A bio-inspired condylar knee joint for leg amputees and for knee implants

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Abstract

This paper presents a novel bio-inspired condylar prosthetic knee joint developed at the University of Bristol. The bio-inspired condylar joint mimics the structure and biomechanics of the human knee joint. The joint contains an inverted parallelogram four-bar mechanism combined with a cam mechanism. The joint has a favourable mechanical advantage compared to a hinge joint. The joint is also compact and robust. An adult-sized prototype joint has been designed and tested. The prototype joint contains a long cable for the ligaments with a mechanism for adjusting preload. Compared to other prosthetic joints, the condylar joint has the advantages that it is simple and closely mimics human biomechanics. The paper presents the design of the new artificial knee joint and presents some of the test results. The joint can be used in artificial legs and also for knee implants.

Keywords: cruciate ligaments, four-bar mechanism, bio-inspired hinge joint, prosthetic joint, moving centre of rotation.

1 Introduction

One of the first recorded artificial knee joints was that produced by Ambroise Pare, a French surgeon, as part of an artificial leg in the sixteenth century. The first implanted knee replacements were carried out in 1972 by John Insall, an English surgeon living in New York, who implanted a prosthesis to replace the three surfaces of the knee - femur, tibia and patella (knee cap) [1]. At present there are around 5,000 leg amputees per year in the UK. In addition there are 70,000 knee replacements carried out each year in the UK. Artificial knee joints are an important medical device that enables many people to maintain walking

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and running functions. Ideally, a prosthetic knee joint for leg amputees or knee implants should (i) mimic the motion of a human knee, (ii) fit within the envelope of a human knee, (iii) be lightweight, (iv) mechanically efficient and (v) be shock absorbing. These are very difficult attributes to achieve because of the tight space limitations of the human knee and because of the complex biomechanical movement of the knee joint [2, 3].

Prosthetic knee joints generally contain four-bar mechanisms in order to produce a moving centre of rotation as happens with the human knee. Some common designs are shown in figure 1. There are two main categories of control of prosthetic knee joints - microprocessor control and mechanical control. Microprocessor control involves the use of an electronic unit which evaluates and makes internal adjustments to control the motion of the knee. Mechanical control involves the use of a mechanical hinge which is automatically controlled by a four-bar mechanism.

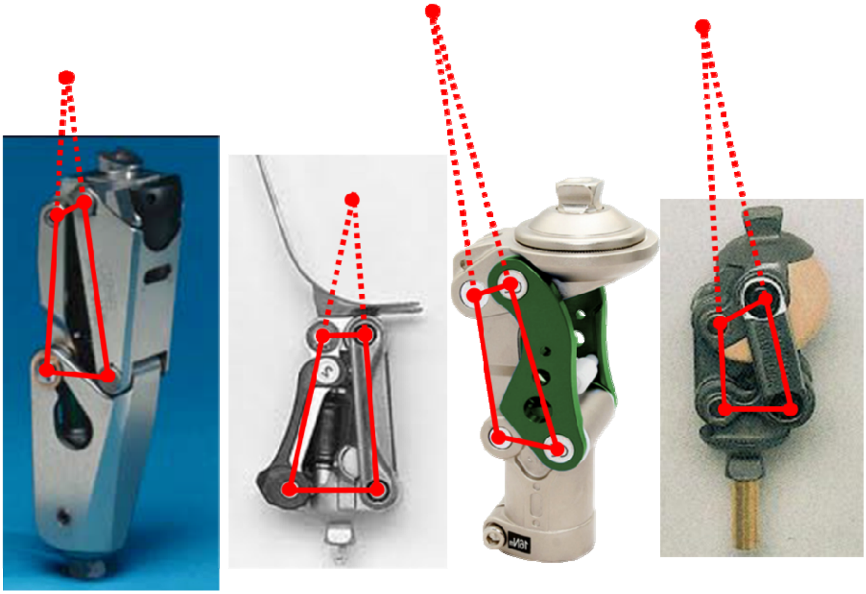


Figure 1: Instant centres of rotation for several polycentric prosthetic knees [6–8].

