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Polycentric Prosthetic Knee Joint: A Review

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Abstract

A variety of polycentric prosthetic knee joints have been manufactured globally over the past decade and there has been ambiguity over prescription criteria, design parameters, kinematic performance of its various designs and counterparts. This article presents technical developments in analysis performed on polycentric prosthetic knee joint in the rehabilitation of trans-femoral amputees. A review has been made on polycentric knee models used in developed and developing countries with respect to design, modelling, kinematic, finite element analysis (FEA), and optmisation technique. The results reveal important research work to develop and implement standardized measures on prosthetic knee joints for their effective use, function, durability, and cost effectiveness. There is continuous progress to address limitations. However, more research is still required for developing more functional prosthetic knee joints by simplifying fabrication techniques. A computer aided modelling, design and analysis is used as an effective tool to optimize and validate prosthetic component design including its quality, performance, safety.

Keywords:

Amputation;
Analysis;
Design;
Finite element;
Modelling;
Polycentric;
Prosthetic Knee

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I. Introduction

World Health Organization (WHO) estimated that there are 40 million amputees throughout the developing world. As per Census 2011, the population of persons with disabilities in our country is about 2.68 crore which is 2.22% of total population of the country. Amputation is one of the major causes of disability in India [1] but only about 5% of them have access to any form of prosthetic devices. The most effective way to regain walking ability is by the use of a proper designed prosthetic system (Fig. 1). There are many options available for different prosthetic components; however, prescription criteria are based mainly on subjective experiences of physicians, therapists, and prosthetists [2, 3]. Out of all prosthetic components for a trans-femoral amputee, prosthetic knee joint is the most crucial component that can affect the overall performance of walking and ADL [4]. The optimal design of a particular of knee joint is fundamental in order to restore the lost functionality and aesthetic aspect of the amputee's locomotion [5]. Lower limb prostheses for transfemoral amputations differ by the kind of thigh and shank joint (single-axis and polycentric) and by the control methods [6]. Single-axis knees have a fixed center of rotation are relatively inexpensive and with high accuracy simulate the motion of the knee (Fig. 2).

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Fig 1. Above Knee amputation and Prosthesis

The polycentric knees (Fig. 2), position of the instant center of rotation (ICOR) continuously changes with changing of the angle of knee flexion. Among all knee devices, the four-bar linkage polycentric knee 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 [7, 8].

Fig 2. Single axis vs Polycntric Prosthetic Knee

In the mid-1990s, a number of key publications elucidated about prosthetic rehabilitation in developing countries which helped to identify the problems and deficits in prosthetic services, and more importantly the steps that would be needed to improve existing practices [8-16]. One of the key issues relating to prosthetic practices is poorly functioning components including knee joints [4]. In an extensive literature survey from 1994 to 2010 on lower limb prosthetic technology in developing world, J. Andrysek suggested that irrespective of continuing action to improve prosthetic technology, there is a requirement for prosthetic components to be more functional, durable, cosmetic [16].

Prosthetic Knee joint has emerged as a viable development for use in transfemoral and higher level of amputee rehabilitation. In order to better understand and evaluate recent progress and achievements that have been made in this regard, we performed a comprehensive review of the literature, presented in this paper.

II. Methods

A. Literature Search

A systematic review of articles from 1994 to 2017 has been conducted in the present work. The review covers both the technological developments of Polycentric Knee Joints for prosthetic rehabilitation of transfemoral and higher level lower extremity amputees. Relevant articles were obtained through a search of articles in the PubMed, Medline, EMBASE, and the Cochrane Controlled Trials Register databases (Rehabilitation and Related Therapies).

B. Study Selection

The following topics were selected for review:

1) Mechanism
2) Designing and Modelling and
3) Kinematic analysis of polycentric knee joint

1. Study of Polycentric Knee Mechanism

The four bar linkage is of three types, namely : the four bar linkage with elevated instantaneous centre, the hyper-stabilized four bar knee mechanism and the voluntary control four bar mechanism [17]. The elevated instantaneous centre provides for stability at heel contact while the hyper-stabilized knee is more of a locked knee mechanism which provides alignment stability for less active amputees. The voluntary control four bar mechanism provides stability at heel contact as well as heel push off as it provides more control and is preferred by aggressively active amputees [18].

