. The clamping tool (a modified Vise-Grip™) has a long extension of one of the cylindrical jaws so that the extended jaw can be passed through both medial and lateral holes (drilled just posterior to the flexures) when one flexure is cold formed by clamping the jaws together. The extended jaw is then passed through both holes from the opposite side when the other flexure is cold formed. This special tool and procedure creates an in-line formation of the flexures (**Figure 9a**). If the flexures were formed along separate medial alignments (**Figure 9b**), they would act like two out-of-line hinges and "binding" stresses and strains would reduce the free action and service life of the flexures.

The final step in creating the double flex-

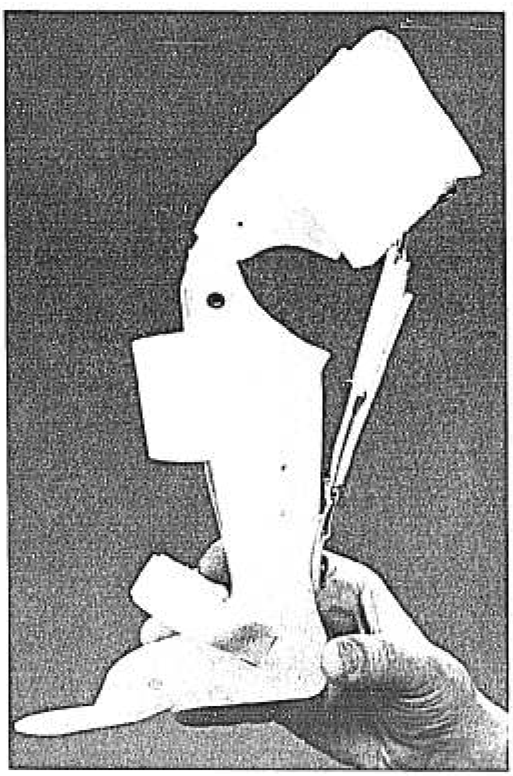


Figure 3. This knee-ankle-foot orthosis for knee extension contracture reduction utilizes polyurethane flexures for the knee joint motion.

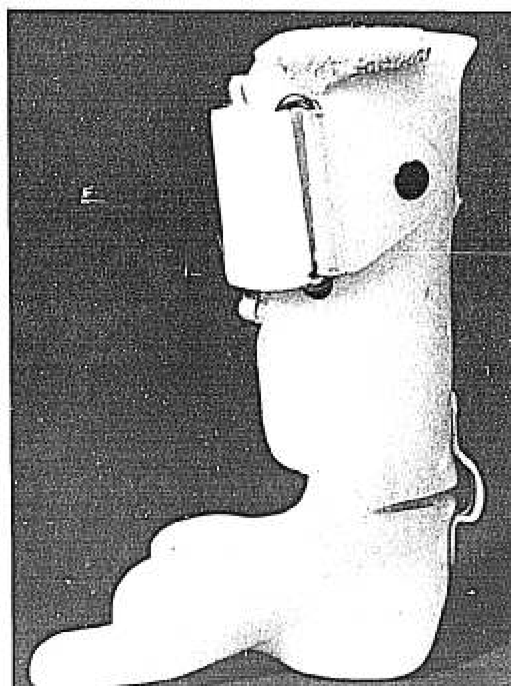


Figure 4. The integral polypropylene flexure design involves creating a greater shell thickness where each flexure will be located and then careful removal of material to form the flexures.

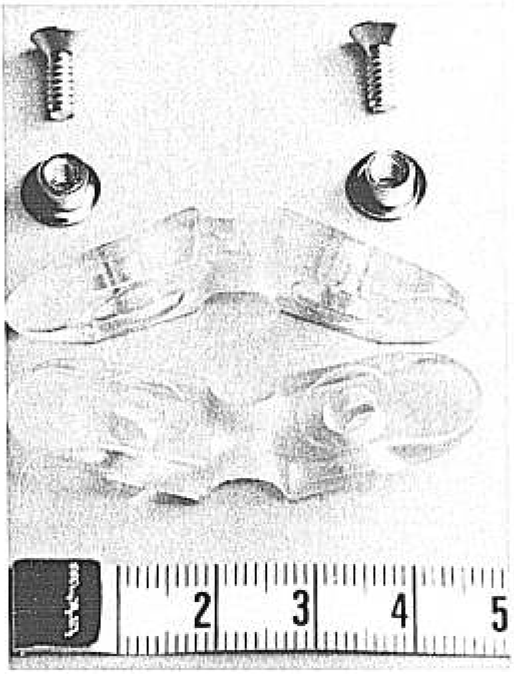


Figure 5a. A set of the injection molded polyurethane flexures and mounting hardware.