Biomechanical variables, such as a moving centre of rotation, have an important effect on the energy requirements of walking and running in able-bodied persons [4]. In the literature, prosthetic knee joints have been classified according to the level of complexity [5]. The most complex of these is the polycentric prosthetic knee (four-bar knee) which has its instantaneous centre of rotation (ICR) located at the intersection of the anterior and posterior links which is located above the knee joint as shown in figure 1. While the ICR moves anteriorly to the ground reaction force, resulting in an increase of the knee extension moment, the stability of the prosthesis is maintained. Hence, the four-bar configuration enables an optimisation of the swing and stance phase during locomotion and an increase of the knee stability.

This paper presents a bio-inspired condylar knee joint for prosthetic applications using a crossed four-bar mechanism (inverted parallelogram mechanism) which has the same advantages of a parallelogram including compactness, high stiffness and locking in the upright position.

2 Biomechanics of the human knee joint

2.1 Biomechanics of the knee joint

The human knee joint is more complex than a hinge joint because during locomotion, rolling and sliding occur at the joint interface. There are three different types of structures defining the knee joint behaviour: static (geometry and anatomy of the joint surfaces), active (muscle tensions) and passive (ligaments). The knee joint comprises the articulation of the femur over the tibia (tibiofemoral joint). The main functions of the knee are to absorb and transmit the load while allowing rotation of the joint. The femur has a convex surface and the tibia a matching concave surface which allows the bones to roll over each other. Straightening of the leg is called extension, whereas bending of the leg is called flexion.

The motion of the knee is commonly modelled as a planar four-bar mechanism as shown in figure 2. The motion of the knee is guided by the anterior (ACL) and posterior (PCL) cruciate ligaments. The crossed four-bar mechanism is an inverted parallelogram mechanism. At different knee flexion angles, the ICR is located at the point at which the ACL and PCL cross. The centre of rotation follows an elliptical pathway (‘J’ curve) [9] and moves typically by around 2 centimetres in a healthy adult knee joint [10]. The motion of the four-bar mechanism is compatible with the cam profile of the condylar bones.

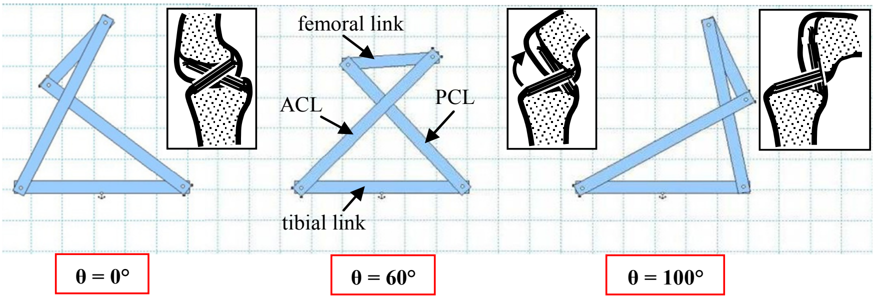


Figure 2: The four-bar mechanism of the human knee joint.

Another important feature of the human knee joint is that the joint locks in an upright position. This reduces the work performed by the quadriceps muscles during standing [10]. The supporting structures of the mammalian knee joint such as ligaments, menisci, and articular surfaces (femoral condyle, tibial plateau) help guide and provide stability during the joint's motion [12–14].

2.2 Key design features of knee with biomimetic potential

The key features of the human knee joint that are of interest for a bio-inspired prosthetic joint design are:

- Separation of structural (compression joint) and kinematic (four-bar mechanism) functions;
- Curved (condylar) joint giving high conformity and therefore high stiffness and strength;
- Moving centre of rotation giving potential for optimal mechanical advantage;
- Simplicity of design giving potential for compactness and robustness;
- Locking in upright position.

By having a separation of functions it is easier to achieve optimisation of design because the two mechanisms can be optimised fully for their particular function. The compression joint is optimal because it avoids bending moments by forming a simple compression joint. In contrast, joints like the hip joint have high bending moments because of the offset between the ball and the main structural members. Whereas the hip joint is vulnerable to failure due to impact bending loads, the knee joint is relatively robust. A component is generally more structurally efficient when bending moments are minimised because bending moments are a type of force amplification [15, 16]. The simple compression joint of the knee leads to it being a very compact and optimal joint.

