Lead Article

Sockets, Linings, and Interfaces

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A prosthesis, whose Greek source means "put to," must of necessity have contact with the residual limb or stump. The functions of this contact region or socket (perhaps supplemented with lining, sock, and further attachments or harness), are to allow the transmission of forces, bending moments, and torques between the amputee and the prosthesis to be as comfortable as feasible in order to sustain body weight and permit locomotion for lower-limb amputees, and to allow purposeful activities by upper-limb cases. Prolonged and vigorous use of a prosthesis should not cause pain, pressure sores, blisters or corns from friction, nor edema from restricted return circulation. Proper ventilation should also prevent such accumulation of moisture as to cause skin maceration.

Challenging as these major tasks are, they should not lead to neglect of some of the less obvious functions of a prosthesis. The changing pattern of pressure distribution on the body from the prosthesis should provide important sensory feedback on external forces, on positions of remote portions of the prosthesis, and on events such as knee extension. Professor Ernst Marquartdt,[1] realizing the value of the limited sensory information transmitted to the residual limb of an upper-limb amputee by the older soft leather socket, was reluctant to change to rigid plastic laminates despite their other advantages. It should also be possible to control remote joints and locks or external sources of power by small reflex or voluntary motions of remaining muscles in the residual limb and through sensing of mechanical motion or myoelectric activity.

Historical Notes

Naturally there is a long history of attempts to meet these challenges, that is scattered in patents, papers, catalogs, and atlases.[2] There are records of wooden prostheses and peg legs since antiquity, which presumably were padded with fabric or leather. Medieval prostheses, made by armorers, probably had leather or other materials for liners. In the past century, molded leather shells or lacers supported by metal side bars and cuffs, adapted from orthopedic appliances, were used extensively. These allowed slow adaptation to radial displacement and deliberate readjustment of circumference, and provided some tapered flexibility of radial stiffness above and below the proximal and distal reinforcing cuffs. The typical American artificial limb carved out of wood was completely rigid, though it could be carved deliberately to produce enlargements as desired and could be lined, completely or in selected portions of the circumference, with leather.

Felt, wax-impregnated materials slowly displaced under pressure at body temperature, and resilient or slowly compacted foam plastics or rubbers have been used by various developers. Diagonally woven straps or cords (sometimes called Chinese Magic Finger Grip in the U.S., or Nuremberg Witch's Finger in Germany) have been suggested repeatedly as resilient sockets and perhaps as suspension. Parallel vertical cords between upper and lower rigid frames have also been used for both flexibility and ventilation.

End-Weight-Bearing

Some early sockets attempted to provide direct end-weight-bearing on the unrestrained end of the amputated residual limb. Typically, the amputated end of the bone without deliberate plugging developed only a thin and flexible closure to resist transmission of end load to the medullary canal, causing discomfort or pain. In addition, the ring of bony cortex tended to produce painful direct loading on the skin at the distal end of the residual limb. Early attempts to leave flaps or pads of muscles or other tissues across the distal end merely led to atrophy.

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Grey, a former apprentice of James Potts who developed the coordinated-motion above-knee prosthesis later called the Anglesea Leg, was very critical of such misguided efforts to develop end-weight-bearing.[3] Except for the Syme,[4] the knee disarticulation, the Gritti-Stokes amputation levels, and some attempts to deliberately plug the end of a long bone[5]—all relatively rare—there were few attempts to attain any end contact, let alone end-weight-bearing.

For generations most prostheses, especially the typical above-knee, caused considerable constriction in the proximal third of the socket, required trial-and-error fitting, and left relatively unsupported the distal end of the residual limb. Because the residual limb was considered "a bowl of jelly," it was constricted proximally but extruded distally in an attempt to secure a firm grip to assist both axial support and control of bending moments. Fortunately, the common firmly-knitted woolen stump sock between the limb and the prosthetic socket—folded over the socket brim and closed at the distal end—supported the skin, fascia, and internal tissues in resisting this distal extrusion and lengthening.

