Analysis of Four-bar Linkages Suitable for Above-knee Prosthesis

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Analysis of Four-bar Linkages Suitable for Above-knee Prosthesis

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Abstract: Four-bar linkage above-knee prosthesis provide a greater toe clearance in the swing phase and stability in the stance phase in comparison to the single-axis knee joint. Just because of its simplicity, the four-bar linkage is still the most commonly preferred mechanism because it permits the prosthesis to be sufficiently stable and replicates the natural movement of the joint. The authors present a basic/simple kinematic model using a four-bar knee prosthesis. In all eight different configurations are evaluated and examined using a program with the use of the arrangement. These configurations of the four-bar linkage mechanism will enable the prosthetist to assess the mechanical advantage of different four-bar designs. Also, plots of the angle of flexion vs. increase of toe clearance of these eight configurations is provided to enable comparative advantage for the user. It was noticed that the entire length of the prosthesis gets shortened while moving from the extension to the flexion phase. This aspect minimizes energy consumption during the initial phase of motion. All configurations of four-bar knee linkages have been examined and the results show that they have nearly the same energy conservation.

Keywords: Four-bar linkage knee, Prosthesis, Amputation, mobility, Knee stability

1. Introduction

Many people in the world have lost their natural lower limbs due to some major disease or accident. This may result in a disturbed normal gait. To restore the mobility, a lower limb prosthesis is very suitable and is usually selected by the level of amputation. Mainly two types of amputation are commonly encountered; one is below-the-knee (B-K) amputation and the second is above the knee (A-K) amputation or transfemoral amputation. Transfemoral amputation is one of the common types of lower limb amputations and involves the femur. In case an amputee has to apply a force with his/her residual limb to initiate the motion and control it the entire prosthesis is involved in the process. On the cantrary, in the case of a below-knee prosthesis, there is no problem in the design. However, in the above-knee prosthesis, the designer has to consider a more complicated joint, where enough care is required to ensure stability during the stance phase and toe clearance during the swing phase of the gait cycle, which are the two major criteria for the consideration [1]. In prosthesis industry two types of prosthesis are commonly available; one is the single-axis prosthesis and the other is polycentre Single-axis prosthesis[2]. The single-axis knee is used to support the residual limb but has a poor functional quality to satisfy normal walking[3-8]. Mostly, designers have considered four-bar linkage mechanisms for the knee joint to ensure stability in the stance phase and toe clearance in the swing phase of the normal gait in comparison to the single-axis knee[9, 10]. An amputee has a better voluntary control of the entire prosthesis while using a four-bar knee mechanism because of the change in the position of the instantaneous centre of rotation (IC). One of the major advantages of the four-bar mechanism is that an amputee has to apply less effort as compared to the single-axis knee to initiate the motion and control the motion in the stance phase. A polycentric knee can fulfill the requirements of an amputee, particularly extra toe clearance for uneven terrain, provided it is suitably designed.

Four bar linkage knee mechanism has to satisfy two functional requirements for the user; the first is the kinematic motion of the knee and the second is the position of the load line, and the mechanism must be taking care of these two requirements together [11]. However, an amputee with weak hip muscle can only maintain their stability during the stance phase by shifting the knee centre behind the load line. With the increase in flexion angle, the instantaneous centre of the four-bar linkage knee should quickly move downwards. It is reported that a higher knee center can give a good stability in the standing phase [12]. A person has to apply more effort to initiate the motion if the knee centre is low, which is so difficult for the person having weak muscles. The effect of design variables in lower limb prosthesis on normal gait was analyzed in detail [13]. With weak muscles, the higher the location of the instantaneous centre the lesser will be the effort required. A new four-bar knee prosthetic was developed by Jaipur artificial limb center, India [14]. An external four-bar knee prosthetic mechanism was also developed for persons having pelvic limb amputations to the transfemoral level [15]. It is reported that a six-bar linkage has more design flexibility and has more instant inactive joints resulting into zero relative velocity as compared to a four-bar linkage, thus a six-bar linkage knee is found to be more stable in the stance phase of the walking cycle [16]. Redcliff investigated the knee stability during the stance phase of the gait and derived the stability equation for a four-bar mechanism [17]. A four-bar knee model was developed with the application of a magneto-rheological (MR) damper for the use of the A-K Prosthesis [18]. It is investigated that there is a correlation between ankle and hip joint range of motion if the knee joint is not functioning well due to knee osteoarthritis (OA) [19]. In such a case the walking patterns are adversely affected due to the affected limb. Still, the four-bar linkage knee mechanism is the first preference of many designers for above-knee joint prosthesis because of its simplicity and functional advantages. The different type of the four-bar mechanisms studied in this paper, namely, 3R32, 3R30, 3R46, 3R55, 3R70, 3R72, and Hosmer knee. The main objective of this study is to compare different four-bar configurations which are suitable for above-knee prostheses and to examine their performance on stability and toe clearance with the view to help decision making for the proper choice.

