A Flexible, Air-Permeable Socket Prosthesis for Bilateral Hip Disarticulation and Hemicorporectomy Amputees

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ABSTRACT

Active people with congenital absence or amputation of both lower limbs present fundamental prosthetic challenges that have not previously been addressed in the known literature. Those challenges are heat dissipation and the avoidance of thoracic skin shear trauma. The latter challenge is more significant in the subgroup of such people whose amputations are tertiary to spinal cord injury and pressure sores. The design reported in this paper consists of an air-permeable fabric socket suspended within a shell frame that promotes heat dissipation, reduces skin shear trauma, and permits upright weight-bearing and practical wheelchair function and mobility. The prosthesis is independent of the wheelchair and is self-suspending during transfers and nonwheelchair mobility. The prosthesis does not include legs and feet.

Keywords: *Prosthetics; hip disarticulation; hemicorporectomy; translumbar amputation; air-permeable socket; fabric socket.*

Introduction

People with spinal cord injury commonly develop pressure sores that may become infected and possibly require plastic surgery. In some extremely severe chronic cases, the consequences of multiple recurrences and surgical interventions lead to high-level amputations, including bilateral hip disarticulation or even higher, up to hemicorporectomy. The loss of both legs dramatically reduces the amount of skeletal structure and skin surface area available for weight-bearing. Continued efforts to sit upright, even for short periods on the best of cushions, lead inevitably toward further skin breakdown with little or no remaining surgical options for wound coverage or closure.

Most people with these high-level amputations use a prone cart for mobility or stay in bed full time. Some receive what is commonly referred to in the literature as a "bucket" prosthesis: laminated rigid or semiflexible socket fabricated to fit the lower half of the torso. The body of literature on this topic is surprisingly large and repetitive, and does not address some very important factors the authors believe must be taken into account when designing for this amputee group.

Socket Design Factors

All of the articles the authors found showed variations on a single-socket approach, using either thermoplastic or laminated materials.[1-7] In most cases the inner surfaces of the sockets were lined with foam padding.[1-4,7] Most included some type of hinge opening or access door to make donning easier.[1-3,7] Several articles also illustrate systems of ambulation using prosthetic legs.[1,2,5,6] There are inherent limitations or problems associated with such sockets relating to heat dissipation, shear trauma to tissues covering the lower thorax, and changes in the client's abdominal volume and shape.

Except for what we exhale in our breath, virtually all of the heat our body produces must be dissipated through the skin. If both legs are amputated, the body loses approximately 36% of total skin surface, using the "rule of nines."[8] If half of what remains of the torso is then placed into a non–air–permeable socket, the body is left with only about 45% of the original skin surface exposed enough to dissipate heat by convection and evaporation. Adequate heat dissipation is an absolute physiological necessity and should receive consideration whenever we attempt to design orthotic or prosthetic systems for children or adults with multiple-limb deficiencies.

The laminated sockets shown in the literature have no provision for protecting the skin from shear strains. In the authors' experience, it is usually people with paraplegic levels of spinal lesion who proceed to extreme levels of amputation. Therefore, with full function of the upper torso, the twisting and bending actions of daily life result in sliding and shearing motions within the upper one-third of a conventional laminated or thermoplastic torso socket. In such sockets, unevaporated perspiration increases the friction coefficient and those motions result in shear damage to the skin and subcutaneous tissues when there is sensory deficit reaching up to the lower thorax. The authors have seen ample scar evidence of such trauma.