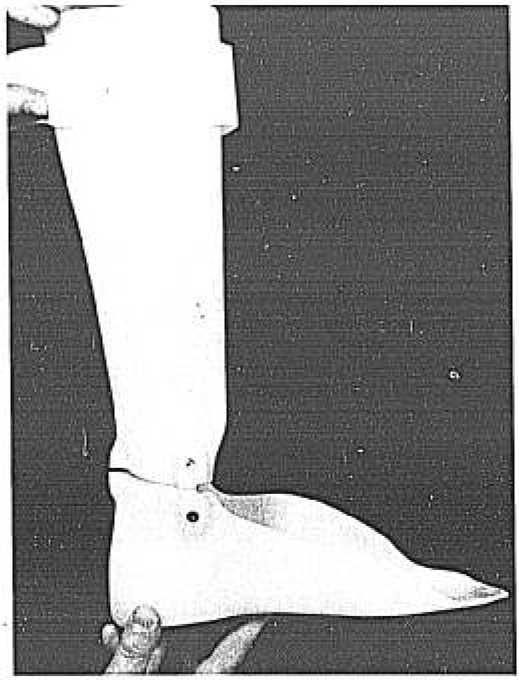


Figure 5b. An example of an ankle-foot orthosis with the polyurethane flexure installed. This AFO has free dorsiflexion and plantarflexion is stopped at 0°.

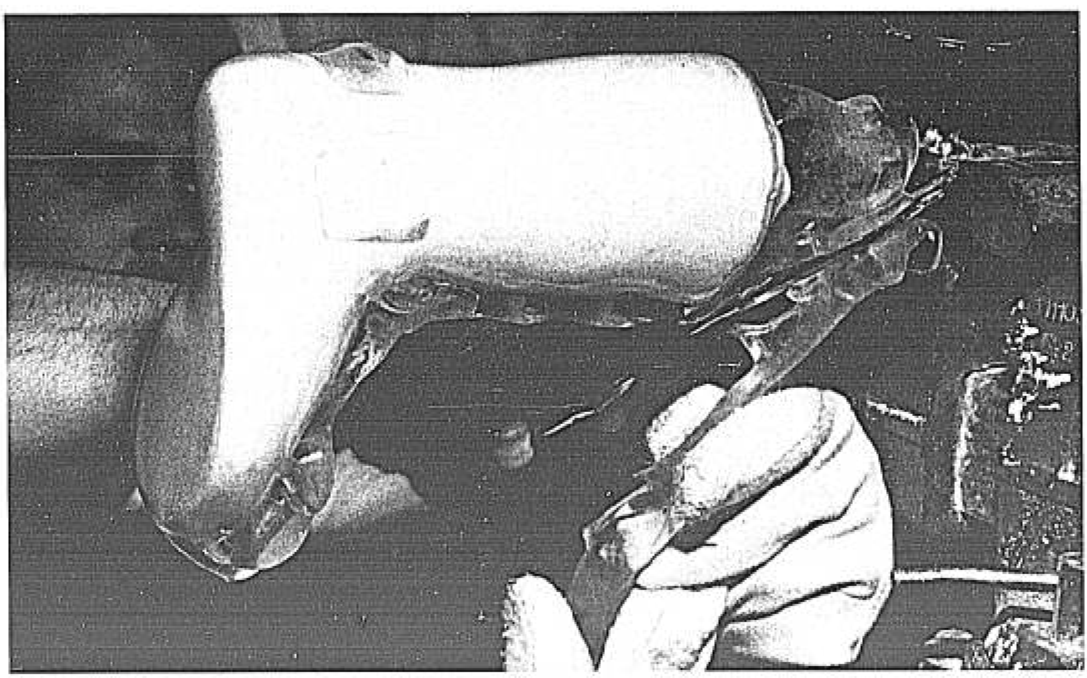


Figure 6. When the plaster model is covered with 5 mm thick polypropylene, small additional pieces are added in the area of each malleolus (centered just below the apex) and straight posteriorly at the Achilles tendon.

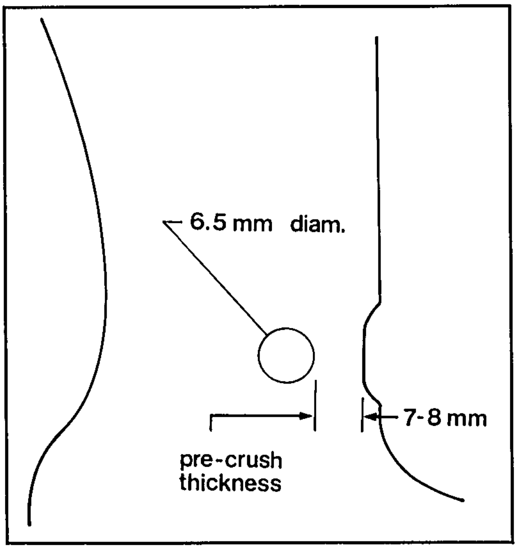


Figure 7. Each flexure location is determined and a 6.5 mm diameter hole is drilled. The anterior border of the hole defines the posterior surface of the flexure. The anterior trim line is carefully cut back to within 7 or 8 mm of the drilled hole. This completes the pre-crushing preparation of the flexures.

