

Prosthesis Management of the Cancer Patient With High Level Amputation¹

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Prosthesis and orthotics management of patients who have suffered from major surgery due to cancer has, in the past, not addressed the unique problems associated with this disease. For these patients, one must consider not only the physical effects of amputation or other major surgery, but the psychosocial situation as well. Amputations due to cancer usually differ from other kinds of amputation in the severity, i.e., massiveness, of the amputation. This and the insidiousness of the disease obviously affect patient management.

This report represents part of the results of a comprehensive effort to establish an aggressive patient management program which deals with the prosthetic/orthotic needs of the patient. Psychosocial aspects were studied also.

Objectives

The objectives of this research were the design, development, testing, and utilization of a cost-effective limb prosthesis/orthosis system for people who have undergone amputations/tissue resections due to cancer. The specific amputation levels considered for which respective devices were designed included hip

disarticulation, hemipelvectomy, and fore-quarter. Another objective was the design of orthoses for lower limb tissue resections.

The total rehabilitation process for this type of cancer patient was to include an aggressive early intervention program involving several pertinent professional disciplines. This was believed to help dissipate the psychosocial consequences of radical surgery.

Special Considerations for the Cancer Patient

Cancer is a disease that is associated with uncertainty and fear on the part of the patient. Unlike many other diseases that are specific to certain portions of the body, this one is insidious and frequently defies containment. The individual, on being labeled with the term "cancer," is frequently demoralized and confused as regards, to say the least, his future employment. This person must be made to know from the very onset that many disciplines are working together and are committed to his resumption of a lifestyle that is as normal as is practicable.

The amputation levels selected for the prosthetics research (Chart 1) were chosen in part

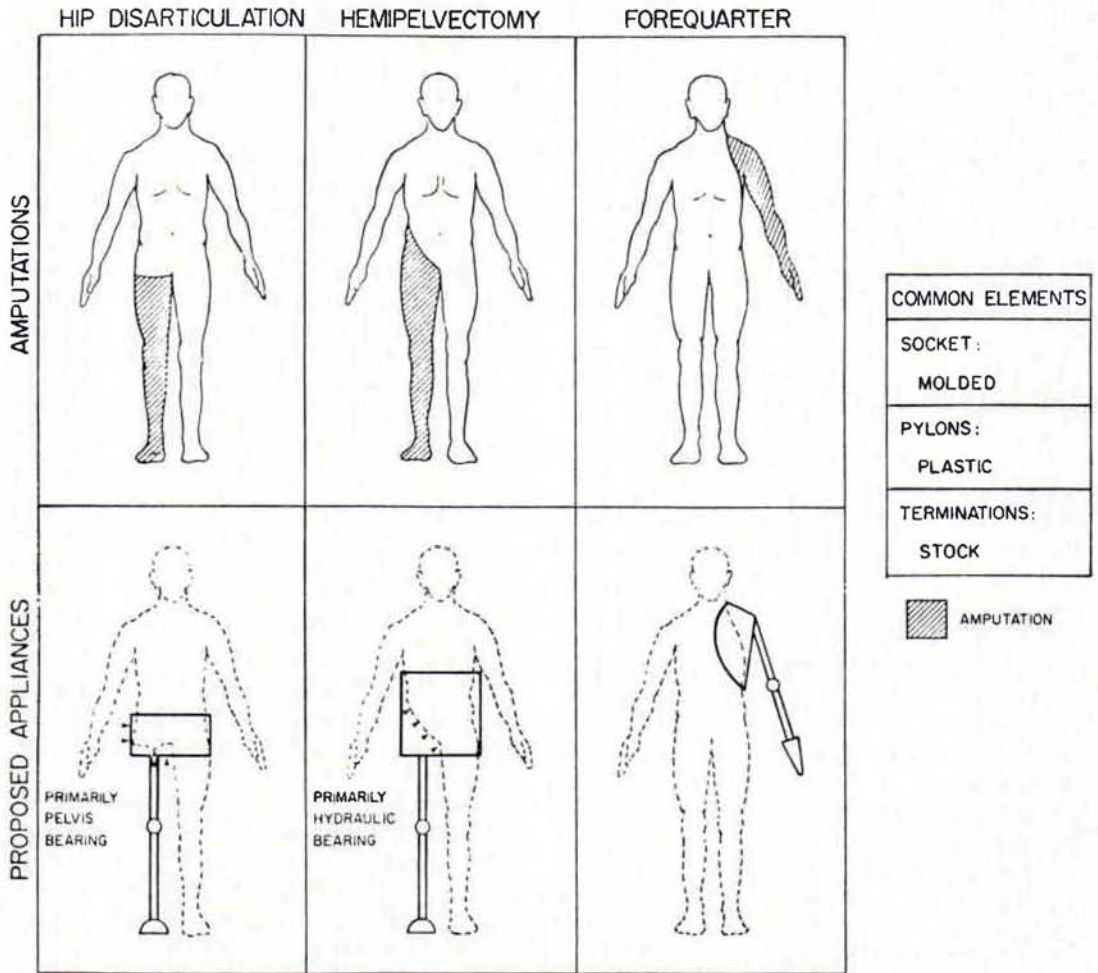


CHART I

because of their prevalence in cancer care and because when amputations are at such a high level, the probability of patient acceptance of a device is decreased. This is a result of the massiveness of the appliances, discomfort, and resultant difficulties of control. Control can be enhanced by reduction of weight, and, in the case of forequarter amputation, by myoelectric control.

Early fitting through direct molding of a thermoplastic prosthetic socket for lower-limb amputees does, in part, mitigate the discomfort factor by reducing edema. It allows quick fitting and early mobilization of the patient with a preparatory prosthesis.

Plastic pylons are lighter, less expensive, and more readily adjusted than a comparable unit of aluminum which is presently used in modular prostheses.

In spite of early prosthetics management, high level lower-limb amputees may not wear their prostheses because of discomfort caused by the socket and the difficulty in controlling a biarticular system which hip-disarticulation and hemipelvectomy prostheses constitute. Thus, design and development of an improved socket and control system was another important consideration.

The application of modularity in orthotics for cancer patients is expected to result not only in a cost reduction if these components can be mass-produced, but more importantly, it permits immediate fitting of orthoses. This allows rapid diagnostic evaluation of the type of orthosis required and results in an improved delivery system.

This report includes only our work with the hip-disarticulation and hemipelvectomy cases.

Prostheses for Hip-Disarticulation and Hemipelvectomy Cases

PATIENT REFERRAL AND ORIENTATION

The first nine months of actual patient participation, beginning in May, 1978, involved referrals from within N.Y.U. Medical Center by the patient's physiatrist. Due in part to the death of Dr. K. Francis, the original consultant orthopedic surgeon on the project, patient referral diminished. It was for this reason that

an official agreement between N.Y.U. Medical Center and Sloan-Kettering Memorial Hospital was established in April 1979.

Most of the participants were in-patients at the time of evaluation for candidacy and initial fitting.

Patients were referred to the project either by the surgeon or through the recommendation of the physical therapist from Memorial Hospital, with the approval of the surgeon and/or physiatrist.

Except for a few out-patients, most patients (plus family members for pediatric patients) were seen bedside at Memorial Hospital for orientation. The project was explained to the patient, stressing the value of early ambulation with bilateral weight-bearing. The fitting procedures using direct molding of a thermoplastic material and the general time-sequence and approximate number of sessions needed for fabrication and fitting were discussed. In addition, the experimental nature of the project was stressed. Patients were told that problems with technique and materials could arise. To augment the orientation session, slides depicting the exact molding technique were shown with detailed description. The intention was to eliminate any apprehension and confusion prior to the actual fitting sessions.