Stump Socks

One or more stump socks were typically worn between a hard socket wall and the residual limb. Stump socks were worn for reasonable as well as fallacious purposes.[6] Knitted fleece socks provided a slight degree of resiliency and thus redistribution of local radial pressure, especially when freshly laundered. Inevitably, there were mismatches between the residual limb and socket wall caused by slow changes in the limb with edema, atrophy, obesity, or sometimes growth or muscle development. Axial displacement, inaccuracies in the trial-and-error carving of a wooden socket, or even of modification of a plaster model of the residual limb before preparing a plastic socket also led to mismatches. Sock resiliency can overcome minor discrepancies and improve comfort and addition of a sock can help compensate for shrinkage of the residual limb.

A major function of the sock is to cling to the residual limb but slide with respect to the socket wall if there are relative motions between stance and swing phases of walking or caused by discrepancy between the natural proximal joint and an external mechanical joint. (This important function is impeded if the socket wall is rough or if a perspiration-soaked sock can stick to the wall but chafe the skin.) The sock should also absorb perspiration, provide wick-like action, and allow for ventilation. The closed end or "toe" should provide some support of the distal tissue.

Other than a circular cross-section, addition of one or more socks inevitably distorts the fit. In the triangular below-knee case, although the soft tissues in the posterior portion can change, the bony portions do not, so a spot liner is more appropriate than additional socks.

Sometimes the stump sock was misused by patients to compensate for gross changes which required major refitting, or because of misunderstandings or lack of training. About 1947 Dr. John Young of Mellon Institute and this author met a below-knee amputee who wore five firmly packed socks. Though he did not believe in a "green sock," we finally persuaded him to purchase new socks in order to accompany a newly refitted prosthesis adapted to only one or two socks and to wash the socks daily. Such distortions, however, should not distract from the legitimate uses of stump socks.

Suction Socket

The suction socket above-knee prosthesis was and is routinely fitted with direct contact against the skin of the residual limb. The original suction socket of the Parmelee patent of 1863[7] may have been intended as total contact, though the evidence is not clear.

A version of the suction socket which came from Germany in 1946–47, was routinely fitted with a "suction chamber" extending below the end of the residual limb. During donning, the tissues were pulled down through a snugly fitted proximal third by a tube of stockinet which was withdrawn through the valve hole in a side wall, thereby creating a significant distortion and elongation of the residual limb. In some cases, the distal end developed chronic edema or discoloration from disturbed return circulation or small hemorrhages.

These problems, as well as basic principles, contact dermatitis, blisters and corns from friction, and cysts just proximal to the brim, were among the major difficulties discussed by Barnes[8] and Levy[9] in their classic treatment of dermatological problems of the amputee. They emphasized the importance of avoiding stasis in the distal residual limb in encouraging total contact and reducing proximal constriction.

THOUGHTS AND THEORIES

After the issue of *Artificial Limbs* by Barnes and Levy was published in 1956, this author was appointed Fulbright Lecturer, based at the Orthopedic Hospital in Copenhagen. In an informal memorandum[10] based on years of observations and discussions concerning fitting of both dental and limb prostheses, three major themes were developed:

I. Minimize the stiffness gradient between the rigid socket wall and the flexible skin; i.e., taper flexibility of the socket brim.

II. Approximately match wall stiffness to that of the tissue supported.

III. Provide a porous wall capable of "breathing" slowly.

We may consider each theme in turn. Both theory and practice can be useful. Practice can develop to a considerable extent without theory; we walked before we learned about the biomechanics of locomotion, and Watt built steam engines before Carnot developed the basic cycle for all heat engines or Rankine the cycle for steam engines. Yet theory can guide our efforts toward improvements, show the areas where greatest progress can occur, and point out the ultimate limits so we do not waste our efforts.

Tapered Flexibility

The first theme was eventually published as the introduction to an extensive series of theoretical and experimental papers by Bennett.[11, 12] The series ended with limited clinical trials of sockets with flexible brims made of plastic laminates. These sockets appeared to be helpful for patients previously troubled by chronic or recurrent cysts, but the mechanical durability of the laminate was so poor that the sockets often lasted only six months.