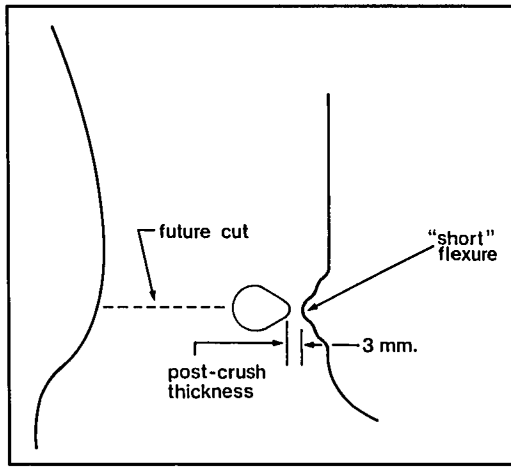
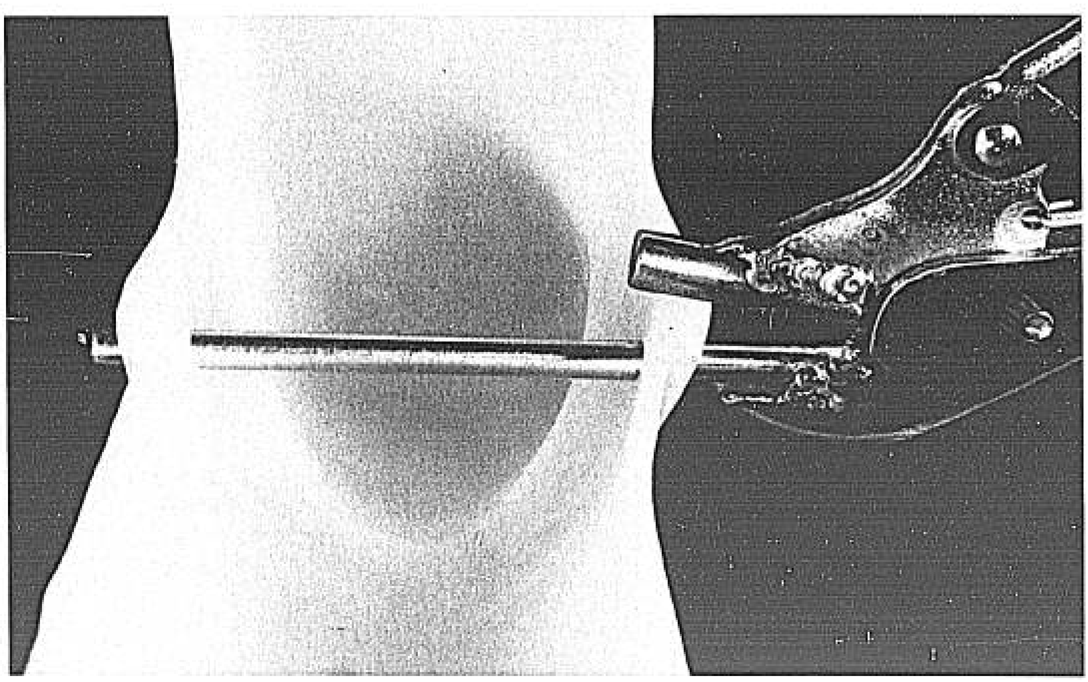


Figure 8b. (See below).

ure joint is to "free" the flexures by cutting through the solid section of the AFO shell posterior to the flexures. If the AFO is to stop plantarflexion, those cut surfaces will be the "stops" and it is often appropriate to modify those surfaces to dampen the stop-



Figures 8a (above), b, and c. Modified Vise-Grip™ pliers are used to crush-finish the flexures. The special pliers have cylindrical jaws; one of them of extended length. The extra long jaw is passed through both medial and lateral 6.5 mm holes (8a) and near post is crushed to the dimensions indicated in 8b. The long cylindrical jaw is then passed through both holes from the opposite side and the other flexure is crushed to final configuration (8c).

