Evaluation of the Polycentric above Knee Prosthesis

S.S. Chauhan, S.C. Bhaduri

Abstract

The optimal design of human lower limb prostheses, in particular of knee devices, is fundamental in order to restore the lost functionality and aesthetic aspect of the amputee's locomotion. Among all knee devices, the four-bar linkage is still the most widespread mechanism, since, despite its simplicity, it allows the prosthesis to be sufficiently stable and, at the same time, to replicate the natural motion of the joint with a sufficient accuracy. This paper presents an optimization procedure for the synthesis of a four-bar linkage for knee prosthesis. Starting from an experimental reference motion and given some patient-specific requirements related to his capacity to control and to stabilize the prosthesis, the procedure identifies the four-bar linkage that best-fits the experimental motion, at the same time respecting the given specifications. During optimization procedure a set of four bar knee configurations are evaluated to allow a more normal gait to be achieved. Geometry of these new designs increases stability while allowing swing flexion, thereby rendering a locking feature unnecessary. Simulation shows that increase in instant center will be apple advantage for the user and also minimize the energy consumption. Extra toe clearance as compared to single axis knee is also providing a more natural gait.

Keywords: Gait Cycle, Optimization, four-bar synthesis, knee prosthesis, four-bar centrode

1. Introduction

The knee joint in a standard artificial limb is traditionally of the single-axis type which in the past provided an acceptable function for many amputees. In this design, knee stability during weight-bearing is achieved by positioning the knee axis in such a way relative to the body-weight action line when the knee is extended [1]. In addition, a moment from active hip extension muscles is required during the weight-bearing phase of the walking cycle. Single axis knee mechanisms are relatively inexpensive and simple to manufacture but provide limited stability because of the fixed knee centre. Since the centre of rotation of the knee joint in a normal person is not a fixed point but move relative to thigh during walking [2], the prosthesis with fixed single axis could not provide the natural pattern of walking. Therefore a polycentric knee mechanism can solve the problem of art. In a polycentric knee mechanism, the knee centre is the instant centre (IC) of rotation of the thigh relative to the shank and this changes its position as the knee flexion changes. The knee stability is controlled by the location of the knee centre providing better voluntary control than a single axis knee with or without a brake [3]. The ability of the person to

S.S. Chauhan , Mech. Engg Department, IEC College of Engineering and Technology, Greater Noida
sschauhan3456@gmail.com
S.C. Bhaduri , Mech. Engg Department, Global Institute of Technology of Technology, Jaipur
shishirbhaduri@lycos.com

control knee stability is influenced by the height of the instant centre of knee rotation above the floor [3]. A high knee centre provides improved leverage for the voluntary control of knee stability. Single axis knees cannot make practical use of this fact because any significant change in the vertical position of the knee joint is cosmetically unacceptable. Michael JW [4] described that four-bar linkage knees provide greater toe clearance daring the swing phase of walking than do single-axis knees. The design negated the need for a joint lock thereby increasing the functionality & mechanical advantage of the artificial knee joint and consequently increases the efficiency of the prosthesis and decreasing the energy requirement for the amputee patient. The reintroduction of the lock in a polycentric four bar knee defeats the original concept of the joint [5]. The goal of this work is to design polycentric knee mechanisms to replace the locked knee. The new design aims to enable a more normal gait by allowing swing flexion without compromising the stability the user needs during weight bearing. Previous study on motion analysis has been also validating the design of Knee prosthesis. [6,7]

2. Methodology

In this design, knee stability during weight-bearing is achieved by positioning the knee axis in such a way relative to the body-weight action line that knee is extended. In addition, a moment from active hip extension muscles is required during the weight-bearing phase of the walking cycle. From the biomechanics and knee stability equation of polycentric knee mechanism [3], the instant centre curve traced by the mechanism should have the following characteristics. 1) During early stance it should be high to decrease the effort required from the hip muscles, 2) it should be well behind the hip-heel load line during early stance, 3) the curve should be behind the load line for about 15-20 degrees of knee flexion, 4) the instant centre curve should be continuous.

