The Polypropylene Solid-Ankle Orthosis[†]

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For many years, the bracing of paraplegic patients has been a discouraging problem to the orthotist. The marked increase in the number of children paralyzed by myelodysplasia has compounded the orthotist's problems, for with these patients, growth is a complicating factor while their potential to walk is generally greater than is the case with other types of paraplegics.

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Approximately one quarter of the children with myelodysplasia are paraplegic from the L3-4 level, and therefore have active hip flexors and knee extensors. However, they are not able to walk with conventional bracing as well as one might expect. Despite the use of crutches, their gait becomes progressively worse as they grow older, and their balance becomes more perilous.

The myelodysplastic child, flail from the knees down, can be compared, in one sense, to the bilateral below-knee amputee. When fitted adequately the bilateral BK amputee ambulates very well even though proprioception and peripheral sensation are absent. If the same principles that make the bilateral BK's performance possible were applied to myelodysplastic patients, could not their ambulation
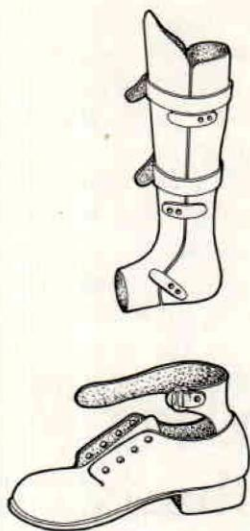
Fig. 1

Initial Design of the Solid-Ankle Orthosis.

be improved? Attempts to answer this question are reported in this paper.

THE DESIGN PROCESS

The initial design (Fig. 1) consisted of a two-piece molded plastic laminate (polyester) with stainless steel retention bars to "lock in" ML stability. This design was successful in providing stabilization needed for improving balance, and in improving the gait of the first youngster fitted, a seven-year-old boy who wore the orthoses for eleven months without incident before outgrowing them. Later, with other patients, the following problems arose:

1. Some of the children and parents had difficulty in applying the bi-valved shells without unwittingly pinching the skin.

2. Fabrication of the bi-valved shells required an excessive amount of time because of dif-ficulty encountered in aligning the retention bars.

3. The shoe tended to migrate laterally as the patient walked.

In an attempt to simplify the fabrication technique, and at the same time make the orthosis easier to don, a one-piece laminate consisting of a modified rigid anterior shell and a flexible calf cuff was devised (Fig. 2) and tried. A Velcro closure fastened to the shoe and passing over the instep replaced the cosmetically objectionable posterior tee strap used in the original design.

Several weaknesses showed up in the second design:

1. Failure of the patient or parent to fasten the instep strap securely permitted the exposed heel to move up and down against the back of the shoe, and caused ulcerations.

2. The distal edge of the anterior portion of the shell pressed downward on the instep as the weight of the body pressed against the proximal end. This action resulted in a shearing
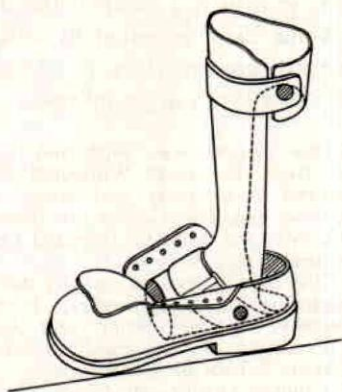

Fig. 2

The Second Design of the Solid-Ankle Orthosis.

effect, and caused an ulceration across the instep.

3. The instep strap did not prevent the more active child from walking out of the shoes. It was also cosmetically objectionable, because of the bulk over the instep.

The anteroposterior "rocking" action of this design with its resulting skin breakdown over the instep is related to the fact that it is quite impossible to cast a flail foot in a position of weightbearing and at the same time maintain an optimum position of balance. Therefore, allowance for compression of the foot during weightbearing had to be "guesstimated" when preparing the positive model. A cleaner design was clearly necessary.

It now became evident that the most practical design would have to be foolproof in terms of the device being applied day after day by either patient or parent. It was also evident that complete encasement of the foot, top and bottom, was not

Fig. 3

Present Design of the Solid-Ankle Orthosis: Polypropylene Shell with a Plastazote Lining.

practical. Needed was a shell that could be donned easily and worn *only* as intended. The present design (Fig. 3) functions well and meets these criteria.

