A COMPENSATING SHOULDER JOINT
TO ASSIST THE SHORT TRANSHUMERAL AMPUTEE
T. Walley Williams, III, MA
Liberating Technologies, Inc

THE PROBLEM TO BE SOLVED
The typical problem patient has a transhumeral amputation 30 to 60 mm below the axilla. No matter how well the socket is made, the moment arm in the socket is too little to sustain the four foot-pound torque of a typical advanced prosthesis when working out in front. Matters get worse if the prosthetic terminal device carries a load. A prosthesis that solves this problem must compensate for the gravitational torque generated by the prosthesis itself so that all user generated torque can be used to position the prosthesis and to support the terminal device load.

Identifying the Problem
The problem became obvious when attempting to fit the two short transhumeral amputees shown above. While the amputee on the right has been lost to follow up, the one on the left has received several advanced sockets from Next Step in Manchester NH. He has a full range of motion without his prosthesis, but even with improved interface designs, he still has difficulty holding the prosthesis out in front at an angle sufficient to do useful work. As a manual worker, this is precisely what he needs. The compensation mechanism discussed in this paper has evolved since meeting this patient in 2006.

ONE INTERFACE FOR STABILITY AND ONE FOR CONTROL AND POSITIONING
The user’s stabilization and suspension interface is a modification of the X-frame used for most shoulder disarticulations. The center of the X is moved down to accommodate the user’s remaining arm making the frame look like a giant U-shape with the contacting arms wrapping around front and back. The four contact surfaces are located for maximum stability while still permitting the user full motion of the shoulder and arm.

The user’s primary control interface is a short socket without the long stabilizing wings present on most transhumeral sockets. The exact shape of the new socket must be optimized for maximum production of flexion-extension and abduction-adduction torques. With a fleshy limb, a uniform cylinder couples these motions to the prosthesis only poorly. Randall Alley, CP and Matthew Albuquerque, CPO have made several sockets of advanced design for such patients to improved coupling between the humerus and the socket during motion. These advanced shapes without the stabilizing wings are ideal for a prosthesis with compensation.
The Two Sockets Are Joined by a Three-Element Two-Axis Bearing Mechanism

The first element is a thin but large-diameter flexion-extension bearing attaching to the humeral socket on the lateral side as close to the side of the arm as possible. To enable the amputee to flex and extend naturally, the axis of rotation of this joint must pass through the center of the humeral head. In the model in figure 2, the flexion-extension bearing is shown on the right with the strut that joins the humeral control socket below it. To fulfill the closeness constraint, the joint must be as thin as possible. The one discussed here is only 11mm thick. And it must permit the user to extend the arm 15° rearward and to forward flex 175°. The user’s anatomy makes it probable that the plane of the flexion joint will be rotated forward of the sagittal plane by 20° (See figure 5).

The second element is a wide flat strut bent to follow the curvature of the user’s shoulder. It mounts both the flexion and abduction bearings. As long as this strut is subjected to simple bends without any twist, the axes of rotation of the joints will pass through a common center. (See figure 4.) This strut must be adjusted to fit the user so that the common center also passes through the center of the humeral head. The angle between the two axes will typically be 80° to 90°.

The third element is the abduction bearing on the left. Typically it will be similar to the flexion bearing. The fixed part of the bearing attaches to the X-frame, while the movable part attaches to the strut. The constraints on the abduction joint are that it be as close to the user’s back as possible and that the axis of rotation must pass through the center of the humeral head.

DESIGN OF THE BEARINGS TO ACCOMMODATE REMOTE COMPENSATION

Since there is no practical way to compensate for large gravitational torques in a thin bearing assembly, the compensation forces must be applied to one element of the bearing by a remote mechanism. Solid linkages can do the job, but a cable is simpler. Consider the image in figure 3. A ring with a pulley groove and the plate above it trap the outer race of the main ball bearing. For the flexion joint, this plate is part of the strut joining the two bearings. The inner race and

Figure 2. The bearing assembly elements are two flat, thin bearings and the cross-strut that joins them. This configuration is for a right shoulder. The left bearing is affixed to the frame and is the abduction joint, while the right bearing is for flexion.

Figure 3. The flexion bearing showing a cable in the pulley groove of the large-diameter outer race. An idler pulley redirects the cable to pass down the thin strut on the right into the arm. This strut attaches to the compensator below the remaining limb.
the remaining elements are attached to the humeral socket by the arm on the right. The allimportant compensation cable passes around the large pulley groove until it is redirected by the small pulley associated with the second ball bearing. The other end of the cable is attached to the compensation mechanism in the arm distal to the user’s remaining limb. While figures 2 and 4 show an adduction bearing identical to the flexion bearing, the final design will offer a free swing joint without the “handle”. It should be apparent that there is little room on the back of the X-frame for a compensation mechanism.

Figure 4. The two bearings are joined so that the axes cross. The cross point must also pass through the center of the humeral head

Figure 5. The glenohumeral head of a left arm is viewed in cross section from above. The joint location favors flexion about an axis that is tilted forward about 30°.

THE COMPENSATION MECHANISM

There are a number of constraints on the size and shape of the compensation mechanism. In the flexion case, it must be located distal to the user’s residual limb or be sufficiently thin to fit along the lateral wall of the control interface between the inner and outer walls. Likewise, the adjustable-length strut that attaches the bearing to the compensator must be as thin as possible, and the mechanism should be as small as possible. Finally the compensation itself must vary with the angle of flexion with no compensation at full extension and a maximum at 90° of flexion. The maximum torque should be adjustable to accommodate users with varying arm lengths and types of prosthetic components.

Prototype LTI Compensation Mechanism

The bearings and compensators were developed together. Once a cable had been selected to link the two mechanisms together, it was obvious that the compensator should have a pulley the same diameter as the pulley in the bearing assembly. The bearing pulley requires a tangential force that is zero at full flexion and maximum at 90°. This then becomes the requirement for the compensator pulley. The ideal tangential force follows the sine function, and there are a number of classic mechanisms that can approximate this force. Figure 6 shows the prototype compensator which uses a gas strut to generate the required force. Gas struts are widely used to compensate for the weight of automobile hatch backs. To generate an ideal force, the gas strut should be long compared to the diameter of the pulley. In a prosthetic application an approximation of the sine function is good enough. The strut in figures 6-8 is short which causes
maximum compensation to occur at 105° rather than 90°. This is not a problem since the user can still generate considerable force with the short remaining limb. An important variable is the maximum torque. The gas struts are available in three force levels 200, 300, and 400N. By attaching the output of the strut to the pulley at three different radii, a total of nine equally divided force levels can be generated.

Problems with the Prototype

The prototype in figure 6 has worked for testing the concepts behind the design, but there has been a practical problem — the 400N force from the maximum force strut put too much cross torque on the pulley bearing. A redesign with a large diameter ball race will solve that problem. The other bearings will require attention too. Finally a thin molded cover will make it easier for technicians to mount the assembly in the arm.

Figure 6. The gas strut is shown in the position of maximum tangential force. The cable from the bearing parallels the long axis of the assembly. The two marks show the location of the maximum force position of the pulley. Note that two thinner marks for zero compensation are on a line about 15° from line between the pulley and strut axes.

Figure 7. The fully extended strut produces no tangential force. The angle between this position and that of full force is about 105° not 90°.

Figure 8. An extra 15° before hitting a limit stop facilitates free swing and tasks requiring extension. Note the two extra holes for the end of the strut.