3. Design Equations

For synthesis purpose of four bar linkage mechanism as knee joint the shank will be considered as being the frame and the knee block as being the coupler(Figure 1) as presented by Hobson, D.A [8]. A reference line coordinate system is drawn at any convenient point in the frame link. The crank pins A and B on the knee block rotate about their crank centers O_A and O_B respectively. The link $O_A A$ is taken to be link 2, the coupler AB is link 3. And the second crank $O_B B$ is link 4, each with respective lengths L_2, L_3, L_4 and respective angles θ_2, θ_3 and θ_4. The angle of each link is measured in a counterclockwise sense from the positive direction of the x-axis. The loop equations for the coordinates of B are written in the counterclockwise and clockwise sense as follows:

$$X_B = X_{OB} + L_4 \cos\theta_4$$
$$= X_{OA} + L_2 \cos\theta_2 + L_3 \cos\theta_3 \quad (1)$$
$$Y_B = Y_{OB} + L_4 \sin\theta_4$$
$$= Y_{OA} + L_2 \sin\theta_2 + L_3 \sin\theta_3 \quad (2)$$

In this application, the input is through the knee block (the coupler). So the independent variable is taken to be θ_3. Equations1 and 2 are rewritten with one dependent variable. θ_2, to the left of the equality and with the remaining quantities on the right.

$L_2 \text{ Cos } \theta_2 = L_4 \text{ Cos } \theta_4 + C_1$ (3)

$L_2 \text{ Sin } \theta_2 = L_4 \text{ Sin } \theta_4 + C_2$ (4)

Where,

$C_1 = X_{OB} — X_{OA} — L_3 \text{ Cos } \theta_3,$ (5)

$C_2 = Y_{OB} — Y_{OA} — L_3 \text{ Sin } \theta_3$ (6)

These are both constants for any input angle θ_3.

Equations 3 and 4 are squared and added to yield equation 7,

$L_2^{\ 2} = L_4^2 + C_1^2 + C_2^2 + 2C_1L_4 \text{ Cos } \theta_4 + 2\, C_2\, L_4 \text{ Sin } \theta_4$ (7)

After rearranging and collecting terms, this results in the equation of motion:

$A \text{ Sin } \theta_4 + B \text{ Cos } \theta_4 = C,$ (8)

Where;

$A = 2\, C_2L_4,$ (9)

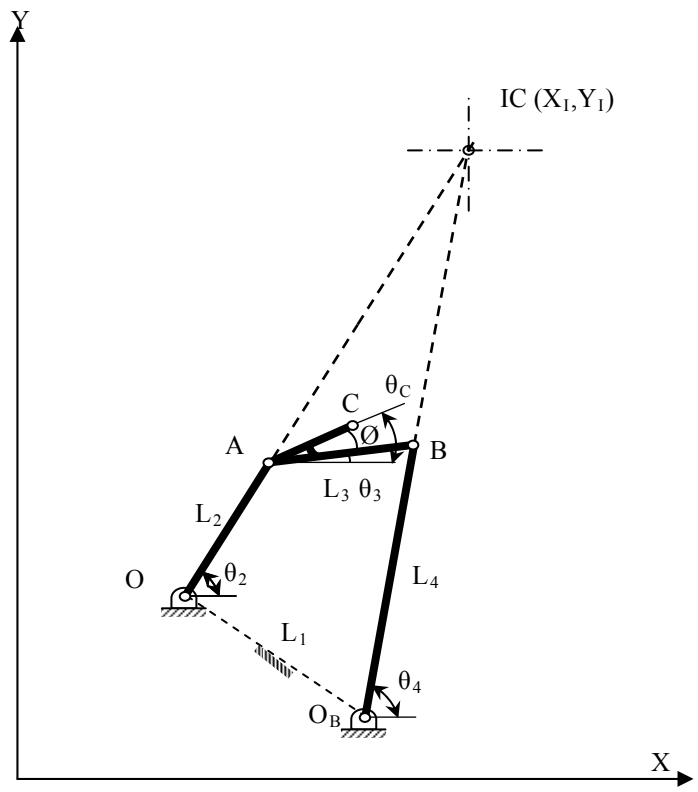


Figure 1: Configuration of a four-bar linkage with coupler point CP

$B = 2C_1L_4$, (10)
$C = L_2^2 - L_4^2 - C_1^2 - C_2^2$, (11)
These are constants for any input value of θ_3, and C_1 and C_2 are defined in equations 5 and 6. Equation 8 is of little direct use because it is an implicit transcendental function of θ_4. This is made an explicit equation by substituting:

$$Sin\theta_4 = \frac{2\tan\left(\frac{\theta_4}{2}\right)}{1+\tan^2\left(\frac{\theta_4}{2}\right)}, \qquad Cos\theta_4 = \frac{1-\tan^2\left(\frac{\theta_4}{2}\right)}{1+\tan^2\left(\frac{\theta_4}{2}\right)} \tag{12}$$

Equation 8 reduces to a quadratic in $\tan\left(\frac{\theta_4}{2}\right)$ with the solution:

$$\theta_4 = 2\tan^{-1}\frac{A \pm \sqrt{A^2 + B^2 - C^2}}{B + C} \tag{13}$$

Coordinates of point B and point A.

$X_B = X_{0B} + L_4 \cos\theta_4$ (14)
$Y_B = Y_{0B} + L_4 \sin\theta_4$ (15)
$X_A = X_B - L_3 \cos\theta_3$ (16)
$Y_A = Y_B - L_3 \sin\theta_3$ (17)

Knowing the coordinates of A and O_A, we can compute the angle θ_2.

$$\theta_2 = \tan^{-1}\frac{Y_A - Y_{OA}}{X_A - X_{OA}} \tag{18}$$

From the coordinates of the crank centers and the crank angles, the coordinates of the instant center, IC, can be found from the geometry of Figure 1. After reducing the equations, the x- and y- coordinates of the instant center are:

$$Y_I = \frac{Y_{OB} + \left(X_{OA} - X_{OB} - \frac{Y_{OA}}{\tan\theta_2}\right)\tan\theta_4}{1 - \frac{\tan\theta_4}{\tan\theta_2}} \tag{19}$$

And $X_I = X_{OA} + \frac{Y_I - y_{OA}}{\tan\theta_2}$ (20)

The coordinates of the coupler point (C) are given by equations as:

$$\theta_{CP} = \theta_3 + \phi \quad (21)$$

$$X_C = X_A + Lc \cos \theta c \quad (22)$$

$$Y_C = Y_A + Lc \sin \theta c \quad (23)$$

These equations define the motion of the mechanism and of any point, C, on the coupler. Using the equations 19 and 20, two approaches are used to develop the for-bar knee mechanism. First the graphical analysis is performed to determine and show pictorially what will be effect on instant center position when the lengths of the various link and the coupler angle were varied. Secondly, an optimization analysis is performed. Optimization is determining the maximum increase in the height of the instant center at stance phase subject to reasonable length limitations.

4. Optimization of Linkage

Designing a knee mechanism for a desired motion is being done using optimization [8,9,10,11]. The equations outlined in above section have been used in such a manner that a four-bar linkage can be analyzed. The position of the instant center is computed for various coupler angles and the displacements of a coupler point such as C are computed. The motions of the linkage can now be compared to the desired motion by some criterion function and a series of linkage parameters systematically adjusted until the criterion function is either minimized or within desired limits. The optimization problem is expressed in the subsequent paragraph:
The changing parameters must be observed and regional constraints applied such that the final mechanism conforms to them.

4.1 Objective function

The optimization problem minimizes the sum of squared distances between the ith experimental position of the reference point (X_{RCi}, Y_{RCi}) at the ith experimental flexion angle and the respective position of the coupler point C at the same flexion angle (X_{Ci}, Y_{Ci}) , computed according to the equations (22), (23).

$$V_F = \sum_{i=1}^{n} (f_i) + \sum_{i=1}^{n} \left[(X_{Ci} - X_{RCi})^2 + (Y_{Ci} - I_{RCi})^2 \right] \quad (24)$$

Where, f_i is a penalty value added to the criterion function, so that all ICR points remain inside the voluntary control zone.