Fig. 3 is a typical four bar linkage knee. The thigh and shin are considered as a link or bar joining at different points. Together, all four links join at four points to complete the four bar linkage.

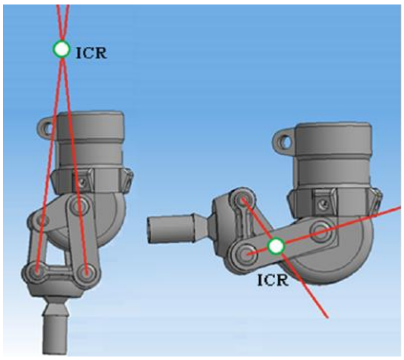

Fig 3. Typical four bar linkage knee showing orientation of Instantaneous center of rotation (ICR) at different knee flexion

2. Design and Modelling in Polycentric Knee

(a) Design

The designing of budget trans-femoral prosthesis can be obtained by utilising concept of artificial knee joint based on the four-bar mechanism. Its kinematic dimensions were determined by multi-criteria optimization based on systematic study of parameter space of points uniformly distributed in multidimensional cube [19]. Technique of synthesis is described in detail [20]. To date, polycentric prosthetic knee has been studied in detail [21, 22]. Commercially, a set of designs offered by the world known manufacturers of prosthetic devices are available: Ossur, Otto Bock, Hosmer, Endolite, Teh Lin and others [20]. However, it should be noted that almost all of them are significantly different from each other, not only by constructive but also by functional characteristics.

Thus, it can be stated that, despite the advantages of these design options, none of them is globally optimal. However, all of them, obviously, satisfy certain quality criteria taken into account when designing a polycentric prosthetic knee joint. Approaches to the solution of these joints optimization problems which described in the literature are based on traditional methods of the mechanisms theory, the practical realization of which was made possible by the introduction of computers in computational practice.

(b) Modelling and mathematical model of Polycentric Knee Joint

Currently, from the measurements obtained from CT scan or MRI images and available literatures of the knee, approximate size of the prosthetic knee joint can be constructed using Computer based software for different sagittal radius and flexion angles [23]. Measurement of the relevant parameters of the knee including mean, variance etc are the important to design the knee prosthesis. In trans-femoral prosthetic system, anatomical knee is replaced by a polycentric mechanism, which is exposed to high levels of structural stress. Therefore, mathematical models of the mechanics knees are commonly used to kinetic analysis and simulation and determine possible failures [17]. This paper describes the procedure for determining a kinematic model of a four bars polycentric knee using a geometric analysis and the Grasshof Law for a double rocker.

Let an optimized PMAK has a four bar linkage structure. Its design scheme is shown in Fig. 4 and proposed by Poliakov et al. [20] as discussed below. In this mechanism *AB* is the input link. It is assumed that it is tightly associated with the hip and moves plane parallel relatively to arbitrarily still link O_1O_3, fixed to the shank, which is associated with moving system of coordinates $O_1x_1y_1$. During the motion relative to the joint *A,* link *AB* rotates at an angle θ_3 which is taken as an independent generalized coordinate. Thus, $\theta_2 = \theta_2\ (\theta_3)$ and $\theta_4 = \theta_4\ (\theta_3)$ - the functions of the generalized coordinate θ_3. Rotation angles of all links are measured from the positive direction of the x-axis and considered positive if directed counterclockwise.