3 Biomechanics of walking, running and squatting

An understanding of knee kinematics during daily life activities (walking, running and squatting) is necessary to be able to design an effective prosthetic knee. There are several terms which are commonly used for characterizing gait that are unified among researchers. A gait cycle is usually defined as the movements and events that occur between successive heel contacts of the same foot [17, 18]. The gait cycle has two phases: stance (foot on the ground) and swing (foot off the ground). These two states vary depending on the activity as shown in figure 3. While normal walking is defined in terms of double support, two limbs in contact with the ground, running is identified by its double float period, no contact of both limbs with the ground.

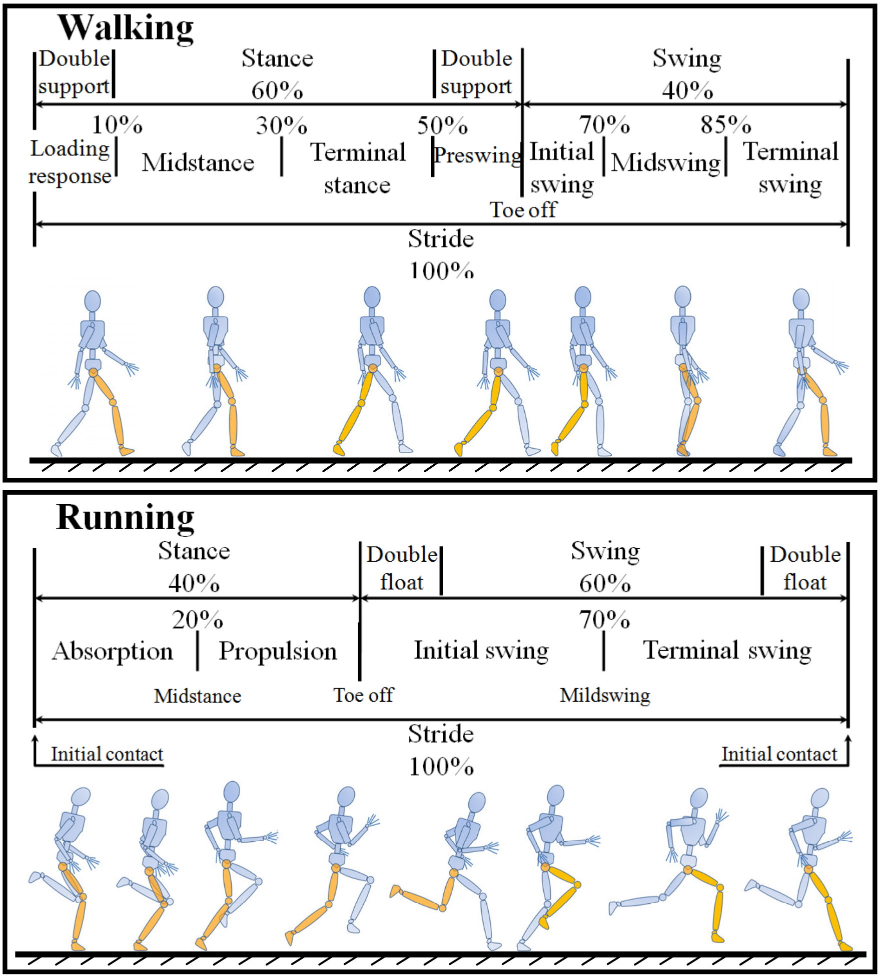


Figure 3: Gait cycle terminology used for walking and running adapted from [17].

For athletes, the squat exercise enhances athletic performances while minimising risk of injuries [19]. The squat exercise is also commonly used in knee rehabilitation because it is a weight-bearing exercise whereby the patient utilises his own body-weight [20, 21]. There are usually two types of squat, the half squat or full squat, depending on the degree of knee flexion. The half squat is when the body stands upright and gradually flexed until the thighs are parallel with the ground (approximately between 0 – 90 degrees of knee flexion). The deep squat involves squatting down until the posterior thighs and shank makes contact with each other [22]. Throughout all these knee movements, the passive characteristics of the anterior-posterior motion are related to the shape of the articular surfaces and ligament function [23]. Thus, the typical activities of daily living show that knee motion is activity dependant and requires a complex set of moving parts acting together which can accept, transfer and dissipate loads generated at the ends of the long mechanical lever arms of the femur and the tibia. Figure 4 shows a deep squat with a flexion angle of 140 degrees.