Other factors which influenced the overall configuration of the present design are:

The superior-anterior border of the solid-ankle (SA) shell is located at the level of the tibial plateau for two reasons: 1) to control unwanted AP tibial motion by providing a lever arm equal to the length of the tibia, and 2) to avoid any impingement upon the knee joint.

The vertical length of the anterior panel is related to the patient's weight—the heavier the patient, the longer the panel; i.e., sufficient surface area should be provided to keep pressure on the skin under 7½ psi. to avoid skin breakdown.

The width of the anterior and posterior cutouts are determined by the diameter of the malleoli and relate solely to the application and removal of the shell.

The superior border of the posterior portion, and the space between it and the inferior border of the anterior panel are explained in the section on TRIMLINES.

The width of the side panels, at ankle and heel levels, are kept as broad as possible to provide strength for resistance to pressure from the body against the anterior panel in the AP plane. Obviously, the width of these panels is also influenced by the diameter of the malleoli; i.e., the width of the anterior cutout.

The degree of the slope given to the side panels of the foot portion of the shell at their distal ends is determined by the depth of the vamp of the shoe. Material is removed gradually until the shell can be slipped into the shoe with ease.

Ending the bottom distal edge at the metatarso-phalangeal joints is a compromise in order that commercial shoes can be used. Even if custom made shoes were used and the bottom of the shell was continued to provide a complete inner sole, AP alignment (as described under SHOE MODIFICATIONS) would be totally dependent upon the casting technique, and would make casting and fitting even more difficult.

In an effort to determine the order of importance of various clinical observations, 16 mm motion pictures were taken of several spina bifida children. The films were slowed to 2 frames per second and the children's gaits were studied individually. The gaits of both crutch and non-crutch walkers were analyzed. The walking patterns of the non-crutch walkers were the most revealing. The youngsters without crutches must keep their legs and feet in constant motion in order to maintain their balance, whether or not they wear conventional bracing. Their bilaterally flail feet are 'converted', as it were, to ball-and-socket-like joints about which their tibiae roll continually and uncontrolled. Add to this the fact that these children lack the sensory perception to know where their feet are at any given moment, and it be-

comes apparent that positive control of this 'out-of-phase' motion of the tibia is the first order of business. The films were helpful in making it possible to identify other specific features of these pathological gaits. Further work in these areas is now in progress.

Prior to August 1970, all of the shells, including the present design, used polyester laminations. Except for the initial design (Fig. 1), all laminations used were inadequate in strength, becoming warped and distorted in a short time despite liberal reinforcement with glass cloth, fiberglass roving, and woven polypropylene cloth. The distortion allowed unwanted motion of the foot within the shoe, causing pressure sores over bony prominences. Attempts to eliminate the distortion led to heavier, thicker shells which were unacceptable because of shoe fitting and cosmesis problems. Since molded polypropylene was substituted for the plastic laminate problems of distortion have been virtually eliminated.

All shells are now being lined with ⅛ in. thick Plastazote which seems to decrease the possibility of sores, especially when friction, rather than pressure, is suspected to be the cause. Observations made of the gaits of myelodysplastic children, with and without the SA orthoses, provide the basis for the suspicion that friction is also a problem.

Although it has been stated that polypropylene has eliminated the problems of distortion, it is not intended to imply that the SA shells made of polypropylene remain completely inflexible when subjected to

the torques which these pathological gaits generate. Quite the contrary. The ability of polypropylene to *yield* to these forces, within ranges dictated by a given gait, yet consistently *return* to its original form without fatiguing, has eliminated distortion.

Examination of the twisted laminated shells made it apparent that the children were attempting to rotate their tibias externally while wearing the SA orthoses, and that they must be generating quite high torques in the transverse plane while walking. Evidently, the laminated shells would not yield until they fatigued. It seems reasonable to assume that the tibia, in or out of the shell, is the least able to resist the torque and, therefore, when in a laminated shell, the malleoli would rub against the non-yielding material surrounding it. The polypropylene 'follows' the tibia as it rotates externally with each step. At the same time the polypropylene shell's two side panels are turning about the vertical axis of each panel, and displacement between the malleoli and the shell is reduced. However, it cannot be totally eliminated. The Plastazote appears to absorb the residual displacement between the leg and the shell and keeps the malleoli from rubbing against the polypropylene. The Plastazote lining is too thin to act as a resistance to pressures caused by poor anatomic alignment or to a shell which is either too tight or too loose. Its use is not related to control of motion.

