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Bio-Mimetic Design and Performance Analysis of Passive Polycentric Knee Joint using Anthropomorphic Artificial Tendon

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Abstract—*Polycentric knee prosthesis use four bar mechanism to enable natural gait performance by amputees. Human knee consists primarily of three bones namely femur, tibia and patella along with ligaments called ACL (anterior cruciate ligament), the PCL (posterior cruciate ligament) which restrain the motion between bones. Conventional Single axis knee prosthesis rely on friction adjusted by a bolt for gait control. Other expensive knee prosthesis use hydraulic system to regulate swing of prosthetic shin with change in walking speed. Both hydraulic and friction knees can be either single axis or polycentric in nature. A polycentric human knee joint enables the femur to roll and slide on tibial plateau. We have developed a passive prosthetic knee joint design which has coupler link acting as ligaments and knee stiffness similar to that of natural knee. Resistive torque by tendons in natural knee was replicated using non-linear spring element in prosthetic model. Spring element tested under tensile load showed 3 phase stiffness characteristics similar to that of knee tendons. Kinematic analysis of linkages and stress analysis of knee joint was carried out. 3D printed prototype was tested to validate kinematic performance of prosthetic knee joint in comparison with the natural knee torque characteristics.*

Keywords*: Prosthetic Knee, Passive Knee joint, Knee torque characteristics.*

1. INTRODUCTION

Amputation causes impairment in balance, walking co-ordination and inculcation of fear of falling [1]. With majority of amputation happening because of accidental trauma or vascular disease, the demand for knee prosthesis is high [2]. The World Health Organization (WHO) has estimated that there are about 30 million amputees in developing countries as of 2010 [3]. A locked knee results in stiff-legged gait, which requires numerous compensatory efforts that significantly increase the heart rate of amputee during walking [4]. Studies conducted on children and adults show that the slope of relative torque-angle curve first increases until peak torque is achieved around 80 degrees and then begins to decrease [5].There are many polycentric prosthetic knee in the market which utilize either actuators or artificial muscles for controlling knee movement and torque for standard gait [6]. The model under consideration has a polycentric knee with passive joint system which returns energy during later phase of gait cycle after push-off [7]. Natural knee torque characteristics is replicated by a bungee cord acting as a tendon with nonlinear load-deflection curve [8]

The objective of this study is to achieve kinematic performance of knee prosthesis similar to that of natural knee. This includes achieving non-linear torsional stiffness of knee, mathematical modelling of governing torque-deflection equation and validation of range of motion. Kinematic model of knee joint was used to find knee torque characteristics. Experimental verification of knee torque was carried out by measurement of force required to flex the knee with incremental change in flexion angle

2. METHODOLOGY

The product of the force applied to a joint and the perpendicular distance between the line of the force and the joint center of rotation can be defined as knee torque. The relationship between torque and passive knee angular flexion was found to be non-linear whose slope first increases and then decreases along the range of motion. Tendons bind muscle and bones and are made up of longitudnally running collagen fibers. Bungee cord exhibits similar structure with latex fibers in place of collagen tightly packed together. Force Applied by Quadriceps tendon Figure 1 and Patellar tendon in figure 1 at a distance enables angular displacement of tibia with respect to femur. To facilitate angular movement of prosthetic knee at required torque rate, a bungee cord of was fixed between femoral condyle and tibia plateau

