A bionic joint with HSLD stiffness to isolate vibration

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EXTENDED ABSTRACT

1 Introduction

As society ages, the demand for prosthetics is rising rapidly. However, most of the existing lower limb prostheses adopt rigid joints, which transmit the impact of heel-strike upwards during each step cycle of walking or running, causing discomfort to the user and changing the normal walking gait [1]. A bionic joint combining the function of vibration isolation and load bearing is needed. Many bioinspired vibration isolators with high-static-low-dynamic (HSLD) stiffness have been proposed to satisfy the requirements [2]. Nevertheless, their sizes, determined by the structure, are commonly too large to be placed within the narrow space between joint surfaces. The goal of this work is to design a bionic joint with HSLD stiffness to isolate vibration, the mechanism of which will be analyzed and the performance of which will be tested.

2 Mechanical structure

The mechanical structure of the bionic joint designed for lower limb prostheses (Fig. 1A, B) is inspired by the human knee joint [3], with a round femur surface and a flat tibia surface. A pair of C-shaped menisci with wedge-like cross-sections locate between the joint surfaces, with the ends fixed at the tibia. On compression, the axial force of the knee joint will push the meniscus to rotate outwards, and then be balanced by the circumferential restoring force of the surrounding elongated elastic band, as shown in Fig. 1C.

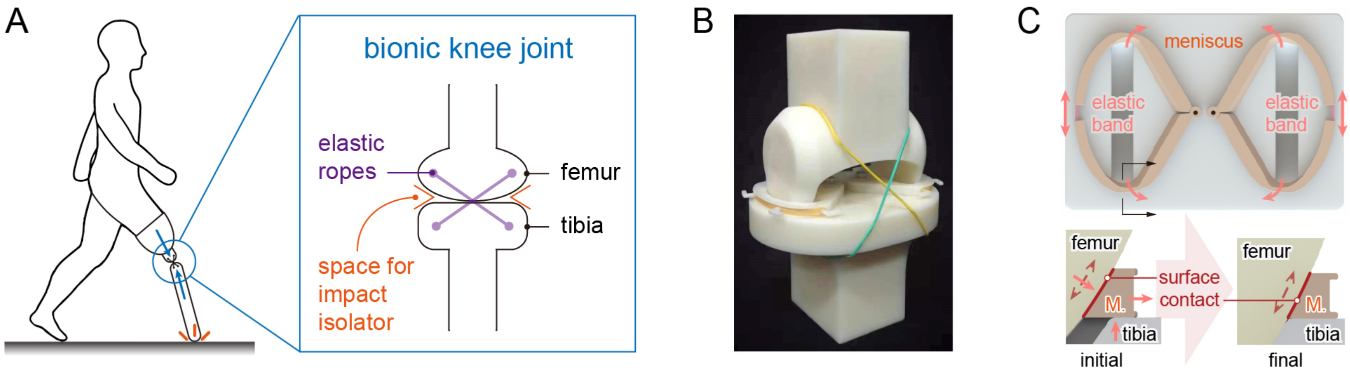

Figure 1: Mechanical structure of the bionic joint with HSLD stiffness to isolate vibration. (A) Concept of the bionic knee joint for a prosthesis. (B) Prototype of a bionic joint with vibration isolator. (C) Movement of bionic meniscus structure on compression.

To avoid stress concentration during the collision process, the meniscus should keep surface contact with joint surfaces at different states of compression. Considering the meniscus movement relative to the femur: a combination of upward translation Δz and outward rotation $\Delta\theta$, the sufficient and necessary condition for surface contact can be expressed under cylindrical coordinate as

$$\exists\, \Delta z = H(\Delta\theta), \quad s.t.\ \forall r,\theta, \quad \Delta z = h(r,\theta) - h(r,\theta-\Delta\theta). \tag{1}$$

where $z = h(r,\theta)$ indicates the contact surface.

Eq. (1) is equivalent to

$$z = h(r,\theta) = \alpha\theta + f(r) \tag{2}$$

indicating that the contact surface satisfying surface contact should be a generalized helical surface, which is determined by the pitch α and the generatrix $f(r)$.