Just as residual limbs change volume, so do torsos, except much more so with weight gain or loss or physiologic cycles. As torso volume changes, so do the perimeter contours. Slipping too far in-

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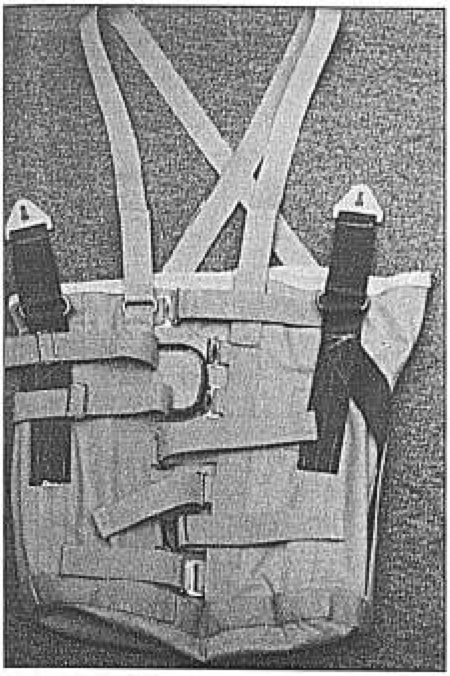

Figure 1. **The fabric torso socket resembles a corset with a bottom. It must be very carefully fabricated and fit because it determines the distribution of body weight pressures against skin surfaces which are usually without any protective skin sensation. Note the two black suspension straps which will be reflected downward over the top edge of the frame to the external fixation truss studs (Figure 4). Also note the shoulder straps.**

to a rigid socket after a volume loss will certainly cause excessive pressure on bony areas of the pelvis and thorax. Rigid or semirigid torso sockets simply cannot adjust well to volume and contour fluctuations. The result is a very basic problem with continuity of fit.

Every experienced prosthetist has a healthy respect for the challenges presented by a young and active client with an insensate residual limb. That is not unlike the socket design challenge presented by a person with a combination of spinal cord injury and bilateral hip disarticulation or hemicorporectomy.

Method

The first author has attempted to design prosthetic-orthotic technology solutions for six people with a combination of spinal cord lesion and bilateral hip or higher amputation. In the first two cases, a fabric corset variation of

Figure 2. **A client donning the fabric socket. This usually occurs in bed. Slipping into the frame shell is also usually done while in a supine position and the two suspension straps are pulled over the superior trim line of the frame to snap onto the lateral truss studs.**

the Newington thoracic suspension design[9-12] was attempted. Both were limited technical successes (ulcer areas were unloaded, heat dissipation was adequate, and thoracic suspension was tolerated for several hours at a time) but were functional failures because of two shortcomings. First, skin tolerance really must approach at least eight hours to be practical and acceptable for regular daily use by active adults. Second, suspending the sockets from the wheelchair frame significantly restricted mobility and activity within the chair. Subsequently, such referrals to this facility have received the flexible air-permeable socket and frame design.

This prosthesis design consists of a fabric socket flexibly suspended within a rigid frame. It incorporates design features that provide for heat and moisture dissipation, safe levels of pressure and shear management, volume changes, mobility, and cosmesis. Four persons with amputations have been fitted with what has proven to be a practical design that goes well beyond the conventional concept of a flexible socket.

This new socket is crafted of fabric and looks much like a corset with a bottom (Figures 1, 2, and 3). Adding the

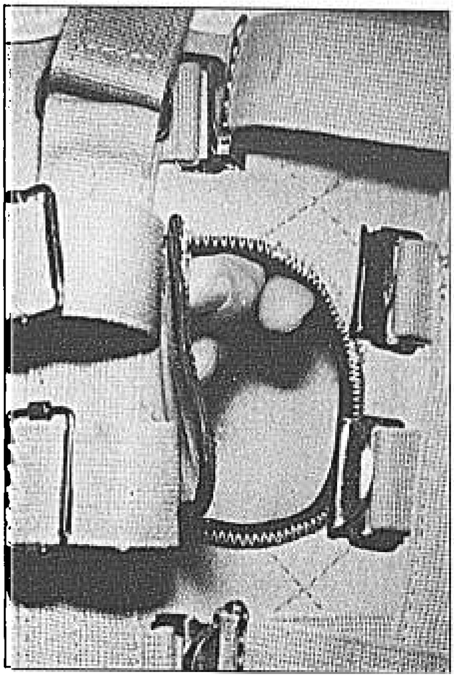

Figure 3. **In some fashion, the urinary drainage line is usually fed through the overlapping closure components. Depending on location, it may require a small "trap door" as seen in this photo.**