Considerable time was spent with patients in the orientation session, often repeating and reinforcing the important facts about the project. During their actual participation in the project, however, several patients still had misconceptions and questions which had previously been discussed. To augment the conveyance of the initial information and ensure its reinforcement, a patient brochure was written. The questions and information discussed in this brochure reflect some of the common misunderstandings and points that the patients did not grasp.

When the patient agreed to participate in the project, he was asked to sign consent forms, one for Memorial Hospital records, and one for NYU Medical Center records. At that time, basic measurements were taken of the amputation site. These were used as guidelines for cutting a blank thermoplastic pattern for the socket of the preparatory prosthesis to be fitted at a subsequent session.

In addition, pertinent personal data were noted. The medical chart was also consulted for diagnosis, past and present medical history, and possible regimen of chemotherapy or radiation, if already planned, as this would affect the patient's schedule and tolerance, as well as the type of preparatory prosthesis to be fitted.

Depending on the patient's physical stamina and endurance, the protocol for one or more sessions was decided upon. If the patient did not demonstrate any physical limitations hindering his/her endurance, fabrication and fitting the prosthesis all in one session was to be attempted.

PREPARATORY PROSTHESES

To accomplish one of the major objectives of this research, i.e., early ambulation through cost-effective means, this particular aspect of the project was concerned with the search for a material which would allow direct molding of a socket on the patient. The conventional method is not only time-consuming but costly, since the conventional socket is plastic laminated over a plaster mold from an impression of the patient's body. Again, to minimize cost and to permit ready adjustability, a pylon-type prosthesis utilizing a thermoplastic tubing was designed. An alternative to a direct molding socket was the design of a ready-made totally adjustable socket.

Molding the Socket

Aquaplast™ was found to be the most suitable material for the purpose described. While a number of other materials have been experimented with earlier in the project, they are not described in detail here since the results of such experimentation have been included in progress reports.

Aquaplast is a low-temperature thermoplastic polyester which softens in 60 deg. C (140°F) tap water. Moldability is evident as the material turns from a cloudy opaque appearance to transparency. Its elastic properties allow stretching in any direction. It is also self-bonding. Inconsistencies in the molding properties of Aquaplast due to the amount of stretch and stickiness caused some initial molding problems. After appropriate follow-up with the manufacturer, however, most of the problems

were alleviated.

From the measurements taken during patient orientation, a socket pattern is cut from the Aquaplast sheet material. The molding procedure takes place with the patient standing between parallel bars. Cotton stockinette is pulled up and over the patient's amputation site and body to protect the skin from the stickiness as well as the heat of the material. Pressure relief felt pads are placed over the iliac crest(s) extending to the anterior superior spine on the sound side and involved side, using medical adhesive spray.

A hydrocollator is used to heat the Aquaplast until clear. Once it is softened and completely transparent, it is draped and stretched over the body. The ends can be closed together by pinching anteriorly, as the material sticks to itself. Precise molding must be accomplished at this point in a relatively short time because the Aquaplast cools and sets quickly. Thus, an additional person may be needed. Using an elastic webbing around the waist just superior to the iliac crests, pulling forward and downward, proved to be the most effective way to ensure accurate contouring (Fig. 1). Molding the distal



Fig. 1. Preliminary steps in molding for the hip-disarticulation socket.

end of the socket is done effectively by pulling a length of 12.5 cm or 15 cm (5 or 6 in.) wide piece of cotton stockinette diagonally toward the iliac crest of the sound side (Fig. 2). The



Fig. 2. Molding for the hip-disarticulation socket.

stockinet must be sufficiently long to tie a knot just superior to the anterior superior spine. This establishes and imparts a crucial anatomical dimension in the socket. It optimizes the interface and thus control of the prosthesis. Care must be taken to eliminate and/or smooth out all irregularities, as the Aquaplast tends to shrink as it cools. During this time, the patient is instructed to stand tall and erect in a comfortable position, with both iliac crests level.

When the Aquaplast cools and becomes opaque again, trim lines and reference lines for prosthetic alignment are marked. (Fig. 3) In the frontal plane, a plumb line is marked on the socket at a position under which the prosthetic foot will be placed. This is usually a point 7 to 8 cm from the center of the heel of the sound foot. In the sagittal plane, a plumb line is projected on the socket in line with the patient's medial malleolus.

The socket is then removed from the patient by cutting it anteriorly with heavy-duty surgical scissors or a cast cutter, if necessary.

The procedures described above are practically identical for hip disarticulations and hemipelvectomies, with the exception that with a hemipelvectomy patient, the superior trim line of socket is somewhat higher than for a hip disarticulation, extending to the level of the xiphoid process. Even though the crest of



Fig. 3. Marking reference lines and trim lines on the Aquaplast cast.

the ilium may be missing in the hemipelvectomy patient, the elastic webbing is still used in the same manner to impart a waist level on the amputated side for cosmetic reasons and to enhance suspension.

Pylon

Polyvinylchloride (PVC) tubing is used for the pylon and is attached distally to a solid-ankle cushion-heel (SACH) foot, and proximally at the measured height to the Aquaplast socket (Fig 4). For lightweight and pediatric patients, 1-inch (I.D.) PVC is used. For heavier patients, 1 1/4-inch (I.D.) tubing is needed. PVC tubing is available commercially from plumbing supply houses since it is widely used as cold water piping. The proximal end of the PVC tubing is split in such a way as to produce three wings of approximately 15-20 cm length. Heating these wings allows easy contouring to the Aquaplast socket at a point where the center of the tubing coincides with the plumb lines previously marked on the socket. The wings, and thus the pylon tubing, can now be attached securely to the Aquaplast socket by means of a heated Aquaplast patch of appropriate size to cover and extend beyond the wings of the tubing as well as the proximal 5-7 cm of a specially-made PVC plug which fits into the tubing and is held in place with a hose clamp.

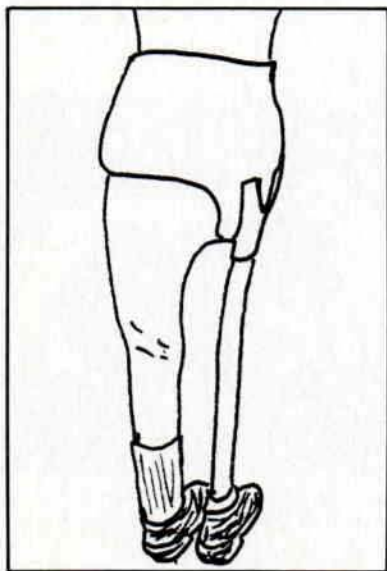


Fig. 4. Schematic of first stage prosthesis. No articulated joints are used.

Any rough edges on the trim line of the socket can be smoothed with sandpaper. Velcro closures are attached across the anterior opening in a criss-cross fashion to minimize socket displacement on weight-bearing and in the swing phase of walking.

It should be noted that this type of pylon does not include a hip joint or knee joint. The reasons for this design are discussed under Patient Application.

Pylon with Hip Joint

A pylon incorporating an Otto Bock No. 06-7E4 model hip joint is used in the second stage of the prosthetics management of high level lower-limb amputees. To permit the patient to sit with greater comfort and ease and to allow an improved, relatively safe, gait pattern. It is applied approximately two weeks after the fitting of the first pylon, on the assumption that by that time sufficient stump changes have taken place to warrant socket replacement and the patient will have mastered the use of the first pylon.

