A Review Study for Measurement, Analysis and Evaluation
Four Bar Polycentric Knee

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Abstract. When a transfemoral amputee missing his knee joint, a polycentric mechanism is used as technical substitute to restore the gait function. The motion ability of transfemoral amputee is dependent on the performance of prosthetic knee. Recent results on the kinematic analysis of four-bar polycentric knee mechanism are reviewed in this article. Different experimental tests on data of above-knee prosthetic limb such as F-socket, gait analysis, ground reaction force, static loading, fatigue life and static prosthetic alignment, etc., were used to analyse the gait cycle and to improve the comfortability of amputee after using prosthetic limb, and to increase the stability of prosthetic knee after using. Finally, the optimization techniques included selection of the optimum dimension of polycentric knee is dependent on the data of ICR trajectory estimated from kinematic analysis of four-bar mechanism. These optimization techniques have significant effect on improving the mechanical properties of polycentric knee and reducing its cost.

Keywords: Gait cycle, Polycentric knee, ICR, Optimization, Knee mechanism.

1. Prosthetic function
A prosthesis is an artificial medical device used to replace a missing body part. The most basic function of lower limb prostheses is to provide the structural support that would otherwise be provided by the missing or removed portion of the skeletal system. Advanced prostheses will contain characteristic to provide stability control, energy storage and release and physical damping. These features replace some of the missing function or altered musculature. Lower limb amputations fall into a number of different categories depending on which level the transaction is made on the limb. As shown in figure 1, a transfemoral amputation involves the bisection of the femur, this is the second most common level of amputation after the transtibial level [1-2]. During a transfemoral amputation, the femur is transected above the knee joint and the portions of the hip adductor and extensor muscles controlling the femur are removed [3]. The procedure naturally shortens the effective lever arm of the adductor muscles and this is part of the reason transfemoral amputees face higher energy expenditure levels during normal walking [4]. There, various investigations are presented for studying the mechanical behavior of different biomechanical part, as knee joint, foot part, below knee parts, above knee parts, hip joint, and other biomechanical parts, [5-23].
Figure 1. Different levels of lower limb amputation [2].

So, the investigation included calculating mechanical properties as strength, modulus of elasticity, hardness, and impact resistance, for biomaterials used. In addition, the investigation included calculating the different mechanical behavior as stress analysis under static and dynamic load, creep behavior, fatigue characterizations, dynamic behavior and other parameters [24-36]. Therefore, different techniques for improving the mechanical properties for materials are used to manufacture the biomechanical parts investigated, such as, reinforcement with different fiber types and volume fraction, different powder reinforcement, natural reinforcement fiber, and Nano reinforcement, [37-53]. An experimental and theoretical technique was used to calculate more mechanical properties and behavior of biomechanical parts, and the results were compared [54-71].

2. Cause of amputation
Thirty million have lost their limbs worldwide [72]. The loss of limbs is associated with various cases such as disease, traffic accident and war operations [73]&[74] which involves removing a limb (arm, leg) or part of it [75]. In war and post-war zones, many amputations are the result of trauma from direct conflict or from the explosion of landmines and other Explosive Remnants of War (ERW). Landmines and ERW remain active even well after the conflict may have ended, exposing all kinds of civilians to traumatic injuries and amputation of their limbs, including young and active children. There are currently millions of uncleared landmines around the world and each year 2-5 million are added. These weapons currently claim an estimated 2000 casualties per month [76]. Most of these are non-fatal yet cause serious damage to the lower limbs, often leading to the need for amputation [77]. Traffic accidents are also a leading cause of amputation in many developing countries. Again, many factors contribute to the higher number of traffic accident related amputations. Quite simply, there are more vehicles, more pedestrians, fewer road safety standards, and a generally poorer road infrastructure [78].