bottom to the corset was a significant advance because even at very modest pressures, bottom areas can significantly share the load so that peak pressures on other surfaces can be lowered to levels that are tolerable on a nearly continuous basis. A rigid outer frame (Figures 4 and 5) provides suspension points for the flexible socket and a stable base for upright positioning. It fits around the sides, front, and back of the fabric socket snugly enough to maintain alignment, but loosely enough to allow air circulation around the socket (Figure 6). The frame is generously fenestrated to promote air exchange. The person's normal activities move the fabric socket enough to pump air in, out, and around the air space between socket and frame, facilitating heat and moisture dissipation. The fact that the frame is relatively close fitting, lightweight, and totally independent of the wheelchair is a big advantage for safer and greater levels of function in and out of the wheelchair. One of our clients who has a young daughter frequently takes advantage of being able

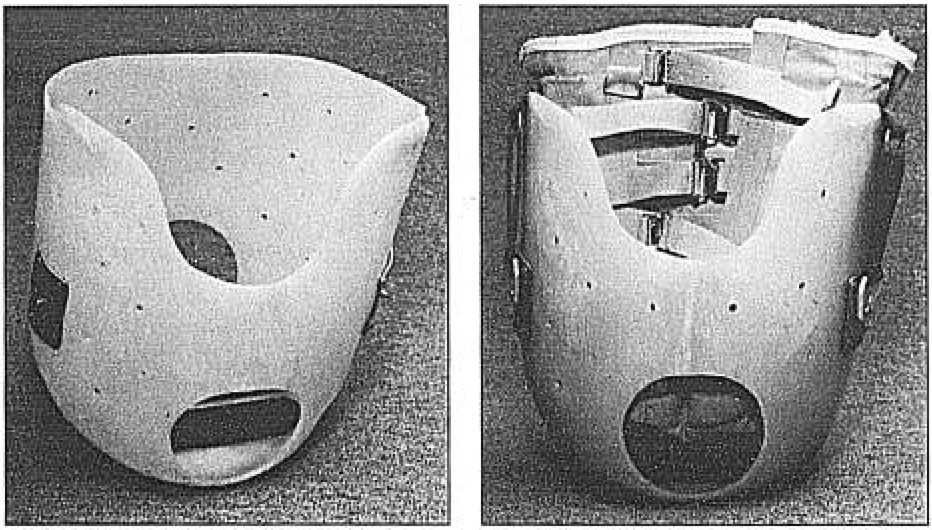

Figure 4. **These photos show the frame shell and how it relates to the socket. Bilateral truss studs are visible as well as both large and small air ventilation holes.**

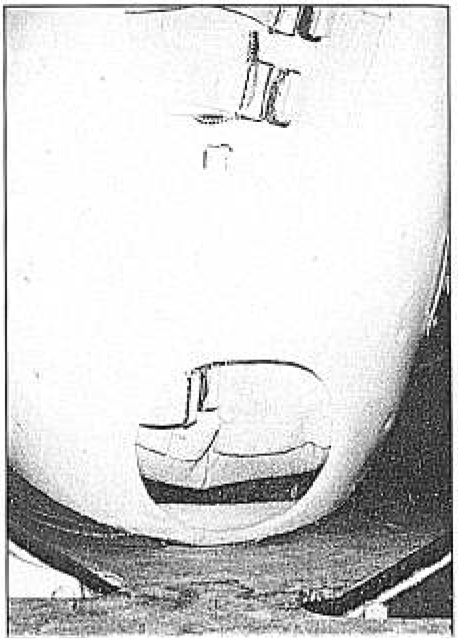

Figure 5. **This close-up view through one of the lower fenestrations shows the necessary gap between the bottom of the fabric socket, fully loaded, and the floor of the frame shell. At least one of our clients has found this space to be a very convenient location to stow his urine collection bag.**

to safely leave her wheelchair and move around on the floor, the grass, or on a sandy beach. Good upper-body strength allows her to independently transfer between floor or ground level and wheelchair (Figure 7).