4.2 Design variables and Constraint Functions

Referring to figure 1, eight parameters are required to vary. These are: X_{OA}, Y_{OA}, X_{0B}, Y_{OB}, L_2, L_3, L_4, and the starting value of θ_3. The mechanism constraint functions are referred to the constraints imposed on the geometry of the linkage and the shape of the centrode curve. First constraint incorporated in the

formulation is the regional constraint such that the linkage must always lie within the confines of the prosthesis and no link could be shorter than a predetermined length. A Grashoff criterion check was always made and only crank-type mechanisms were allowed (1 + s <p + q). In this way a solution was always guaranteed as the parameters were changed. The second constraint is the size constraint so that the mechanism is cosmetically acceptable. Therefore the average width of the knee (Posterior to interior) of the four bar mechanism should be less than or equal to 81.28 mm

i.e in figure1, $L_1 \leq 81.28$ mm

Height of the knee mechanism should be within the range i.e. one of the vertical link should not exceed to the average height of the anatomical knee joint.

i.e. $L_4 \leq 95$ mm

It was experienced with the use of graphical analysis that the IC of four bar mechanism will be high and retain their position up to 15-20 degree of knee flexion by maintaining some initial angle of the coupler link. For making the initial angle of coupler link it is necessary that L_2 should be less than L_4

i.e. $L_2 \leq L_4$

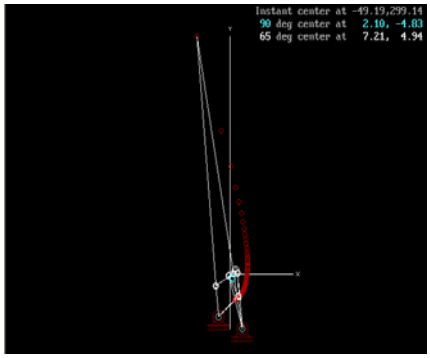
Initially the coupler angle is $\alpha = -25^0$ (-ve sign is taken for anticlockwise sense)

4.3 Selection of Linkage Dimensions

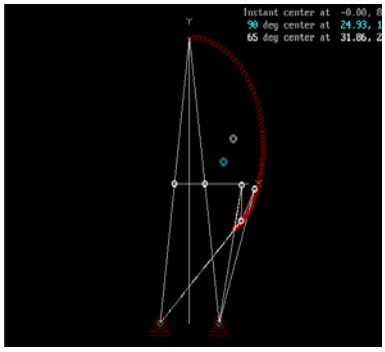
The position of instant centre of four bar linkage mechanism is governed by the design parameters of four bar mechanism as described in optimization procedure. Several trial dimensions are selected during optimization procedure and their initial values at the standing position of prosthesis are graphically determined. Out of various trials with corresponding dimensions are shown in table 1.

Table 1 Dimensions of linkages of four-bar linkage mechanism for different trails at standing posture of prosthesis

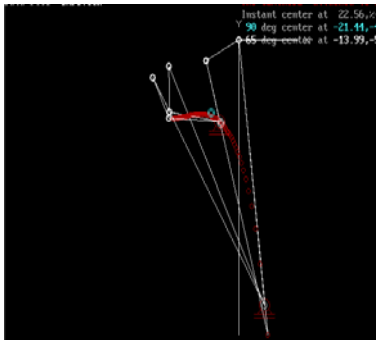
Design Parameters(mm)								
Trials	X_{OA}	Y_{OA}	X_{0B}	Y_{OB}	L_2	L_3	L_4	θ_3(deg.)
1	-17.5*	-54	17.5	-69	39.21	30.01	70.12	30
2	-25	-80	25	-80	80.15	23	82.96	0
3	-18	-50	20	-168	38	37	171	32
4	-20	-75	20	-55	66.06	29.58	56.29	17.6
5	-15	-48	15	-44	41	22.47	47.54	20.85
6	-13.5	-43	13.5	-49	28.07	23.05	50.33	40.6
7	-19.05	-75.57	19.05	-50.17	62.35	26.75	48.23	22.92
8	-35.19	-25.79	21.25	-58.27	35	17.67	90	25.11