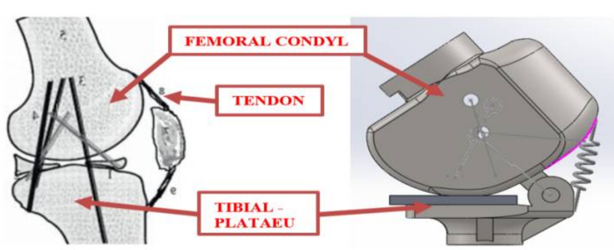

Figure 1: Structure of Human Knee Vs Prosthetic knee

Stiffness Characterization of Bungee cord

The required bungee stiffness for the prototype was determined by performing regression of Load-Deflection data from tensile test of bungee cord in figure 2. According to litrature, response of a tendon can be divided into 3 regions [8]. First is the toe region where collagen fibers straighten which results to increase in stiffness. Second Region is phase of constant stiffness of tendon where slope remains constant and region 3 is where micro-crosslinks between fibers fail and stiffness again decreases. Further loading of tendon past this point leads to tearing of tendon. Stiffness of the bungee cord was found by linear regression load-elongation data in region 2 given by equation 1. Resistive force induced in the bungee cord for all three domains was given by Equation 2

$$Fy = 0.0296x + 9.8962 \quad (1)$$

$$Fy = 0.5077x^{0.6366} \quad (2)$$

Where X is the deflection of bungee cord from its initial length during tensile test on a UTM. Constant value in equation 1 corresponds to force exerted by bungee cord at 4% strain value which can be seen in figure 2. According to literature, region 2 of constant stiffness lies beyond 4 percent strain. Force generated by the cord was resolved to in the direction normal to the femoral member to give torque vs knee angle characteristics

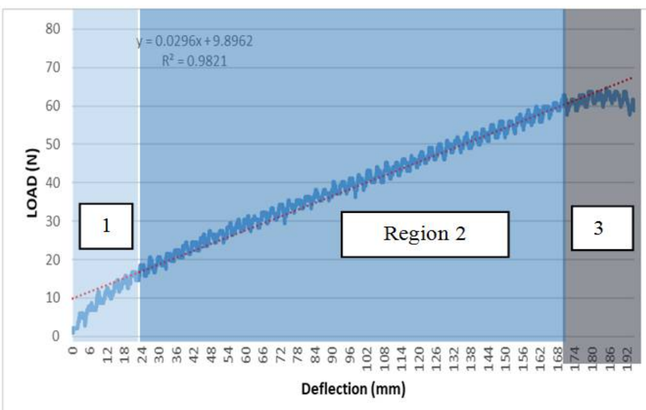

Figure 2: Load Vs Deflection Curve of bungee cord

3. POLYCENTRIC KNEE MECHANISM

- For a polycentric knee femoral condyle rolls and slides on tibial plateau with the help of ligaments. For passive knee joint motion the ACL (anterior cruciate ligament), the PCL (posterior cruciate ligament) perform restraining action to enable relative movement between femur and tibia. Each of the ligaments was modeled as a straight rigid link that is attached to the tibia at one end and the femur at the other end. Revolute joints were used make a four bar mechanism which mimics motion of Tibia and Femur relative to each other. The co-ordinates of ACL and PCL with reference to center of femoral condyle was calculated from O'Connor [9].

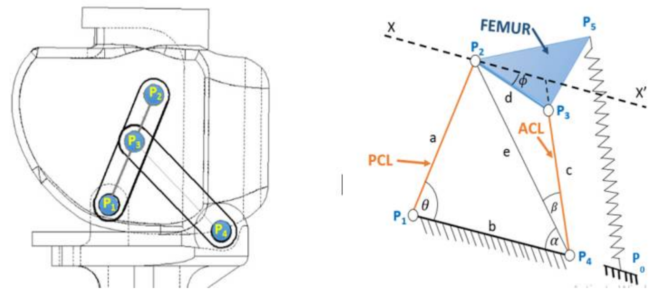

Figure 2: Polycentric Knee Joint and Equivalent Four Bar Mechanism

- Force exerted by the bungee cord can be found out by substituting the value of deflection of cord (P_5 –P_0) in stiffness equation 1. Equivalent kinematic chain of prosthetic knee is shown in figure 2 where Link A and Link C are the ACL (anterior cruciate ligament), the PCL (posterior cruciate ligament) respectively. The femoral condyle is approximated in the form of a ternary link with elastic cord attached to point P_5.
- Both ACL and PCL are joint to the femur at point P_2 and P_3 respectively. Angle (ϕ) is the angle of knee flexion plot of which with respect to flexion Torque gives characteristic Knee-Torque curve. Angle (ϕ) is defined with respect to line XX' which is parallel to P1–P_4. With Positon of Joint P1 and P_4 fixed, equation of positon of other points can be found out by the sine and cosine rule for triangles using link lengths. Length P_4–P_2 varies with (θ) and can be found out be equation 3