Fit and alignment are identical to the first pylon fitted. The placement of the hip joint is the same as that for Canadian hip-disarticulation prostheses. Distally the hip joint is adapted to the PVC tubing, and proximally it is attached to the socket by means of a specially designed

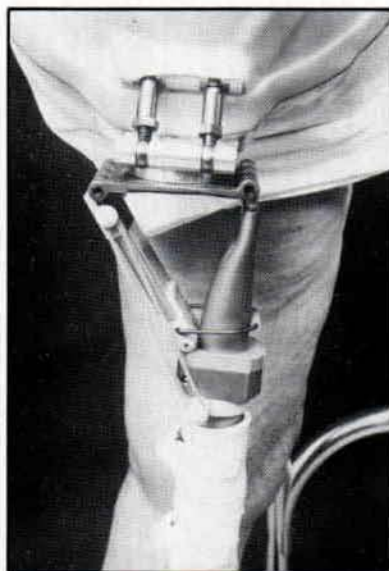


Fig. 5. Hip joint in the second stage prosthesis.

disc with adjustment capability for abduction and adduction (Fig. 5). Attachment to the socket itself is by means of monel straps held to the socket by a patch of Aquaplast as described in the previous section. Change in alignment, other than abduction or adduction, can be accomplished through the excellent thermoplastic characteristics of PVC, i.e., heating the tubing for making the desired change in alignment.

Prefabricated Adjustable Socket with Pylon

Early in the project it was believed that many patients would be undergoing chemotherapy and radiation therapy and, thus, would present severe volume changes in the amputation site and delayed wound healing. For that purpose, a prefabricated adjustable socket and pylon was designed. This preparatory prosthesis consists of a prefabricated plastic molded pelvic girdle, commercially available for Milwaukee braces and low-profile Boston spinal orthoses. The girdle is adapted to PVC tubing and SACH foot (Fig. 6). To provide weight-bearing, an adjustable hammock is inserted in the girdle under the amputation site (Fig. 7). The hammock not only provides adjustment for volume changes but consists of a throw-away material, e.g., sterilized stockinette or towel. Circumferential adjustment is possible through the posterior

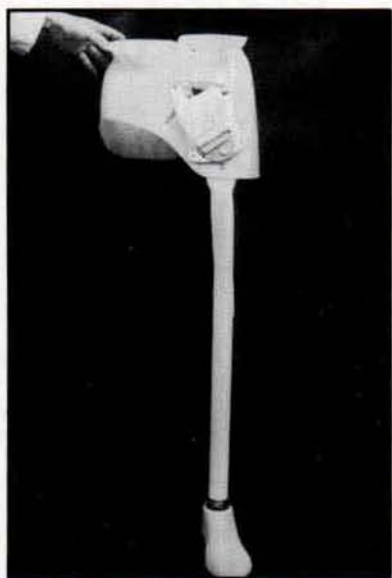


Fig. 6. Anterior view of the second stage prosthesis with prefabricated adjustable socket.

opening in the girdle. This design was tested on a hip disarticulation amputee who was, indeed, able to ambulate on this preparatory prosthesis. As the project progressed, however, it was found that these patients could be managed just as well with the Aquaplast socket.

Patient Application

Protocol of Prosthetics Management

As stated, one of the fundamental goals of the project was to fit cancer amputees with a temporary device as soon after surgery as medically feasible. The protocol of early prosthetic intervention evolved as follows. Once the patient is orientated and medically cleared to participate, the fabrication and fitting procedures are carried out in the manner described above. The first socket is attached to a pylon and SACH foot, without a hip or knee joint. Both joints are excluded from the design of the first socket to insure optimal stability for the patient and expedience in fabrication. The entire procedure, from molding of the socket to attaching the pylon and foot, to final alignment can be accomplished in three to four hours. Following this, gait training is initiated. The patient is asked to stand with the prosthesis and practice equal, bilateral weight-bearing. Basic body mechanics necessary for effective ambulation are taught. In addition to a posterior

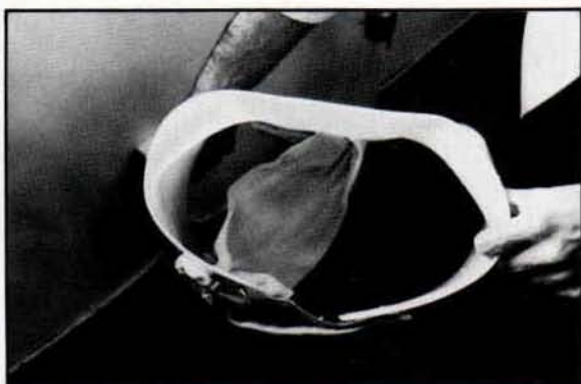


Fig. 7. Top view of prefabricated adjustable socket showing the adjustable hammock that provides weight-bearing

pelvic tilt used to initiate swing phase, the patient also practices maintaining both sides of the pelvis level. This latter movement is accomplished by contracting the contralateral abductors and is especially valuable to master early in the rehabilitation program. When such patients are not wearing a prosthesis, the pelvis or remaining tissue on the involved side is often allowed to drop. This habit frequently becomes a comfortable and natural part of the patient's body mechanics, and is difficult to reverse when prosthetics training ensues.

Progressive gait training activities are carried out in subsequent physical therapy sessions. Ambulation is limited within parallel bars until the patient acquires skills of equal weight shifting, defined and smooth pelvic tilt, and minimal trunk deviations. The patient then progresses to using a walker, forearm crutches, or canes outside the parallel bars. As with any temporary device, using at least one cane is recommended to prevent full weight-bearing on the amputation site so soon after surgery, as well as for safety reasons.

Although this first prosthesis does not have a hip joint, a modified sitting posture is still possible. The patient is able to sit leaning back on the edge of a chair with the uninvolved side on the seat, or on a stool or high chair where less hip flexion is necessary.

After a few weeks of prosthetics use, and once safe ambulation and basic skills have been achieved, it is expected that the area about the amputation site will have fluctuated sufficiently to warrant fitting of a new socket, which can be made in the manner described above.

At this stage, of gait training, the patient is likely to be ready for a pylon with a hip joint. An obvious advantage of the hip joint is less restricted movement and greater comfort in sitting. Also, the hip flexion motion available in the swing phase improves the gait pattern. Having the essential ambulation skills already mastered, the addition of a hip joint requires only minor changes in body mechanics, for safe use of the prosthesis. Improved sitting convenience and gait pattern allows the patient to wear the second preparatory prosthesis several hours at first; then, depending on tolerance, gradually progressing to a full day. Instructions are given to be mindful of sharp red areas and pressure spots, and to report any pain or pinching. Fitting adjustments can be made readily by spot heating the Aquaplast material.

The ultimate goal of wearing this progression of preparatory prostheses is to expedite the pro-

cess of accepting and utilizing a permanent prosthesis, perhaps as early as two months after surgery. Not only can early containment of body tissues in a socket prevent edema and promote healing, but the patient is more likely to become a functional ambulator with a definitive prosthesis. Current practice of prosthetics management indicate this to take at least three to six months post-surgery without a temporary prosthesis. What results is a patient who has not borne weight bilaterally for several months, and who has adjusted to a fast gait pattern with crutches and one limb. Thus, the rejection rate of the permanent prosthesis for such high level amputees is rather high. The protocol developed in this research of using a succession of at least two preparatory prostheses serves to alleviate this problem through early intervention, by maintaining bilateral body schema in ambulation.