3. Prosthesis components
A lower limb prosthesis for transfemoral amputees consists of four major parts: the socket, knee joint, and foot/ankle unit as shown in Figure 2. Socket is usually made from plastic polymer laminates, reinforcement textiles such as fiberglass, carbon fiber, and nylon which is added to provide the structural support [79] & [80]. For transfemoral amputees, the prosthetic knee joint is the most critical component of the prosthesis, as its purpose is to replace the true knee. The function of a good prosthetic knee joint is to mimic the function of the normal knee, such as providing structural support and stability during stance phase but it is able to flex in a controllable manner during swing phase. The prosthetic knee is connected to the prosthetic foot by the shank, which is usually made of an aluminum or graphite tube. The function of the foot and ankle is to provide a stable weight-bearing platform while offering mobility function by
changing position and responding to ground reaction force vector (GRFV) during gait on different walking surfaces [81].

Figure 2. Lower-limb prosthesis components [82].

4. Gait cycle
Gait refers to the manner of walking and a gait cycle is indicated to the time interval between two sequential occurrences of one of the walking events. The gait cycle can be divided into two general phases: stance phase and swing phase. The stance phase is known as the support phase and defined as the time period of the cycle when the foot is in contact with the ground. The swing phase is defined as the time when the foot is in the air. [83]. The full gait cycle can be classified to eight phases with different durations and objectives as seen in Figure 3. These phases are initial contact, loading response, mid stance, terminal stance, pre-swing, initial swing, mid swing, and terminal swing.

Figure 3. Normal human walking cycle illustrating the events of gait. Adapted from [84].

Initial contact represents the beginning of the gait cycle when the foot touches the ground. The position of each joint determines the initial loading condition placed on the limb [83]. In loading response, the body weight is transferred onto the forward limb. Stability for weight bearing and shock absorption are the two critical objectives in this phase. The limb must bear weight in an unstable position, where unstable refers to the instant the knee tending to flex by the effect loading during this phase [1]. The knee flexion is approximately bounded by 20 degrees generated by quadriceps muscles [85]. During mid stance phase, the knee is brought back to a fully extended position and the entire body weight must be supported with one limb while the other is advanced forward past the stationary foot [83]. Terminal stance marks the second half of the single limb support task. The body weight moves ahead of the forefoot of the planted limb as the hip extends and the heel rises. The other limb has now completed terminal swing and has progressed well beyond the supporting foot [1]&[81]. Pre-Swing is the final phase of stance. In this phase, the opposite limb makes initial contact and body weight is rapidly transferred to the opposite limb. Increased ankle plantar flexion and knee flexion of the trailing limb prepares it for the beginning of the swing-phase [1]. The two main objectives in initial swing phase are foot clearance of the ground and the
beginning of swing-limb advancement. Increased knee flexion coupled with ankle dorsiflexion clears the toe above the ground while hip flexion advances the limb forward [1]&[81]. As the toe clears the ground, the inertia of the shank causes the knee to extend to a maximum of approximately 70 degrees [85]. In mid swing phase, the limb advancement continues with further hip flexion, however the knee angle begins to decrease as gravity causes the knee to extend. The objectives of foot clearance and limb-advancement from initial swing remain [1]&[81]. Finally, limb advancement is completed in terminal swing phase by the full extension of the knee. The end of this phase, and of the complete human GC, is marked by initial contact with the ground of the swinging limb[1]&[83].

5. Prosthetic knee development
The design of knee can be developed to meet the minimal requirements of swing phase, kneeling and sitting. According to [86], knee mechanism can be classified into two kinds: monocentric and polycentric. Monocentric knee (single axis knee) has fixed axis of rotation which has limitation in the control. However, polycentric knee is easier to control and move stable through swing and stance phase the mechanism of polycentric knee manage the instant centre of rotation (ICR) for any angle during knee flexion. Knee mechanisms fall into different categories; pneumatic, constant friction, locking, hydraulic, polycentric, etc. [87]. All types above can be classified under the category of non-microcontroller prosthesis. The microcontroller prosthesis is defined as the ability to adapt the activity of prosthesis such as timing of the stance phase or swing phases of gait under the microcontroller automatic control [88] as shown in Figure 4.

![Figure 4. Classification of knee joint mechanism [88].](image-url)
6. Prosthetic limb tests

6.1. F-Socket test
Colombo et al [89] improved the design of lower limb prosthesis through pressure analysis at the interface residual limb-socket. The experimental setup was based on (Tekscan F-Socket System) to measure the contact pressure of the interface between residual limb and socket. Tekscan system exploited medical sensors 9811E within a pressure range between 0 and 517 kPa as shown in Figure 5.