CLINICAL EXPERIENCE

Since August 1970, 58 cases have been fitted with the third design using polypropylene. Of these,

52 were bilateral and 6 were unilateral. The patients' ages range from one year and 5 months to 67 years. There were 33 females and 25 males. The group includes 47 with spina bifida, 4 who are traumatic paraplegics, 2 with head injuries, 2 with transverse myelitis, 2 with club foot and one suffering from a cerebral vascular accident. Seven of the group required polypropylene thigh cuffs attached to the SA shells with conventional metal lateral uprights and knee joints.

The feet of spina bifida patients present fitting problems unlike other paraplegics. Although the majority of the L3-4 patients present a valgus hindfoot accompanied by pronation of the forefoot during weightbearing, because they are growing children bony deformations which are not always evident when standing occur often. The orthotist must be able to recognize and accommodate for several conditions which may appear while he is attempting to place such feet in the optimum standing position for casting. If the relationship of each condition to optimum control of motion of the foot-ankle complex is not understood, a high percentage of failures is inevitable.

CASTING TECHNIQUES

Casting techniques vary somewhat with respect to the functional condition of the feet.

When both feet are supple

If the patient's feet are supple and little or no resistance is encountered when each foot is passively brought into the optimum position of balance, the casting technique is as follows:

The apices of the malleoli are marked on the skin. A mark is placed ½ in. below the head of the fibula and anteriorly at the level of the tibial plateau. Marks are placed on the skin every two inches between the apex of the lateral malleolus and the mark ½ in. below the head of the fibula.

Linear measurements are recorded from:

1. The apex of the lateral malleolus to the mark ½ in. below the head of the fibula. (Identification of the head of the fibula serves as a guide for determining the lateral proximal trim line.) Pressure upon this thin-skinned area must be avoided.

2. The proximal, superior surface of the instep to the mark at the level of the tibial plateau which will be the proximal anterior trim line.

3. A Ritz stick is used to obtain the width between the medial and lateral borders at the ball of the foot. This measurement is taken with pressure upon the forefoot to simulate the condition imposed by a laced shoe.

Circumferential measurements are recorded for each 2 in. increment.

A double layer of tube gauze is pulled over the foot and leg. A length of rubber tubing is placed along the parasagittal line for protection when the cast is cut for removal later. Two layers of elastic plaster bandage are wrapped from a point distal to the ball of the foot to approximately 1 in. proximal to the tibial plateau. A single layer of extra-fast-setting plaster bandage is added.
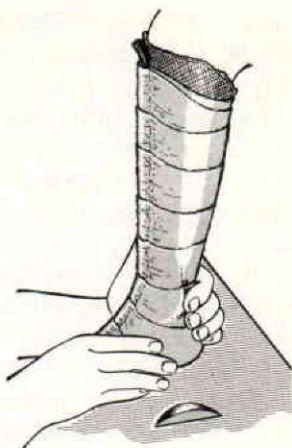

Fig. 4

A navicular pad (shown in readiness) is inserted under the longitudinal arch between the wrapped foot and the footboard and held in place while the plaster is setting.

The seated patient's foot is then placed on a flat board, and is checked to be sure its AP relationship to the tibia is 90°. While the plaster is setting, the orthotist must maintain the foot in an optimum medio-lateral position by holding the heel in the neutral position and pressing downward on the forefoot to approximate the pressure of a firmly laced shoe. The longitudinal arch is maintained by placing a rubber navicular pad* between the cast and the board (Fig. 4). Throughout the holding procedure, care must be taken to be sure that the tibia remains vertical over the foot while the cast is setting. It is often necessary to have either the patient or an assistant grasp the knee to ensure correct tibial alignment until the cast is sufficiently set for removal. The use of warm water and the extra-fast-setting outer layer

* Rubber navicular pads are commercially available in various sizes.

of non-elastic plaster bandage help to reduce the holding time.

