A bioinspired compliant knee joint for walking robots, prostheses and exoskeletons

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1. Summary

• We present a novel design for a bicondylar joint that mimics the physical mechanisms in the human knee.

• The joint replicates the smooth condyles, compliant ligaments and tendon driven actuation of the human joint.

• As a result, the moment arm the actuators can impart changes with angle and the locations of the cable ('tendon') attachment points affect the shape of this curve.

• A simple kinematic model is used in the design process to generate the tibia profile and to select the cable attachment points so that the joint moment arm best matches that in the human knee.

• In the kinematic model we show that the by using our joint the minimum actuator volume for stair ascent may be reduced by 12% compared to a joint with a constant moment arm.

• The joint has been manufactured and tested in a specially made squatting test rig. Here we show that the moment arm of the joint is similar to both that predicted by the model and the human extensor moment arm.
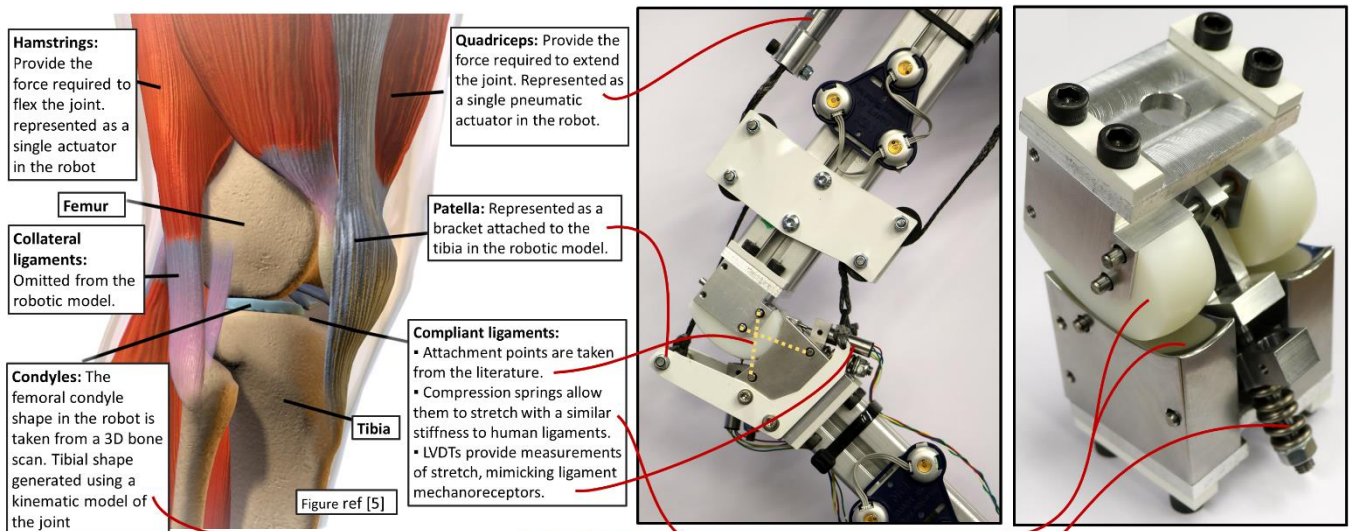
2. Background

Bioinspiration in walking robots has been used to great effect in order replicate the overall dynamics and achieve some of the efficiencies of human gait [7]. However it has often been the case that those robots that achieve similar levels of efficiency perform less well at high load tasks [8]. To address this, we are focusing on the specific mechanical properties and geometry of the human knee. For example, in humans the largest knee moments required to perform high load tasks are found in the midrange of motion which matches the location of the maximum moment arm [2, 9]. At the extremes of motion the moment arm is smaller, reducing both the total distance the muscles need to move and size of moment at the point where it could have a damaging hyperextending effect.

Our joint has been designed and manufactured with two smooth curved surfaces (condyles) that slide and roll over each other as the joint rotates; two ligament-like springs with the ability to measure stretch hold the joint surfaces together; Actuators drive the joint via cables representing tendons (Figure 1). The resulting joint therefore obtains many of the mechanical properties of the human knee.

Prior work in the area by Etoundi et al [6] has investigated the benefits of condylar joints without tendon driven actuation, compliant ligaments or such a stringently bio-inspired geometry. They showed that the design might have mechanical benefits for mechanical advantage and out of plane stiffness. We take the concept further with the anticipation that a closer representation of the human knee will further improve mechanical advantage for the common high load tasks that human legs perform. This, we hypothesis, will lead to both a reduction in actuator sizes required for tasks such as stair ascent and more human like walking. Additionally, we are in the process of investigating the use measurements of stretch in the compliant ligament-like springs for estimating joint angle. This work is still in progress although initial results are discussed in a paper currently under review [3].

Hamstrings: Provide the force required to flex the joint. represented as a single actuator in the robot

Femur

Collateral ligaments: Omitted from the robotic model.

