

## Evaluation and Analysis of Different Types of Prosthetic Knee Joint Used by Above Knee Amputee

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**Abstract.** Four prosthetic knee joints (polycentric knee weight activating-4bar and friction, extension assist controlled), (single axis knee weight activating and friction, internal extension assist controlled), (single axis knee weight activating-4bar and hydraulically, controlled) and (polycentric knee geometric locking-6bar, hydraulically controlled) for a trans-femoral patient were tested. The tests were conducted to find the maximum velocity as well as discussing the most comfortable prosthetic for the patient and walking stability for these prosthetic knees by examining the gait cycle and measuring the ground reaction force (GRF), using force a plate device. Also, the interface pressure was measured between socket and stump muscles by using F-socket device to get the stress distribution during walking with a prosthetic knee. Results manifested that the polycentric knee geometric locking - 6bar, hydraulically controlled is the best because of the good homogenous distribution of GRF between the healthy and prosthetic limb, during which the difference between both the healthy and prosthetic limb is with the least value (4%). And, K4 gives the minimum value of differences in contact pressure between the left and right limb with a value of (24%), it also imparts the maximum symmetry between the left and right limb according to the gait cycle parameters. The best results of the interface pressures and Kenova velocity are achieved when K4 is used with (132.4KPa, 0.71m/s), respectively. Finally, the polycentric knee geometric locking - 6bar, hydraulically controlled is the best according to the ANSYS results during which it yields the minimum values of Von-Mises stress with 14.24MPa and a maximum factor of safety of 3.11.

### Introduction

Prosthesis substitutes or supplements for the missing or defective body part. Trans-femoral prostheses are manufactured, specifically for persons who have undergone trans-femoral amputation. The prosthetic leg contains a socket, a prosthetic knee, shank and a prosthetic ankle. The prosthetic knees and ankles models of prostheses are manufactured to mimic the natural size, weight, and motion as close as possible. Traditionally, unilateral trans-femoral prosthesis has always been made symmetric to the intact leg[1].

**Sapin, 2008,** [2] analyzed the gait configurations of trans-femoral amputees with the help of two different single-axis knee joints with a hydraulic swing phase control with and without knee-ankle link, and the influence of a mechanical Hydracadence® knee-ankle link was studied. A comparison was also made between the gait configurations of two groups of amputees with individuals with normal gait in order to assess particular functionalities of knee joints.

**Kenton R. Kaufman and James A. Levine, 2008,** [3] studied the quantity of energy efficacy of movement and free-living physical motion energy spent by trans-femoral amputees with the use of a mechanical and microprocessor operated prosthetic knee they studied the quantity of energy efficacy of movement and free-living physical motion energy spent by trans-femoral amputees. To calculate the relative walking efficiency, using a mechanical and microprocessor controlled prosthetic knee, a precise measure of oxygen amount under steady-state settings was obtained.

**Dale Berry and Mark D. Olson, 2009,** [4] evaluated the feltre-laxation, safety, manoeuvrability, cosmetic qualities, opposing effects as well as the welfare of the microprocessor operated C-Leg and

non-microprocessor operated inert prosthetic knees. **Marcelo Peduzzi de Castro et al., 2013, [5]** investigated and compared between the residual lengths of the limb orientated with the energy efficiency of the participants with trans-femoral amputation. Twenty-six adults associated with severe, trauma-unilateral trans-femoral type amputations were divided into two groups. They undertook metabolic analysis testing in addition to gait. **Jumaa S. Chiad and Muhammad S. Tahir, 2016, [6]** fabricated a trans-femoral prosthetic that was made of four laminated layers (1bamboo,2 carbon fibres and another bamboo layer) instead of the layers of a laminated prosthetic (4 perlon,2 carbon fibres and another 4 layers of perlon),which is presently the most widely used for fabricating prosthetic sockets. Pressures were used as the boundary conditions for simulation with the aid of the ANSYS 14.5 SIMULATION PROGRAM. The data obtained showed an increase in each of the tensile and yield stresses in addition to Young's modulus and endurance stresses.

### Knee Mechanism

**Single Axis Knee Mechanism.** The basic engineering mechanics may help to explain how the muscle moments exerted by the amputee influence the load. Consider the diagrams in Fig. 1.