When "correction" results in forefoot supination

Though the patient may present an everted heel accompanied by severe pronation when standing, the position of the forefoot in relation to the hindfoot may not be the same when the os calsis is passively placed in the neutral position. If bony deformation, i.e., wedging, has occurred, the forefoot will be in *supination* when the heel is held in an optimum position of ML balance.

In such cases, the degree of supination present must be accepted and special care must be given to the exaggerated space between foot and board in the area normally considered the longitudinal arch. This space must be fitted with a suitably steep sloping navicular pad before casting. Once this pad is shaped, it is inserted between the cast and the footboard, as described in the casting procedure above. This will en-sure that weight can be borne along the medial border without the foot reverting to pronation when standing in the orthosis. Failure to accommodate for this condition at the time of casting will result in ulcerated sores over both the medial malleolus and the navicular bone.

When there is fixed equinus present

With the heel in a fixed position of equinus, the foot cannot be brought to neutral in the AP plane without the heel (which takes the forefoot with it) rolling into valgus. The orthotist must note the point at which the heel begins to roll laterally as he dorsiflexes the patient's foot. This "trigger" point indicates the amount of equinus which must be accepted to ensure optimum ML balance. It usually occurs between 5 and 15° of equinus, i.e., 5 to 15° short of the sole of the foot being 90° to the tibia. To allow for the fixed equinus, the footboard is raised at the heel end to a degree equal to the fixed equinus heel (Fig. 5). The cast is then applied as described previously. Care must be taken to see that the tibia is perpendicular to the floor, *not* the inclined footboard.

It is necessary that *both* feet be cast in the same degree of eqinus in order to provide optimum control of AP balance to the patient. When one foot has a fixed equinus heel and the other has not, the foot which has no fixed equinus must be cast in a position of equinus equal to that of the other foot. When both feet present different degrees of fixed equinus, both feet are cast in the position of the one with the greatest amount of equinus.
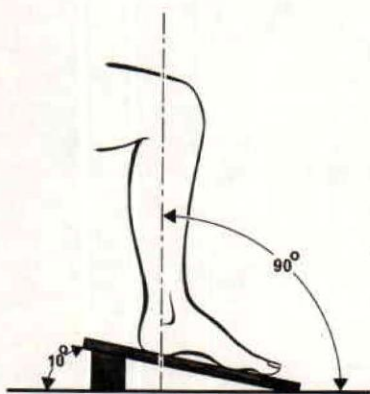

Fig. 5

An example of the positioning of the leg and foot when equinus must be accepted to achieve optimum balance in the M-L plane.

When a calcaneal deformity is present

Occasionally a child will have a marked calcaneal deformity owing to contraction of the pretibial muscles without opposition to the paralyzed triceps sura muscles. Weightbearing over a period of time may cause the calcaneous to rotate downward and backward.

The abnormal posterior rotation is usually fixed and must be accepted. When casting such a foot it is important to hold the forefoot on the footboard while an assistant applies pressure upon the anterior aspect of the knee in order to obtain an AP relationship between the foot and the tibia as near to 90° as circumstances will permit. The SA shell combined with a snugly laced shoe will maintain the alignment obtained in the cast.

Some spina bifida patients with calcaneal gaits may have had repeated ulcerations on the bottoms of their heels due to excessive pressure, and so much tissue has been destroyed that there is no semblance of a heel contour left. In such cases, a normal heel contour must be added to the positive model to prevent the patient from walking out of his shoes. Silastic foam is used to fill the hollow between the shell and the hindfoot.

When the heel is in fixed valgus

When the os calsis cannot be brought into the normal ML weightbearing alignment, ulcerated sores are likely to develop about the medial malleolus and the navicular bone. If surgical correction of the deformity cannot be made, the foot is cast in the best position possible and extra padding is incorporated within the orthosis to prevent skin breakdowns in the areas mentioned.

THE POSITIVE MODEL

The negative cast is cut along the rubber tube, removed and sealed, and a positive mold is poured. The positive model is carved to the circumferential measurements. Reliefs for the malleoli and any other bony prominences which have been noted, are carefully placed and bonded to the model.

