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LigamentalJoint: A Tough and Ultra-lightweight Revolute Joint

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1 Introduction

Biomimetics is usually a promising approach to reproduce animal behavior, although most biomimetic robots are still inferior to living organisms in practical use, such as integrity and lightness. Observing the conventional biomimetic robots to find out the cause, the difference between living organisms and industrial products will be highlighted. The animal joint has superior movability although there is some errors of mechanical property due to the repetition of damage and reproduction. For example, when designing the leg joint with one-degree-of-freedom, most robot designer employ a high-precision pin hinge joint composed by a shaft pin and a bearing. In contrast, the pin hinge joint is rarely used in nature. That is to say, the conventional biomimetic robots have been able to reproduce the structure of living organisms at superficial-level, but not at element-level. Each machine elements have been selected from standardized and existing industrial products, therefore the implementation of the robots have been limited by convention of industry.

The pin hinge joint has been significantly employed in industrial designing, however have following disadvantages.

- Load concentration is likely to occur by greatly limiting the degree of freedom of the system.
- Weight of the mechanism increases to prevent destruction by the load concentration.
- Movability is significantly impaired when some deteriorations vary the constraint conditions of the mechanism (e.g. machining error, distortion and rust).

The conventional robots with many pin hinge joint are expensive and heavy, and yet delicate against disturbance such as impulsive forces. Therefore we often had to deal with robots for overprotective. In contrast, the animal body have highly flexibility and lightness to adapt to harsh environments. Additionally, the animal joint has superior movability although there is some errors of mechanical property due to the repetition of damage and reproduction. Considering from above, the animals seems to adopt a robust design against mechanical error and deteriorations.

The biomimetic approaches of animal's functional elements without using the industrial designs have been mainly tried in the field of biofabrication. Biologists propose several biocompatible materials by replicating the living organisms [1]. Also, several studies [2, 3] that tries to replicating the living organisms in the field of robotics. Although these studies copied the biomechanical functional element directly by tailor made approach, and lacking mass productivity. To achieve both mass productivity and function, we need to redesign the functional element of living organisms from an engineering viewpoint. By learning the fundamental features from the element-level functions in animal body structure, we redesign the conventional machine element while taking advantages of living organisms.

The aim of this study is to alternate a functional element with a biologically designed module by redesigning the machine element that has been employed conventionally in industry. As an example, we focus on the ligament mechanism of the human knee joint and propose an new revolute joint, *LigamentalJoint*. In the design method, we employ a minimalistic approach to be free from tailor made designing. Specifically, we take advantages of the knee joint mechanics while taking care not to impair the function of the conventional pin hinge joint and give importance to engineering practicality. We envision our *LigamentalJoint* to become an effective machine element in the real-world robotics application and the general engineering fields.

2 Design Approach

In this paper, we redesign the conventional pin hinge joint composed of shaft pin and bearing with biomimetic approaches. As mentioned in the introduction, our design approach can be summarized as follows:

Minimalistic design approach:
We extract some fundamental structural features as rough design specification that is employed by the living organisms. Considering the extracted design specifications, we construct new functional elements with minimum required constraints and components based on bottom-up approach.

Hybrid design approach replicating the living organisms for industry:
In designing process, we not only take advantages of the knee joint mechanics, but also focus the engineering practicality by taking care not to impair the function of the conventional pin hinge joint. In that process, to avoid high-precision and tailor made machining, we simplify the shape of the components as much as possible.

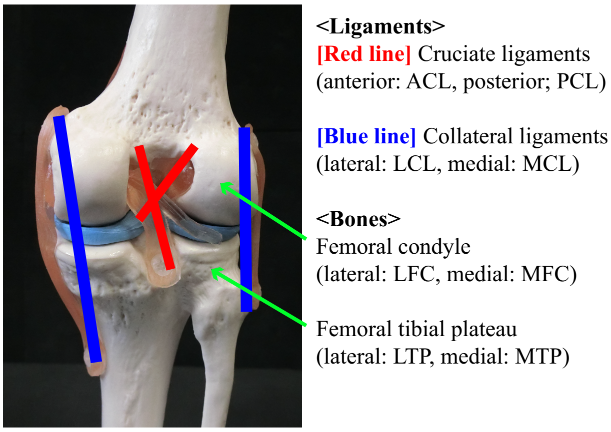

Figure 1: Knee joint model.