After the National Institute of Handicapped Research (NIHR) project at Moss Rehabilitation Hospital began working with polyethylene and polypropylene thermoplastics,[13] Bennett collaborated with that group on some attempts to develop more durable flexible-brim sockets using thermoplastics. These appeared to be promising, but the major focus of the project was on light-weight prostheses.

There have been numerous recent efforts to produce a thermoplastic flexible (and often transparent) inner socket or liner supported by an outer shell or other structure. The Scandinavian Flexible Socket or the similar Icelandic-Swedish-New York (ISNY) Socket, and two recent designs from the New York University Institute of Rehabilitation Medicine[14] are examples. If, as in Figure 5 of "Flexible Prosthetic Socket Techniques" by Lehneis et al., the flexible inner liner projects proximally above the more rigid outer laminate shell, it helps to provide the tapered flexibility and transition from rigid socket to flexible skin which was suggested in theme I,[10] and which seemed desirable from Bennett's work.

Matching Wall Stiffness to Tissues Supported

First, consider the principles. The bony prominences near the surface are very stiff against radial indentation under load, but they do not bulge during walking or change appreciably in size or shape over extremely long periods. In contrast, soft tissues may change much more rapidly by brief displacement of body fluids or in moderate time periods (e.g., weeks) by growth or atrophy. Soft tissues are also much less stiff under loads from internal muscular or hydraulic forces, or from external pressure, provided they can be displaced.

Conversely, if fluid-filled soft tissues are sufficiently trapped to avoid displacement, they will behave like an enclosed fluid under hydrostatic pressure. Within the limits allowed by connective tissue, unsupported soft tissue can be displaced a considerable amount, at the expense of distorting blood vessels from their usual circular cross-sections to oval shapes with the same perimeter but a smaller area. Such displacement can also stimulate nerve endings. These displacements may give the illusion of tissue "compressibility."

Soft tissue can also accumulate excessive fluid, creating flushing and edema, if free to expand radially from the center of the body mass. External support will assist the "milking" effect from the pulsating action of muscles contracting within fascial compartments in pushing fluid into the veins and lymphatics, while on the contrary either external suction or restriction of the return ducts proximal to the tissue considered will favor edema. Similarly, a localized area, with little or no muscular activity that is free from support within a larger region otherwise firmly supported, will cause "window edema" with bulging of skin and tissue through the opening, as in a small opening in a large plaster cast.

Many clinical observations and some systematic tests with sockets, plaster casts, and different designs of prostheses and orthoses relate to this problem of matching socket to residual limb, even though they have been viewed as specific rather than general. The direct comparison of two theories or designs is difficult because methods for preparing the socket and aligning it to the remainder of the prosthesis usually differ. It would seem useful to compare sockets with varying degrees and locations of softness or of flexibility, but similar as to cast, model, and alignment. If different methods or alignments really are needed to optimize results, the reasons should be studied.

The original Navy "soft" socket for below-knee amputees of the late 1940's, provided a limited but equal degree of softness in all regions of the circumference. The cast was prepared with the residual limb dipped in relatively dense dental stone while it hardened. Weight was shifted to the cast after the impression was firm but not quite completely set. The socket was formed over a plaster model without modification or contact with the sock-covered distal end of the residual limb. The distal wall was intended to be tangent to the tapering residual limb. The later Navy "closed-end" socket also provided some additional thickness of cellular rubber in contact with the entire distal end of the residual limb, tapering toward the side walls, with the entire socket lined with vinyl. The Schindler soft socket was formed with gores of foam rubber tailored to fit the warped surface of the plaster model, more precisely than was possible with the single sheet wrapped around the model in the simpler Navy technique.

The Blevens below-knee socket provided an oval pad of sponge rubber, with tapered edges, trapped between layers of stump sock over the calf region of the residual limb. After this pad was compressed and forced through a snugly fitted proximal portion, it could expand into an enlargement in the rigid socket wall below the popliteal region. It permitted both activity of the remaining remnants of calf musculature, which tended to atrophy in conventional hard sockets, and provided or assisted in support of the prosthesis in swing phase. Its possibilities for control signals remain unexplored.