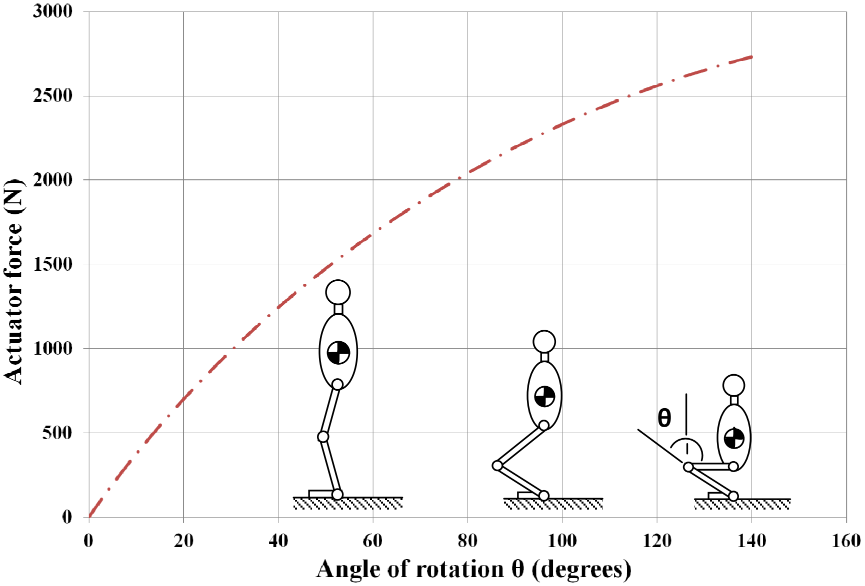
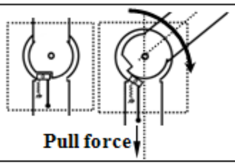
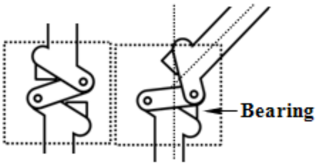
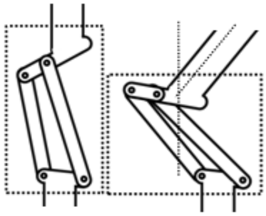
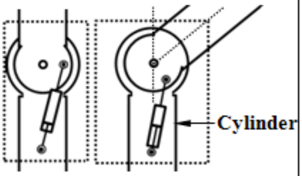
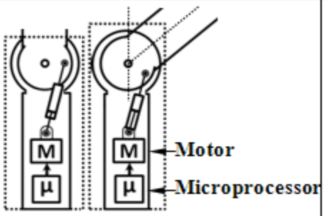
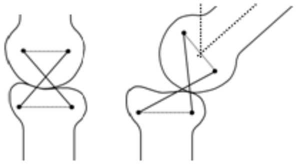


Figure 4: The force required for a deep squatting motion for the four-bar hinge.

4 Existing prosthetic knee joint design for artificial legs

Table 1 shows different existing prosthetic knee joint designs together with the condylar joint with their respective advantages and drawbacks. The manual locking knee locks in the straight position during walking and can be manually unlocked in sitting position by pulling a cable. The stance control knee contains a weight-activated friction brake preventing the knee from bending and buckling when the amputee puts weight on the prosthesis. The polycentric knee, called four-bar knee, is used by a wide range of amputees due to its complex mechanism which allows flexibility in stability settings and variable speeds. Pneumatic and hydraulic knees are fitted with cylinders, containing air or fluid respectively, which controls the speed of the knee flexion. Microprocessor knees are the ‘smart’ knees because due to their active control (microcontroller) they assess the forces acting on the joint and to quickly accommodate for speed, stability and internal adjustments.