In order to unify the following notations were introduced: $l_{O3O1} = x_1$, $l_{AB} = x_3$, $l_{BO3} = x_4$, $x_{O1} = x_5$, $y_{O1} = x_6$, $\gamma_1 = x_7$, $\theta_2 - \theta_F = x_8$, $l_{AP} = x_9$, $\gamma_3 = x_{10}$. Here the symbol *l* denotes the length of the links indicated in the indexes: x_{O1}, y_{O1} - the global Cartesian coordinates of the joint O_1: γ_1 - the inclination angle of the link O_1O_3 relative to the x-axis of the global coordinate system: γ_3 - the angle between the segments AB and AP: θ_F - the knee flexion angle.

From the conditions that the circuit $O_1ABO_3O_1$ is closed, the following can be obtained:

$$\theta_2 = 2arctan\left(\frac{F_1 \pm \sqrt{{F_1}^2 + {F_2}^2 - {F_3}^2}}{F_2 + F_3}\right) \tag{1}$$

$$\theta_4 = arcsin\left(\frac{x_1 sin(\theta_2) + x_2 sin(\theta_3)}{x_4}\right) \tag{2}$$

$$x_{ICR} = x_5 + \frac{\tan(\theta_4 + x_7)\cos(x_7) - sin(x_7)}{\tan(\theta_4 + x_7) - \tan(\theta_2 + x_7)} .x_1 \tag{3}$$

$$y_{ICR} = x_6 + \frac{\tan(\theta_2 + x_7)[\tan(\theta_4 + x_7)\cos(x_7) - sin(x_7)]}{\tan(\theta_4 + x_7) - \tan(\theta_2 + x_7)} .x_1 \tag{4}$$

$$x_P = x_5 + x_2\cos(\theta_2 + x_7) + x_9\cos(\theta_3 + x_{10} + x_7) \tag{5}$$

$$y_P = x_6 + x_2\sin(\theta_2 + x_7) + x_9\sin(\theta_3 + x_{10} + x_7) \tag{6}$$

Where,

$$F_1 = sin(\theta_3), F_2 = cos(\theta_3) - \frac{x_1}{x_3}, F_3 = -\frac{{x_1}^2 + {x_2}^2 + {x_3}^2 - {x_4}^2}{2x_2x_3} + \frac{x_1}{x_2}cos(\theta_3)$$

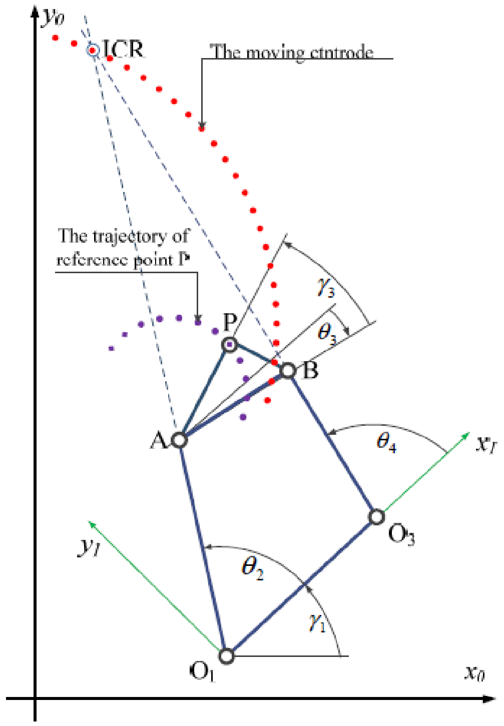

Fig 4. Calculated scheme of a four bar Polycentric mechanism of prosthetic knee joint

It is found that the common materials used in the prosthetic knee joints are Nylon 6, Nylon 6-6, oil-filled Nylon, isotactic polypropylene, acrylonitrile butadiene styrene (ABS), polyacetyl resin (Delrin), stainless steel, aluminum (60- series), titanium, polyethylene (high density), and polyvinyl chlorine (PVC).

3. Kinematic Analysis of Polycentric Prosthetic Knee

The kinematic analysis [24] of four-bar mechanism is performed following the geometry presented in Fig. 5. The a,b,c,d variables are lengths of the links, A, B, O_B, O_A depict joints.The lower link d, corresponds of the mechanism knee distal view part (shank connection). The top link b connected to the proximal part (socket connection). The alignment angles are defined by θ_1 and θ^*.