Results of Patient Fittings

A total of ten patients were fitted with preparatory prostheses. Five patients received full hemipelvectomy amputations (Fig. 8) two received hip disarticulations (Fig. 9), and the re-



Fig. 8. X-ray picture of hemipelvectomy case



Fig. 9. Anterior view of a hip-disarticulation case

maintaining three received modified hemipelvectomies (Fig. 10), i.e., a portion of the ilium was preserved. Four patients were male and six, female. Ages ranged from 11 to 74 years. Four of the patients were in the 10-20-year-old range, two were in their early 30's, and the remaining four ranged from age 57 to 74.

Eight of the ten subjects received their first temporary prosthesis at an average of 16 days after surgery, some as soon as 7-9 days after the amputation. The first two patients in the project, however, were not fitted until seven weeks postsurgery, because the referral system from the surgeon at that time was still being refined. As a result, referrals for these two patients were not received until well after the surgery date. The majority of patients received two temporary sockets, the second usually having a pylon with a hip joint.

Although a preparatory prosthesis can be fitted in the hospital setting in a matter of three to four hours, in time it was realized that it is less strenuous for patient and prosthetist to change the original protocol to a two-stage fitting. Additional time was sometimes needed for realignment and for readjustment of the socket by spot heating or padding for pressure areas. When a pylon with hip joint was used, another 30

minutes were necessary. Although patients usually did not have to stand for more than 20 minutes at one time in the parallel bars, most of them nevertheless did not have the endurance or physical tolerance to stand up and sit down periodically for this length of time. Not only did most still feel generally debilitated from their recent surgery, but several of the patients were undergoing highdose chemotherapy treatments during this period. Nausea, vomiting, diarrhea and a total loss of stamina and energy are serious side-effects of such treatment. Thus, it was often very difficult to complete the procedure in one session. One of the patients did, however, bear through a four-hour session of fitting a socket and pylon with hip joint. Her satisfaction and gratification to stand and walk with a prosthesis by the end of the afternoon, make it a well-worthwhile effort, but she was clearly the exception. Most of the other patients were seen in two sessions: the first for socket fabrication, the second for final fitting and alignment. Between these sessions, the pylon with hip joint and socket were assembled in the prosthetics laboratory, so that less time would be demanded of the patient. Scheduling problems arose most often because of interference with chemotherapy treatments



Fig. 10. X-ray of amputee in whom part of the ilium was preserved.

and the complications which resulted. Patients needed at least two days after a chemotherapy session to recover sufficiently from its effects to resume ambulation training.

Gait deviations common to the majority of patients were 1) the overflow of thoracic extension associated with the posterior pelvic tilt and 2) vaulting on the non-prosthetic side in the initiation of swing phase. Trunk rotation during prosthetic swing phase was more prevalent in patients with hemipelvectomy than in those with hip disarticulation. This is not an unexpected finding since there is a lack of bony control on the involved side; thus, these patients exhibited excessive rotation with resultant circumduction. Verbal cuing, visual feedback, and constant reinforcement reduced this deviation to an acceptable degree.

Bearing weight on the amputation site was, for the most part, painless once all uneven surfaces in the socket were smoothed out. Two patients had problems with phantom pain which interfered with training and function. One older woman reported experiencing pain after she ambulated and the prosthesis was removed. The other patient was pediatric and experienced sharp phasic phantom pains while standing in the prosthesis. Since his standing toler-

ance was very limited initially because of this, his training was limited for the first two weeks. Once this dissipated, training resumed at a normal rate. Only one patient had a markedly difficult time shifting weight to the prosthetic side during initial gait training sessions. She exhibited lateral trunk flexion to the prosthetic side and inadequate extension in prosthetic stance phase. This improved with more gait training. Another patient had problems with excessive medial placement of the pylon, resulting in adduction of the pylon upon weight-bearing. This was corrected by heating the PVC pylon near the socket attachment point, and simultaneously translating the tubing laterally and in abduction while the material was pliable. Once cooled, it maintained this alignment. During the course of her gait training, the same patient began to flex her sound knee excessively during the stance phase. On the basis of new measurements taken, it was evident that there was considerable shrinkage, that allowed her to slip further into the socket. This, in effect, made the prosthesis appear shorter. Hence, knee flexion compensated for the leg length discrepancy. A new socket molding was, therefore, indicated.

Early in the project, it was assumed that

shrinkage would be a common phenomenon for several weeks after surgery. This would precipitate the molding of a new socket two or three weeks after the first one, at which time a hip joint could be attached. In actuality, significant shrinkage occurred in only two patients, both female, in their seventies, and overweight.

The five youngest patients, ages 11 to 32, gradually gained weight during the weeks following surgery, despite short intervals of rapid weight loss immediately following chemotherapy treatments. Thus, rather than shrinkage, it was actual weight gain in half the patients that necessitated change of socket within three weeks postsurgery.

Only one patient did not receive a hip joint in the "second phase" prosthesis. Her prognosis had deteriorated rapidly during the period of usage of the first prosthesis, and she expired soon after that. The youngest subject seen, weighing less than 90 pounds, and standing less than five feet tall, could not be provided with the Otto Bock hip joint as this was too bulky and too heavy.

An inexpensive hinge was designed for this patient. Consisting of a piano-type hinge, it was attached distally to a PVC plug designed for attachment of the SACH foot to the PVC pylon. In this case, however, the PVC plug is placed upside down in the proximal end of the pylon. The distal portion of the hinge is attached to this plug and the proximal portion to the socket. Advantages of this particular hip joint design are low weight, low cost, ready availability, and ease of application. This design was subsequently used in four additional pediatric and adult patients.

As patients progressed to a new socket with a hip joint, most regarded it as a welcome change. Except for one patient who wore the preparatory prosthesis six to eight hours a day, usage in the home was limited with the non-articulated pylon (first phase prosthesis). One of the older patients reported using it with a walker in the home for moderate distances. Some of the pediatric patients wore it for a half hour to one hour at a time a few times a day. The reasons for such limited use were mainly attributed to difficulties in sitting.

Two patients developed wound infections early in their gait training, and had to discontinue wearing the prosthesis until they were

medically cleared. Lack of usage by one of the pediatric patients was the result of poor cooperation on the part of the parents. In this case, many communication difficulties existed, with instructions frequently misunderstood. Another patient became overwhelmed by drastic personal and family problems after her participation had started. She cancelled or missed several gait training sessions. After an extended period of time, she was discontinued from the project.

The second phase prosthesis with pylon and articulated hip joint allowed the subjects to sit more comfortably. Most of them learned to initiate hip flexion for the swing phase and to control extension in the stance phase during the first physical therapy session. A few required cueing and reinforcement to fully weight-shift over the prosthetic leg during the stance phase to attain a position of extension. After more practice sessions, this movement became increasingly more natural. Less exaggerated and forceful pelvic tilt was needed to initiate swing phase than with the non-articulated Phase one prosthesis. This made ambulation smoother and easier for some patients. The increased weight and bulk of the hip joint and additional surrounding materials did not seem to cause concern for any of the patients. Transition to use of the heavier prosthesis is believed to have been eased by training with the lighter, simpler, and safer Phase one preparatory prosthesis.

The second phase prosthesis was used by the majority of the subjects functionally, indoors and outdoors. Wearing time ranged from three hours to 14 hours a day, the older patients using walkers, and the younger patients, forearm crutches.

As with the Phase one prosthesis, there was some dissatisfaction with certain aspects of the prosthesis. Although general mobility had definitely improved, walking speed was slower with the prosthesis than without it, i.e., with one leg and crutches. This particularly limited function for one of the younger patients who spent much of his time outdoors. One of the adult patients reported he was unable to get in and out of his car when wearing the prosthesis. Understandably, many patients were not pleased with the cosmesis of the temporary prosthesis. Even though they still consented to participate, they felt that the straight plastic

pylon without a knee joint or foam cover was crude and socially unacceptable.