Fabrication Methods

Carved sockets obviously required skill of the prosthetist and tolerance of the user, who was initially asked to try to fit the residual limb into an unduly tight space which was gradually enlarged until a tolerable fit was achieved. Did the residual limb become engorged or injured in the process? Did the amputee eventually tolerate a certain amount of discomfort as he "broke in" the hard limb—or perhaps broke down the soft tissues to conform more closely to the not-quite-perfect fit? Or did he become sensitized to discomfort, aware of its location and cause, and even more demanding?

Sockets made over plaster models prepared from plaster casts seem more likely than those carved purely from measurements for an immediate accurate fit, or a fit with minimal trials and adjustments. Even so, the prosthetist usually considers that the manual distortion of the wet plaster during the process of taking the cast and "rectification" of the positive plaster model is necessary to avoid an unduly loose fit, often regardless of the resiliency of stump sock or foam lining. Could this view be the result of past experience in preparing casts from residual limbs which have become enlarged from being unsupported while below the body during the preparation period? Would little or no rectification be needed if the amputee were supine with the residual limb elevated for an "appropriate" period immediately before casting? Have a few anecdotal accounts of such attempts leading to excessively tight sockets reflected unduly long elevation times? Did the Navy dip impression allow the denser dental stone, while still fluid, to squeeze fluids from the tissues by an approximately correct amount before solidifying?

Because the socket must transmit the necessary axial forces, bending moments, and torques described by Radcliffe[15, 16, 17, 18] for all major levels of the lower limb, and Taylor[19, 20] for the upper, the socket wall must be reasonably firm in at least some areas and the interior bone(s) must transfer forces through the skin to the wall in both proximal and distal regions.

Retention of Fit

A precisely made hard socket fit with direct contact (as in the suction socket) or with a single thin stump sock might be effective for a time, but it might encounter difficulties even with muscular activities or large motion of the proximal joint as in sitting and bending. More important discrepancies would occur over longer periods from edema, growth, or atrophy.

Completely uniform softness might also be questioned because it does not match just those relatively limited areas which alter cyclically with muscular activity or over some time span. Perhaps more critically, uniform softness allows areas of high pressure, intended to match individual tolerance to high pressure, to sink into the soft material and thus to shift some load to areas where the designer desired lower pressure. Beginning in the prosthetics schools in 1957–58, emphasis upon socket planning based on anatomical and physiological considerations and upon avoidance of erratic constriction and looseness was a healthy development.

Some Suggestions

The local radial stiffness of the socket wall might be approximately comparable to the stiffness and physiological motion of the tissue which it touches, though changes should occur gradually from place to place to avoid high local shear stresses in tissue. Thus, the wall near bony prominences might be quite firm if precisely fitted to a nonedematous limb.

Obviously this notion seems the opposite of the usual concept of cushioning the bony prominences. Much of the traditional objection to a hard socket wall in contact with a bony prominence may be due to two difficulties: (1) unduly concentrated pressure because of poor fitting or displacement from the correct position, or (2) slippage and friction from inadequate suspension or joint location, leading to formation of blisters and bursae.

Relatively soft walls opposite soft tissue might allow muscle bulging or tendon tightening at every motion of the limb yet rebound to prevent window edema when relaxed. The stiffness might be chosen to allow deliberate gripping of the wall for control and suspension, somewhat comparable to the German "Haftprothese"[21] with muscular bulging to grip a rigid wall to supplement an above-knee suction socket as well as to help support the Blevens below-knee prosthesis. Some softness opposite tissues which tend to change rapidly might also compensate for slight changes such as growth.

Adequate, relatively firm areas must be found for biomechanically necessary forces, including those generating bending moments and torques. In the below-knee case, for example, counterpressure from the posterior wall is needed to hold the condyles anteriorly on their sloping supports. In the above-knee case, the distal lateral and the proximal medial aspects of the femur must generate, yet tolerate, substantial forces to oppose the moment created by body weight acting upon it through the center of gravity appreciably medial to the center of support of the prosthesis during stance phase.