2. Methodology

2.1 General Concept

To analyze different types of four-bar configurations for the knee joint, some important parameters need to be understood. These parameters are well discussed in this study and also described in the literature. The selection of parameters for the designing of a four-bar knee mechanism is an open choice for the designers, and we have selected increasing the toe clearance during swing and knee stability during the stance phase of the walking cycle as the deciding criteria for choosing the mechanism. Knee stability during the stance phase of the walking cycle is derived by locating the knee center behind the load line (i.e. line joining hip to foot) and is based on the weight-bearing criterion when the knee is fully extended. In addition to that, an amputee applies hip extension moments with the help of a group of muscles to stabilize the joint.

The instantaneous centre curve traced for the mechanism should have the following characteristics as obtained from the biomechanics and knee stability equation of the polycentric knee mechanism [20].

a. Effort required from the hip muscles is reduced when the knee center is high during the early stance phase nearly about 15^0 of knee flexion.

b. The knee center should be well behind the load line during the initial stance phase.

c. The instantaneous center curve should be behind the load line and should be continuous for about 15^0 to 20^0 of knee flexion.

Lower limb knee prostheses should be so designed in such a way so that they can restore stability during walking and voluntary control of the prosthetic knee in the stance phase. Redcliffe [11] derived the Eq. 1 used for deciding the stability of the knee joint during the stance phase, Hip moment can be calculated to stabilize the joint by the following equations.

$$M_H = \frac{L}{Y}(PX - M_K) \quad (1)$$

In the above equation

M_H =Moment exerted by the muscles at hip joint.

M_K= Knee moment created by mechanical or hydraulic controller

L=the overall length of the prosthesis.

P= the load passing through the load line as shown in figure 1(a).

Y= the vertical height measured from the heel to the instantaneous centre.

X = the distance of the instant centre of the knee from the load line.

Therefore, in equation no 1 the knee stability is governed by three independently parameters: M_K, Y and X.

M_H can be reduced to zero if the mechanism is capable of developing a brake moment:

$$M_K = P.X \quad (2)$$

$$M_H = (P.L)\, X/Y \quad (3)$$

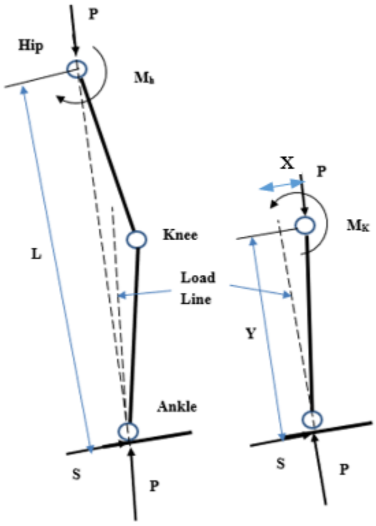


Fig. 1: Knee stability equation
(Where, K=either single axis or instant centre of four-bar linkage, S=Share force, P=Ground reaction force)

A four-bar linkage typically does not incorporate a brake mechanism hence the simplified eqn. 3 can be used in place of eqn. 1 to estimate the hip extension moment required as the position of the instant centre changes during heel contact and push up of the gait cycle.