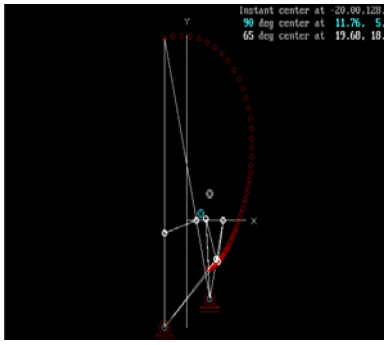
Type 1



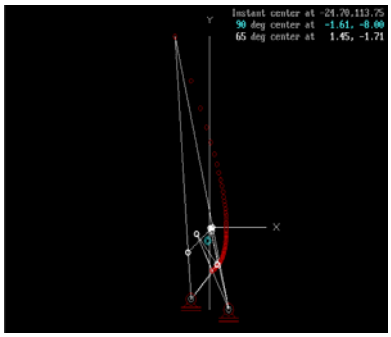
Type 2



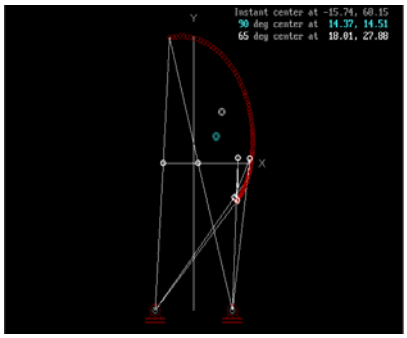
Type 3



Type 4

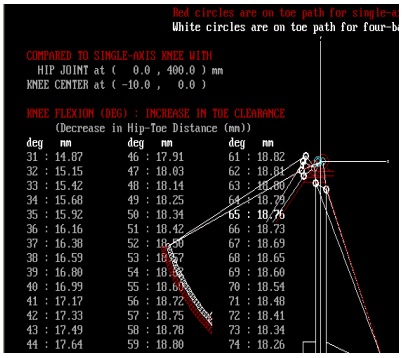


Type 5

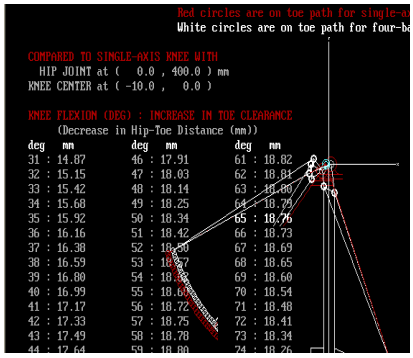


Type 6

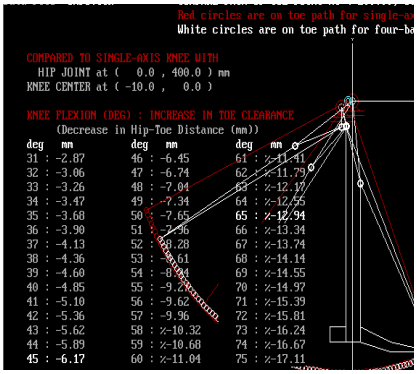
Figure 3. The centrode of the Knee mechanisms where the fixed reference is with respect to the shank.