This can be explained by considering the combination of joint force and extension moment acting at the hip joint. Consider Figures 3.7(b) and (c). The hip extension moment  $M$  in (b) can be replaced by two equal and opposite forces of quantity  $F$  separated by a distance  $D$  which has a similar extension moment as  $M:M = (D) \times (F)$ . These couples of forces  $F_1$  and  $F_2$  are now positioned on diagram (c) in a manner such that  $F_2$  is in-line with the actual force  $F$  and they cancel each other out [7].

**Four-Bar Polycentric Knee Mechanism.** Four-bar linkage knee is a specific class of polycentric knees. The knees are described by four elements joined at four separate points. The four elements include the thigh, shin and two links. Figure 2 illustrates the derivation of equation (Eq. 4), which gives the magnitude of the hip extension moment  $M_h$  that would be needed to offer knee steadiness as a function of the axial load  $P$ , the magnitude of an existing brake moment  $M_k$ , and the x-coordinate (forward offset) and y-coordinate (elevation) of the instant: centre at heel contact. Note that a friction brake will normally offer a moment  $M_k$  which surpasses the value of  $P$  times  $x$ , therefore the required hip moment  $M_h$  becomes zero.

Summation of the moments about the hip is

$$-M_h + SL = 0 \quad (1)$$

$$\text{Shear force } S = M_h/L \quad (2)$$

Summation of the moments about the knee is

$$SY - PX + MK = 0$$

$$(M_h/L)Y - PX + MK = 0 \quad (3)$$

Solving for hip moment  $M_h$  gives

$$M_h = (L/Y) (PX - MK) \quad (4)$$

For a typically four-bar knee,  $MK = 0$

$$M_h = (L/Y) PX = (PL)X/Y$$

Where,

P: Axial load force, Mh: Extension moment about the hip joint on amputated side, MK: Break moment supplied by the knee mechanism, K: Either single axis or instant centre for a four-bar linkage. [7]. Six-Bar Mechanism provides the possibility of increased range of knee motion, better cosmetic, improved stance phase stability and swing phase control as compared to four-bar designs, as shown in fig 3.

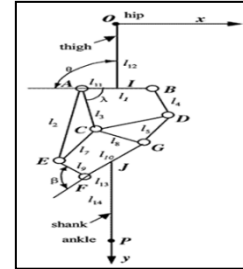
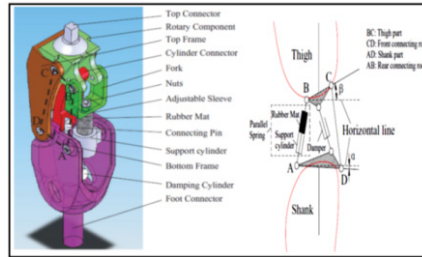
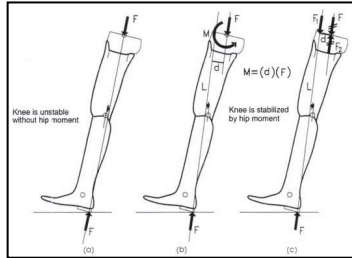


Fig. 1: A single force F, acting along the load.

Fig. 2: A typical four-bar linkage knee.

Fig. 3: Configuration of a six-bar mechanism.

**Experimental Work Structure**

The experimental technique is a tool used to evaluate the mechanical behaviour of a structure under the effect of various parameters, with agreement results values [8-10]. Information for the only case study is presented in table 1. The prosthetic knee joints used are labelled and described in table 2 and shown in (fig 4).

Table 1: Case study information.

Table 2: Description of the used prosthetic knee joints types.

Type of amputation	Unilateral (left leg)
Cause of amputation	Trauma
Gender	Male
Height	160 cm
Wight	50 kg
Age	23
Type of socket	Quadrilateral
Type of foot	Single-axis foot

Label	Commercial name	Knee axis	Stance phase control	Swing phase control
K1	3R20	Polycentric- 4bar	Geometric locking	Friction& extension assist
K2	3R22	Single	Weight activating	Friction & internal assist
K3	3R45	Single- 4bar	Weight activating	Hydraulic
K4	3R60	Polycentric- 6bar	Geometric locking	Hydraulic



Fig. 4: Types of the used prosthetic knee.

