COMPUTER-AIDED DESIGN OF POLYCENTRIC KNEE MECHANISMS

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ABSTRACT: The purpose of the paper is to relate in capsule form the present status of a research and development effort on polycentric knee mechanisms for above knee (thigh) and through knee amputees. The method employs a mathematical model of a four bar mechanism which is optimized by a rotation of co-ordinates technique on a digital computer. The optimization is based on a predetermined criterion function which in turn is dependent upon the requirements and restraints of a specific mechanism.

INTRODUCTION: The knee joint in a standard artificial limb is traditionally of the single axis type which, in the past, has provided acceptable function for many thigh amputees. In this design, knee stability during weight bearing of the prosthesis is achieved by the positioning of the knee axis relative to the body-weight action line so that a locking moment at the knee is created. In addition, active hip extension supplements the contribution of the off-set knee joint to assure that the knee will not collapse during weight bearing.

However, this system unfortunately means that the amputee must walk over a fully extended (straight) knee during weight bearing which is physiologically abnormal and contributes to the unnatural appearing gait of the above knee (thigh) amputee. Further, when amputations are performed through the knee joint, the resulting long stump leaves insufficient space for the single axis knee mechanism. In this case, single axis side joints are required, resulting in greater fabrication time and an unattractive appearing finished appliance due to the excessive width of the knee.

These and other shortcomings of the single axis design have encouraged designers to seek alternative mechanisms for knee devices. From among several possibilities the four bar linkage, which yields polycentric action of the centre of knee rotation, was chosen for thorough investigation. A previous attempt [1] has been made at using the four bar linkage for a knee mechanism by first using an adjustable model to find the optimal linkage configuration. Due to the number of parameters involved this approach is most laborious and an optimized linkage has not materialized.

For our purposes a mathematical model of the linkage has been established and a Fortran IV computer program has been written so that computations associated with the optimizing technique could be carried out on a high speed digital computer.

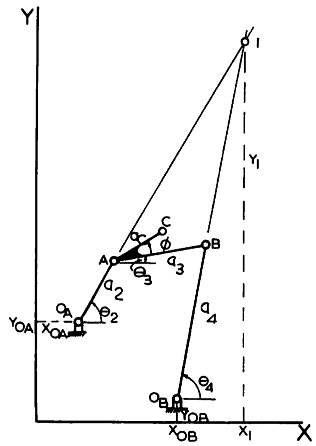

FIGURE 1

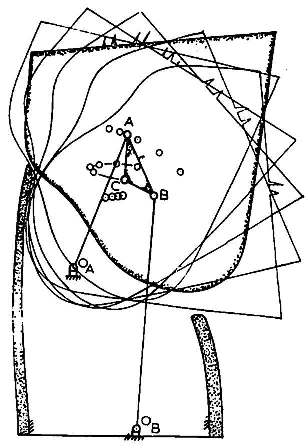

FIGURE 2

EQUATIONS OF MOTION: In developing the mathematical model, consider the four bar linkage shown in Figure 1. The angle of the links a_2, a_3 and a_4 are taken as θ_2, θ_3, θ_4 respectively. Equation for the X and Y co-ordinates of point B can be written in two ways:

$$X_B = X_{OB} + a_4 \cos\theta_4 = X_{OA} + a_2 \cos\theta_2 + a_3 \cos\theta_3$$

$$X_B = Y_{OB} + a_4 \sin\theta_4 = Y_{OA} + a_2 \sin\theta_2 + a_3 \sin\theta$$

Consider that all the link lengths and coupler angle, θ_3, (knee flexion angle) are known. With sufficient mathematical manipulation (*), the values of θ_4 can be determined. Knowing θ_3 and θ_4, the co-ordinates of points A and B can also be determined. Knowing co-ordinates of A and O_A the angle θ_2 can be computed from the following equation:

$$\theta_2 = \tan^{-1} \frac{Y_A - Y_{OA}}{X_A - X_{OA}}$$

* The missing details on the mathematics are available from the authors (4).

From the co-ordinates of the crank centres and crank angles the co-ordinates of instant centres I can be found;

$$Y_I = \frac{Y_{OB} + \left(X_{OA} - X_{OB} - \dfrac{Y_{OA}}{\operatorname{Tan}\Theta_2}\right) \tan\Theta_4}{1 - \dfrac{\tan\Theta_4}{\tan\Theta_2}}$$

$$X_I = X_{OA} + \frac{Y_I - Y_{OA}}{\tan\Theta_2}$$

Also the co-ordinates of any point on the coupler such as C can be determined from the equations;

$$X_C = X_A + AC \cos \Theta_C, \qquad Y_C = Y_A + AC \sin \Theta_C$$

The above equations permit the computerized analysis of the four bar linkage. Positions of the instant centres for various coupler (knee angles) and the displacements of the coupler point such as C are computed.

Establishment of the mathematical model of the four bar linkage in equation form means that the linkage, whose configuration is simply a reasonable guess, may be rotated through the various positions of knee flexion for purposes of analyzing the instant centres (centrode). Motions of the instant centres of the "guessed" linkage can now be compared to those which are desired by a criterion function and the linkage parameters systematically adjusted until the criterion function is either minimized or brought within desired limits. The criterion function is in turn based mainly on how close the output from the "guessed" mechanism approaches that of the "desired". Also, consideration is given in the criterion function to the horizontal and vertical displacements of a point on the coupler, as these factors have a bearing on the cosmetic result. The method used for optimizing the linkage was by Rosenbrook's Method[2] of rotating co-ordinates using a modified computer sub-routine ROTATE[3].

Two example linkage configurations, one for the thigh and the other for a through knee case, were optimized using the above process. Figure 2 illustrates an early result showing the linkage configuration and the knee block contour which yields a consistent clearance gap between the knee block and the shank, as the knee is rotated from the standing to sitting positions.

CONCLUSIONS: A computerized optimizing technique has been developed which may be used as a design tool for the purpose of optimizing a four bar mechanism. Two example trials have been carried out, on knee mechanisms, however, a suitable linkage configuration has not yet been arrived at for the two above mentioned levels of amputation. Further work is continuing in an attempt to arrive at linkages yielding acceptable function in terms of stability and acceptable cosmetic effect. Once a suitable configuration has been obtained, a prototype knee unit will be fabricated and evaluated on amputees. Further development will include a swing phase control unit at the knee in order to dampen undesirable inertia forces of the swinging shank.

The application of the developed four bar optimizing technique is not limited only to problems involving knee linkage design but may generally be applied to four bar problems in which a known desired coupler output can be specified to which a reasonable first guess can be made. The developed model and program complete with flow diagrams can be made available by the authors[4] for those wishing to extend the application of this linkage synthesizing technique.

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