So far, we have proposed a bionic meniscus structure located between joint surfaces, with a generalized helical contact surface to keep surface contact during the compression process. The mechanical characteristics will be analyzed in the next section.

3 Forces and dynamics

Firstly, we analyze the force equilibrium of the joint and meniscus. On compression, the axial load exerted on femur F_z is balanced by the vertical component of contact pressure p_z, and the axial moment about rotation axis caused by p_θ is balanced by the circumferential restoring force T of surrounding elastic band, as shown in Fig. 2A. Recalling the expression of the contact surface in Eq. (2), the axial load-displacement relationship can be established as

$$F_z = \int p_z \mathrm{d}S = \int \frac{r}{\alpha} p_\theta \mathrm{d}S = TR_0/\alpha = k(\delta + R_0\Delta\theta)R_0/\alpha = k\delta R_0/\alpha + (kR_0^2/\alpha^2)\Delta z = F_0 + k_d\Delta z \tag{3}$$

where the initial force $F_0 = k\delta R_0/\alpha$ indicates the capacity of load bearing and the dynamic stiffness $k_d = kR_0^2/\alpha^2$ corresponds to the performance of vibration isolation.

As shown in Fig. 2B, these two indices can be regulated by the pitch α, the stiffness of elastic band k, and the pre-elongation δ. To achieve an HSLD stiffness, the parameters should be designed to increase δ and α and select proper k according to actual requirements.

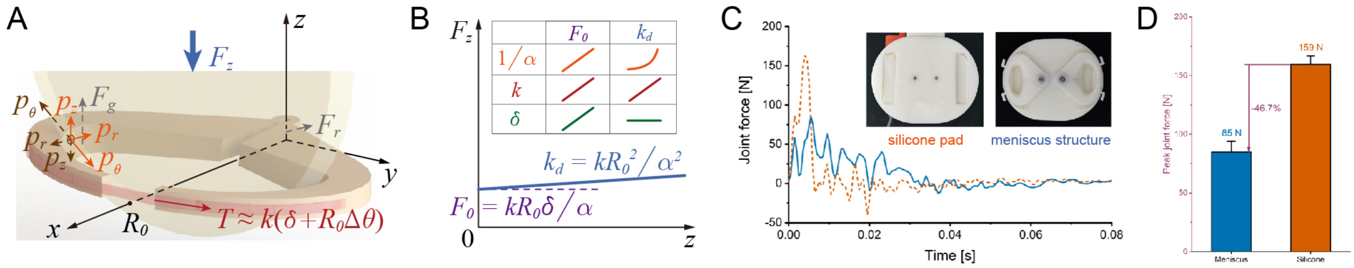

Figure 2: Forces and dynamics of the bionic joint with HSLD stiffness to isolate vibration. (A) Force analysis. (B) Load-displacement curve of the bionic joint on compression. (C) Joint force versus time on collision. (D) Peak joint force on impact compared between silicone pad and bionic meniscus structure.

Collision experiments are then conducted by releasing the bionic joint freely from a height of 14 cm. The performance of the bionic meniscus structure is compared with that of a 6-mm thick silicone pad. The acceleration of the femur is recorded by IMU and used to evaluate the joint force. As shown in Fig. 2C, D, the meniscus structure reduce the peak force by 46.7%, showing its great ability in vibration isolation.

So far, we have discussed the parameter selection to achieve an HSLD axial stiffness in the bionic joint and tested its performance in reducing the peak joint force and acceleration of the proximal link through collision experiments.

4 Conclusion

In this work, we propose a bionic joint with an artificial meniscus structure located between joint surfaces. The meniscus structure is wrapped with elastic bands to balance the axial loading via wedge-like cross-sections, and the contact surface is designed to be helical to keep surface contact during the compression process. With proper parameter selection, the axial load-displacement curve can achieve an HSLD stiffness, which is believed to be capable of isolating vibration. The collision experiments further validate the dynamic performance of the bionic meniscus in reducing joint force and acceleration of the proximal link. The proposed bionic joint may be applied in the design of prostheses, exoskeletons, and robots.

Acknowledgments

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