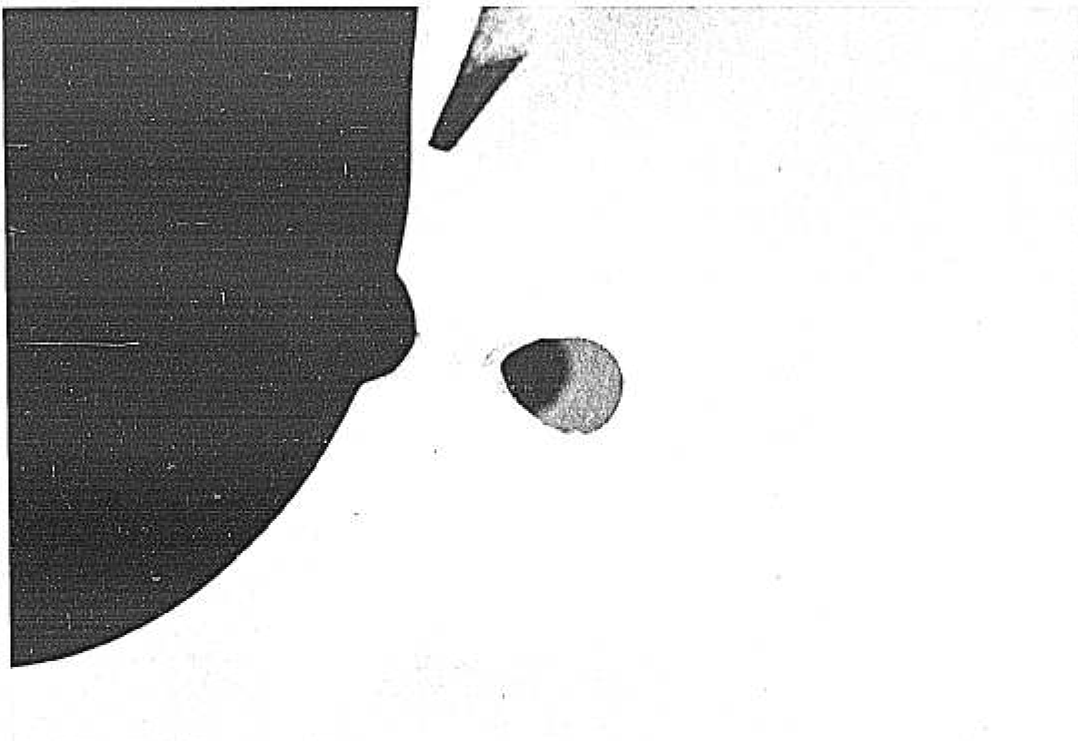
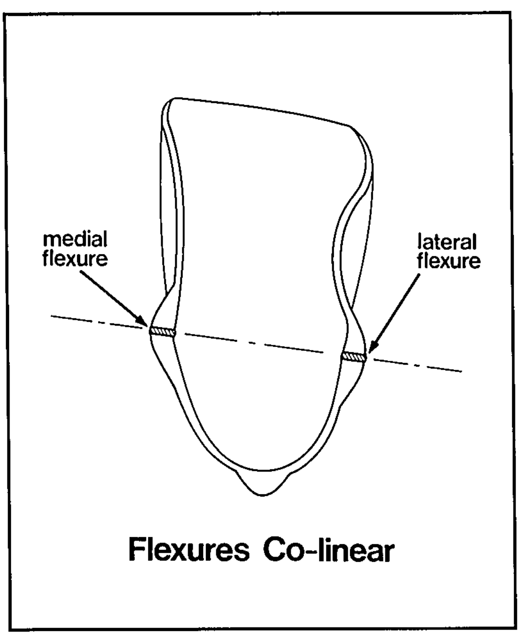
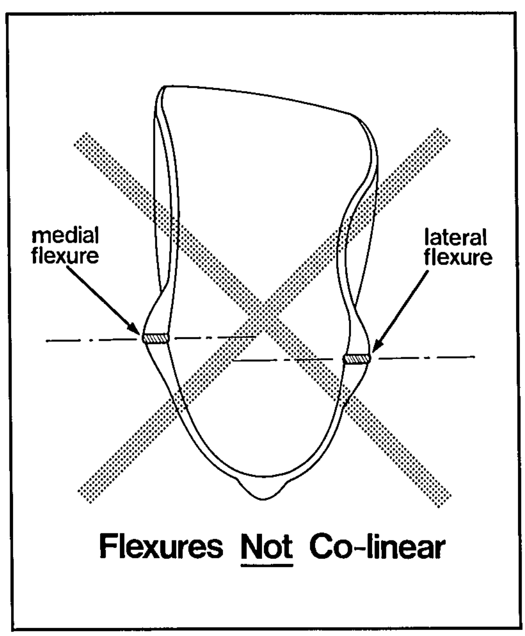


Figure 8c.





Figures 9a and b. The extended jaw of the Vise-Grip™ ensures that the crushing action creates two co-linear flexures as diagrammed in 9a. If the two flexures were formed with independent alignment as in 9b they would not function freely and bending stresses would be elevated.