Generally, there were no mechanical problems with either of the preparatory prosthesis designs, except with some of the earlier Aquaplast material. Of the total number of sockets molded (at least two per patient), three Aquaplast sockets eventually cracked. According to the manufacturer, some of the material had a limited shelf-life, e.g., three months, after which it tended to crystallize. This was rectified in later production runs.

DEFINITIVE PROSTHESIS

Biomechanical Analysis

Hip Disarticulation

The ideal hip disarticulation socket for weight bearing should have as much horizontal area as possible. Conversely, the ideal socket for swing phase should have as much vertical area as possible to minimize "pistoning." This conflict has been empirically reconciled in a socket of diagonal shape with an upward concavity as viewed in the frontal plane (Fig. 11).

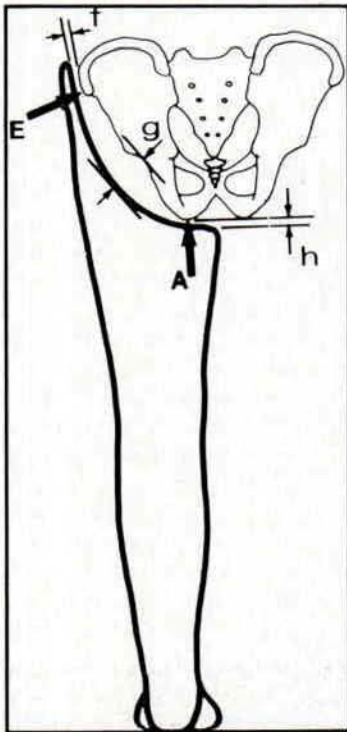


Fig. 11. Transverse cross-section of part of a conventional hip-disarticulation socket.

When one considers the human pelvis as seen in Figure 12, Vectors A, B, and C indicate areas that most effectively receive weight-bearing forces from the socket. Vector D could lessen pistoning. These might be termed primary vectors in that they directly affect the functioning of a prosthesis during midstance and during the swing phase. All horizontal vectors might be termed secondary in that they serve a stability role—preventing the prosthesis from moving away from the pelvis in the antero-posterior and medio-lateral directions. Horizontal vectors will only be cancelled by equal and opposite vectors on the contralateral side. This results in a "squeezing" of the patient, and discomfort. It is, therefore, desirable to maximize the primary and minimize the secondary vectors.

Early socket design was fundamentally in accord with the above, but full advantage was not taken horizontal surfaces of the pelvis. Basically, these sockets took a square form (Fig. 13). The ischial tuberosity was the primary transmitter of weight-bearing loads to the pelvis. Soft tissue was left to support indirectly

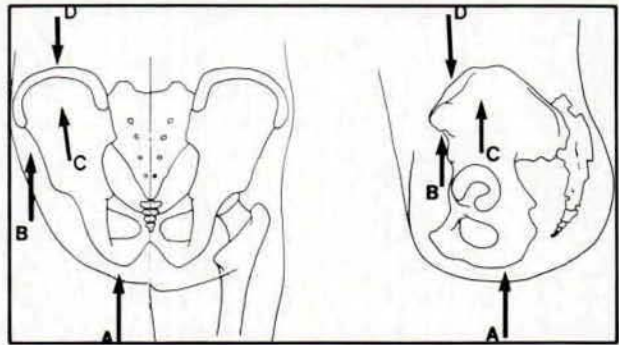


Fig. 12. Schematic of hip-disarticulation showing areas that bear weight most satisfactorily (A, B, C) and an area useful in controlling piston action (D).

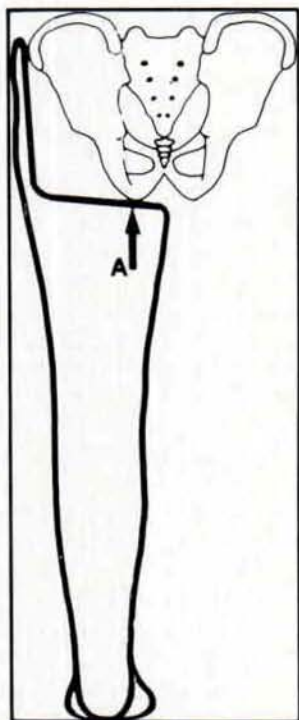


Fig. 13. An early design of socket for the hip-disarticulation case. The ischial tuberosity bore most of the downward vertical load.

the remainder of the pelvis. This was followed by a design which is currently accepted as standard and basically has a diagonal form (Fig. 11). More of the pelvis is thus directly supported.

It seems logical to extrapolate to a socket which has a "w" shape (Fig 14), in which even more of the pelvis is supported directly. Superimposition of the above figures (Fig. 15) emphasizes the regularity of the evolution.

Looking more closely at the relationship between the socket and the pelvis in figures 11 and 14, the great disparity among theoretical distances f , g , and h , as compared to that among distances i , j , k , will be noted. This is a strong indicator of more efficient use of the pelvis in bearing weight more directly rather than "floating" in soft tissue which results in pistoning while the horizontal or weight-bearing surfaces of the pelvis are not used to their fullest potential. Also, the tendency of soft tissue to flow away from the central region to the bony regions should tend to "pad" the latter for better stress distribution.

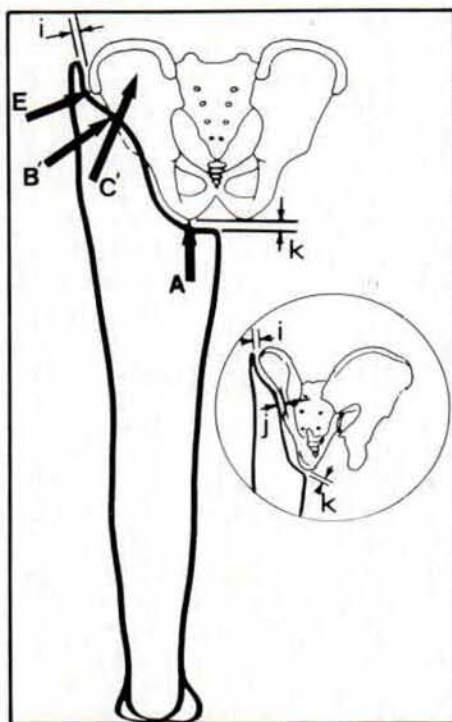


Fig. 14. "W" socket designed to spread the weight-bearing load on a hip-disarticulation stump.

Hemipelvectomy

Establishing a socket design to transmit primary (weight-bearing) loads to the body in the case of hemipelvectomy can be approached as has been done with hip disarticulation, i.e., by considering that horizontal surfaces are best for weight bearing (Fig. 16). Theoretical primary weight-bearing areas are indicated by vectors A, B, and C.

A theoretical proposition can follow. Let vector D of Fig. 17 be the vertical component of all the forces transmitted to the body by the proposed socket (less B and C). Vector E is drawn for comparison; it represents the vertical component of all the forces transmitted to the body by a conventional socket (less B and C). Note that D, if extended upward, would pass closer to the center of gravity of the body than E would.

