IMPROVED COMPENSATION OF GRAVITATIONAL TORQUE AT THE SHOULDER

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A simple analysis of prosthetic shoulders reveals that they are mainly used to position the orientation of the elbow in relatively few fixed positions. For some tasks the elbow needs to be positioned forward of the shoulder (Forward flexion). For desk and table tasks the preferred positions are both forward and out (flexion and abduction). For a few tasks straight out angles are appropriate (abduction). What all of these positions have in common is the need to compensate for the gravitational load of the prosthesis as the angle with respect to the vertical is increased.

The paper on the Z-axis shoulder joint [1] shows that by first moving away from the vertical in the abduction direction one need only provide one strong locking joint to take care of the gravitational load. However, the amputee still requires considerable effort to move the arm out, and the lock mechanism must be made stronger to accommodate the load. These two problems can be addressed by compensating for all or part of the gravitational load.

THE COMPENSATION PROBLEM

Once the compensation problem has been limited to motion about a single axis, it has a simple mechanical solution. Consider a bar hinged about an axis through point P (Fig. 1). The bar has been moved out away from vertical an angle φ. Regardless of how complex the prosthesis may be it can be modeled as such a bar with all the mass m concentrated at the center of mass. The force due to this mass is shown as a vector W=mg (weight W = m times g the gravitational acceleration). If the center of mass is a distance L from the pivot, then the torque due to the weight is $T = WL \sin \varphi$. To counteract this torque, a torque must be generated that also contains a $\sin \varphi$ term in its defining equation.

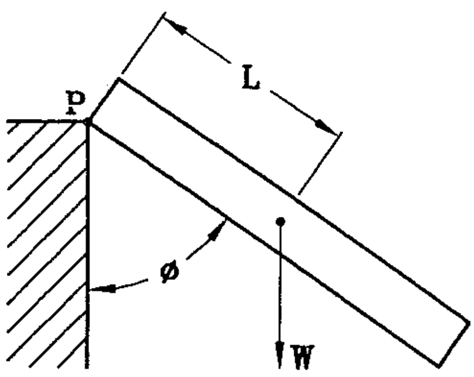

Fig. I. The arm modeled as a bar

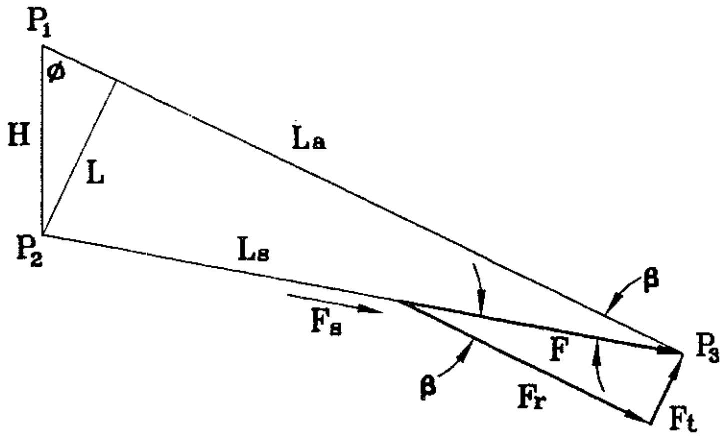

Fig. 2. Geometry of the spring compensated joint.

There is a simple scheme for generating such a counteracting torque. It consists of two hinges aligned vertically with the axes passing through P_1 and P_2 (Fig. 2). The upper arm member is a bar with a third hinge point P_3 some distance L_a out along the bar. Between P_2 and P_3 there is a compression spring of variable length L_s. In the general case, the arm is elevated an angle φ.

To establish the sine relationship note that the angle between L_a and L_s is β. The Force F due to the spring can be resolved into two vectors, one radial or parallel and one perpendicular or tangential to the arm. Only F_t the tangential force can cause a torque about P_1. What is the relationship of F_t to φ?