**Gait Cycle and Ground Reaction Force Testing.** For this test, a tactile force and gait cycle measurements system was used, a Walkway Pressure Measurement System (Walkway™ –lied to Pressure Measurement System Evolution Based) is an apparatus that measures the pressure between the floor platform and the feet as in (fig 5). A case study was made in which amputee patients were asked to walk (2m) on the platform, to ensure a clear gait performance, (fig.6). The average of four readings was taken for each joint, on which the test was conducted so as to obtain more reliability and less error. The videos were uploaded into the software, 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.

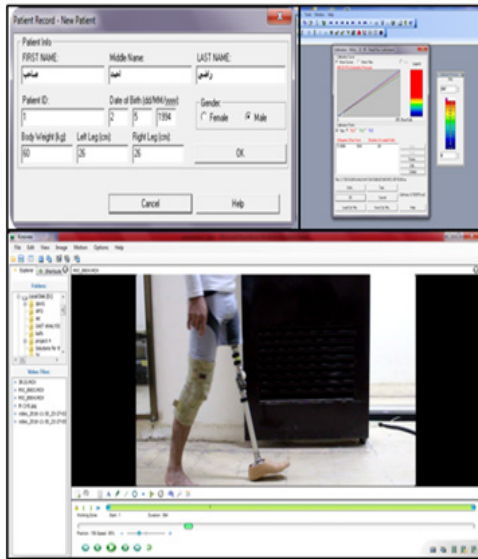


Fig. 5: Kinovea program.

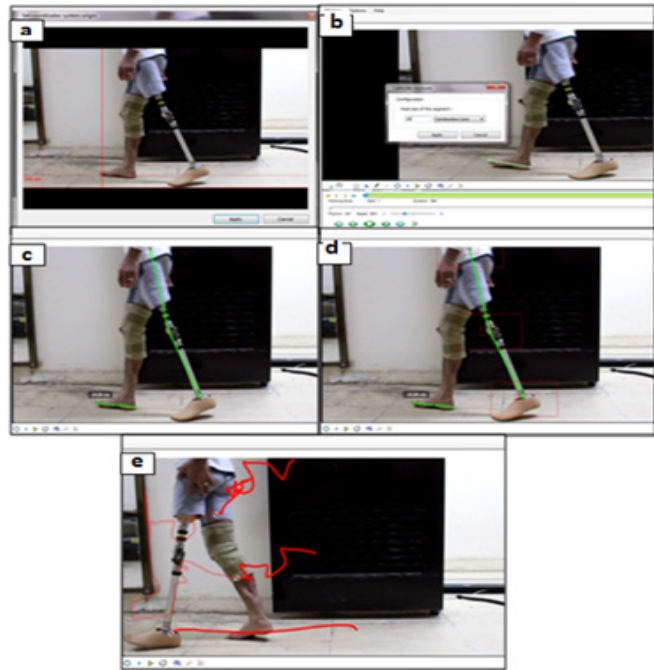


Fig. 6: Motion tracking steps in kinovea, a: setting system coordination, b: reference of calibration, c: locating the markers, d: make path tracking range, and e: path trajectory.

**Interface Pressure Testing.** The interface pressure was measured by the F-Socket Pressure Measurement System that uses an apparatus to measure the pressure between a prosthetic socket and the limb of an amputee. The sensor type (MatScan) is acceptable for this type of dynamic load

**Mechanical tests (Tensile test and Fatigue test).** The material used for the lamination for the above knee prosthetic socket is a composite material made of a number of layers and as follows:

4. perlon, 2 fibres carbon and 4 perlons. These materials were tested to find the mechanical properties through tensile and fatigue tests. A computer numeric control (CNC) machine was used to cut and fabricate the specimens according to ASTM D638 type 4 [40]. The specimens' fatigue properties were found by testing the no. of cycles vs. the stress applied to the material used and obtained its (S vs. no. of cycles) graph, with the aid of a (HSM20) fatigue testing apparatus. The specimens that underwent bending fatigue were fabricated according to the apparatus' manual [47].

## 1. Numerical Work

To determine the stresses with different loading conditions, a finite element analysis for the replacement of the knee is deliberated thoroughly for the duration of different damping. In this research, FEM with the use of the software "ANSYS WORK BENCH 16.1" as a numerical instrument to show the outcome of fatigue rendering on the elements of a structure to find the distribution of the stresses on the contour deformation of the whole and the safety factor areas [11-12]. Eventually, via the use of the finite element method, the numerical results are appraised and compared with the experimental method, to obtain the maximum error between the used technique [13-14].