The sensor was setup by filling of patient form with anthropometric data, 3D scanning of the residual limb, application of sensors over the residual limb, 3D scanning of residual limb with applied sensors and donning of the socket. 3D scans of the residual limb have been executed by using (Microsoft Kinect) with application of 3D scanning software (Skanect), as described in figure 5. The data of pressure are visualized with a color map over 3D residual limb model to evaluate a physical prototype.

6.2. Gait cycle and ground reaction force tests
Kadhim et al [90] tested four prosthetic knee joints. A tactile force and gait cycle measurements system was used; a pressure measurement system (Tekscan-Walkway™) that measures the pressure between the floor platform and the feet.

6.3. Human motion test
Kinovea is a software used to study human motion: capture, observation, annotation and measurement. The videos of gait analysis were uploaded into the program, and the working zone was located according to the end of the sequence of the gait cycle, then a coordination system origin was set to represent the trajectory of the path track as shown in figure 6.

![Figure 5. Sensor data and residual limb acquisition [89].](image-url)
Figure 6. Motion tracking steps in Kinovea, a: setting system coordination, b: reference of calibration, c: locating the markers, d: make path tracking range, and e: path trajectory [90].

The patients were asked to walk on the platform, to ensure a clear gait performance. The tests were used to obtain the maximum velocity and find the walking stability for these prosthetic knees.

6.4. Fatigue life and static loading test
Phanphet et al [91] studied the failure of knee prosthesis under static and cyclic load tests. The optimum design of knee prosthesis was developed to reach the ISO 10328:2006 requirement. The standards force for three amputee’s weight levels at cyclic loading. The ISO 10328 requires applied static ultimate loading and 3,000,000 cyclic loading to the knee prosthesis without failure. The (80 kg) forces were applied to structure of knee prosthesis. A 5 kN servo-pneumatic fatigue machine was used for structure testing with cyclic load 1230 N at 1 Hz speed as shown in figure 7. Two aluminum tubes and top and bottom fixture plate were used to tie the components together.

Figure 7. The structural testing machine [92].

6.5. Static prosthetic alignment
Blumentritt [93] attempted to determine prosthetic alignment for trans-tibial amputees biomechanically using the individual load line as a reference. The L.A.S.A.R. posture (both Co. KGaA & Ottobock SE, Germany) was used to examine and optimize the static alignment in accordance with established
recommendations. The display of load situation in 3D L.A.S.A.R. posture mode for both legs is shown in figure 8. The measurement of forces in horizontal and vertical axis can be present in (image 1) & (image 2). According to the alignment in live image 3, the alignment reference lines was superimposed for the Ottobock components [94].

**Figure 8.** The display of load situation in 3D L.A.S.A.R. Posture mode for both legs [94].

7. **Mechanism of polycentric knee joint**

The localization of the instant center of rotation (ICR) was established by Radcliffe [95]&[96] in order to obtain a suitable four bar polycentric mechanism and full control of these types of prostheses by the transfemoral amputee. There are many aspects to obtain a good stability in accordance with [96]. First, there is the fitting of the stump-socket interface, and second is the residual limb length and strength. Third, the functional characteristics of the foot–ankle and the knee mechanisms should be combined into the prosthesis. Finally, the relative position of the hip joint is considered with respect to the ankle and knee joints (alignment geometry). The mechanisms of four-bar linkage has three different types used in lower limb prosthesis [86]: (1) the four-bar with elevated ICR, (2) the four-bar mechanism with hyper-stabilized, and (3) four-bar mechanism with voluntary control. It is advisable for amputees with limited ability to control stability and geriatric amputees to use four-bar linkage with an elevated ICR as shown in figure 9. It has long anterior link and short posterior link. The links have been designed in this mechanism to give maximum stability at heel contact. The ICR is located behind the load line for full extension at heel contact. It is not required to hip extension moment exerted by the amputee.