In the general case this relationship is not simple, but when L_a and L_s are much greater than H, the distance between P_1 and P_2, the problem can be simplified. To find this relationship, note that by constructing an auxiliary line L two similar triangles can be created. The first is a length triangle with sides L, L_s, and $(L_a - \Delta)$. The second is a force vector triangle. Here the spring force F is applied at P_3 where the force is resolved into F_t the tangential component and a radial component which only acts on the constraint of the hinge. Both of these similar triangles share angle β.

From the force triangle

$$\sin \beta = F_t/F. \qquad (1)$$

and from the length triangle

$$\sin \beta = L/L_s. \qquad (2)$$

By equating the sin β terms

$$F_t = FL/L_s \qquad (3)$$

From the auxilliary triangle

$$L = H \sin \varphi, \qquad (4)$$

so that substitution for L gives

$$F_t = \frac{FH\sin\varphi}{L_s} \qquad (5)$$

There is still a variable quantity in equation (5). L_s varies from greater than L_a at $\varphi = 90°$ to $L_a - H$ at $\varphi = 0°$. Thus our relationship is only approximately correct. Further, the spring force F is not constant. It is slightly greater at $\varphi = 0°$. For practical purposes the compensation will be quite good, however, and substantially better than no compensation.

THE PROTOTYPE MECHANISM

Selecting the compensating gas spring. At present the most popular powered elbow systems use an Otto Bock hand with a Boston or Utah elbow. In either case with a typical adult, the elbow weight is 2 lb. at one foot and the hand weight is 1 lb. at two feet. The total torque to be compensated is thus 4 ft-lb. or 48 in-lb or 5.4 Nm. It is mechanically convenient to have the moment arm at 90° be 1.0 inch plus or minus a quarter inch (26 ± 7 mm). Since some people will be bigger or smaller than average, we selected a 49 lb. (218 N) nominal gas strut to achieve approximately the correct values. The spring selected is lockable, a desirable feature, and is supplied by Bansbach [2]. The actual measured values are 55.1 lb. (245 N) compressed and 42.8 (190 N) extended. Measuring between the pivot points the spring is 7.25 in. (184 mm) fully extended and it compresses 1.3 inches (33 mm).

Design of the mechanism. Since our prototype wraps some parts around others in a way that obscures operation we show here a simplified view (Fig. 3). This drawing does not address the Z-axis motion which can be seen in the second drawing (Fig. 4). The gas strut is free to move whenever a small rod inside the main push rod is pushed upward. The mechanism for doing this is not shown but can be a Bowden cable or an electric actuator. Since this rod acts against the gas inside the cylinder, a large force is required and a bias spring is required to make operation easier. Also not shown is the Z-axis rotation lock. It is a variation on a Steeper design with a new activation principle to double the number of lock positions. This permits locking at 9° intervals.

How good is the compensation. To study how well the compensation will work, a set of calculations were done with the geometry determining all values including the length of the spring. This length was then used to calculate the spring force. The calculations were done for three values of the distance H, .75, 1.0, and 1.25 inches (19.1, 25.4, and 31.8) (Fig. 5). In all cases there is too much compensation at small abduction angles and to little at larger angles. The graphs were normalized at 60°. At low angles the compensation is off by about 12% and at high values from -5 to -16%. This is quite adequate.

