Design and Prototyping of Bio-inspired Open Joint with Ligamentous Constraints

Shinsuke Nakashima[1,2], Qi An[1], Atsushi Yamashita[1], Tim C. Lueth[2],

***Abstract*— This paper introduces the bio-inspired open joint for dynamic robots. The joint structure features the integration of the open joint and ligamentous constraint. The proposed structure is made from relatively simple machined components and can be easily repaired. Verification of the proposed approach includes the qualitative evaluation of ROM (Range of Motion). The tests showed that the proposed joint structure can be a relevant approach for replicating the ROM of a human knee joint. Future works include the actuation of the joint system and integration into a real robot.**

I. INTRODUCTION

Impact resistance is one of the fundamental performance indices for legged robots. The improvement of anti-impact performance boosts the robots' mobility and endurance. This motivation has led the researchers to extensive research on robot mechanism design and elaboration of the drive trains. Biological joints have several differences from conventional robot structures. The open joint structure is one of such characteristics. That is, ligaments, joint capsules and muscles restrain the open joint's motion [1]. Then the joint structure achieves mobility and stability without sacrificing each of them. This study targets the development of a bio-inspired open joint that enhances a robot's shock resistance (Fig. 1).

Engineering artificial open joints has been one of the main streams in the field of arthroplasty/prosthesis. One prevalent product is an artificial joint composed of a metallic joint head and polyethylene socket. The material characteristics fit for biocompatible use.

On the other hand, many trials have been made in the robotics community since Shibata's loosely coupled joint [2]. Most of them are for shoulder and knee joints. For knee joints, spring ligaments have been used not only for constraint but also as length sensors for estimating joint angle values. [3]. Another study applied cloth-based ligament-like or tendon-like structures to life-sized legged robots [4], [5]. Furthermore, a pneumatic biped exploited the simple open-joint structure to achieve dynamic jumping and landing behaviour in a repetitive way [6]. Based on the knowledge, this study presents a bio-inspired open joint architecture that integrates the surface contact joint and ligamentous constraints.

[1]The authors are with Department of Human and Engineered Environmental Studies,Graduate School of Frontier Sciences, The University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa, Chiba 277–8563, JAPAN nakashima, anqi, yamashita at robot.t.u-tokyo.ac.jp

[2]The authors are with Institute of Micro Technology and Medical Device Technology, Technical University of Munich, 85748, Garching, Germany shinsuke.nakashima, tim.lueth at tum.de

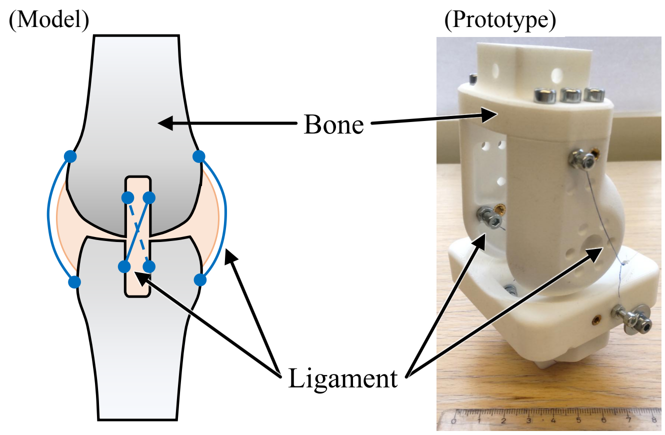

Fig. 1. Research concept. Biomimetic open joint performs shock endurance with a simple structure. The prototype has four ligaments that contribute to the enhancement of stability.

II. BIO-INSPIRED CONCEPTS

The section indicates the design approach of the bio-inspired open joint with ligamentous constraints. Especially, the study focuses on the knee joint.

A. Joint surface

"Screw-home movement" is one of the peculiar motions specific to a human knee joint [7]. A knee joint has only a pitch axis when stretched. However, The movement appears around the yaw-axis for the bent knee. The motion can be useful for pedaling, for instance. For achieving the movement, this research features the contact surface with the envelope of a spherical surface. Most conventional studies utilize cylindrical surfaces for pitch motion, which prevents the motion around the yaw axis. One drawback coming from the spherical surface is the decrease of the contact surface area. For the increase of the contact surface area, applying menisci-like elastic components would be beneficial [8].