Basically this can be accomplished by wrapping the pelvis tightly in the vertical cross-hatched area of Fig. 17, and loosely in the horizontal cross-hatch area when taking a cast. Also, this increases the density of the tissue in

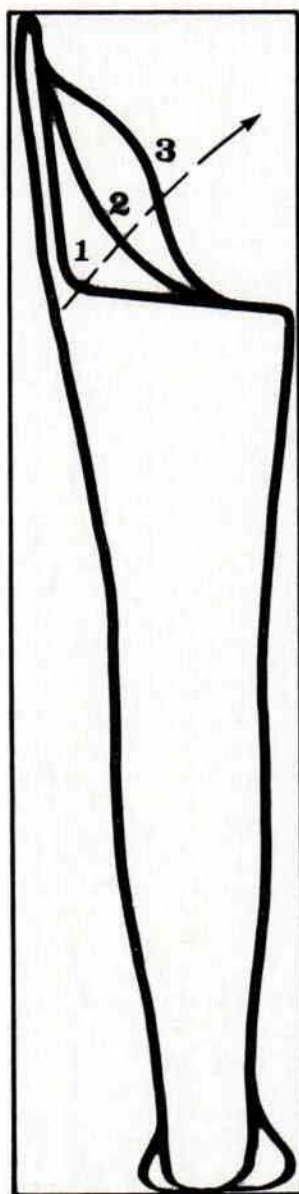


Fig. 15. Comparison of various sockets with respect to area of weight-bearing. 1, "square" socket of early design; 2, concave socket, which represents current practice; 3, "w" socket designed to spread the weight-bearing load even farther than is possible with design 2.

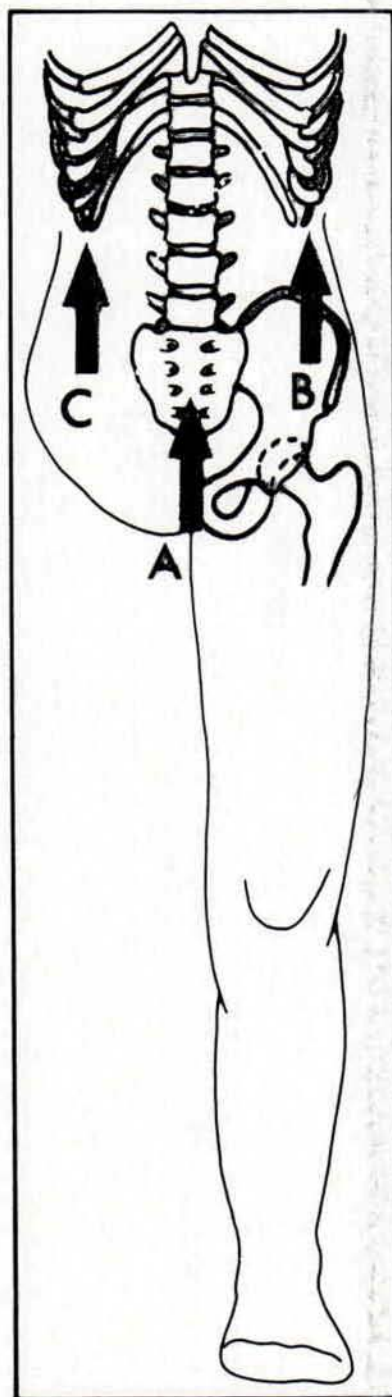


Fig. 16. Theoretical primary areas of weight-bearing for the hemipelvectomy prosthesis, A, B, and C.

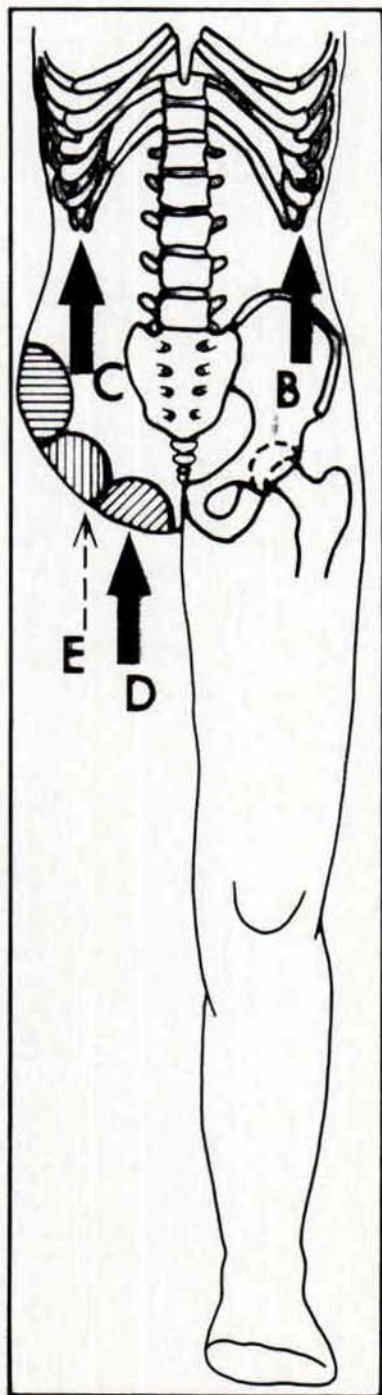


Fig. 17. Vector diagram showing application of forces provided by the new socket design. "D" represents the vertical component of all the forces transmitted by the socket, less "B" and "C", in the conventional design, and is shown here for the purpose of comparison.

the diagonal cross-hatched area which will help to keep the patient from sinking into the prosthesis upon weight-bearing and from stretching the perineum, and thus preventing a common cause of discomfort. This area of increased density is more effective in bearing weight than the other areas, indicating that weight-bearing forces are shifted medially and closer to the center of gravity.

The dashed line of Fig. 18 indicates the shape of the proposed socket in the transverse plane.

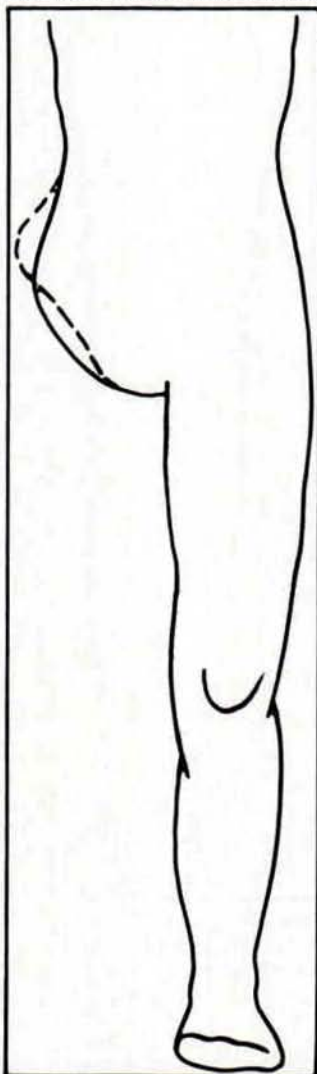


Fig. 18. Transverse cross-section of hemipelvectomy patient. The dotted line represents contour of the proposed socket at the lateral aspect.

SOCKET-FORMING APPARATUS

A socket-forming apparatus in compliance with the biomechanical analyses described above was designed to impart the appropriate biomechanical configuration onto the plaster negative cast to be taken of the patient's pelvis. The apparatus consists of half of a commercially-available plastic molded pelvic girdle used in spinal orthotics, fitted over the contralateral side (Fig. 19). Posteriorly, a flexible polyester laminated section is pivotally attached on the inside of the rigid half shell (Fig. 20). It is adjustable along a diagonal line to accommodate various sizes. This flexible section runs from its attachment posteriorly diagonally under the amputation site and is adjustably attached by means of a Velcro strap to the anterior portion of the rigid half shell. A flexible rubber tubing is attached to the posterior superior corner of the half shell by means of a parachute cord and runs anteriorly over the crest of the ilium to an adjustable attachment clip on the anterior-superior portion of the half shell.