## 2. Results and Discussion

### 2.1. Ground Reaction Force and Interface Pressure

Results for the gait cycle test evinced that the average maximum (GRF) for the different artificial prosthetic knees, types K1, K2, K3 and K4 were (50kg, 48.75kg, 50.25kg, and 47.75kg), respectively, as shown in fig.7(a,b,c, and d). In the curves of fig. 7 The recorded average contact pressure in the foot for the different artificial knees types K1, K2, K3 and K4 were (183.3, 178.6,

168.5 and 180.25) Kpa respectively as shown in figure 8. The results demonstrated that the artificial knee type K4 is the best because of the good homogenous distribution of GRF between the healthy and the prosthetic limb, during which the difference between both healthy and prosthetic limb has the least values with 24%.

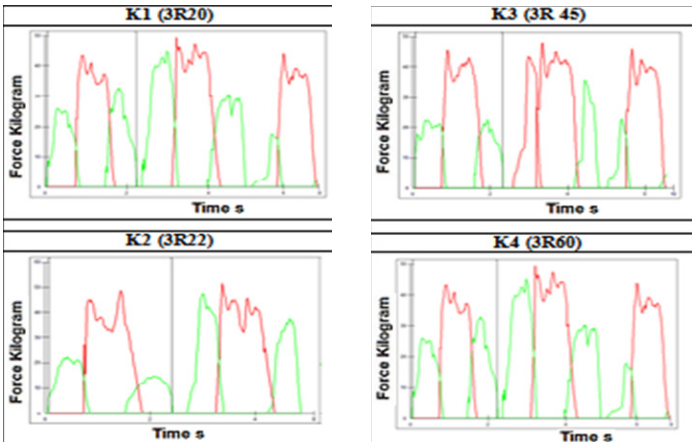


Fig. 7: Force vs. time curve for different types of knees.

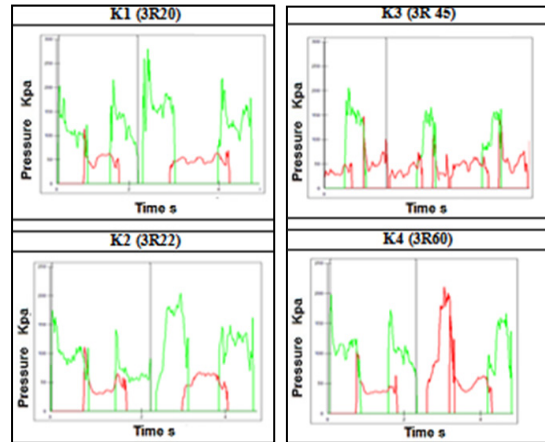


Fig. 8: Pressure vs. time curve for all types of knees.

Table (3) reveals the values of the recorded maximum interface pressure for different types of artificial knee types. It's clear that the knee joint K4 gives the best reading with the F-socket sensor. This is because it yields the minimum reading of interface pressure with a value of (132.42 KPa).

Table 3: The interface pressure of the prosthetic knee joints.

Prosthetic knee	Interface pressure (Kpa)
K1	158.1
K2	150
K3	145.09
K4	132.42

### 2.2. The Kinovea Test

The estimated velocity values for normal walking are (0.4, 0.64, 0.60 and 0.71) according to K1, K2, K3 and K4, respectively, as in fig. 9(a, b, c, and d) m/s. It is clear that the best type of knee is K4. This type of knee gives the best velocity with a value of 0.71 m/s, which is the nearest to the normal gait cycle velocity in comparison with the other types of artificial knees.

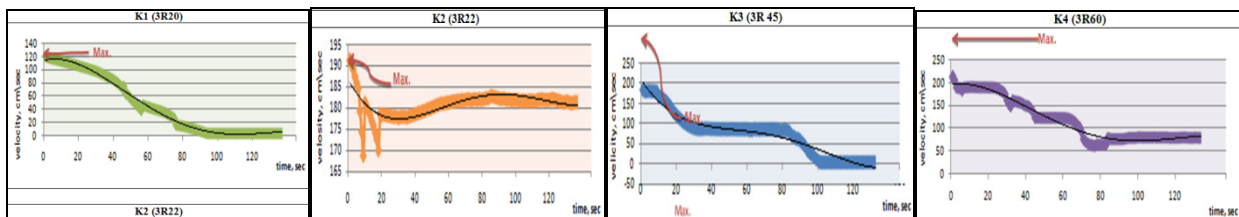


Fig. 9: Velocity with time curve for different types of prosthetic knee joints.