The fabric socket is configured and sized to provide for weight-bearing by hydrostatic principles. The person with amputation learns quickly how to adjust the closures when donning the socket in the supine position (Figure 2) so that position and snugness within the socket is correct and consistent. Adjustable closures accommodate volume changes and the fabric automatically adjusts to accommodate associated contour changes. The fabric socket is suspended by straps passing over the superior trim line of the frame (Figures 8 and 9), one near the right midline and the other on the left. That manner of suspension allows the fabric socket to do a small but significant amount of flexing, twisting, and pistoning within the more stationary frame, eliminating virtually all of the abrasive rubbing action that would otherwise affect the skin.

The entire system consists of (1) a custom Lycra™ or cotton/Lycra body sheath (Figures 2, 7, and 9); (2) the fabric inner socket (two are provided so that one is always available when the other is being repaired, laundered, or drip drying); (3) a rigid frame with built-in support base and tread; (4) a rigid, dropped-seat platform installed in the wheelchair (Figure 5); and (5) a safety belt installed in the wheelchair.

The Lycra body sheath, an important first line of protection against skin abrasion, works extremely well to contain and organize any loose tissue and, because of its diminished friction, helps the person to slide safely and fully into the partially open fabric socket. The fabric socket must be very skillfully and carefully crafted and fitted by someone who knows how to work with fabric and who understands the principles of how circumference magnitudes relate to soft tissue weight-bearing (hydrostatic) support. In an engineering sense, these principles are akin to the concept of circumference tensioning to achieve "total contact" weight-bearing in a transfemoral prosthesis. The fabric socket begins as a custom corset. The pattern is developed directly on a plaster model or from measurements and acquires a bottom as the fitting proceeds. Reinforcement tape (usually along panel seams) must not pass over prime pressure ulcer sites (bony prominences), and contours must be created so that material is not stretched tight across such high-risk areas.

As the fitting proceeds to the weight-bearing stage, several methods are used to obtain information about pressures in at-risk locations. Simple, inexpensive systems exist (Figure 10) that can display contact pressure on a meter when a thin transducer is placed in an at-risk location. Alternatively, if one can directly observe that the material spanning a bony prominence is slack, one can conclude that contact pressure against that prominence is very minimal. The acid test, of course, is to observe the bare skin after longer and longer periods of weight-bearing. Persistent redness indicates excessive pressure.

The person's cathetering site or urine collection tube is accessed through a hole or out under a special flap-covered opening installed for that purpose (Figure 3). The colostomy site and collection bag are contained within the fabric socket. The colostomy bag is changed or emptied each evening after doffing and before donning the socket in the morning. It will not fill while the person is using the prosthesis since the bag is compressed flat between abdominal