This apparatus may be used not only for hip

disarticulation amputees but for complete and modified hemipelvectomy amputees as well. Prior to wrapping the pelvis with plaster bandages, the apparatus is adjusted to the patient's pelvis (Fig. 21). The most important aspect of this step is to place the flexible section at the appropriate angle as described in the biomechanical analysis around the amputation site and adjusting it as tightly as possible to achieve an appropriate degree of compression. After, the adjustment settings are marked and the apparatus removed, the plaster cast is wrapped and the socket-forming apparatus applied over the wet plaster cast (Fig. 22). It is adjusted in such a way that the adjustment markings are approached within a 1 cm allowance for the thickness of the plaster cast. The plaster is allowed to harden while the apparatus imparts the particular biomechanical configuration. Following this procedure, the negative cast represents very closely the actual fit of the prosthetic socket. Thus, the positive cast requires only minor modifications, involving relief build-ups for the crest of the ilium on the

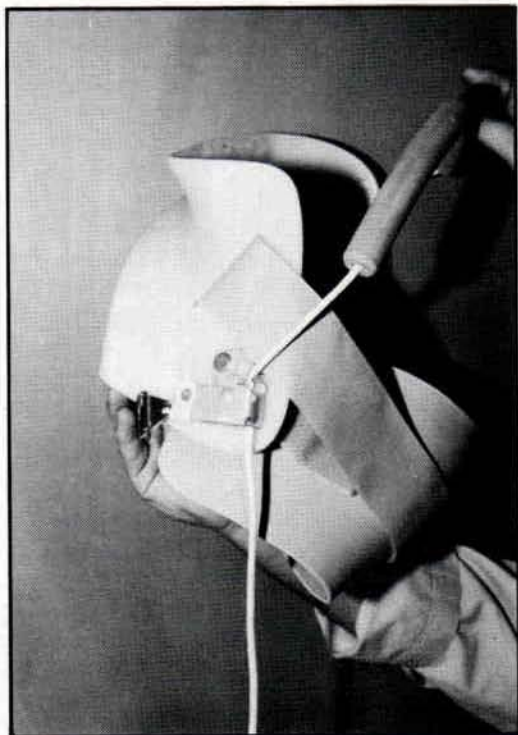


Fig. 19. Apparatus for forming the socket of cast for hip-disarticulation and hemipelvectomy patients.

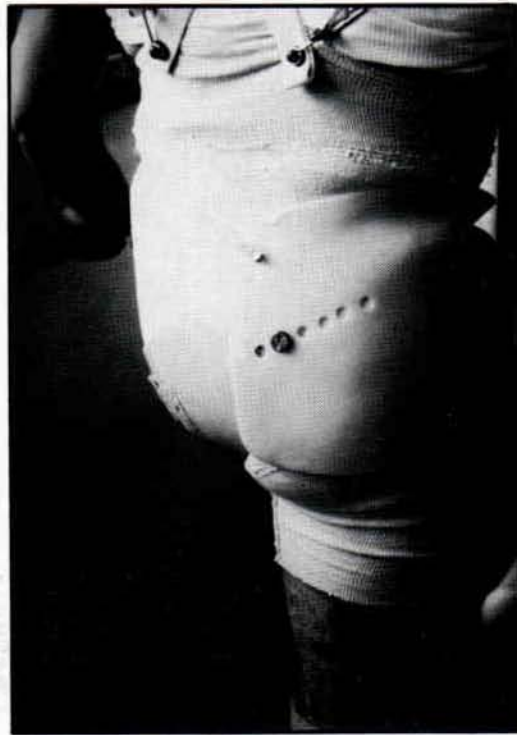


Fig. 20. The socket-forming apparatus in place on patient.

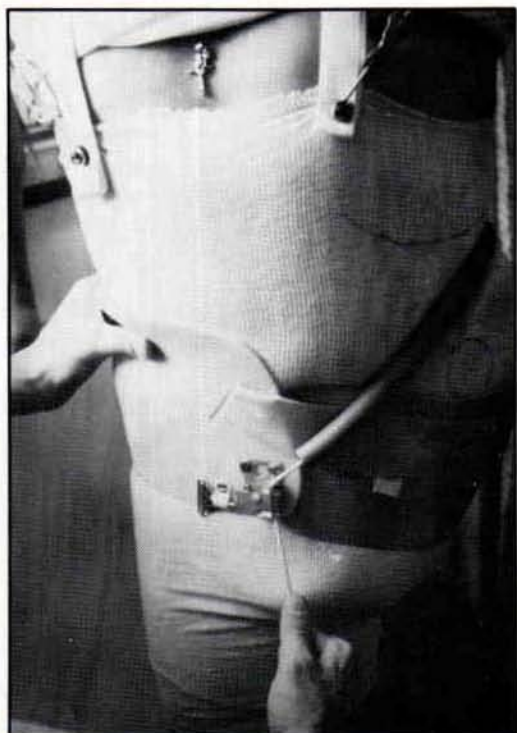


Fig. 21. Adjusting the socket-forming apparatus on the patient prior to application of plaster.

ipsilateral side only.

As mentioned above, the same apparatus is used in casting a hemipelvectomy amputee, although there is no ilium on the ipsilateral side. The procedure is identical, with the rubber tubing in this case placed at the same level as the contralateral side. The reason for this is to achieve a more cosmetic appearance on the involved side, as well as to enhance suspension through the indentation created by the rubber tubing.

Biarticular Control System

Design

While one of the major purposes of the project was to design cost-effective systems for early fitting, described above, another purpose was to advance the state of the art of definitive prostheses by addressing current problems in the control of prosthetic hip and knee joint movement. The conventional hip disarticulation or hemipelvectomy prosthesis may best be viewed as a compound pendulum with practically no coordinated control of hip and knee movement. Whatever control that does exist, is

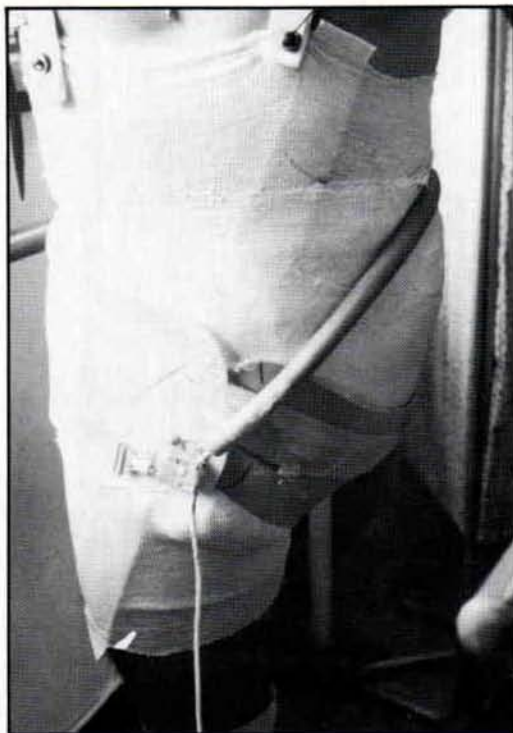


Fig. 22. Lateral view of socket-forming apparatus applied over a plaster wrap during curing stage.

by means of elastic straps, rubber bands, or springs. This results in the patient being limited to one cadence only; e.g., if the patient attempts to walk faster, joint excursion at the hip and knee is increased, which results in unequal step length and timing. Stability in the stance phase is totally dependent on alignment stability. To overcome these problems, a Hydra-pneumatic cylinder⁵ was adapted to an Otto Bock modular system to coordinate hip-knee movement in a "synergistic" way (Fig. 23). This results in greatly improved cadence response of the system due to its hydraulic characteristics, as well as increased stability in the stance phase. The location of attachment points of the Hydra-pneumatic cylinder are critical to proper function of the system. Based on functional analysis, a 6:1 ratio of hip to knee flexion resistance was found to produce optimal hip-knee control. The proximal attachment is located anterior and superior to the center of the hip joint. The distal attachment is located posterior and distal to the knee center. Both the proximal and distal attachments are mounted on adjustable brackets to accommodate for static and