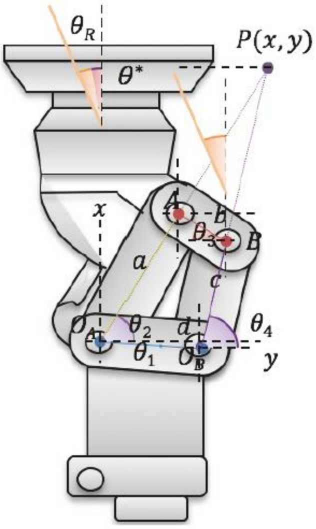

Figure 5. Kinematic Analysis of Polycentric Knee Geometry

The variable θ_R represents the angle of the knee or the system input. It can be calculated as $\theta_3 = \theta_R + \theta^*$. By a geometric analysis, θ_2 and θ_4 angles can be describes in terms of the joints and some intermediate variables as (1) and (2). In some cases these equation may be indeterminate, so must include restriction in evaluating simulation.

$$\theta_2 = 2\tan^{-1}\left[\frac{-B \pm \sqrt{B^2-4AC}}{2A}\right] \tag{7}$$

$$\theta_2 = 2\tan^{-1}\left[\frac{-B \pm \sqrt{E^2-4DF}}{2D}\right] \tag{8}$$

Where,

$$A = \frac{k_2}{2ab} - \frac{dk_1}{a} - \cos(\theta_3) + \frac{d\cos(\theta_1)}{b} \tag{9}$$

$$B = 2\left[\sin(\theta_3) - \frac{d\sin(\theta_1)}{b}\right] \tag{10}$$

$$C = \frac{k_2}{2ab} - \frac{dk_1}{a} + \frac{d\cos(\theta_1)}{b} + \cos(\theta_3) \tag{11}$$

$$E = 2\left[\frac{d\sin(\theta_1)}{b} - \sin(\theta_3)\right] \tag{12}$$

$$D = \frac{k_3}{2bc} - \frac{dk_1}{c} - \frac{d\cos(\theta_1)}{b} + \cos(\theta_3) \tag{13}$$

$$D = \frac{k_3}{2bc} - \frac{dk_1}{c} + \frac{d\cos(\theta_1)}{b} - \cos(\theta_3) \tag{14}$$

$$K_1 = \cos(\theta_1)\cos(\theta_3) + \sin(\theta_1)\sin(\theta_3) \tag{15}$$

$$K_2 = a^2 + b^2 - c^2 + d^2 \tag{16}$$

$$K_3 = b^2 - a^2 + c^2 + d^2 \tag{17}$$

Finally, joint points A, B, O_A and O_B can be calculated as

$$O_A(X_{OA}, Y_{OA}) = [0,0] \tag{18}$$

$$O_B (X_{OB}, Y_{OB}) = [d\cos(\theta_1)\ d\sin(\theta_1)] \quad (19)$$

$$A(X_A, Y_B) = [a\cos(\theta_2) - a\sin(\theta_2)] \quad (20)$$

$$B(X_B, Y_B) = [X_{O_B} + c\cos(\theta_4), Y_{O_B} + c\sin(\theta_4)] \quad (21)$$

The P (x, y) point is located where the projections of the a and c, converge.

$$P_x = X_B + \frac{k_4}{k_5} - d\cos(\theta_1) - c\cos(\theta_4) \quad (22)$$

$$P_y = y_B + \frac{k_4}{k_5} \tan(-\theta_2) - d\sin(\theta_1) - c\sin(\theta_4) \quad (23)$$

For achieving more functional prosthesis, the design and function of a prosthetic knee needs to be greatly improved. Besides, a numerical technique known as FEM [25] has been substantially generalized for the physical system modelling in a broad range of physics and engineering disciplines, for instance, structural analysis, fluid dynamics, heat transfer, etc. Further, FEM plays a vital role in the process of prosthetic design and development. FEM is applied extensively to analyze stress distributions on a prosthetic knee implant or in case of knee joint replacement [23, 26, 27, 28, 29].