B. Elastic ligaments

Compared to conventional axial-driven joints, a bio-inspired open joint does not have rigid constraints such as axes and bearings. The open joint has the risk of dislocation. Therefore, some elastic constraints are necessary to prevent dislocation. For instance, biological open joints adapt elastic constraints such as joint capsules and ligaments. Ligamentous constraints can support a larger load compared to joint capsules. For designing ligamentous constraints, pre-tension tuning is required. It is the main difference between the ligaments and the motor-driven tendons. We adjusted the pre-tension by twisting the ring of a fishing line [9]

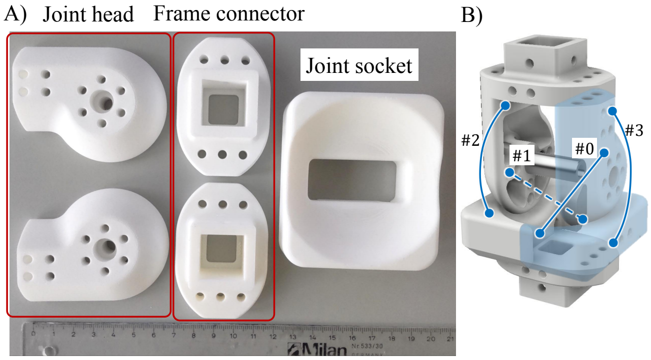

Fig. 2. Joint architecture. A) Components. B) Ligament arrangement.

III. Prototype Design

The section illustrates the prototype design based on the dimensions of human knee joint.

A. Joint surface

As mentioned in Section II-A, the envelope surface was a spherical surface for the designed joint. The radius of the sphere was 30 $[\mathrm{mm}]$. Figure 2 A) exhibits the components of the prototype. We utilized 3D printers for manufacturing them. For the joint head part, a SLS printer was used. On the other hand, a FDM printer was used for the socket and the frame connector parts. The frame connectors were required for connecting the joint surface parts to the aluminum generic frames. The connectors are common for both sides of the joint surfaces, which facilitates component repair. Furthermore, the open joint architecture decreased the components compared to conventional axial-driven joints.

B. Elastic ligaments

The arrangement of the ligaments is shown in Fig. 2 B). The notation follows Table I. Note that “Length” means the ligament length of the initial posture. Each ligament functions as a displacement limiter for a range of motion. Hence, the ligament length should be determined to determine the joint range of motion. For designing ligament parameters, it is useful to take analytical methods and data-driven approaches utilizing a dynamics simulator.

TABLE I
Notation of the Ligaments

Number	Terminology	Length $[\mathrm{mm}]$
#0	Anterior Cruciate Ligament	55
#1	Posterior Cruciate Ligament	55
#2	Lateral Collateral Ligament	61
#3	Medial Collateral Ligament	61

C. Importing to simulation

For simulating bio-inspired open joints, collision management should be taken into account. The simulator should deal with the collisions on the convex and concave joint models. For instance, the concave morphology of the socket part will be hidden by the single convex hull with planar surfaces. Therefore, convex decomposition for the joint head parts and the socket parts is indispensable. Figure 3 illustrates the result of convex decomposition. We used a third-party software library [10] that supports CoACD algorithm [11].

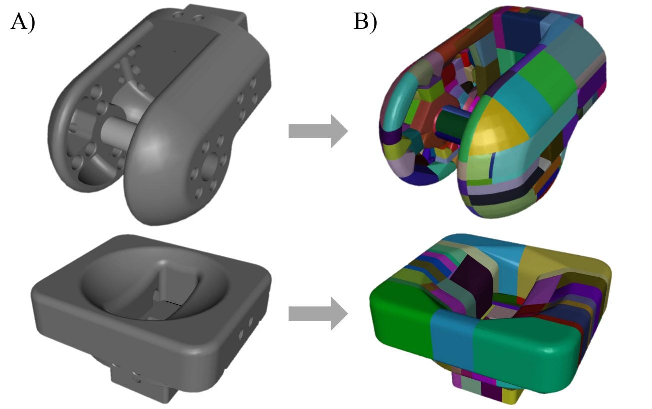

Fig. 3. Result of convex decomposition.