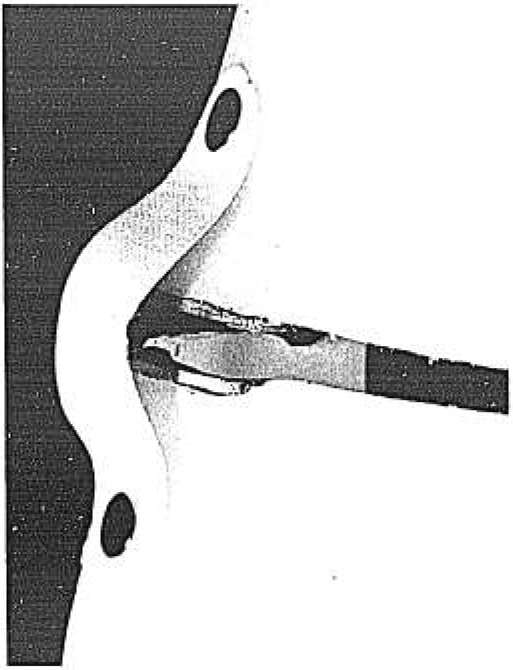


Figure 10. The cut surfaces creating a plantarflexion stop may be modified as appropriate. This shows leather contact pads for quieter function. Those surfaces may also be built up by welding to change the plantarflexion stop angle.

ping click noise or to slightly change the angle at which plantarflexion stop occurs (**Figure 10**). If plantarflexion is to be allowed in the orthosis, additional material is removed posterior of the flexures as shown in **Figure 11. Figures 10** and **11** also show a simple method for limiting dorsiflexion by using a posterior tether strap when desired. When fabricated correctly, the result is a very close-fitting, cosmetic double-flexure joint with a single-axis action. More detailed fabrication instructions are available from the authors.

The polypropylene flexures are much more rugged than they appear to be. During the course of use they will appear to be undergoing damaging changes (high strain areas turn milky white) which are actually the normal non-destructive way polypropylene responds under fatigue cycling. However, no material is indestructible and if they do break, replacement is very difficult.

To facilitate double-flexure installation and replacement (if necessary), we have de-

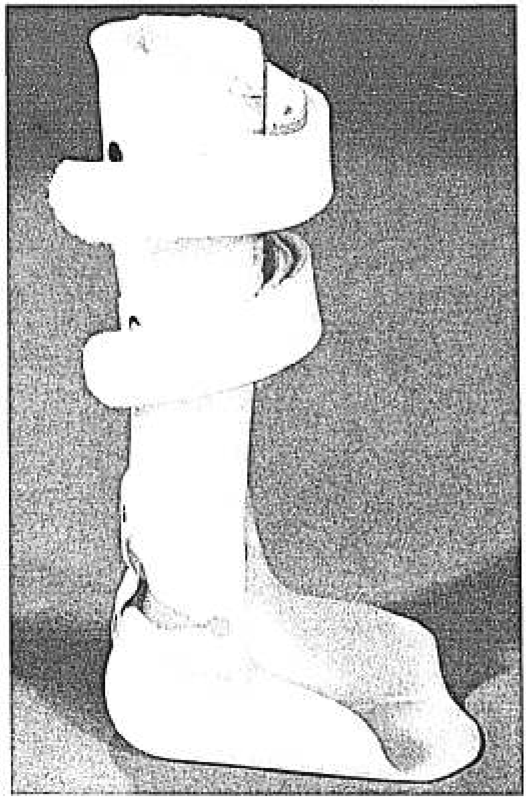


Figure 11. It was desired that this AFO should have free plantarflexion and limited dorsiflexion. A wedge of shell material was removed posterior of the flexures. A dacron strap acts as dorsiflexion stop.

veloped an injection-molded polyurethane flexure unit and corresponding fastening hardware. Fabrication is simplified. Extra shell thickness is created in only one location; at the Achilles tendon where the plantarflexion stop will be (if there is to be one). The pre-manufactured flexure units are positioned in the desired locations under the snug-fitting hosiery which is pulled over the plaster model prior to covering with hot polypropylene sheet (**Figure 12**). Vacuum assist forming pulls the hot polypropylene into a close-formed shape around the underlying flexure units. When the polypropylene shell is cool and rigid, it is removed from the plaster model, the flexure units are pulled out and a horizontal U-shaped portion of shell material is removed forward of where the centerline of the flexure will be (**Figure 13**). That material removal is to provide clear-