**Figure 9.** Three types of four-bar mechanism used in lower limb prosthesis [86].
At push off, the amputee generates hip flexion moment. The individual is able to move the load line behind the ICR by the individual. The initiation of knee flexion is performed in minimal effort. The arrangement in four-bar knee mechanism hyper-stabilized is similar to the four-bar mechanism with estimated ICR. However, there is significant difference in kinematic behavior when the dimensions of the mechanism have small changes. The position of ICR is well when it located behind the load line (Figure 9). It is not required to hip extension moment that exerted by the amputee. At push off the ICR is still located behind the load line. The voluntary control in (figure 9) has been designed in four bar mechanism to give to the user amputee the ability to achieve the stability in the prosthetic knee at both heel contact and push off. The voluntary movement of the knee to the stable location is performed in the full extension.

8. Trajectory of polycentric knee joint

The following methodology has been proposed by Hobson and Torfason [97] to describe the mechanism of four-bar polycentric knee and find the desired trajectory of ICR. The revolute joints of four-bar mechanism are centrode at points $O_A, A, B$ and $O_B$. The upper link $AB$ is connected to socket part. However, the shank is connected by the lower link $O_AO_B$ as shown in figure 10.

![Figure 10. Configuration of a four-bar linkage with Coupler point C](image)

The lengths of bars are $a_1, a_2, a_3$ and $a_4$. The angle $\theta_i$ represent the angle of each bar and measured in anticlockwise. The coordinates position of point B are defined as follows [97]:

\[
\begin{align*}
    x_B &= x_{OB} + a_4 \cos \theta_4 \\
    &= x_{OA} + a_2 \cos \theta_2 + a_3 \cos \theta_3 \\
    y_B &= y_{OB} + a_4 \sin \theta_4 \\
    &= y_{OA} + a_2 \sin \theta_2 + a_3 \sin \theta_3
\end{align*}
\]

The input can be represented by the coupler link angle $\theta_3$. The equations (3) & (4) are the function of the angle $\theta_2$ and can be written as [97]

\[
\begin{align*}
    a_2 \cos \theta_2 &= a_4 \cos \theta_4 + C_1 \\
    a_2 \sin \theta_2 &= a_4 \sin \theta_4 + C_2
\end{align*}
\]
Where:

\[
C_1 = x_{OB} - x_{OA} - a_3 \cos \theta_3
\]  
\[
C_2 = y_{OB} - y_{OA} - a_3 \cos \theta_3
\]

By squared and added Equations (5) and (6)

\[
a^2_z = a^2_4 + C^2_1 + C^2_z + 2C_1a_4 \cos \theta_4 + 2C_2a_4 \sin \theta_4
\]

Rearranging the terms in Equations (9), the following equations are obtained [97].

\[
A \sin \theta_4 + B \cos \theta_4 = C
\]  
\[
A = 2C_2a_4
\]

Where:

\[
B = 2C_1a_4
\]
\[
C = a^2_z - a^2_4 - C^2_1 + C^2_z
\]

For different inputs of the angle $\theta_3$, these constants can be found. $C_1$ and $C_2$ can be defined by equations (7) and (8). The constants in equation (10) is a function of the angle $\theta_4$. It is necessary to make it explicit from the following substitutions [97].

\[
\sin \theta_4 = \frac{2 \tan(\frac{\theta_4}{2})}{1+\tan^2(\frac{\theta_4}{2})}
\]

\[
\cos \theta_4 = \frac{1-\tan^2(\frac{\theta_4}{2})}{1+\tan^2(\frac{\theta_4}{2})}
\]

By reducing the equation (10) to a quadratic form with function of $\tan (\theta_4/2)$, the solution can be presented as follows [97].

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

Two different solutions for angle $\theta_4$ were provided from equation (16). One is positive and the other is negative. Selected of the sign depend on mechanism configuration. The A and B coordinates can be calculated from the following procedure when the angle $\theta_3$ is proposed and the angle $\theta_4$ is calculated [97].

\[
x_B = x_{OB} + a_4 \cos \theta_4
\]
\[
y_B = y_{OB} + a_4 \sin \theta_4
\]
\[
x_A = x_B + a_3 \cos \theta_3
\]
\[
y_A = y_B + a_3 \sin \theta_3
\]

With knowing A and OA coordinates, the angle $\theta_2$ can be found.