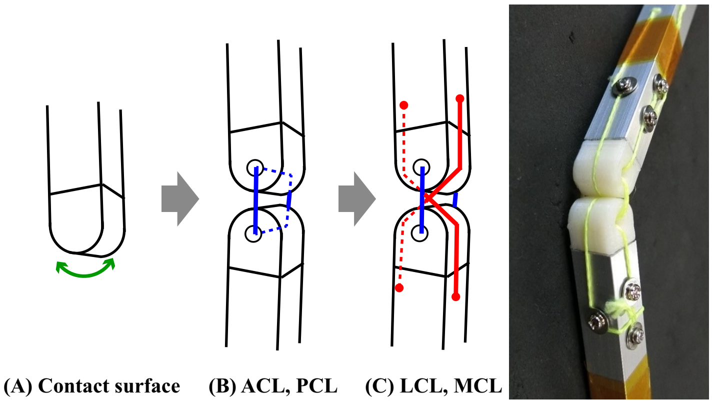

Figure 2: Design procedure and the *LigamentalJoint*.

In following section, we show a case design of a revolute joint by applying the proposed design approach.

3 Mechanical Design

3.1 Feature Extraction of Human Knee

First, we observe the human knee and extract the mechanical features. We show a joint model in Fig. 1. The mechanical constraint of human knee structures is mainly composed by rolling contact and ligaments [4]. The geometric mechanical properties of the knee joint is decided by the surface profile of the femoral condyle (LFC, MFC) and the tibial plateau (LTP, MTP). The rolling motion of the knee joint guided by the cruciate ligaments (ACL, PCL), and the collateral ligaments (LCL, MCL) are assuming a role to constraint the degree-of-freedom about undesired bending and twisting motions. In the observation of knee model, we extracted the following mechanical features from the human knee structure.

- Not adopting the pin hinge joint that is employed in conventional revolute joint in industry.
- Converting the compressive and shearing stress in shaft pin and bearing into tensile forces in the ligament system that contributes mechanical constraint.

3.2 Mechanical design

Next, we construct new functional elements by applying necessary constraints bottom-up by considering the extracted design specifications. The designing steps is shown in Fig. 2 (left), and the design procedure is denoted below.

(A) Design a simple contact surfaces (the side of cylinder) to simplify the geometric property of rolling motion of the femur over the tibia.

(B) Collocate the cruciate ligaments (ACL, PCL) to constraint the direction of the revolute motion, and place a slit to prevent the ligaments from coming into contact with the rolling surface.

(C) Collocate the collateral ligaments (LCL, MCL) to restrict the twisting motion.

The designed joint named *LigamentalJoint* is shown in Fig. 2 (right). The joint have a wide range of motion (approximately fully foldable), a reduction of the number of components, low cost ,and high productivity without high precision machining. In addition, the particularly important advantages is lightness and robustness. Supporting the loads by tension member enables a weight reduction; the wire is no need to consider the destruction by buckling.

This design has some features of the human knee. The joint have a flexibility that absorb some undesired loads from unknown environment. It seems that the design is effective for field robotics, especially for robots positively utilize some environmental interaction. Moreover, the joint has a feature that the center of rotation changes according to the joint angle. That feature give some mechanical advantages [2]. On the other hand, the disadvantages of the design is a compliance of the joint and a difficulty to collocate the rotary actuator and sensor as compared with the conventional. However, the former will be possible to turn to advantage in field robotics, and the latter can be resolved by using the wire or artificial muscle drive.

Acknowledgements

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