FORMING THE SA SHELL

The modified positive model is placed in a vise, heel end up. A coat of shellac and a single layer of cotton stockinette are applied. The stockinette compensates for the space needed for the patient to wear a stocking within the shell. Should, for some reason, a Plastazote lining not be used the stockinette must be covered with talcum powder to prevent the hot polypropylene from sticking to it.

Rectangular pieces of Plastazote and polypropylene are cut to a size two inches longer than the length of the model from its posterior proximal edge, over the back of the heel, to its distal edge on the plantar aspect of the foot and two inches wider than the largest circumference of the model. The Plastazote lining is ⅛ in. thick. The polypropylene is usually 3/16 in. thick, though ⅛ in. is sufficient for small toddlers and ¼ in. may be necessary for heavy individuals.

The Plastazote is heated in an air circulating oven for 5-6 minutes at 285°F. Two technicians are needed to form both the Plastazote and the
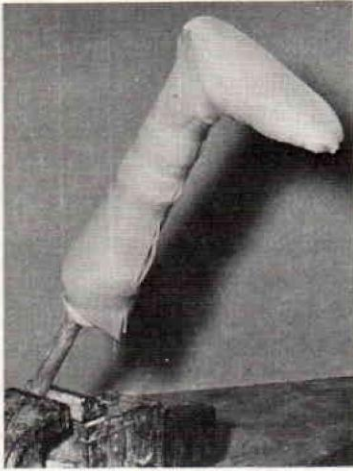
Fig. 6
Plastazote Formed Over Model.

Fig. 7
Placement of Molten Polypropylene Sheet Over Model.

polypropylene. The working time for both materials is short, though manageable when two individuals work as a team. The working time for the Plastazote is approximately ½ minute; for the polypropylene, 1½ to 2 minutes. Should the Plastazote stabilize before forming is completed or an error in the placement is made, it can be reheated whereupon it will return to its original sheet form ready for reuse. Polypropylene is made of "sterner stuff" and cannot be reused.

Once the Plastazote has been formed to the model, excess material is trimmed away and the formed lining is secured to the model with scotch tape along its anterior trim line. (Fig. 6.)

The polypropylene blank is placed in the air circulating oven on a tray covered liberally with talcum powder to prevent sticking, and heated for 20-25 minutes at 400°F. When heated to its plastic state, polypropylene is extremely sticky and stretches easily. When a bond

is desired, the unpowdered surface is placed in contact with the pre-formed Plastazote. If a bond is not wanted, both top and bottom surfaces are powdered before placing the polypropylene in the oven.

Asbestos gloves must be used to handle the material when heated, and they, too, must be powdered to prevent the plastic from sticking to them. When the polypropylene is ready, the tray is removed from the oven, the two technicians lift the blank by its four corners and place it over the model (Fig. 7). Of its own weight, the material will drape itself about the model, and the technicians quickly, yet gently, stretch and smooth the material over the model with their gloved hands. While it is still hot, excess material along the anterior centerline of the

Fig. 8
Trimming Away Excess Material.

Fig. 9
Completed Shell Ready for Trimming.

model is trimmed off (Figs. 8, 9, 10). The form is then wrapped with elastic bandage and allowed to cool.

TRIM LINES (Fig. 10)

The measurement (a) taken from the proximal end of the patient's instep to the tibial plateau is now repeated over the model, and a mark is drawn to designate the proximal end of the shell anteriorly. The length (c) of the anterior panel of the shell will vary with the size of the patient, usually 4-5 in. for adults and 3-3½ in. for children. A diameter measurement (d) is taken obliquely from the proximal end of the instep to the apex of the back of the heel. One-half inch is deducted from the diameter measurement (d) and the remainder determines the size of the opening from
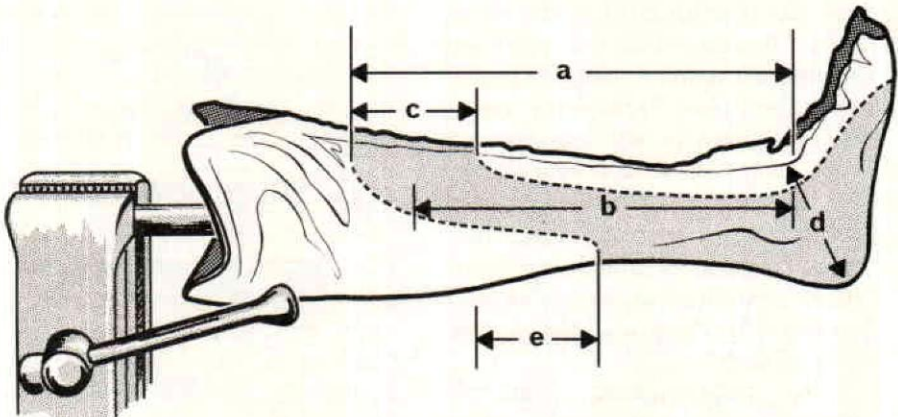