A typical link arrangement of single axis is shown in fig.1 and four-bar knee is in fig 2. The stance and swing phase characteristics of the knee have been selected to compare the different four-bar configurations. The first parameter in the stance phases, the knee stability, is one of the important critical factors where a prosthesis user has to prevent any type of buckling. In Eq.3, the x/y ratio at the heel strike is an important parameter, which varies for different knee configurations. A negative heel strike ratio x/y results in an ample advantage for the user to control the knee without applying any hip moment, and is desirable. The second parameter is in the swing phase when the knee has to push off while a prosthesis using person has to apply a moment through the hip to shift the load line behind the instant centre of rotation. Further, from equation 3, if the x/y ratio is close to the load line then an easy push-off can be performed at this stage of walking. The third parameter the toe clearance, is to be maximized which again depends upon the configuration of the four-bar mechanism. To maximize toe clearance as the knee passes from flexion to extension, the overall length of the prosthesis will be shortened [10)]. It is not possible in the case of a single axis knee, while in a four-bar mechanism the striking length of the prosthesis decreases. Since an amputee consumes energy during walking, therefore the shortening of the prosthesis length results into minimization of the energy consumption during walking. The prosthesis designer has to consider this factor to reduce the unproductive effort applied by the user for the motion.

2.2 Kinematic arrangement of four-bar knee prosthesis:

Using a four-bar mechanism with elevated IC, a prosthetic knee has been designed for many years and is presented in figure 2. In this arrangement socket or thigh portion of the prosthesis is connected with the coupler of the four-bar mechanism, while the fixed link is connected to the shank [18)]. The other two moving links of the mechanism will be creating a polycentric movement of the knee joint. These links are called anterior and posterior links. It has been observed that the anterior link is long whereas the posterior link is short. The extended lines passing through anterior and posterior links intersect at a point which is known as IC. When the knee flexes this IC generates a curve that is called centrode. Many combinations of link lengths, pivot locations, and adjustment of extension stop can be taken to fulfill the functional requirements. Further, the lower limb prosthesis kinematics can be obtained by the combined motion of the hip joint and thigh motion. The load line passing through the hip joint and the ankle joint forms a significant line in the design. This line is also known as the load-bearing line and its direction and location can be measured with the help of force plate during walking. Its direction and location are constantly changing with respect to the axis of the prosthesis. The load line direction can be observed from the medial side for a trans-femoral amputee and is directly concerned with the prosthetic knee stability. The knee stability equation is derived in figure 1. An amputee can control the direction of the load line, which has been observed in the mediolateral view with the use of his active flexion-extension musculature about the hip joint of the residual stump. This is the leading the concept of the voluntary control of knee stability and forms the main interest of the polycentric prosthetic knee designers. The elevated IC improves the stability during the stance phase and allows an amputee to initiate the motion with less energy. Another requirement of the knee is a cosmetic appearance at 90^0 flexion. However, while sitting it is required to move the knee center quickly downward with knee flexion. The designer has to keep a consideration for the initial stance phase of the gait cycle, which is $10\text{-}15^0$ of initial knee flexion. After the stance phase, the amputee has to initiate the knee flexion in the swing phase of the gait and apply the hip moment to lift the prosthesis from the ground.

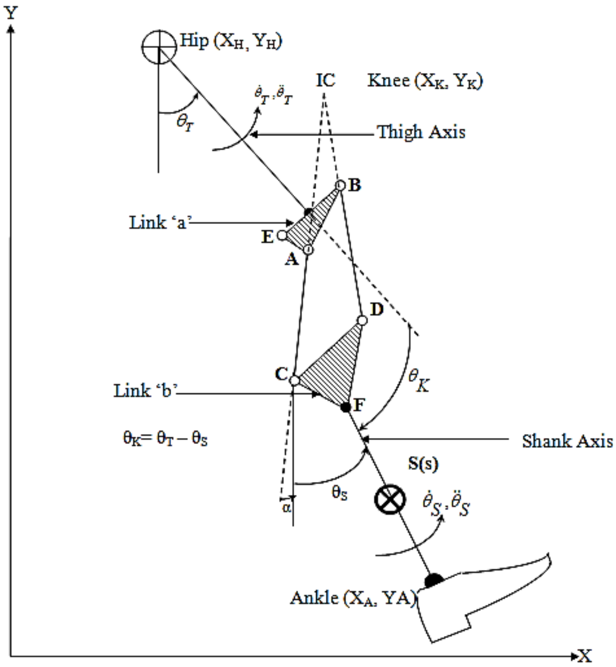


Fig. 2: Relative motion analysis of thigh and shank [18]

