KINEMATICS OF PROSTHESIS SHOULDER JOINTS

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Upon reviewing Mr. Karg's article I was impressed by the clarity of his description of the ring shoulder joints. He told a long story in little more than one typewritten page, while I shall be content if these technical remarks take less than four pages. This development was the result of a long series of theoretical studies and amputee trials of various types of shoulder prostheses, conducted principally under sponsorship of the Veterans Administration. Cooperative efforts of the Department of Engineering and the School of Medicine at UCLA led to definition and adoption of minimum functional requirements for prosthesis shoulder joints.

Minimum Functional Requirements of Prosthesis Shoulders

Prosthetists have long recognized various functional requirements for prosthesis shoulder joints. They seem to attach the most importance to those factors which, according to their personal experience, may best help the bilateral shoulder amputee carry out the activities of daily living. Thus some men believe that stability is the most important requirement, so they eliminate the joint. Others use the Hitchcock passive abduction shoulder joint[1], the UCLA passive friction shoulder joint[2], or similar constructions. Experience with various techniques, as well as studies by Keller et al[3], Blaschke[4], and others at UCLA, have resulted in specification of the following design criteria:

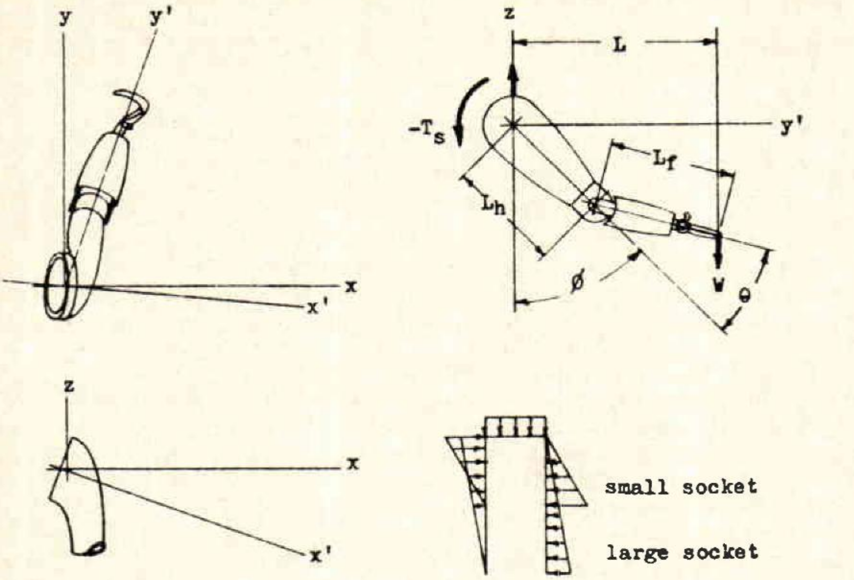
1. the prosthesis-torso coupling must be stable,
2. action must be reliable,
3. anterio-lateral elbow positions must be provided,
4. for humeral-neck prostheses, stump clearance must be provided.

Other considerations include cost, weight, and comfort, but these functional criteria were given primary consideration.

Our first design studies disclosed that eating and toileting could be accomplished if simultaneous shoulder flexion and abduction were used to position the humeral section. Since this position was found to be useful for a number of other activities, commercially available shoulder bulkheads were modified to give a swivel action in a plane, with the pre-positioned setting held by a spring-loaded disc clutch. This assembly was mounted with its plane of action vertical but skewed with respect to a parasagittal plane. Although the desired action was achieved, the joint was expensive and heavy, and it failed to provide clearance for a humeral neck stump. In addition, it gave amputees a very broad-shouldered appearance because its posterior rim necessarily was mounted to clear the scapula, and the skew angle brought the anterior rim still farther out. These factors, as well as problems of tissue loading under the socket, were taken into consideration in a kinematic analysis of the amputee-socket-joint complex.

Shoulder Joint Torques and Socket Reaction Forces

It is apparent from the principles of levers that the torque in a prosthesis shoulder joint is equal to the product of the applied load times its lever arm. Further, equilibrium of the prosthesis requires an equal reaction force and an equal reaction torque. These reactions are transmitted through the shoulder to the socket where they are equilibrated by distributed pressure in the body tissue. Although this pressure distribution varies with socket fit, a rough approximation can be obtained by assuming linear



Approximate pressure distribution

LEGEND:

- x - frontal axis
- x' - ring-joint axis
- y - parasagittal axis
- y' - arm axis
- z - vertical axis

- ϕ - humeral flexion angle
- θ - elbow flexion angle
- L - effective lever arm
- L_f - forearm length to load
- L_h - humeral length
- T_s - shoulder torque
- W - load

FIGURE 1

FORCE, TORQUE, AND PRESSURE RELATIONS

elastic properties for the tissue. Accordingly, for a load consisting of a weight at the terminal device, socket-tissue pressure will vary from zero at the top of the socket to a maximum at the bottom rim of the front wall of the socket, and oppositely on the back wall. These force, torque, and pressure relations are summarized in Fig. 1.