Table 1 Summary of FEA performed on prosthetic knee joint reviewed

Study	**Title**	**Aim**	**Technical Work**	**Conclusion**
Phanphet et. *al.* (2017) [30]	Above-knee prosthesis design based on fatigue life using FEM and design of experiment.	To improve the design of knee joint from the existing model.	Structural test by FEA, Morrow's approach for fatigue analysis,	The optimized design confirmed finite element prediction.
Diaz et al. (2016) [31]	External knee prosthesis with four bar linkage mechanism	To design and construct a prosthetic knee external four-bar mechanism.	FEA used to obtain a safety factor.	The device is intended to be incorporated into a modular prosthesis and work in an optimal control mechanism to regulate the acceleration walk.
Lapapong et al. (2014) [32]	Finite element modeling and validation of a four-bar linkage prosthetic knee under static and cyclic strength tests	To present a procedure to simulate the static and cyclic strength tests for Polycentric knee.	FEM to simulate the prosthesis under the tests, stress distribution induced and fatigue life. Explicit nonlinear transient stress analysis is applied to determine the strength of prosthesis.	The validation results confirm the fidelity of the proposed finite element model.

In a recent study, Phanphet et. *al.* [30] with an objective to improve the standard of existing knee prostheisis found that a joint bar with uniform thickness of 9.3 mm, square shaped pyramid with cross section length of 13.5 mm and a stopper diameter of 10 mm optimal for best design. The test result confirmed the finite element prediction that the knee prosthesis can withstand more than 3,000,000 cycles of cyclic loading and does not fail under ultimate loading. It was found that the optimum prosthesis passed the requirements of the ISO 10328 structural test. In another study Diaz et al. [31] established the knee mechanism to support the weight of a person upto one hundred kilograms using a FEA incorporating three materials: 6063 aluminum, 304 stainless steel and bronze. He found that it was possible to obtain a safety factor in the prosthesis that will provide peace of mind to the user on a fracture of the device. As a result he developed a cost effective prosthesis that mimics the motion of the knee with greater stability. The work of Lapapong et al. [32] outlined the virtual static and cyclic strength tests of a four-bar linkage prosthetic knee for ISO 10328:2006 standard. FEM was applied to construct a model of the prosthesis under the tests. The technique of nonlinear dynamic analysis was employed to estimate the stress distributions induced on the structure of prosthesis. The simulation results show that the prosthesis sample is sufficiently strong enough to surpass both of the static and cyclic strength tests. The validation results, further, reveal that the proposed finite-element model is able to sufficiently compute the structural stresses in all cases. Some of other studies of FEA on polycentric prosthetic knee joints found similar importance [32]-[37].

3. Conclusion

Polycentric knee joint mechanisms, incorporating four and six bar mechanisms have been utilized successfully to enhance stance phase stability and swing-phase kinematics in developed countries. However, due to their increased complexity and associated costs, repairs and maintenance, these mechanisms have been deemed less appropriate for use in developing countries [38, 39].The application of polycentric prosthetic knee mechanisms made of steel or duraluminium is preferred where as use of titanium or carbon, can make it lighter, but are more expensive [40]

FEA is carried out to optimize and validate each step of a prosthetic component design including its quality, performance, and safety. Displacement, strain, and stress of the components under internal and external loads are calculated using the displacement formula of the FEM [41]. FEA and Taguchi method was shown to be an effective method in optimizing the structural design of prostheses. Further prosthetic design can be facilitated based on the degree of importance of the design factors on the structural behavior of the prosthesis. Gait analysis of amputees using the suggested monolimb design is needed to validate experimental result [42]. Designing and synthesis of a knee mechanism for a desired motion is being done using optimization. The changing parameters must be observed and regional constraints applied such that the final mechanism conforms to them.

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