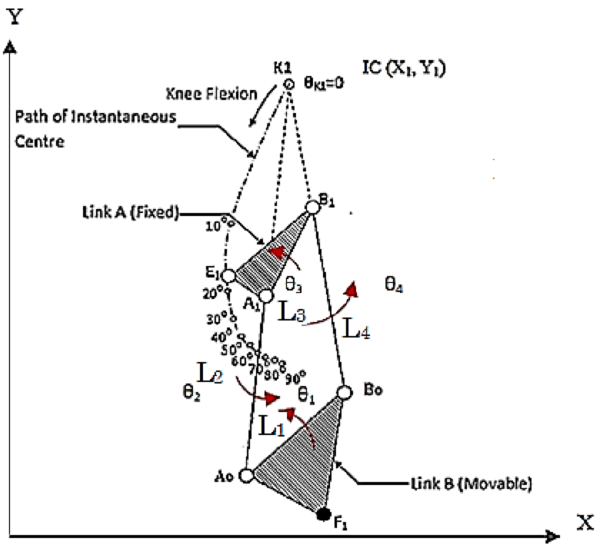


Fig. 3: Kinematic arrangement and path of instantaneous centre of the four-bar knee mechanism

2.3 Synthesis of the four-bar linkage

For synthesis purposes, an initial four-bar configuration suitable for the knee joint has been selected as shown in fig. 3. This configuration is just similar to the configuration used by Radcliffe [20] the shank is connected with the link CDF and the socket is connected with the coupler link ABE. In fig 3 a coordinate system is used as a reference line at any suitable location in the frame link. The knee block is connected with the coupler link via crankpins A_1 and B_1 on the knee. It rotates about crank centers Ao and Bo respectively. The link A_oA_1 is considered as link 2, the coupler A_1B_1 as link 3. The second crank B_oB_1 is considered as link 4. The links have respective lengths L_1, L_2, L_3, and L_4 and respective angles θ_1 θ_2, θ_3, and θ_4. The link angles are measured in a counterclockwise sense from the positive direction of the Y-axis. Each joint is represented in the X-Y frame by a vector containing its elements as shown in figure 2.

The loop closer equations for the coordinates of B_1 of four bar mechanism in the clockwise and counterclockwise sense are written as follows:

$$X_{B1} = X_{BO} + L_4 Cos\theta_4 = X_{AO} + L_2 Cos\theta_2 + L_3 Cos\theta_3 \quad (3)$$

$$Y_{B1} = Y_{BO} + L_4 \, Sin\, \theta_4 = Y_{AO} + L_2 Sin\theta_2 + L_3 Sin\theta_3 \quad (4)$$

In this application, through the knee block (ie coupler) the input is given. So that the coupler angle θ_3 is considered as independent variable. Therefore, Eq.3 and 4 are modified with one dependent variable θ_2, by taking to the left side; and the remaining parameters on the right side.

$$L_2 \, Cos\, \theta_2 = L_4 \, Cos\, \theta_4 + C_1 \quad (5)$$

$$L_2 \, Sin\, \theta_2 = L_4 \, Sin\, \theta_4 + C_2 \quad (6)$$

Where,

$$C_1 = X_{BO} - X_{AO} - L_3 \, Cos\, \theta_3,$$

$$C_2 = Y_{BO} - Y_{AO} - L_3 \, Sin\, \theta_3$$

For any input angle θ_3 these values are constants.Then, Squaring and adding Eq.5 and Eq. 6we get equation 7,

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

The equation of motion is obtained by rearranging and collecting these terms.

$$A \, Sin\, \theta_4 + B\, Cos\, \theta_4 = C, \quad (8)$$

Where;

$A = 2\, C_2L_4$,

$B = 2C_1L_4$,

$C = L_2^2 - L_4^2 - C_1^2 - C_2^2$

These are the constants for any input value of θ_3. Also, C_1 and C_2 are defined in eq. 5 and eq. 6.