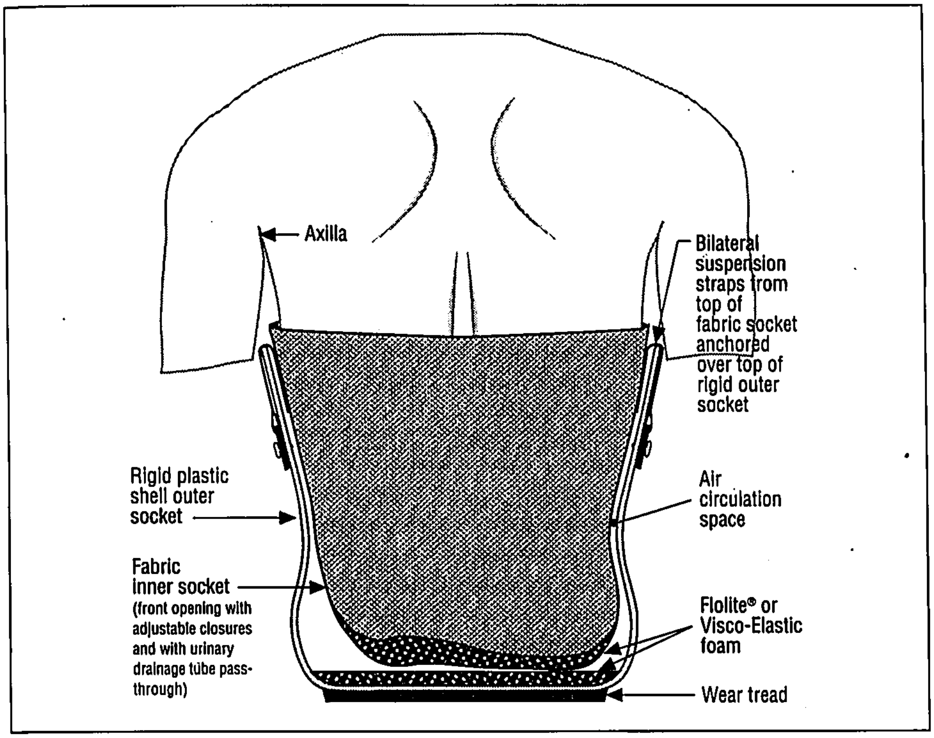

Figure 6. **This P-A sketch gives a cross-section diagram of the prosthesis. The jelly envelope component shown in the bottom of the fabric socket may or may not be necessary depending on the shape and condition of the residual torso and bony prominences.**

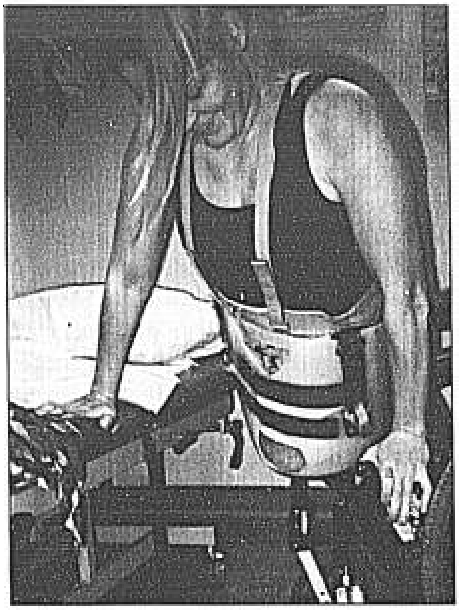

Figure 7. **When the socket-to-frame suspension straps are configured correctly and anchored for minimal pistoning, the over-shoulder suspenders are effective. Independent transfers between wheelchair, furniture, floor, automobile seat, grass, etc., are possible with good upper body strength.**

skin surface and the fabric socket. There is ample time for stool elimination during nighttime hours.

Proper location and installation of the suspension straps are very important. When the straps are in the correct A-P location and right-left balance, the fabric socket lines up naturally within the frame socket without undue interface contact pressures. Those same straps, when sewn correctly, serve a second important purpose: they firmly connect the frame to the fabric socket, reversing their suspension roles during transfers.

The alignment of the prosthesis with respect to vertical is important to the function and comfort of the person with the amputation. That alignment is dependent on the exact orientation of the base of support under the frame socket. As the person becomes accustomed to upright function and weight bearing in the prosthesis, he or she will have definite feedback regarding orientation in space. Changes in the person's vertical alignment are easily made by wedging the tread of the "footprint," i.e., the area of the frame base in contact with the resting surface. Sense of stability and ease of function are greatly affected by changes in A-P and right-left tilt and the prosthesis user must be invited to give directions. The stability and function of the person will also be affected by the size and shape of the perimeter outline of the roughly elliptical or circular footprint of the prosthesis and by the hardness of the tread material.