\[
\theta_2 = \tan^{-1} \frac{y_B - y_{OA}}{x_A - x_{OA}}
\]

From the intersection of straight lines passes through links 2 and 4, the coordinate of ICR is calculated [97].

\[
X_1 = \frac{y_{OB} - y_{OA} - x_{OB} \tan \theta_4 - x_{OA} \tan \theta_2}{\tan \theta_2 - \tan \theta_4}
\]
\begin{equation}
\gamma_1 = \gamma_{OB} + \tan \theta_4 (x_1 - x_{OB})
\end{equation}

The coupling point coordinates with the distance \(a_c\) can be determined. It is between line AB with an angle \(\varphi\) as following [97]

\begin{equation}
\theta_c = \theta_3 + \varphi
\end{equation}

\begin{equation}
x_c = x_A + a_c \cos \theta_c
\end{equation}

\begin{equation}
y_c = y_A + a_c \sin \theta_c
\end{equation}

9. Optimization of polycentric knee joint

The following studies examined the optimization methods used in polycentric knee joint and can be summarized in table (1).

| No. | Researcher Name | Year | Title | Aim | Technical method | Conclusion |
|-----|-----------------|------|-------|-----|------------------|------------|
| 1   | Soriano et al [99] | 2020 | "Performance comparison and design of an optimal polycentric knee" | Optimized novel and stable polycentric four bar mechanism knee joint with voluntary control configuration | Genetic algorithm method | Optimal dimension of four bar polycentric mechanism was performed from the data of ICR trajectory in order to create a model. The Genetic algorithm method seeking to reduce the prosthetic knee cost and improve its mechanical properties. |
| 2   | Eqra et al [100] | 2018 | "Optimal synthesis of a four-bar linkage for path generation using adaptive PSO" | Perform adaptive inertia weight particle swarm optimization (AIW-PSO) on the path synthesis of four bar mechanism. The performance of an adaptive solution method was investigated on this problem. | Adaptive Inertia Weight PSO (AIW-PSO) | The AIW-PSO implementation showed good results for path synthesis problem in comparison with other methods. The results were selected from the viewpoint of time, accuracy and ease of implementation. |
| 3   | César et al [98] | 2013 | "Optimization of the Design of a Four Bar Mechanism for a Lower Limb Prosthesis Using the Taboo Search Algorithm" | The error between the trajectory of instantaneous center of rotation (ICR) and the path of four-bar mechanism was minimized | Taboo Search Algorithm | The combination of bars lengths is investigated and all of them in the range of stability. |
| 4   | Pfeifer et al [101] | 2012 | "An Actuated Transfemoral Prosthesis with Optimized Polycentric Knee Joint" | Optimize four types of knee joints to approximate a physiological peak torque versus joint angle versus joint velocity profile. | Grid Optimization | The result of optimization in four-bar mechanism produce uniform torque through the range of motion (ROM) of the knee. |

10. Conclusions

The analysis and evaluation of four-bar polycentric knee used in prosthetic limb for transfemoral amputee was reviewed in this research. The gait analysis of human shows that the polycentric knee has been utilized for many amputees because it is successful to enhance the stability during stance phase and the kinematic in swing phase. The conclusions of this article can be summarized as follows:
1. The experimental tests applied on prosthetic limb (F-socket, gait analysis, ground reaction force, static loading, fatigue life and static prosthetic alignment) have significant effect on the development of the prosthetic limb and increasing the stability of prosthetic knee.
2. According to Radcliffe [29], the mechanism of four-bar linkage can be classified into three types: (1) mechanism estimated by ICR (2) hyper stabilized mechanism (3) voluntary control mechanism.
3. The kinematic analysis of four-bar polycentric knee was based on the Grashof law double rocker with length bar condition \((a_2 + a_3 \leq a_1 + a_4)\).
4. The optimization techniques in many studies focused on selecting the optimum dimension of polycentric knee mechanism based on the data of ICR trajectory calculated from kinematic analysis of four-bar polycentric knee and verifying the stability to be set the ICR behind the load line, [102-104].
5. It can be observed that there is no evaluation studies on selecting the optimum prosthetic knee from different types of knee joints. This study will be performed in next research to develop a technical method in selection and evaluation.

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