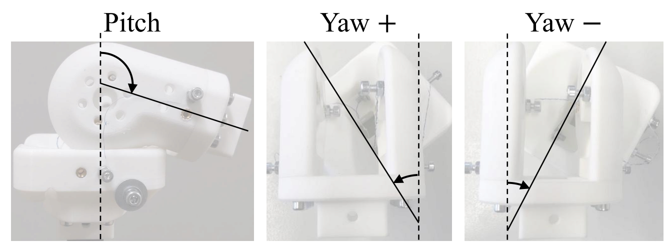

Fig. 4. Result of evaluation.

IV. Preliminary Evaluations

We qualitatively evaluated the range of motion of the bio-inspired open joint prototype with ligamentous constraints. Fig. 4 exhibits the evaluation. For pitch motion, the joint reached 100 $[^\circ]$. The value was less than the human knee joint’s active flexion of 120 $[^\circ]$ and passive flexion of 150 $[^\circ]$ [7]. The joint surface design should be improved to increase the range of motion. About yaw-axis motion, both internal and external rotations achieved 30 $[^\circ]$ which is akin to the human knee joint’s capability. On the other hand, the rotation movement generated unexpected motion around the pitch and roll axes. Motion decoupling by rearrangement of ligaments is of future works.

V. Conclusions

This research tackled the development of bio-inspired open joints with spherical surface contact and ligamentous constraints. We validated the approach through preliminary experiments. The preliminary study qualitatively showed that the joint modules cover vast areas by manual operation. The future works include the actuation of the joint assembly and integration to the real robot.

Acknowledgment

This work was in part supported by JSPS KAKENHI Grant Number JP22K17973, JSPS Overseas Research Fellowship 202460145, and JAEA Nuclear Energy S&T and Human Resource Development Project Grant Number JPJA24H24020026.

REFERENCES

[1] P. K. Levangie and C. C. Norkin. Joint structure and function: a comprehensive analysis. 3rd. *Philadelphia: FA. Davis Company*, 2000.

[2] M. Shibata, T. Yoshimura, and S. Hirai. Loosely coupled joint driven by sma coil actuators. In *Proceedings 2007 IEEE International Conference on Robotics and Automation*, pages 4460–4465, April 2007.

[3] F. Russell, Y. Zhu, W. Hey, R. Vaidyanathan, and P. Ellison. A biomimicking design for mechanical knee joints. *Bioinspiration & Biomimetics*, 13(5):056012, aug 2018.

[4] Y. Asano, K. Okada, and M. Inaba. Musculoskeletal design, control, and application of human mimetic humanoid kenshiro. *Bioinspiration & Biomimetics*, 14(3):036011, apr 2019.

[5] M. Onitsuka, M. Nishiura, K. Kawaharazuka, K. Tsuzuki, Y. Toshimitsu, Y. Omura, Y. Asano, K. Okada, K. Kawasaki, and M. Inaba. Development of musculoskeletal legs with planar interskeletal structures to realize human comparable moving function. In *2020 IEEE-RAS 20th International Conference on Humanoid Robots (Humanoids)*, pages 17–24, 2021.

[6] K. Hosoda, Y. Sakaguchi, H. Takayama, and T. Takuma. Pneumatic-driven jumping robot with anthropomorphic muscular skeleton structure. *Autonomous Robots*, 28(3):307–316, Apr 2010.

[7] I. A. Kapandji. Physiologie articulaire, ishiyaku pub, 2010.

[8] L. Yang and Z. Zhao. A meniscus-like structure in anthropomorphic joints to attenuate impacts. *IEEE Transactions on Robotics*, 40:3109–3126, 2024.

[9] S. Makino, K. Kawaharazuka, A. Fujii, M. Kawamura, T. Makabe, M. Onitsuka, Y. Asano, K. Okada, K. Kawasaki, and M. Inaba. Five-fingered hand with wide range of thumb using combination of machined springs and variable stiffness joints. In *2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, pages 4562–4567, 2018.

[10] K. Zakka. obj2mjcf, 2024. https://github.com/kevinzakka/obj2mjcf (access February 6, 2025).

[11] X. Wei, M. Liu, Z. Ling, and H. Su. Approximate convex decomposition for 3d meshes with collision-aware concavity and tree search. *ACM Transactions on Graphics (TOG)*, 41(4):1–18, 2022.