Fig. 10
Trimlines

a, from proximal end of instep to tibial plateau; b, apex of lateral malleolus to ½ in. below fibula head; c, from tibial plateau, 3-5 in., depending on length of leg; d, diameter, from proximal end of instep to apex of heel; e, proximal edge of posterior panel—diameter, d, less ½ in. from lower edge of anterior panel. Dotted lines show anterior/posterior cut-outs.

back to front through which the foot must pass to don the shell (e) and thus defines the proximal border of the posterior trim line. These three marks, designating the top and lower edges of the front panel and the top edge of the back panel, are then connected together (care being taken to avoid the fibula head, b) to produce the design shown in Figure 3. A Stryker cast cutter is used to cut the open anterior and the upper posterior areas of the design. The anterior panel is then cut along its center line where the ends of the blank had been drawn and stuck together during the forming. The shell can be spread and removed from the mold. The Plastazote lining, which has now adhered to the inner surface of the polyproyplene shell, is peeled back from the vertical sides of the anterior panel. The vertical edges are beveled, butted together and welded by using a special electric gun* in which heated nitrogen is used to fuse polypropylene welding rod to the seam. The distal edge of the foot portion of the shell is immediately proximal to the first and fifth metatarsophalangeal joints. All edges are sanded with a highspeed sander to bring the rough cut to the finish lines of the design, as shown in Figure 3.

Very little final trimming is necessary if the suggested trim lines are observed. A heat gun may be used to reshape the edges when necessary. All edges are sanded smooth, a strip of ⅛ in. Plastazote is beveled and cemented inside to cover the vertical seam of the lining along the weld line. A 2-inch wide Velcro closure is attached, posteriorly (Fig. 3).

THE SHOE

High-top shoes are not necessary. A conventional laced oxford is generally used for children and the lightest weight laced oxford available (such as "Hush Puppies") is recommended for the adult traumatic paraplegic. Experience has proved that it is not necessary to delay fitting the patient with shoes until the SA shells are completed. Shoes one and one-half sizes longer and two widths wider than the patient's regular size provide adequate accommodation for the shells.

SHOE MODIFICATIONS (Fig. 11)

A full-length metal shoeplate is incorporated into the shoe to augment the overall control function of the SA orthoses. The shoeplate prevents out-of-phase motions of the
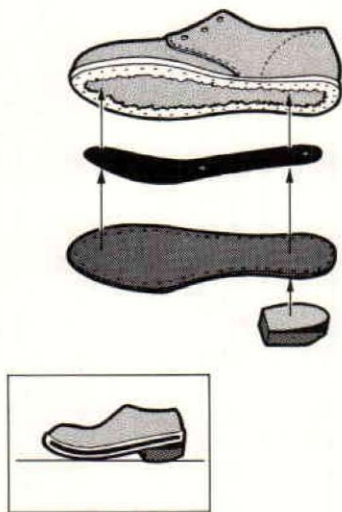

Fig. 11
Shoe Modifications

* Kamweld Highspeed Welder, Model 10-HS, 650 watt heating element and special welding tips which hold the welding rod.

flail MP joints whenever the body's center of gravity moves anterior to the lateral midline. In essence, its function mimics that of the forefoot portion of a prosthetic foot. Since the shoeplate prevents the shoe from flexing, its resistance to floor reaction forces also prevents the anatomic forefoot from jamming into the shoe and causing ulcerations along the 'flexion crease' which normally forms across the top of a shoe. It is much easier and cheaper to provide control of the MP's in the shoe than to incorporate such control into the shell.*