Table 1: Different prosthetic knee designs for amputees.

Knee designs	Schematic	Compactness (1: poor, 5: good)	Adjustment for sitting	Locking system for standing	Range (degree)
1 Manual Locking Knee 		4	Y	Y	0 - 140
2 Stance Control Knee 		3	Y	N	0 - 150
3 Polycentric Knee 		2	N	N	0 - 160
4 Pneumatic/Hydraulic Knee 		1	N	N	0 - 160
5 Microprocessor Knee 		2	N	N	0 - 130
6 Condylar hinge joint 		5	Y	Y	0 - 160

5 The novel condylar knee joint

Figure 5 shows the prototype model of the bio-inspired condylar hinge joint. The design mimics the curved profiles of the human knee joint in order to achieve the benefits of high conformity and high stiffness and strength. The design also copies the four-bar motion of the ligaments. However, the ligaments are positioned differently to a human knee. Instead of locating one set of crossed members in the centre of the joint as with the human knee joint, the design has two sets of cruciate ligaments with one set on each side of the joint. This provides stability and alleviates the need for additional ligaments to surround the joint.

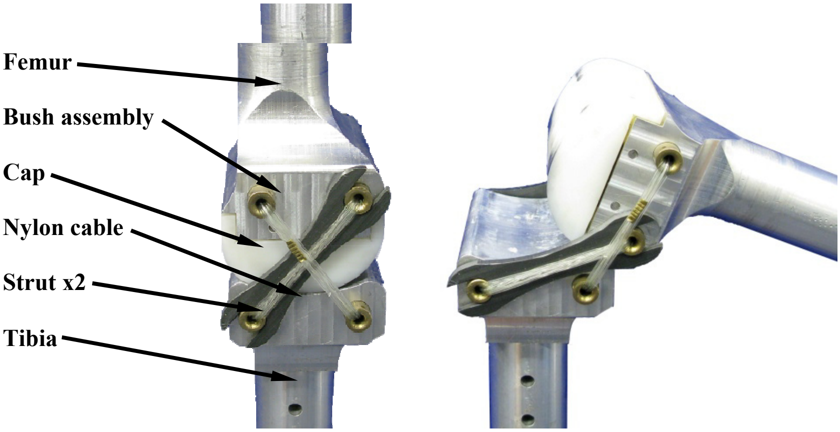


Figure 5: Prototype condylar hinge joint.

The femur and tibia components taper down to a 35mm circular section which is approximately equal in size to human bone. The femur component has a white nylon end cap in order to provide an appropriate material for sliding and rolling against the metal tibia. The curvature of the femur and tibia components was designed to match the moving centre of rotation of the four-bar mechanism. The prototype gives 160 degrees of smooth motion whilst maintaining joint integrity. Another difference with the human knee joint is that the cruciate ligaments are not separate ligaments but one continuous ligament which is threaded through the joint. Both the tibia and femur components have two holes drilled across their whole length with brass brushes inserted as shown in figure 4. There are a number of advantages of having a continuous cable threaded through the joint:

- The cable has no need for anchor pivot points.
- The cable is only one component.
- The cable holds the joint in the lateral position.
- The upper and lower condyles have no cut-out.

Early prototype testing showed that the joint is very sensitive to the level of tension in the cable. If tension is too high the friction is high, but if tension is too low the knee is unstable. A reliable tension was achieved by creating compliance in the cable system. This was accomplished by having a single long continuous cable threaded through each tension sleeve. In addition, the cable consisted of a single fine wire that was threaded through the joint 11 times.

By having one continuous cable, the length of the cable is very long. The total cable length in the prototype is 3.124m. Over this length, it was feasible to create a compliant cable that could have adjustable preload. Adjustment of preload was achieved through the use of a threaded joint in the brass bushes that adjusted their length. Changes in bush length changes the cable length and hence cable tension. The individual cable wire was made from monofilament nylon of 0.65 mm diameter. It was joined using specially designed crimps. The cable assembly was pre-tightened to give a tension of 3.7N. The cable assembly has a breaking strength of 2500N.