Eq.8 is not of much direct use because it is contained moving function of θ_4. Following substitution is made to get definite equation:

$$Sin\theta_4 = \frac{2\tan\left(\frac{\theta_4}{2}\right)}{1+\tan^2\left(\frac{\theta_4}{2}\right)}, \quad Cos\theta_4 = \frac{1-\tan^2\left(\frac{\theta_4}{2}\right)}{1+\tan^2\left(\frac{\theta_4}{2}\right)} \quad (9)$$

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

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

At this moment, θ_3 has been stated and θ_4 has been calculated. The coordinates of point B_1 and point A_1 are determined as follows.

$$X_{B1} = X_{B1O} + L_4 \operatorname{Cos} \theta_4$$
$$Y_{B1} = Y_{B1O} + L_4 \operatorname{Sin} \theta_4$$
$$X_{A1} = X_{B1} - L_3 \operatorname{Cos} \theta_3$$
$$Y_{A1} = Y_{B1} - L_3 \operatorname{Sin} \theta_3$$

The angle θ_2 is computed by knowing the coordinates of A_1 and Ao.

$$\theta_2 = \tan^{-1}\frac{(Y_{A1} - Y_{AO})}{(X_{A1} - X_{AO})}$$

In figure 3 from the geometry of the four bars mechanism and the crank centers coordinates and the crank angles, the coordinates of the instant center, IC, can be evaluated. After rearranging the equations, the x- and y- coordinates of the instant center can be evaluated from Eq. 10 and Eq. 11 as given below:

$$Y_I = \frac{Y_{OB} + \left(x_{OA} - x_{OB} - \frac{Y_{OA}}{\tan\theta_2}\right)\tan\theta_4}{1-\frac{\tan\theta_4}{\tan\theta_2}} \quad (10)$$

And $x_I = x_{OA} + \frac{Y_I - y_{OA}}{\tan\theta_2}$ (11)

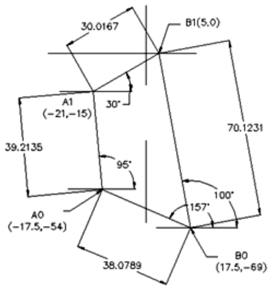
Further, a detailed synthesis procedure, as explained for the evaluation of a four-bar knee mechanism, was used for the four-bar linkage mechanism A-K knee prosthesis[21, 22]. Once the four-bar knee mechanism is designed kinematically, it should also be checked under its structural strength before its actual application to meet the ISO 10328 standards for load bearing.[23, 24]

3. Four-bar knee joint configurations

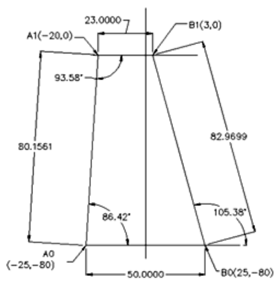
In the four-bar linkages configurations under study the position of IC was traced graphically by extending two vertical links and obtaining their intersection. Mathematically the position of IC can be easily determined with the help of eq. 10 and eq.11 for any type of four-bar mechanism. As the knee flexes the position of IC changes and it traces a curve as shown in fig.3. This curve called corrode, is very important to decide the stability, hip moment requirement, and speed of the shank in the walking cycle. Maximum knee flexion of the different commercially available knee joints is presented in Table 1 for comparison. Each knee mechanism has certain advantages depending upon its configuration and has improved knee stability against a single-axis knee without a knee break. Depending upon the requirement of the amputee and maximum knee flexion a suitable type of knee mechanism has been suggested.

Table 1. Maximum Knee Flexion of different four-bar linkage knee

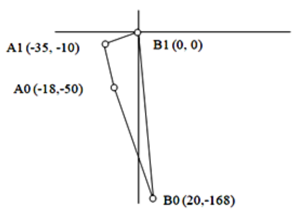
Types of Four-bar linkage knee	Description	Max. Knee Flexion
T1	3R32 Modular polycentric "Four-bar Knee"	110^0
T2	3R30 Modular polycentric "Four-bar Knee"	110^0
T3	3R46 Modular polycentric "Four-bar Knee"	110^0
T4	3R60 Modular EBS Knee with hydraulic swing phase Control	140^0
T5	3R55 Modular polycentric knee with hydraulic swing phase Control	112^0
T6	3R70 Modular Polycentric knee joint with pneumatic swing phase control	135^0
T7	3R72 Modular Polycentric knee joint with pneumatic swing phase control	140^0
T8	Hosmer Knee	155^0