Some appreciation of the importance of these factors can be gained by assigning values to the weight, the elbow and shoulder flexion angles, and the socket and arm dimensions. With the elbow flexed 30° with respect to the humeral section, and the humeral section flexed 60° from the vertical, the forearm will be horizontal. Setting the distance from the elbow axis to the weight equal to twelve inches, and the distance between the shoulder axis and the elbow axis also twelve inches, the effective lever arm is

$$\text{Lever Arm} = L(h)\sin\phi + L(f)\sin(\phi+\theta) = 12\sin 60 + 12\sin 90 = 18 \text{ in.}$$

A ten-pound weight would then produce a torque at the shoulder equal to the product of the weight times its lever arm, or

$$\text{Torque}(s) = T(s) = (\text{weight})\ (\text{lever arm}) = (10)\ (18) = 180 \text{ lb-in.}$$

Lever arms for various combinations of flexion angles can be found graphically by drawing the axes of the humeral and forearm sections to scale and measuring the horizontal distance between two vertical lines through the shoulder axis and the weight.

It can be shown if two elbow laminating rings are bolted together to form a disc-clutch shoulder joint, as is sometimes done, the unavoidable eccentric loading produces a large radial force on the bolt and the holes in the rings. For the conditions given, when using three-inch diameter rings, this force can be as great as 150 pounds, or 6,400 pounds per square inch of projected area. Repeated adjustments of the shoulder then cause galling and wear of the holes in the aluminum rings. This trouble can be eliminated by providing a bearing of larger diameter in the joint.

Going next to the socket-tissue pressure distribution, some trouble may be encountered as exact analysis of this pressure distribution is complicated by the compound curvature of the socket. However, an important principle can be developed qualitatively if the socket shape is approximated by a rectangular box section. This principle relates the socket-tissue pressure to the socket size and explains the discomfort experienced by amputees wearing small sockets. These small sockets are sometimes used to permit a snug fit and maximum possible ventilation. As the maximum pressure within the socket varies inversely with the socket height, we developed a structured socket which comes down eight or nine inches on the chest wall and extends within an inch or two of the sagittal plane, as shown in Fig. 2. This socket, generally referred to as the spar-strut socket, is reinforced with glass bead-