The heel and complete sole of a conventional shoe are removed, and if the shoe has a steel shank, it, too, is removed. Rubber cement thinner is used to remove the entire crepe sole and heel from the uppers of light-weight shoes. The bottom of the shoe's upper is traced and the pattern is reduced ⅜ in. to ½ in. all around. The modified pattern is traced onto the surface of a sheet of hot roll 40/50 carbon steel (either 14, 16 or 18 gauge, depending on the size of the patient), cut out and sanded. The toe end is bent upward for toe clearance. The rest of the shoeplate, from the apex of the ball of the foot to the end of the heel portion, is left flat. Two holes for copper belt rivets are drilled into the plate, one at the heel and the other approximately in the middle of the longitudinal arch area. An acetylene torch is used to heat the plate to a dull red color and then quenched in water to temper. The plate surface is sanded lightly to

*A metal shoeplate was used, from the beginning, for all the shell designs previously described.

remove discoloration caused by the heat, reheated to a blue color, and quenched in water for the second time. Care should be taken, when quenching the plates, to submerge them in the water slowly, toe end first, to prevent warping. The plate is cemented to the bottom of the shoe upper and riveted, thus flattening its longitudinal arch portion to the plate. The sole is stitched or cemented (depending on the type
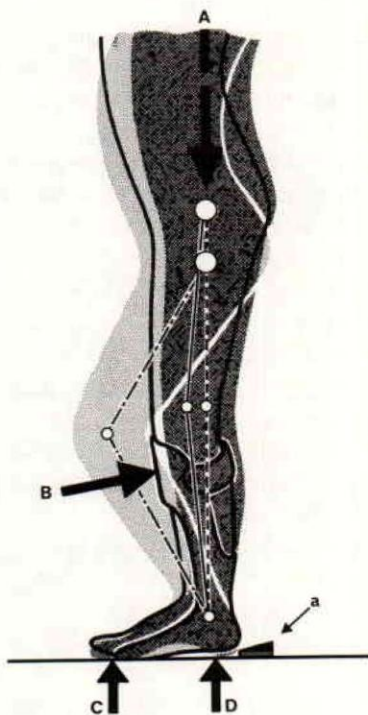

Fig. 12

A-P Balance: Spina Bifida, L3-4 Level. Darkly shaded figure represents normal posture. Lightly shaded figure is without orthoses. Solid black line is with SA shells. A, body's weight; B, counterforce; C, floor reaction force to forward motion; D, floor reaction force to backward motion. C plus D equal A, when standing. Small letter "a". resists counterforce, B, by maintaining knee flexion when standing. Note that excessive lordosis cannot be fully eliminated.

of shoe being used) back onto the upper.

The trimmed shell is inserted in the shoe, which is placed on a level surface, and the heel portion of the shoe is lifted until the vertical edge of the anterior panel of the shell is 3-5° anterior to a line perpendicular to the level surface. When this alignment has been reached, a measurement is taken from the back of the heel to the level surface. A lightweight nuron crepe heel is built on the shoe to the measurement and tapered toward the toe. The usual rounded back portion of the crepe heel is sanded flat at an oblique angle in the anterior-posterior plane to prevent transverse, medio-lateral wobble and to provide a more natural "roll" at heel-strike. This heel setting accomplishes two things:

1. It forces the knee into slight flexion in stance phase which is necessary for these patients' AP balance, since hip flexion contractions and excessive lordosis (which are common to them) cannot be fully reduced (Fig. 12).

2. It prevents the reaction force of the anterior panel from forcing the knee into recurvatum (Fig. 12).

SUMMARY

A single unit, lightweight (6-12 ounce) plastic BK shell that provides control of the foot/ankle complex in all three planes and the knee in the AP plane has been described. The design is based on biomechanical principles embodied in modern prostheses. Hence its name, SA orthosis, denotes it to be an 'orthotic counterpart' to the SA prosthesis and also denotes its function, i.e., the mechanical control of 'out-of-phase' motion of the ankle and foot. The intimate fit of the SA shell provides control of action superior to that which can be obtained with conventional BK braces. In essence, the shell supersedes the function expected of a shoe in combination with conventional BK bracing. For this reason, a much lighter weight, laced oxford is adequate when modified to complement the shell's biomechanical function.

The casting, fabrication and shoe modifications for the polypropylene SA orthosis are presented in detail.