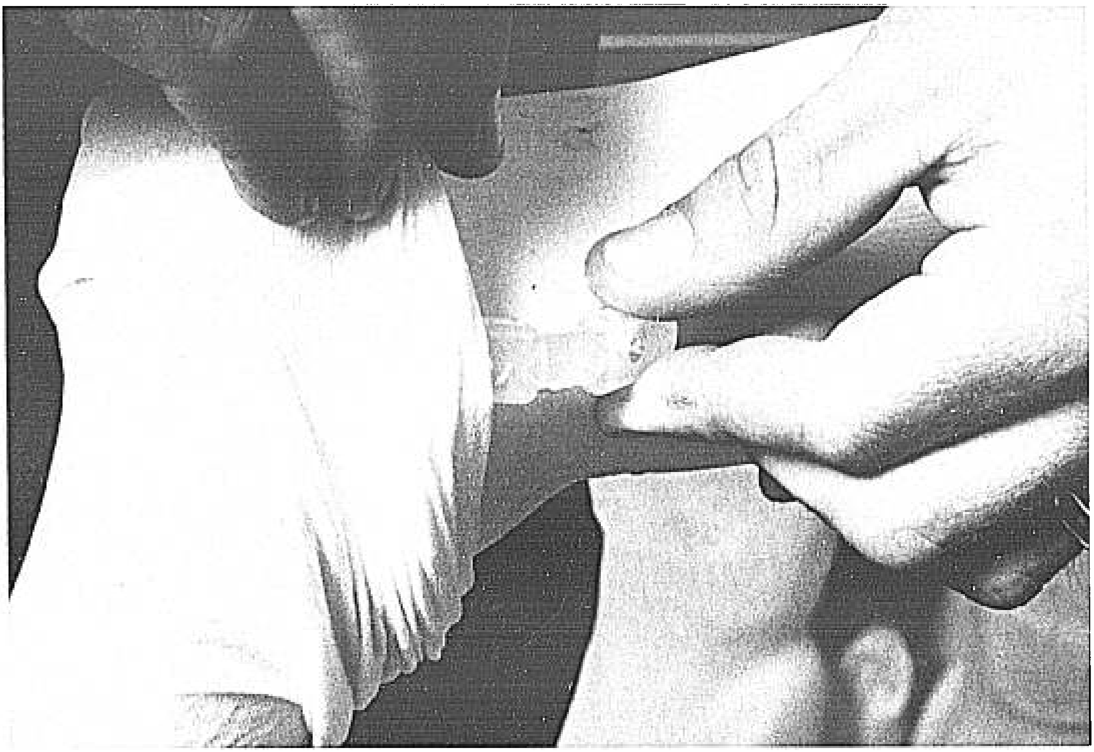


Figure 12. Polyurethane flexure units are held in desired locations by snug-fitting nylon hose, until covered with hot polypropylene. The polypropylene shell molds closely around the flexures.

ance needed for dorsiflexion. Holes are drilled for the flexure fastening screws and the AFO shell is cut through to create separate foot and calf shell sections. The final step is to reunite the two shell pieces by installing the flexure members (**Figure 14**).

The polyurethane flexures have another very important advantage. Polyurethane has a much lower modulus of elasticity than polypropylene. This causes the bending-induced stresses to be lower (in this type of design application), and we can utilize a circular cross-section flexure design rather than the rectangular one used for polypropylene (compare **Figures 9** and **15**). The circular cross-section flexure bends equally well in all transverse directions so no procedure is necessary to co-align the polyurethane flexures.

Durability Testing

In 1986, to facilitate the collection of quantitative durability data, we designed an ankle-foot orthosis testing apparatus (**Figures 16a** and **16b**). The shaft on which the foot plates are attached slowly rotates the AFOs in a backward direction. This causes a slow cycle into maximum dorsiflexion and then, as the orthosis rotates over the top of its circle, the weighted calf section falls, "banging" the orthosis against its plantarflexion stop. The inertia of the weights (1.0 Kgm mounted on the M-L center of the calf section and 1.95 Kgm mounted 12.5 cm lateral of center on a rod through the calf section) causes a very significant torsional, sheer and tension shock to be transmitted to the flexures when the plantarflexion stops break their rotating fall. A counter is mounted on the testing machine to count the rotations. The test apparatus does not tell us how long a given design will serve on a client but it gives excellent data to evaluate and compare the relative values of various design and material modifications meant to improve durability.

Both polypropylene and polyurethane flexure designs are used at Gillette but, be-