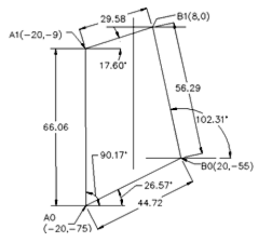
Type 1



Type2



Type3



Type 4

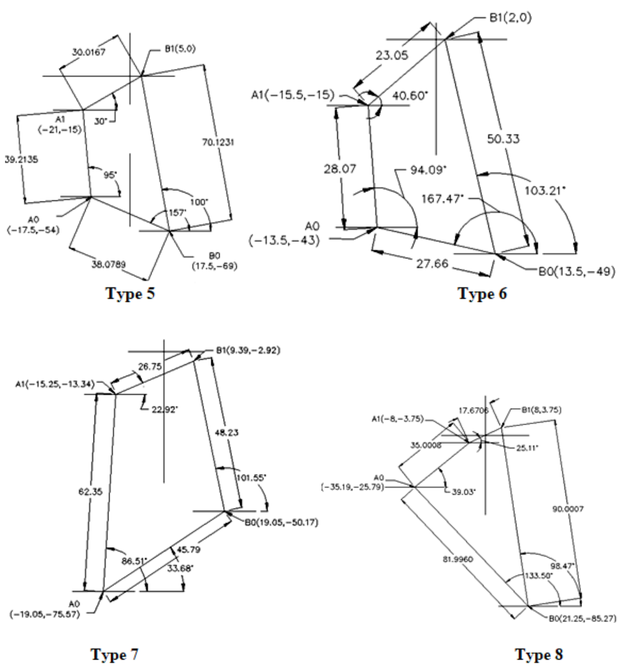


Fig. 4: Four-bar knee configurations

4. Results and discussion

4.1 Stability of four bar linkage knee in stance phase

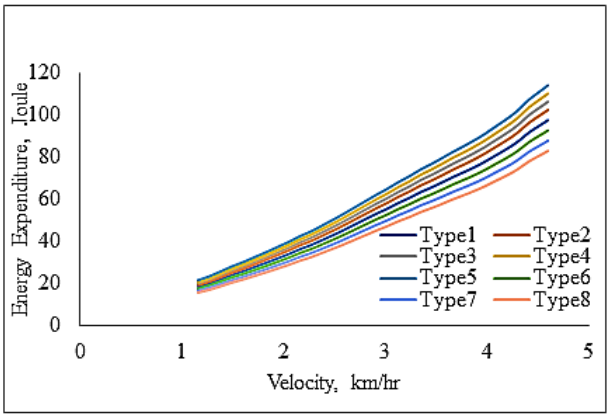
In the lower limb kinematic frame the hip, the heel, the toe, and the knee are taken as hip (0mm, 400mm), knee (-10mm, 0mm), heel (-50mm, -500mm), and toe (200mm, -500mm). Table 1 presents the position of the Instantaneous center of different four-bar linkage configurations in the mid-swing position i.e. 650 flexions and at 900 flexion to satisfy the sitting cosmetic appearance. It has been found that, the position of IC has to maintain the requirement as discussed earlier to ensure the stability criteria. Also, to maintain its cosmetic feature the knee centre moves quickly when the knee flexes towards the anatomical knee.

The results of Increased toe clearance (in mm) vs the angle of flexion (in degrees) of four-bar knee configurations are presented in figure 5. Using the program developed by Professor Charles W. Redcliffe, University of California at Berkeley, these configurations were analyzed. The centrode curve can be compared by using this program, and toe clearance between a specific four-bar and single-axis knee prosthesis. This graph offers a comparative representation of the toe clearance for the selection of a type of four-bar knee configuration. Through the software, the variation between the single axis and four-bar linkage knee was evaluated.

Table 2. Position of Instantaneous Centre (IC) of four bar knee configurations

Four Bar Knee Type	Instantaneous Centre Position (IC)					
	IC		At 90 degree flexion		At 65 degree flexion	
	X (mm)	Y (mm)	X (mm)	Y (mm)	X (mm)	Y (mm)
T1	-49.2	299	2.1	-4.83	7.21	4.94
T2	-0.00	-89.05	24.93	-13.22	31.86	27.42
T 3	22.56	-183.47	-21.44	-45.42	-13.99	-51.43
T4	-20.0	128.33	11.76	5.05	19.68	18.87
T 5	-53.6	123.85	0.07	5.82	3.60	6.85
T 6	-8.74	93.34	8.10	-2.39	13.65	8.17
T 7	-9.04	87.24	9.81	-2.17	15.92	8.88
T 8	7.27	8.63	1.77	-6.79	4.84	-4.70