Condyles: The femoral condyle shape in the robot is taken from a 3D bone scan. Tibial shape generated using a kinematic model of the joint

Quadriceps: Provide the force required to extend the joint. Represented as a single pneumatic actuator in the robot.

Patella: Represented as a bracket attached to the tibia in the robotic model.

Compliant ligaments:
▪ Attachment points are taken from the literature.
▪ Compression springs allow them to stretch with a similar stiffness to human ligaments.
▪ LVDTs provide measurements of stretch, mimicking ligament mechanoreceptors.

Tibia

Figure ref [5]

Figures 1 a, b & c: Bioinspired joint design. Images from paper currently under review [1]

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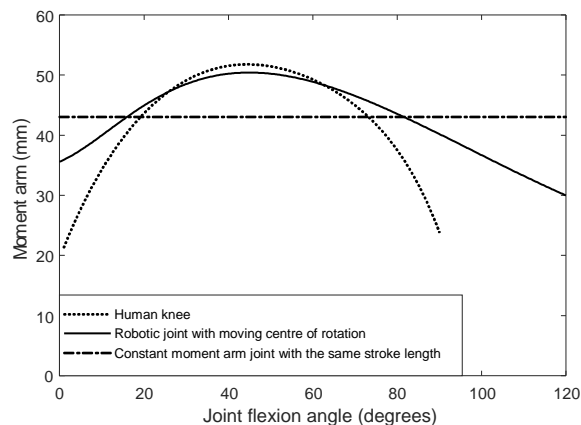E-mail address: felix.russell12@imperial.ac.uk

Figure 2: Predicted moment arm from kinematic model [3]. Human moment arm from data in Krevolin et al [2]

Figure 3: Measured robotic moment arm compared to the kinematic model and the human knee. From paper under review [1].

3. Kinematic model for joint design

A kinematic model was developed to derive a suitable shape for the tibial condyle given values of femur shape, ligament attachment locations and ligament lengths (as a function of angle) - all taken from human studies. Additionally, the model allowed us to estimate the moment arm (as a function of angle) of the actuators about the instantaneous centre of rotation of the joint. The cable attachment points affected the shape of this curve. We therefore performed an optimisation and selected cable attachment points so that the mean absolute difference between the joint's moment arm profile and that of the human knee was minimised.

The model was also used to calculate the required force and actuator stroke length for a high load task, stair climb. For a pneumatic or hydraulic actuator force/pressure x length is proportional to the required volume. The model shows that an actuator volume reduction of 12% may be possible for this task using our joint compared to an alternative with a constant moment arm [3] (Figure 2).

4. Model validation

The optimised design has been manufactured (Figures 1b and 1c) and a squatting rig was built to test the joint and validate the model used to design it. Using a tracking camera the location of the centre of rotation and the moment arm of the extension actuator was calculated (Figure 3). Throughout testing the joint was moved under no actuator load in order to best match the kinematic model. The mean absolute difference between the model moment arm and measured values was 2.6 mm (σ 2 = 1.3) or a 6.1 % (σ 2 = 8.3) deviation [1].

5. Discussion and conclusion

In our joint the maximum moment arm in the kinematic model is 50.4 mm achieved at 44.8º flexion [3], compared to 51.8 mm at 43.9º found in the human knee [2]. Slightly different behaviour was observed in the manufactured prototype of the joint but the overall shape of the curve remained similar. In fact near to extension the manufactured joint was a closer match to the human moment arm curve than the model predicted. We know from previous studies on an earlier version of the design that
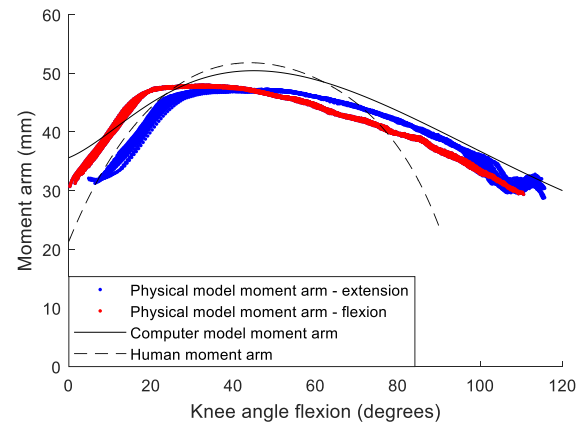
internal and external joint forces have a fairly significant effect on how the ligament-like springs stretch as a function of angle [4] and this may translate into an effect on overall joint dynamics. We are yet to investigate how these forces might affect the moment arm relationship and path of centre of rotation. However, we hypothesise that the relatively small magnitude of spring stretch compared to moment arm length will mean that the effect of forces on centre of rotation and moment arm will be small. Furthermore, we hope that making good use of the antagonistic pair of actuators will give us some ability to control and reduce any undesirable amounts of spring stretch. This will be a topic for further investigation.

To the best of our knowledge, this is the first mechanical knee joint system that combines all these features of the human knee. We anticipate that walking robots, prostheses and exoskeletons will achieve an improved ability to perform both high load tasks and humanlike walking by employing our joint.

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