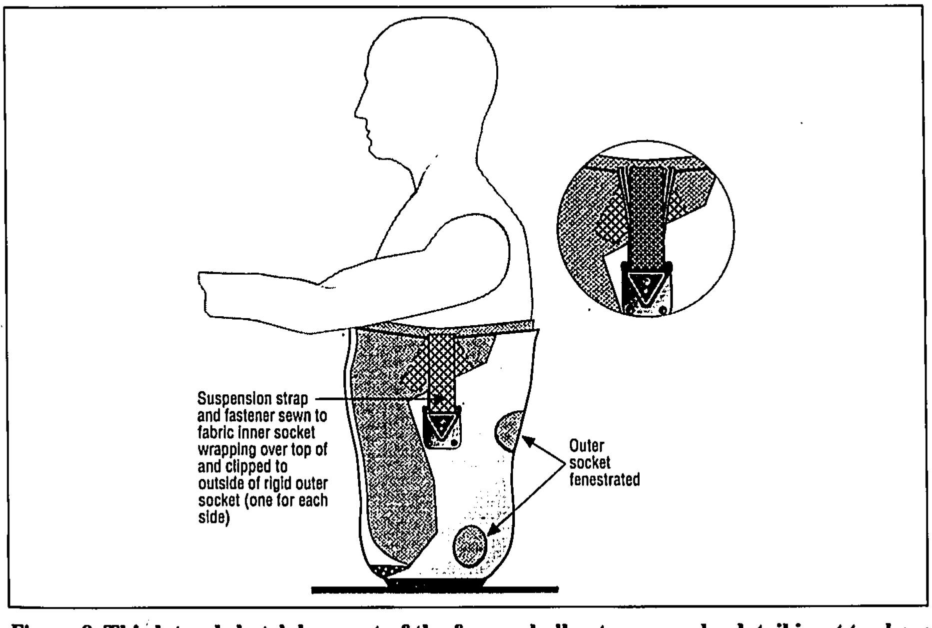

Figure 8. **This lateral sketch has part of the frame shell cut away and a detail inset to show how the socket is suspended.**

Finally, as time goes on, the person will probably request that the top of the prosthesis be lowered. The top of the fabric socket should always be kept somewhat above the top of the rigid socket and should always extend above the level of the lateral costal margin.

Functional Outcomes

Table 1 contains results as of March 1997. To that date, four persons with amputations had received prostheses described above, and all were using them on a regular, daily basis. Only one male patient (P.H.) had a recurrence of pressure ulcer problems. P.H. has been hospitalized many times for urinary infections and pneumonia, and during one of his hospitalizations he developed a pelvic bed sore. His multiple severe health problems have caused rather serious weight loss, and we are doubtful that we can safely accommodate his present condition. The long-term success of these prostheses depends on avoiding the disruptive effect of other health problems and on proper monitoring and maintenance of the prosthesis.

Discussion

Flexible prosthetic sockets have gained considerable popularity in recent years. This new design can support an active and totally insensate part of the anatomy safely within a prothesis. It is, however, worth considering how extremely comfortable and serviceable an air-permeable flexible socket design would be those with full sensation. Since people with amputations at all levels experience excessive heat and perspiration build-up and affiliated problems within their sockets.

The authors would urge that future advances in transtibial and transfemoral socket technology focus on ways to allow fresh air to circulate about the residual limb as it performs its normal function of evaporation and heat exchange without excessive sacrifices of fit or suspension. In the early 1970s, Robert Nitschke and others[13,14] developed a very porous prosthetic socket liner of a material he called Cordo. Perhaps their work should be reexamined in the light of recent progress with new materials and fabrication science.

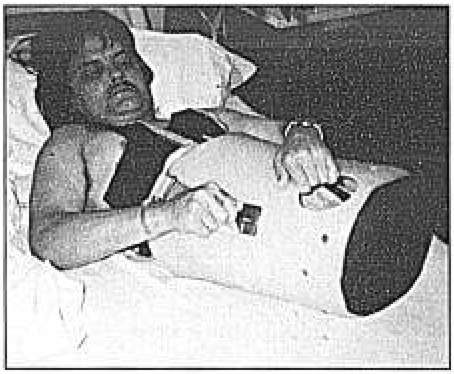

Figure 9. **Client has donned the soft socket, slipped into the frame shell, and is fixing the socket suspension strap ends onto the truss studs.**

It is interesting to note that the critical part of this design (the flexible fabric socket) uses one of the oldest fabrics (cotton) known to humankind and one of the oldest arts (sewing) to effect a new design to meet a very difficult challenge. Indeed, the flexible suspension of a prosthetic socket within a rigid frame is a concept that was used more than 100 years ago. Albert Winkley received U.S. Patent no. 316589 on his "slip socket" design on April 28, 1885. We should all be aware that when we confine our creative thinking to what we can design with new materials and new fabrication processes, we overlook some very rich resources.