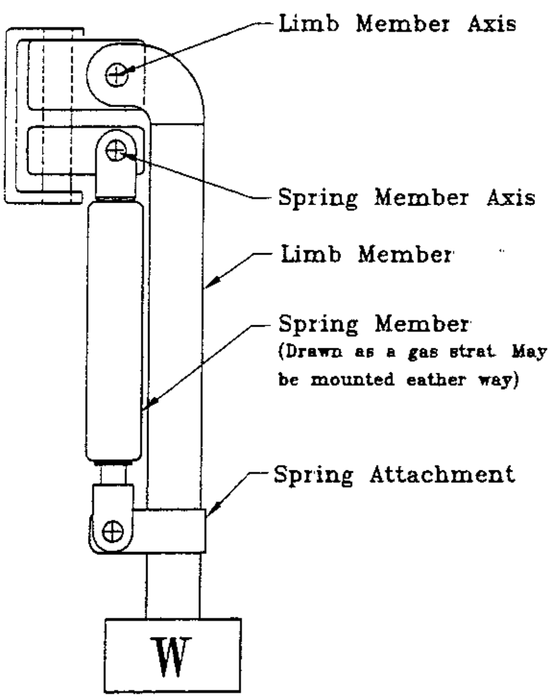

Fig. 3. For proper compensation the three pivots must be aligned vertically. The spring axis is adjustable up and down, but the attachment to the arm is fixed.

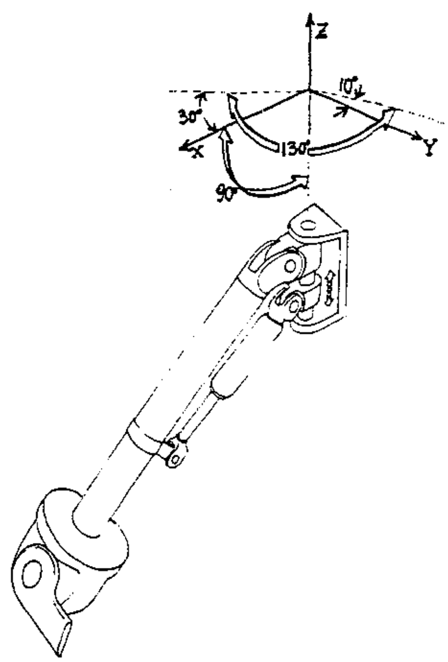

Fig. 4. The prototype can rotate inward about the Z-axis 100° and backward 30°. The Z-axis lock is not shown.

THE SELF-POSITIONING SHOULDER

Consider an amputee with a fully extended arm. The elbow axis is aligned so the forearm will flex forward. As stated before, this combination requires about 4 ft-lb. of compensation in the abduction or outward direction with the arm extended. Flexion of the elbow, however, reduces the moment about the shoulder from 4 to 3 ft-lb. Thus, using a powered elbow an amputee can reposition the outward orientation of the upper arm without using any mechanical force whatsoever. It is merely necessary to unlock the shoulder and to move the elbow joint.

The aim of this research has been to provide an easy way for the shoulder amputee to reach the position of function for eating and desk work. The compensating shoulder joint looks like it will enable the user to reposition with no use of the furniture and with very little body english.

REFERENCES

[1] **Williams, T. Walley, III,** *"The Z-axis shoulder joint — a new concept"*, Proceedings 1997 Myoelectric Controls Seminar Univ. of New B runswick.

[2] Bansbach North America, Melbourne, FL 32934 (Fx 407-253-5546) Model KOA1K-2-032-177/218N.

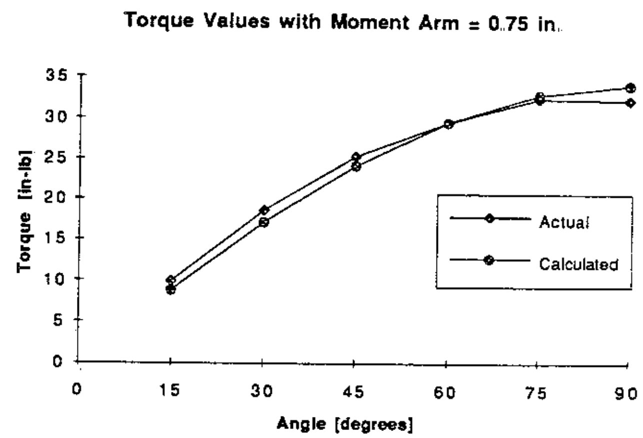

Fig. 5. The sine-of-the-angle correction is better when H is only .75 in. (19 mm), but is still good at larger values. The fall off at higher angles is also unimportant, since these angles are rarely used by amputees.