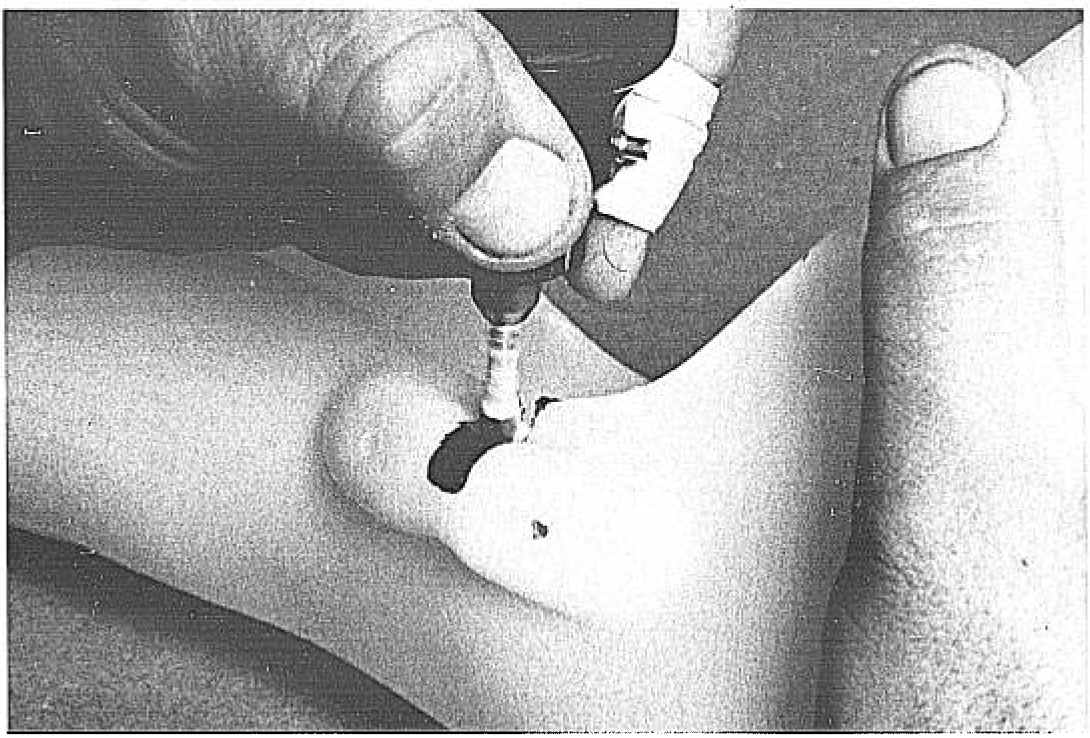
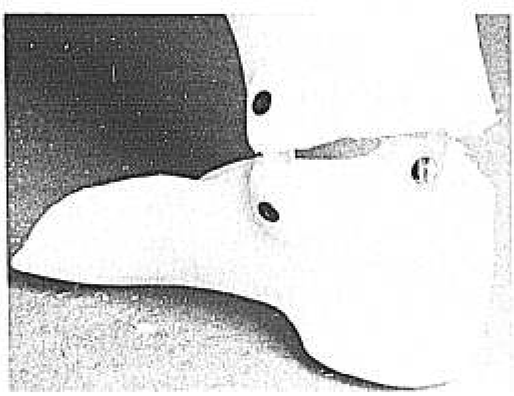
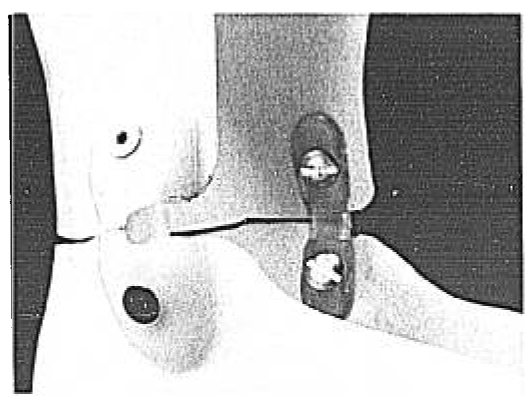


Figure 13. When the AFO shell has been removed from the plaster model and the flexures from inside the shell, a horizontal "U" shaped portion of the shell is removed forward from the flexure centerline. For illustration, the area to be removed is blackened on this photo.





Figures 14a and b. Mounting hardware holes are drilled, the AFO is cut through and the flexures are installed to complete articulation.

cause of fabrication ease, the injection molded polyurethane flexures have become the favorite. The durability testing machine has helped us to identify the best resin formulation and processing parameters. It is also used as a quality assurance test apparatus. Samples from each production batch of polyurethane flexures are tested to ensure that neither the process nor the material has varied from optimum.

In the durability testing program described, the polypropylene flexures yield a

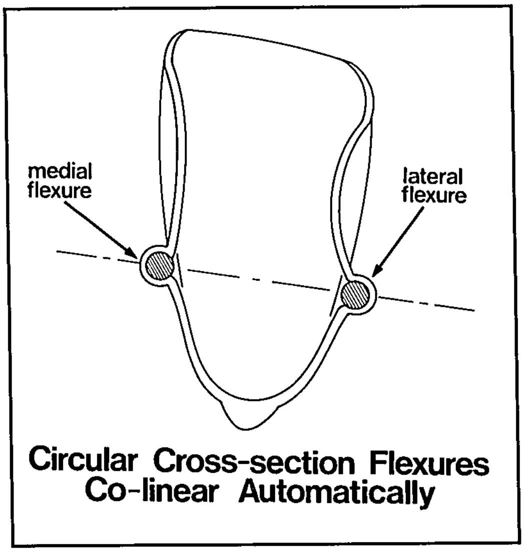


Figure 15. Flexure elements with circular cross-sections are easier to install. Axial symmetry of the bending section gives the flexure equal bending ease in all transverse directions. No special care is required to assure the flexures are co-linear.