$$e = a^2 + d^2 - 2ad\cos\theta \quad (3)$$

- Using Distance P_4 – P_2 angles (alpha) and (beta) were calculated using cosine rule for triangles are given in equation 4 and 5. Geometrical distance between bungee cord anchor point Po and P_5 was found to calculate deflection of cord. Co-ordinates of Points P_5 were represented in terms of link lengths and angle α, β *and* θ which were input variables for this problem dependent on knee flexion angle(ϕ).

$$\alpha = \sin^{-1}\left(\frac{a\ \sin\theta}{e}\right) \quad (4)$$

$$\beta = \cos^{-1}\left(\frac{e^2 + c^2 - b^2}{2ec}\right) \quad (5)$$

Above equations were solved using MATLAB and values of spring deflection were substituted in stiffness equation 2 of bungee cord. Force exerted by the cord was calculated which provides necessary knee flexion torque for gait stability. Natural knee torque has been found to peak around certain 80 degree with decrease slope beyond peak torque. Theoretical Flexion torque for prosthetic knee joint found out by solving governing trigonometric equations peaked at 75.9 degrees. Nature of torque of polycentric knee vs knee flexion angle is shown below in figure 3

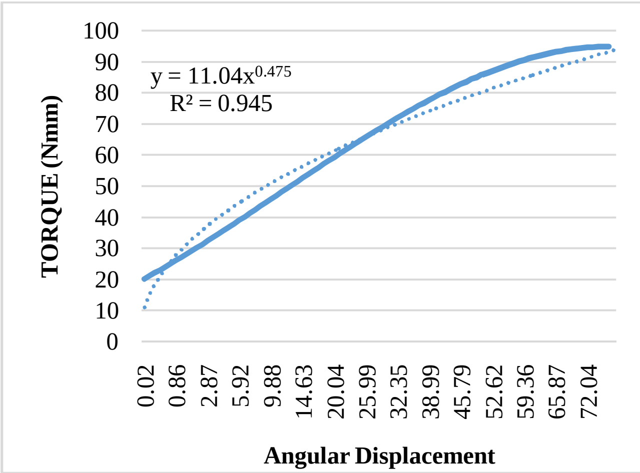

Figure 3: Knee Torque Vs Flexion Angle plot from geometrical model

4. STRESS ANALYSIS

X-ray images of human knee were traced with the help of solid modelling software to make a profile of femoral condyle of prosthetic knee. Tibial plateau was assumed to be flat and size of both tibia and femur were made within the bounding box size of human knee. B-spline profile of femoral condyle had maximum arc radius of 147mm at the bottom. CAD model was analyzed to check the von mises stress with respect to tibia-femur contact stress in human knee joint. A load case of 784N load in Z direction along the direction of tibia was applied. Von mises stress in prosthetic knee joint was found to be 53 percent less compared to stress in human knee joint.[10] Tibial plateau was assigned fixed support so that stress is induced at the tibia-femur interface