In table 2 the position of the instantaneous centre is compared for all the eight knee configurations where a negative value represents the shortening of the leg length as compared to the single-axis knee prosthesis. The minimum toe clearance observes at 23^0 hip flexions and 49^0 knee flexion in the normal walking cycle. [25] The maximum height of the IC Should not be more than 400mm to avoid hyperstablize the knee joint and the minimum value is 100mm because it has been examined that a high IC has higher toe clearance.[26]



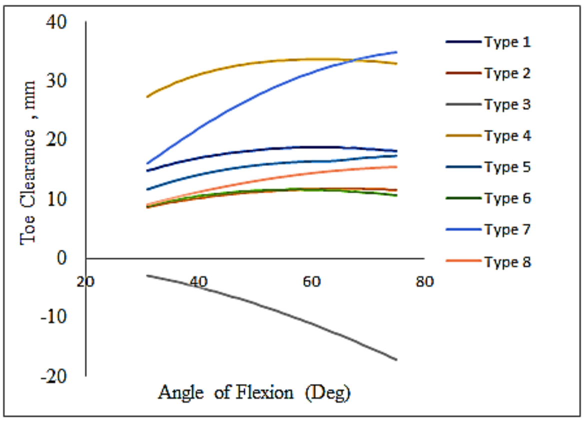


Fig 5: Graph showing Toe Clearance variation vs Angle of Flexion for Eight Polycentric Four-Bar Knee Configurations.

4.2 Energy consumption

The length shortening of the prosthesis is directly proportional to the energy consumption. [10] An amputee requires energy while moving with a prosthesis through muscular activity. A Group of muscles develops the necessary force required for the movement of the body. The ultimate aim of the prosthesis designer is to minimize this energy consumption rate during movement. It was examined that the four-bar knee prosthesis length is reducing while it passes from extension to flexion phase. Therefore, the energy consumption will be less in such a case. Energy consumption in the swing phase of eight different knee configurations was examined and the result is presented in figure 6. It is also noted that in comparison to a single-axis knee the four-bar knee prosthesis shortens its length while moving from extension to flexion and therefore it requires lesser energy consumption.

Results show that all configurations of four-bar knee linkages, which have been examined, are having relatively same energy conservation. Further, many people are habitual of a squatting posture for which extra knee flexion is required. Therefore, the Type 8 knee is most suitable for this particular application. It was also examined clinically that during squatting knee is subjected to a load of 4.7- and 5.6-times body weight. [27] Therefore, this posture will require more energy as compared to normal walking. Similarly, if the knee prosthesis is designed for the consideration of squatting then it will require more energy consumption [28]. Lower limb prosthesis with a polycentric mechanism can be further analyzed as an open-chain mechanism to evaluate toe clearance [29,30,31]. It was shown that polycentric knee geometries can be compared based on their stability, toe clearance, and maximum flexion parameters, with a method for comparing different prosthetic knees on their performance[32].

5. Conclusions

A total of eight four-bar configurations suitable for knee joint were analyzed in this paper. Each configuration has a different design and centrode shape which shows variations of knee stability. The elevated instant centre of a four-bar linkage knee mechanism at the stance phase signifies a higher level of stability, because for the same acting moment the effort required by the group of muscles is less. The results from the theoretical kinematic model and those presented in table 1 show that Type 1, Type 4, and Type 5 knee configurations are having better stability in the stance phase of the gait cycle because a higher IC provides leverage for the voluntary control of knee stability. The kinematic model type 6, type 7, and type 8 have average stability, whereas type 2 and type 3 configurations are having poor stability. Increased toe clearances of the configurations are very suitable for transfemoral prosthesis users. With the help of configurations presented in this paper, a prosthetic designer can take need-based decisions and fabricate a new model for the above-knee prosthesis.

Statements and Declarations

This has been declared that no funds, grants, or other support were received during the preparation of this manuscript.”

The authors have no relevant financial or non-financial interests to disclose.”

Ethical statement

This article does not contain any studies with human participants or animals performed by any of the authors.

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