### 2.3. Mechanical Properties

The mechanical properties ( $\sigma_y$ ,  $\sigma_{ult}$  and E) that were obtained from the mean of the three tests performed on the composite material were later used for testing fatigue as well as being the vital data for the simulation of the prosthetic socket with the aid of ANSYS 14.5 in addition to the analyzing the stress and factor of safety. The values of the results obtained ( $\sigma_y$ ,  $\sigma_{ult}$ , E, Poisson's ratio( $\nu$ )) are 48.3 MPa, 62.3 MPa, 2.2 GPa, and 0.24, respectively.

## 2.4. Stress and safety factor Distribution

The (S-N) curve was drawn by the data obtained from the fatigue tests that were conducted on three specimens for six stress stages, and the resulted data are presented in fig. (10). These results were obtained from the fatigue testing, in which the no. of cycles is recorded on the "fatigue testing apparatus (Table 4). The (S-N) curve that was obtained from this test presents a clue to when the fatigue failure will occur under the fatigue life conditions. From this curve, the stress endurance limit was found 34.5 MPa for the composite material that was used. Figures (11, and 12) represent the Vonmises stress and factor of safety for prosthetic knee For type K1(3R20)

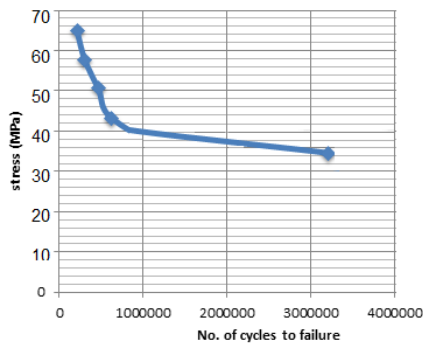


Fig. 10: The (S-N) for socket material.

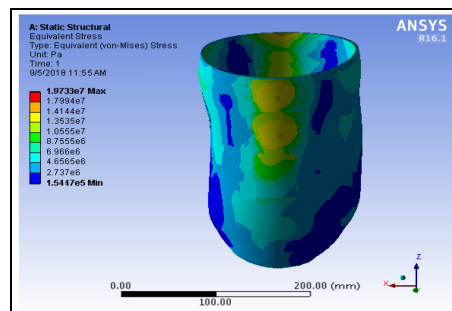


Fig. 11: Von-Mises stress for type K1(3R20).

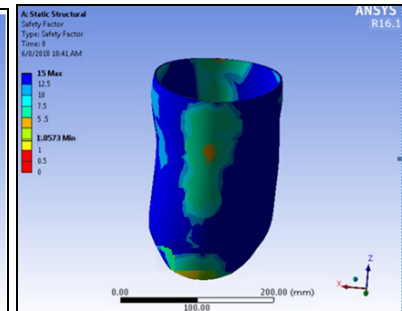


Fig. 12: Safety factor for type K1(3R20).

Table 4: Max, Von-mises stress and Min. factor of safety for different types of prosthetic knee.

Prosthetic Knee Type	Max. Stress	Min. factor of safety
K1(3R20)	19.73	1.85
K1(3R22)	17.55	2.11
K1(3R45)	15.64	2.84
K1(3R60)	14.21	3.11

## 3. Conclusions

- 1) According to the GRF test, and the contact pressure the artificial knee type K4 is the best because of the good homogenous distribution of GRF between the healthy and prosthetic limb, during which the difference between both healthy and prosthetic limb has the least value with (24%).
- 2) According to the gait cycle parameters, the artificial knee joint K4 yields the best symmetry between the healthy and prosthetic limb for the most gait cycle parameters.
- 3) According to the interface pressure results, the best type of knee is K4, which gives (132.42 KPa). This type of knee gives the best velocity with values of (0.71 m/s) which is the nearest to normal gait cycle velocity in comparison with other artificial knee type.
- 4) According to the ANSYS workbench results, the best type of knee is K4, which yields the minimum Vom-Mises stress with a value of 14.241 MPa and a maximum factor of safety with a values of 3.11.

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