The soft tissues, usually present at the distal end, should be encased thoroughly to prevent displacement, extrusion, and edema, yet held precisely in a wall and floor soft enough to prevent localized painful loading. Page,[22] an engineer interested in dental prostheses, discussed with this author in 1946 the concept of "mucostatic" fitting with tissues trapped so that, much like fluids, they behave almost hydrostatically. The tissues should not be distorted from resting position when the cast is taken, nor should they be displaced towards hollows left by grinding away apparent ridges actually needed to fit into folds in the tissue. Past failures to create end-weight-bearing simply by taking an impression under load or placing a pad of foam rubber on a flat socket floor need not eliminate the possibility of total contact or end-weight-bearing by more sophisticated methods.

A socket of the style described might have variable but tapered thickness of resilient material, such as closed-cell foam rubber or plastic. Muscular bulging into such material might be developed as a control signal. Alternatively, but perhaps less precisely, a thin resilient liner might be supported by an outer shell providing firm support where needed but having rounded and outwardly flared windows where expansion should be possible. The thin resilient liner opposite the windows could improve heat transfer, awareness of adjacent surfaces, and comfort when seated. The sockets illustrated by Lehneis, et al.[14] seem reasonable steps, though one wonders whether "selected fenestration over pressure sensitive areas" would be as logical as carefully molded and slightly relieved or padded areas. Certainly the transparent socket materials are advantageous for checking fit, supplementing their value in the flared flexible brim.

Porous Materials

The skin, as Barnes[8] pointed out, normally excretes water, gases and various compounds. An impermeable wall pressed tightly against the skin for many hours at a time can lead to dermatological difficulties.

Leather allows some absorption and passage of these excretions, but deteriorates from their presence. Organic materials trapped in the fine pores of leather tend to decompose. The Army Prosthetics Research Laboratory (APRL) developed a protective slightly permeable coating for leather consisting of a particular grade of nylon dissolved in isopropyl alcohol. It is not still commercially available, as it was not very widely used. Care had to be taken to avoid traces of oil on the leather in order to be coated.

APRL also developed a "starved resin" process, producing a somewhat porous thermosetting plastic laminate. Unfortunately, the irregular holes tended to become plugged with debris from the stump sock, dead skin cells, etc., and no adequate cleansing method was found.

Late in World War II, Quamco was developed for raincoats and aviation clothing to resist penetration by rain or sea water yet allow slow transfusion of perspiration. It received brief attention in the early suction socket program. In recent years, Gore-tex has become increasingly popular for sportswear. Though it is difficult to tailor Gore-tex to complex shapes, the recent availability of a molded sports hat may indicate the possibility of considering an individually shaped socket or at least gently warped segments to mount in a fenestrated socket.

Simple mechanical perforations of the socket wall were used, for example, with aluminum sockets, particularly in England. The holes had to be small enough so that the tissue, presumably supported by a stump sock, did not bulge through them. At the other extreme, the mechanically or electrically perforated plastics, studied around 1949 by the Mellon Institute, sometimes had such tiny holes that organic materials became clogged in them as in leather.

One could imagine a wick-like, minutely perforated liner—and perhaps wall—permitting rapid and effective cleaning and drying. Air flow must permit ventilation yet allow adequate suction suspension, perhaps assisted by muscular gripping as in the Haftprothese, or by a very flexible inner liner collapsing against and adhering to the residual limb, as in a Northwestern University design[23] tested upon both upper- and lower-limb amputees. Care must be taken to provide a suitable balance of wicking capillary pressure in excess of negative air pressure so that moisture is not drawn back into the socket during swing phase. Conceivably, a porous supporting liner within an outer supporting structure might provide total contact and biomechanical reactions for the residual limb, but for a small and slowly ventilated chamber between the two, perhaps serving as a suction chamber during swing phase.

One hopes that a simple, inexpensive, individually moldable material with appropriate range of perforations will become available. Ideally it would be available in various thicknesses, stiffnesses, resiliencies, and strengths and in a choice of transparency or appropriate skin colors. Of course it must also be nontoxic, noncarcinogenic, and odorless.

Until then, however, we must make do with the increasing array of compromise materials and our growing but imperfect understanding of principles of sockets, linings, and interfaces. Bit by bit, we can improve service to the severely disabled patients whom we serve.

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