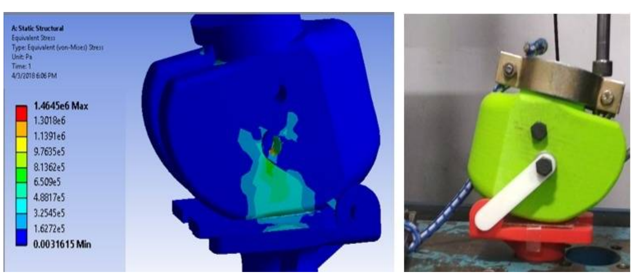

Figure 4: FEA analysis of Prosthetic knee joint and Experimental Setup

5. RESULTS AND DISCUSSION

Range of Motion test was performed first, measuring the angle before and after the full flexion of knee. The base of the tibial member and one end of the bungee cord was fixed to the worktable as shown in figure 4. Force required to turn femoral condyle of prosthetic knee was measured by attaching UTM probe to the clamp on prototype. Vertical displacement of UTM pickup point on knee clamp enabled rotation of femoral condyle. Torque was calculated by product of force by UTM and the moment arm length from prototype geometry.

6. TORQUE RESPONSE

Using power regression of torque VS flexion angle data degree of closeness of experimental and mathematical model of knee was determined. Mathematical model hence verified is usefull for predicting actual knee torque at different flexion angle during stance or gait condition.

A governing equation of Resisting torque was formulated from mathematical model and experimental results by performing regression analysis as shown in equation 5. Where A and B are the constants for best fit line with uncertainity less than 10 percent. Results found are in Table 1.

$$T = A\,\phi^{B} \tag{6}$$

Table 1: Peak torque values from multibody simulation and experiment

	Peak Torque (Nmm)	Constant A	Exponent B	Range of motion (degree)
Simulation	90	11.044	0.4753	75.9
Experimental	61.25	11.631	0.3389	73.5
Error	28.75	0.587	0.1311	2.4

The fitting equation for both mathematical model and experimental data had and confidence level(R^2)values of 0.906 and 0.945 which indicates the degree of agreement between actual values and formulated governing equation. Knee torque value for both experimental data and mathematical analysis peaked between 70 to 75 degree flexion angle in comparison to 81 degree for human knee[4].

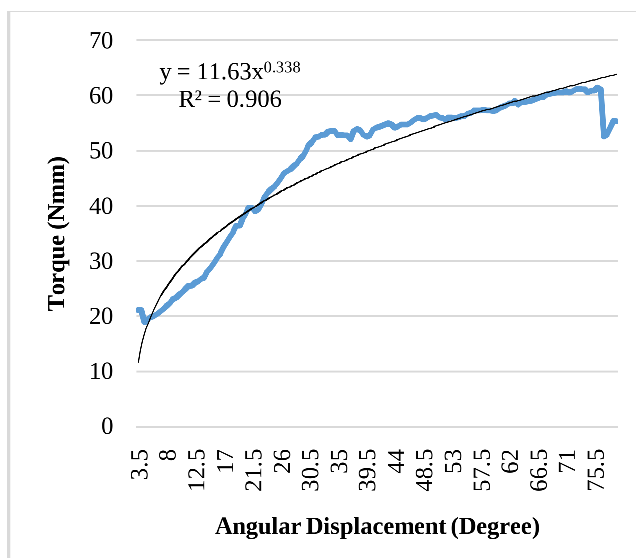

Figure 4: Experimental Torque response with governing torque equation

7. CONCLUSION

The results indicate that range of motion of up to 75^0 in flexion could be achieved with the prototype. Plot of knee torque with knee flexion angle exhibits non-linear characteristics with increase in slope representing angular stiffness of knee joint. Bungee cord as passive spring element in knee joint subjected to tensile load shows similar load-deflection characteristics as that of tendons. Test results show that the stiffness of bungee cord remains constant beyond 4 percent strain and reduces when peak load is applied. Average Torsional Stiffness of knee was obtained from power regression of experimental data. The reported error is minimal in case of torsional stiffness of knee. Both mathematical model of knee joint and stiffness equation of bungee cord was validated experimentally with less than 10 percent uncertainty. Governing equations helps us to design knee joint specific to the needs amputee's weight and utility. Arrangement of preloading of cord facilitates tuning of knee stiffness for various stance phases like sitting and standing. Biomimetic design of coupler link in polycentric knee helps in replication of biomechanical performance of human knee in prosthetics.

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