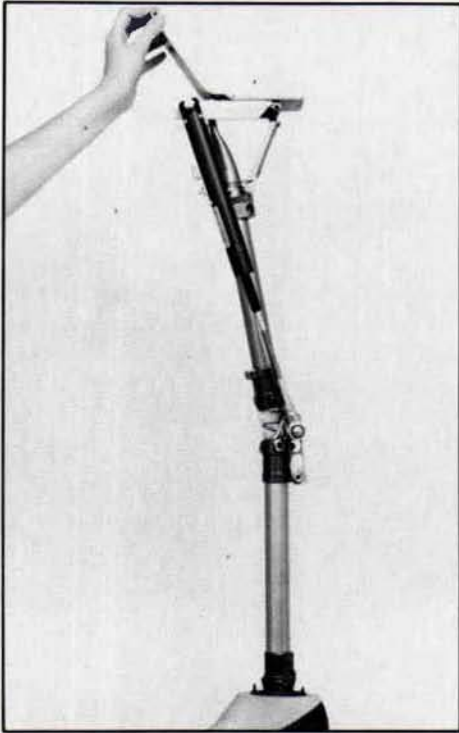


Fig. 23. Lateral view of hip-disarticulation prosthesis in which a hydraulic swing-phase control knee unit is used to control the hip.

dynamic alignment changes.

During early swing phase on the prosthetic side, fluid displacement in the cylinder dampens hip and knee flexion (Fig. 24), while a spring and pneumatic chamber in the cylinder are compressed. In late swing phase, the spring recoils while the pneumatic chamber expands, resulting in hip and knee extension.

Patient fittings

A total of three patients received the definitive prosthesis incorporating the biarticular control system. The first patient, D.S., had had a hip disarticulation 16 months before referral to the project. She had been using a hip disarticulation prosthesis with a spring-loaded hip flexion bias for one year. Her complaints with the prosthesis were knee instability induced by the hip flexion bias and a circumducted gait.

The other two patients, K.M. and R.S., were fitted approximately five months postsurgery. They had previously participated in the project and were provided the series of preparatory

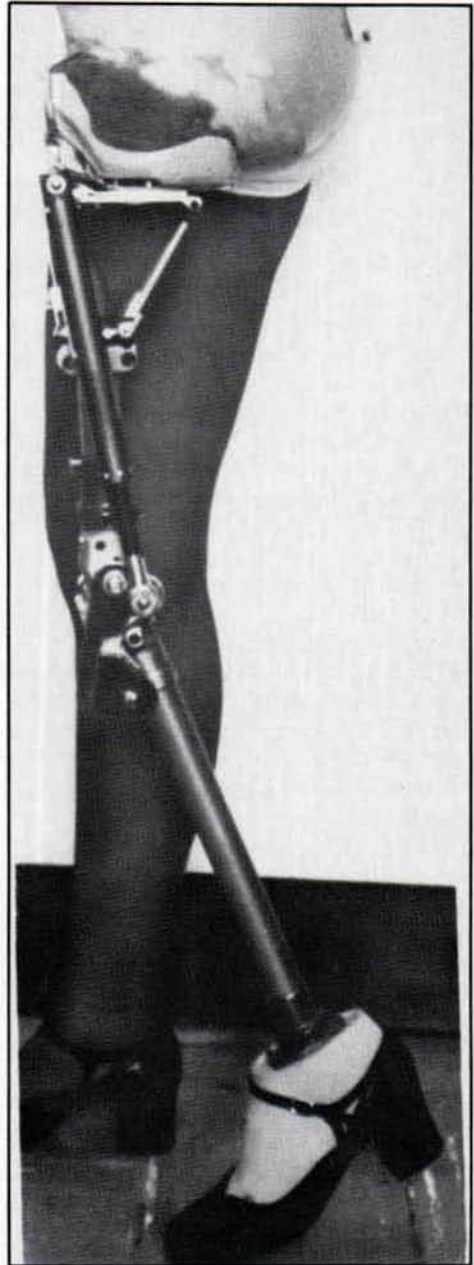


Fig. 24. Lateral view of prosthesis shown in Figure 23 being used by a patient.

prostheses. K.M. was a modified hemipelvectomy amputee who had been using a conventional endoskeletal prosthesis for three months. She was unhappy with her present gait pattern which showed severe circumduction and lack of knee flexion in swing. She expressed a strong

desire to receive a new prosthesis with bi-articular control. R.S. was a regular hemipelvec-tomy amputee who was still using her preparatory prosthesis and who in the past had medical complications which had delayed fitting of the definitive prosthesis.

Physical therapy instruction and training does not differ with this system compared to training with a conventional endoskeletal Canadian-type hip disarticulation prosthesis. What is unique is the monitoring and fine tuning possible with the resistance adjustment of the Hydra-pneumatic unit as well as the mechanical friction of the knee to achieve a smooth, coordinated gait pattern.

Initially, the mechanical knee friction should be decreased to zero while the hydraulic resistance is increased. If lack of training or bad habits cannot justify a patient's difficulty in tilting the pelvis posteriorly to initiate swing, the hydraulic resistance should be decreased slightly. Proper step length may have to be sacrificed initially, but once the tilt improves, hydraulic resistance can be increased again.

When heel rise is too high, resulting in excessive length of time for the prosthesis to extend to the weight-bearing position, the following adjustments are necessary.

If this deviation occurs at the beginning of training, the Hydra-pneumatic resistance should be decreased slightly and the mechanical resistance increased slightly. When the gait pattern improves, resistance in the hydraulic unit once again is increased and the mechanical friction decreased. Both types of resistance may need to be adjusted alternately until the condition for optimal swing is found.

Since D.S. and K.M. had already ambulated with permanent prostheses, much of the gait training involved relearning a proper gait pattern. This was believed to be markedly enhanced with the "synergistic" control system on the basis of clinical observation and patient comments.

The last patient, R.S., who had not yet been using a permanent prosthesis, was the ideal candidate for this project. She had mastered basic body mechanics with the temporary device, and had not developed any negative habits in her gait pattern. She progressed rapidly in her gait training and completed it within one month.

While other patients participating in this project progressed to a definitive prosthesis, they were fitted prior to the development of the bi-articular control system, i.e., with conventional systems, and thus are not described in any detail here. Nevertheless, all five amputees advancing to the definitive fitting stage were provided with sockets made through the use of the socket-forming apparatus. The only difference amongst the sockets was the location of the opening. The more recent sockets were fitted with a posterior opening, which is believed to be more effective for weight-bearing purposes since better advantage can be taken of increased intra-abdominal pressure with a solid anterior socket. Furthermore, any volume changes are better accommodated with a posterior opening since the crucial skeletal relationships, e.g., distance between the anterior superior spines, are not affected in this way.

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Footnotes

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² Institute of Rehabilitation Medicine, New York University Medical Center, 400 East 34th Street, New York, NY 10016.

³ WFR Corporation, Ramsey, New Jersey.

⁴ Otto Bock Orthopedic Industry, Inc., 610 Industrial Avenue, Minneapolis, Minnesota 55422.

⁵ Kingsley Manufacturing Company, 1984 Placentia Avenue, Costa Mesa, California 92627.