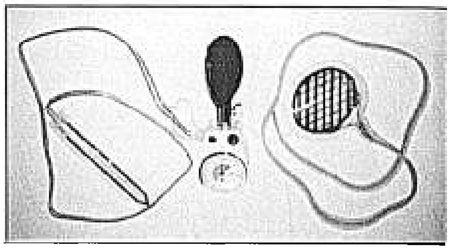

Figure 10. **A simple, inexpensive pressure measuring instrument such as the one in this photo can be used to measure pressures in high-risk locations and guide socket design.**

Conclusion

Bilateral hip disarticulation and hemicorporectomy are extreme and rare amputation levels. However, these do occur because of accident trauma or as a tertiary consequence of pressure sores secondary to spinal cord lesion. These are also similar congenital anomalies. The various prosthetic "bucket" designs reported previously do not adequately address heat dissipation, shear trauma, or torso volume changes. But this new flexible socket and frame design allows nearly normal convective

Client	Diagnosis	Date Fitting Complete	Hours per Day of Usage	Level of Independence
P.H.	1) SCI-T5 Paraplegic 2) Severe decubiti-lower extremity; multiple skin breakdown 3) Bilateral hip disarticulation	4-22-94	8-10	Needs help donning only
D.M.	1) SCI-T7/8 Paraplegic 2) Multiple decubitus ulcers, osteomyelitis 3) Hemicorporectomy	8-16-94	8-10	Completely independent
A.L.	1) SCI-T6/7 Paraplegic 2) Multiple decubitus ulcers; osteomyelitis 3) Bilateral hip disarticulation	1-22-96	8-10	Completely independent
N.R.	1) SCI-T12 Paraplegic 2) Ischial decubitus ulcer 3) Bilateral hip disarticulation	12-16-96	8-10	Completely independent

Table 1. **This table reports results as of March 1997. Since then, one of the clients, N.R., a man with a history of severe alcohol problems, has been lost to follow-up.**

and evaporative exposure of skin to ambient air. The design has proven practical on a very limited number of clients.

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Correction

Figure 1 in the "Preliminary Result of Part-Time Bracing for the Management of Idiopathic Scoliosis" by Christopher J. Roach, BS, and Jack T. Andrish, MD, that appeared in the Summer 1998 issue of the *Journal of Prosthetics and Orthotics* was printed incorrectly. The figure at right is how it should have appeared.

JPO regrets this error and apologizes for any inconvenience it may have caused.

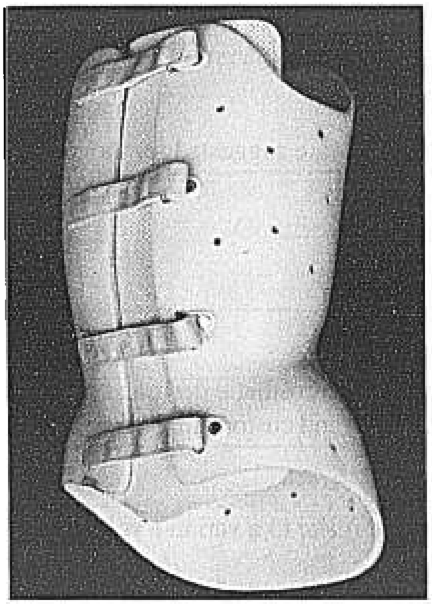

Figure 1. **Front-opening Wilmington thoracolumbosacral orthosis.**