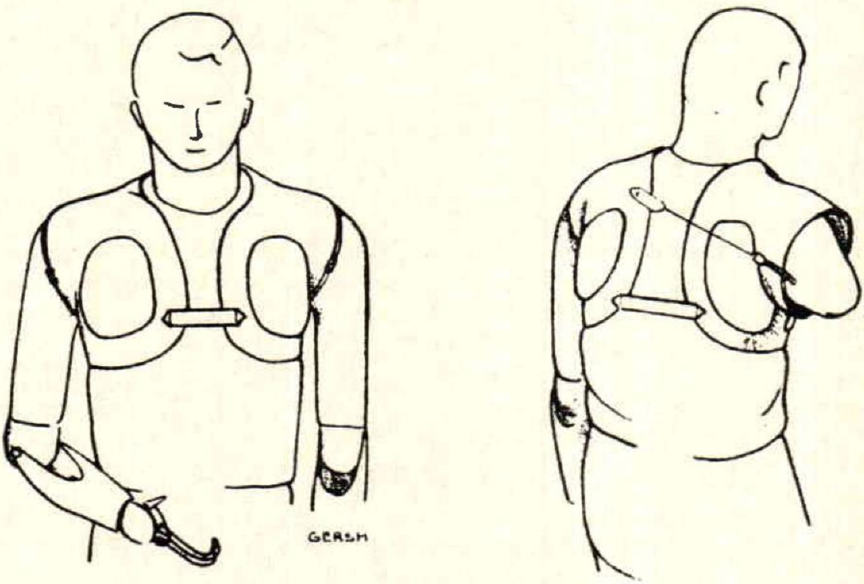


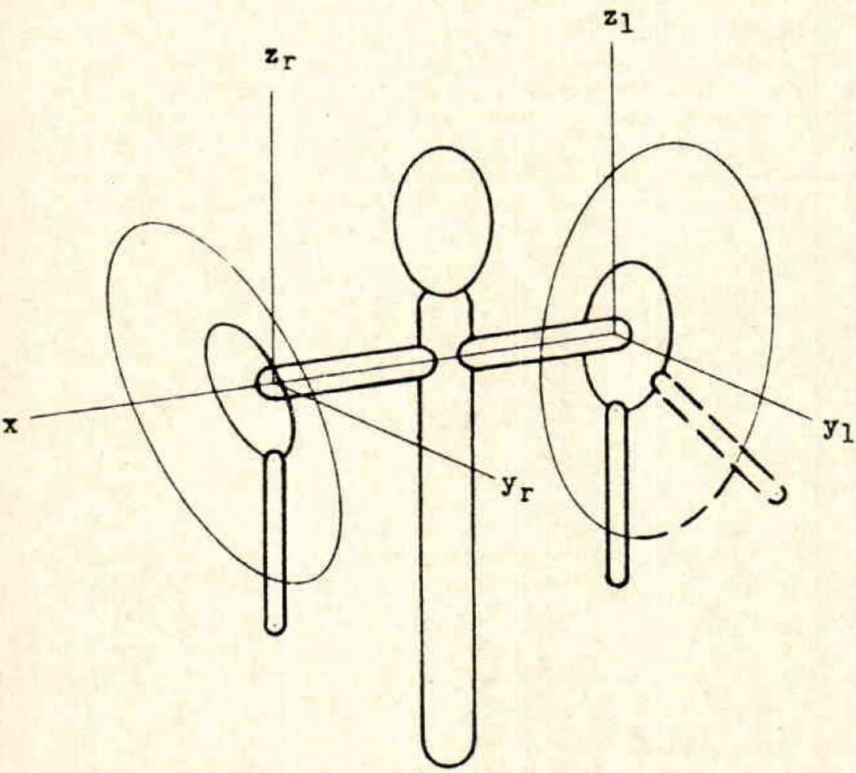
FIGURE 2

BILATERAL HUMERAL-NECK PROSTHESIS

ing around its periphery and up the center strut to permit cutting large ventilating holes, as described by Henderson[5]. Additional ventilation is provided by the clearance through the shoulder joint. By actual test, the load which amputees can carry without discomfort has been tripled and quadrupled by use of this socket, and shoulder movement is impaired only slightly as the socket tends to swivel about the chest wall. This socket structure is an integral feature of prostheses using the ring-humeral neck shoulder joint as described in the next section.

Geometry and Mechanics of the Ring-Type Humeral-Neck Shoulder Joint

Design studies based on the anatomy of the shoulder and the functional



LEGEND:

- x - frontal axis
- y_r - right parasagittal axis
- y_l - left parasagittal axis
- z_r - right vertical axis
- z_l - left vertical axis

FIGURE 3

KINEMATIC DIAGRAM

requirements given above resulted in several feasible motions and mechanisms. Some of these were found to be quite complex, with two-axis swivels, ball bearings, multiple-disc clutches, circular dovetail slides, and other elaborate features. The configuration selected as being most practical as well as feasible was a threaded metal ring mating with a threaded humeral section in such a way that the threads could serve as a swivel bearing. Its mounting and adjustment are described by Mr. Karg, but the geometry of its compound motion may be clarified by the diagram of Fig. 3.

The ring is mounted with its axis centered on the shoulder pivot and inclined ten to thirty degrees below the horizontal so that its plane conforms closely to the body contour. Then if the humeral section is vertical for zero flexion, its axis will generate a conical surface as it is flexed or hyper-extended. This motion combines flexion and abduction into one motion; the amount of abduction present can be varied by rotating the humeral section about a vertical axis during build-up of the ring on the mold. It should be noted that some abduction with hyperextension may occasionally be used in back of the body.

In order to obtain maximum strength from the plastic threads, the ring threads are a modified Acme type, called knuckle threads. Static and dynamic loading tests on a child-size prosthesis and specimens with $3\frac{1}{2}$-inch diameter joints showed that the threads had ample strength. They withstood a side load of 200 pounds at the end of a seven-inch humeral section without any damage and required an axial load of 2,320 pounds to produce failure. The complete socket, humeral section, and ring weighed fourteen ounces, and adult-size assemblies have been made that weighed less.

As Mr. Karg noted, the joint permits complete circumduction of the arm about the shoulder with a fairly natural motion. This feature may give it utility for orthotic work, and there is a possibility of using it with external power for braces and prostheses.

References

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