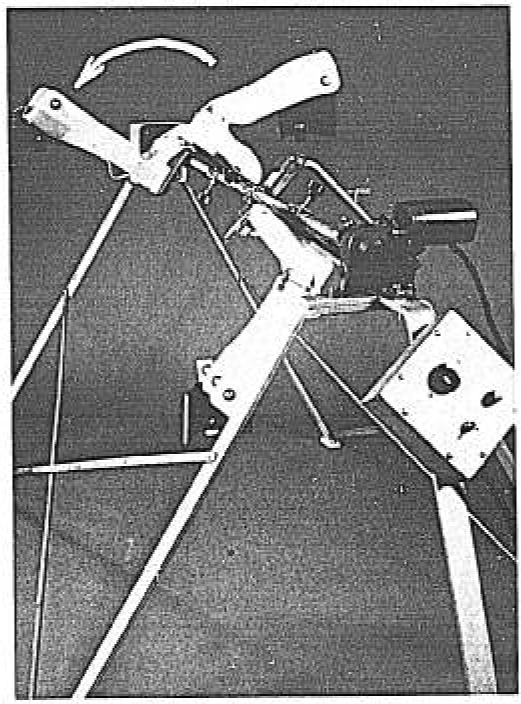
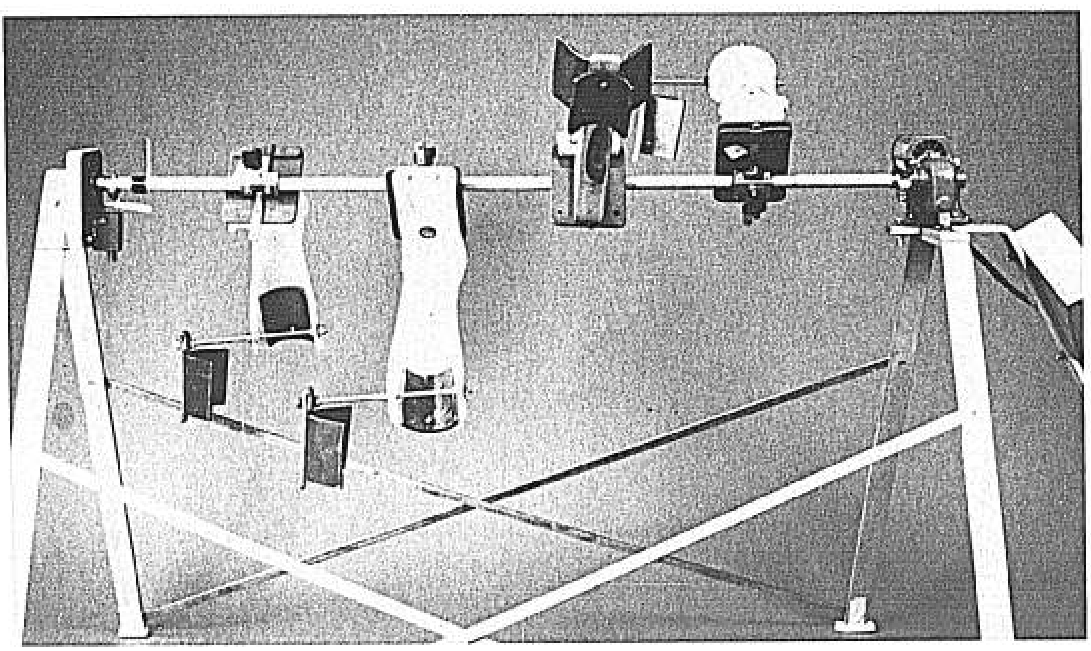


Figure 16b.



Figures 16a and b (above right). The ankle-foot orthosis durability test machine subjects a combination of four orthoses to 14 cycles per minute. Each cycle produces slow dorsiflexion to a maximum of 25° and then a very sharp torsion, shear and tension shock to the flexures as the weighted calf section drops against the plantarflexion stop.

life of about 400,000 to 500,000 cycles. The polyurethane flexures last about 600,000 to 700,000 cycles. The child-size version of the polyurethane design, tested under the same conditions as the adult-size, will last about 500,000 to 600,000 cycles. To give some basis for comparison, we tested two traditional metal AFO designs. In both cases a fatigue crack nucleated at the anterior lateral edge of the stainless steel stirrup near the sole bend. Complete fracture of the stirrups occurred at 168,000 and 125,000 cycles, respectively.

Conclusion

Multiple-flexure hinge joints have been used for millenia. Optimizing flexure designs for orthotic use requires some awareness of design fundamentals and material physical characteristics. Gillette has developed polypropylene and polyurethane designs which have been both field and laboratory tested. They have proven useful in nearly all applications. The polyurethane flexures are easily replaced if fractured.

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