Experimental testing on an early prototype showed that when the joint rotated through more than 60 degrees from the straight, the bearing surfaces slid past one another thus creating instability in the joint. This slippage was due to: (1) lack muscular action to hold the joint together in the artificial joint, and (2) lack of menisci to withstand shear forces and to distribute tensile and compressive loads. This issue was addressed through the use of a compression bar across one diagonal of each four-bar mechanism as shown in figure 5.

The biomechanical design of the artificial knee is very similar to a knee joint in the plain of motion. It should be noted that the condylar hinge requires the extensor and flexor actuator to move through different length ratios as the mechanical advantage changes.

6 Performance

6.1 Test rig

A test rig was designed to simulate a ‘squat’ or ‘leg press’ situation while applying a load on the knee. This was chosen as the knee moves through a large angle of rotation and the loading is constant (equal to body weight). Figure 6 gives a picture and a schematic diagram of the test rig. Initial tests at low load levels were carried out in order to allow the joint to run in. The motor was capable of cyclic loading the joint at a rate of 20 rpm which corresponds to 20 squats per minute. It should be noted that actuation was achieved by directly driving the tibia component and not through tendons in the knee joint. The rig was used to apply 50,000 cycles under load. The rotation of the knee in the sagittal plane during normal walking goes up to 65 degrees and corresponds to a distance travelled of 1 meter. Therefore the tests correspond to a distance travelled of approximately 100 kilometres. The performance of the joint was re-assessed by measuring the friction and stiffness of the joint as well as visually inspecting the bearing surfaces.

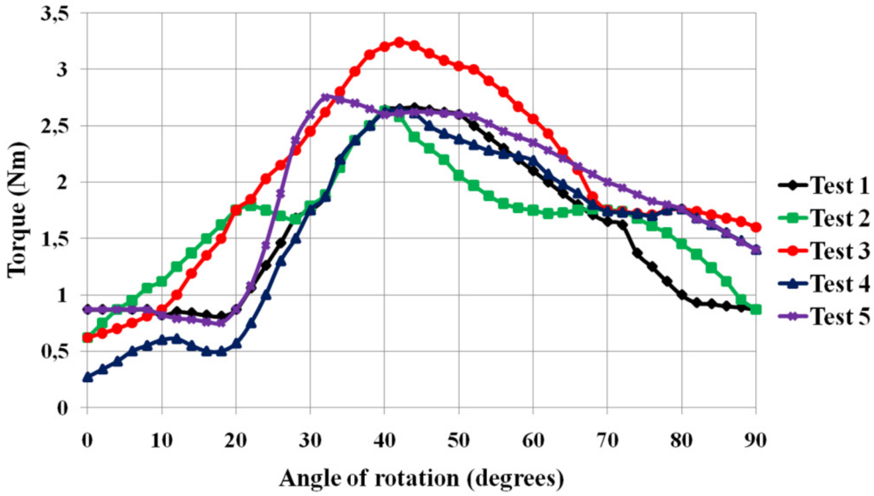


Figure 6: Changes in friction during test program.

6.2 Life testing with 10kg and 20kg loads

Life testing was carried out in five stages as shown in table 2.

Table 2: Test program.

Test number	Number of cycles	Loading (kg)
1	15000	10
2	10000	10
3	5000	20
4	10000	20
5	10000	20

Figure 7 shows the results of frictional tests carried out after the five sets of tests. The reason for doing the frictional tests was to see if pre-tension had been lost due to wear. The results show that the frictional torque profile was reasonably consistent throughout out the tests indicating that pre-tension was consistent and that wear was minimal. Visual inspection also showed that wear was minimal.

7 Conclusions

This paper has presented a bio-inspired condylar design of knee joint for prosthetic applications. The joint mimics the condylar surfaces of the femur and tibia bones in the human knee joint and also mimics the four-bar motion of the cruciate ligaments. The bio-inspired design has the same desirable features of a human knee joint including a moving centre of rotation, high strength, high stiffness, compactness and locking in the upright position. The bio-inspired design could be used for artificial legs or for knee implants. Experimental tests have verified kinematic, stiffness and life performance of the joint. A key feature of the design is its simplicity and similarity to the mammalian knee joint.

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