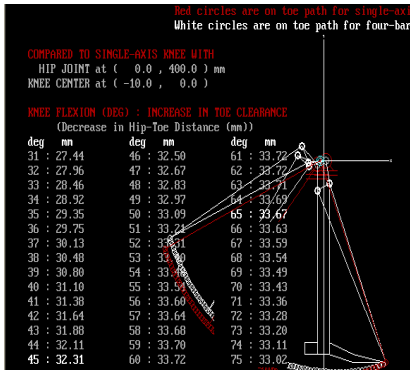
Type 1



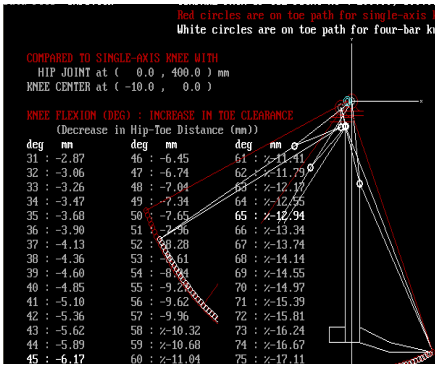
Type 2



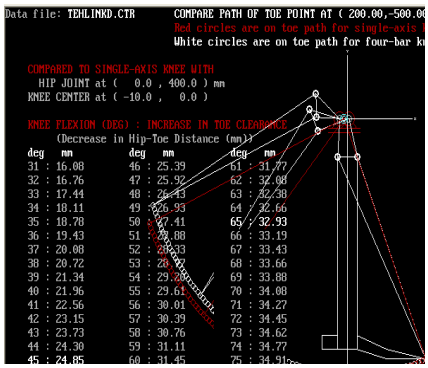
Type 3



Type 4



Type 5



Type 6

Figure 4. Toe Clearance Simulation of 4Bar Knee Prosthesis

5 Results and Discussions

An optimization procedure has been presented for the synthesis of a four-bar mechanism addressed to lower limb prostheses. The procedure makes it possible to synthesize a four bar mechanism which replicates the natural motion of the knee and, at the same time, provides the lower limb prosthesis with a requested level of stability and voluntary control. Total six knee configurations were evaluated during optimization procedure. Simulations of six configurations are presented in Figure 3 and 4. All configurations are suitable for walking with proper toe clearance and few configurations out of them some are capable for squatting posture. These configurations were analyzed with the use of the program developed by Professor Charles W. Redcliffe, University of California at Berkeley. This program can also compare properties between a standard single axis knee prosthesis and specific four-bar knee prosthesis. Figure 3 shows the curve path for the instant center (also known as the centrode of the four-bar) during flexion. This figure is found with respect to the shank as the fixed reference, and the shape of this centrode is helpful in gaining a general idea about the stability of the four-bar. The high instantaneous center in figure3 clearly shows less effort required from the hip muscles during early stance. The IC tends to remain behind the load line for several degrees of flexion and curve is also continues. Figure 4 offers a representation of the centrode with respect to the socket as the fixed reference and is useful for determining information about toe clearance. Minimum toe clearance was measured experimentally 2cm and maximum value is 20 cm for the group of normal subjects reported in previous study [6]. Winter [7] reported a mean minimum toe clearance of 1.29cm at knee flexion angle is 23^0 in their study. The configurations of four bar knees in figure 4 the least amount of toe clearance provided 1.2cm more clearance than the single axis knee. All of the four-bar knees provided more toe clearance than the reported amount for normal walking.

References

1 Radcliffe, C.W. and Lamoreux, L.W. UC-BL pneumatic swing phase control unit for above-knee prostheses: Design, adjustment, and installation. Bull.Prosth.Res. (1968) 10-10. 72-89.

2 Maquet Paul, G.I.: “Biomechanics of the knee” Springer-Verlag, berlin, (1976) PP.55.

3 Radcliffe CW. The Knud Jansen lecture: above-knee prosthetics. Prosthet Orthot Int 1977;146-160.

4 Michael JW. Prosthetic knee mechanisms. Phys Med Rehab 1994; 8:1:147-64.

5 De Vries. J. Conventional 4-bar linkage knee mechanisms: a strength-weakness analysis. J. of Rehab. R&D, 1995, 32(1): 36-42.

6 Chauhan SS, Bhaduri S C, “Kinematics and kinetics measurement of normal human locomotion through gait analysis-A Pilot Study” I. Journal of Medical Sciences and Technology (2009), Volume 2, Issue 2, Page(s): 29-36.

7 Winter DA. Foot trajectory in human gait: a precise and multifactorial motor control task. Phys Ther 1992; 72:1:55-66

8 Hobson, D.A., L.E. Torfason "Optimization of four-bar knee mechanisms - A computerized approach," Journal of Biomechanics, 7, 371-376 (1974).
9 Hartenberg, R. and Denavit, J., "Kinematic synthesis of linkages," McGraw-Hill, 1964.
10 Winter, D.A., "Overall principle of lower limb support during stance phase of gait," in Journal of Biomechanics, 13, 923-927 (1980).
11 Dewen Jin, Ruihong Zhang, "Kinematic and dynamic performance of prosthetic knee joint are using six-bar mechanism" journal of rehabilitation and research and development, Vol. 40 Number 1, 2003, PP. 39-48