2017 14th International Conference on Ubiquitous Robots and Ambient Intelligence (URAI)
June 28 - July 1, 2017 at Maison Glad Jeju, Jeju, Korea

Design Optimization of a Wire-based Ellipsoid Joint for Bionic Wrists

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Abstract *– A wrist joint is important for positioning hands to desired position and orientation. It is necessary for prosthetic arms to develop a wrist joint with multi-DoF and light-weight. An ellipsoid joint of a human wrist is suitable for light multi-DoF prosthetic arms, but has limited RoM. In this research, RoM of the ellipsoid joint was improved by optimizing design parameters. The optimized paths of ligaments and tendons of the joint increase the RoM by approximately 25%. The ellipsoid joint with large RoM developed in this research will significantly improve the performances of prosthetic arms and other safety arms.*

Keywords – Bionics, Prostheses, Wrist, Ellipsoid joint, Optimization.

1. Introduction

Human wrist joints have important role of positioning a hand to desired position and orientation. The lack of wrist degree of freedom (DoF) increases unnecessary motions of whole body. The wrist DoF affects to body motions more largely than hand DoF in several tasks of daily livings [2]. Despite its advantages, conventional bionic arms were designed without wrist joints. Therefore, for improving the performance of bionic arms, light weight and multi DoF wrist joint is required.

An ellipsoid joint of human wrists has characteristics suitable for bionic wrist; light weight and dexterity. An ellipsoid joint has 2 DoF rotation in a small volume. Also, adjustable rotation axes of the ellipsoid joint can increase dexterity of wrists. However, the ellipsoid joint has problems to solved; friction from a large contact area, small joint stiffness, and limited range of motion (RoM).

Previous research of the author was conducted for less friction, larger joint stiffness, and larger RoM [1]. However, RoM of the joint was still small compared to human wrists. In this research, optimization of design parameters was conducted to maximize RoM of the joint.

2. Design of an Ellipsoid Joint

2.1 Limitation of Previous Research

In the previous research, kinematic characteristics of an ellipsoid joint were studied [1]. Relationship between surface design variables (radius of curvature and distance between joints) was analyzed and selected for larger RoM and stability. Human-inspired design, two carpal rows structure, was conducted to increase the RoM. As a result, we achieved RoM of 42 degrees, which is still smaller than RoM of human wrist joint of 70 degrees.

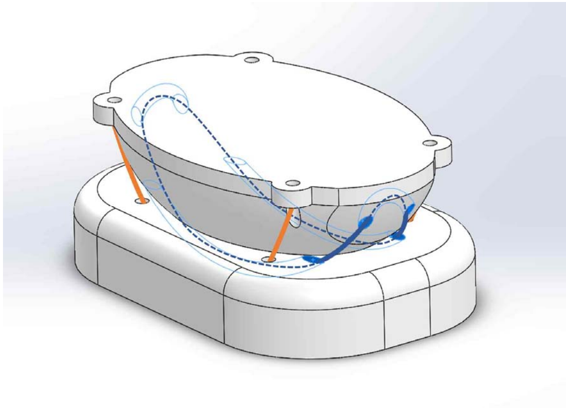

Fig. 1. Ellipsoid joint with twisted wire ligament. Blue lines represent the ligament wire, and the orange lines represent the tendon wire.

2.2 Ligament Path Points

Novel ligament structure with high linear stiffness was developed in the previous research [1]. This structure can greatly increase the linear load capacity of the joint without loss of rotational performance.

In fact, path points of ligaments could limit RoM of the joint. During the small joint motion, ligaments moved through the holes with very little friction. However, when the joint angles exceed a threshold angle, ligaments are elongated without motion. At this point, RoM of the joint was limited, in assumption which stiffness of the ligament was large enough. Therefore, positioning of the path points of ligaments is very important to improve the RoM of the joint.

2.3 Tendon Path Points

Ellipsoid joints above were actuated by linear actuator through 4 tendons. 4 tendons, positioned in diagonal edges of the joint, were pulled when the joint is actuated.

When the joint is rotated, a distance between two path points of the tendon that was pulled by linear actuater is shortened. The shortest distance of the tendon path can be adjusted by positioning the path points. Therefore, RoM of the joint can be limited by path points of tendon also.

Effect of the path points of ligaments and tendons must be anlayzed for large RoM of the joints. In the next section, path points of wires are analyzed and optimized to achieve maximum RoM of the joint.

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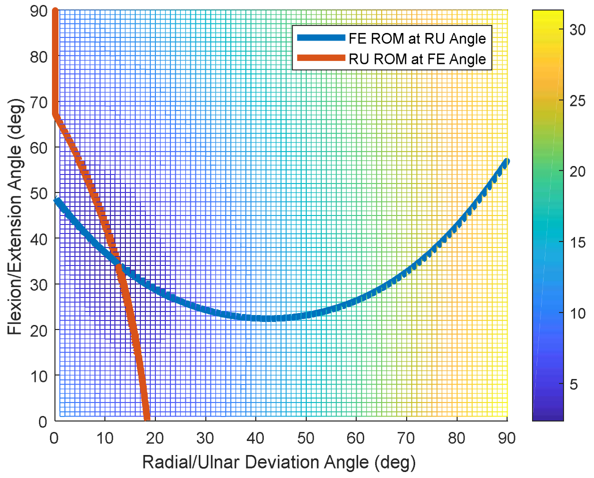

Fig. 2. Optimized RoM of the joint. Blue line is RoM of flexion / extension at a certain angle of radial / ulna deviation. Red line is RoM of radial / ulna deviation at a certain angle of flexion / extension of the joint.

3. Optimization of Wire Path

3.1 Simulation of Parameter Variation

In order to analyze the kinematics of path points of ligaments and tendons in MATLAB, some assumptions need to be established; (1) joint rotation should be occurred at rotation center perfectly, (2) tendons and ligaments are moved without slacks, and (3) bending of wires from contact with joint surface are ignored.

Result of analysis represents tendency of each path points. Tendon path points of lower body with concave surface increase RoM when they are closer to the center of the joint. Tendon path points of upper body with convex surface have inversed tendency of lower body's. Ligament path points have similar tendency with tendon points; in lower body, closer; in upper body, farther.

Optimization for maximizing RoM was conducted, and results of optimization were shown in Fig. 2. RoM of flexion / extension rotation was increased about 23%, and RoM of radial / ulnar deviation rotation was increased about 28% in simulation.

3.2 Testbed for Evaluation

Prototype of the joint with initial and optimized path points was manufactured by using 3D printer. A testbed for tendon driven actuation of the joint was configured.

RoM of the joint was measured on testbed. When 1 of 2 directional rotation was fixed at certain angle, rotation of another direction was fully actuated for measuring RoM.

Similar to the simulation, RoM of flexion / extension rotation was increased about 26%, and RoM of radial / ulnar deviation rotation was increased about 35% in experiment. Increment of RoM by experiment is larger than simulation. It seems the simulation model was strictly constrained because of elasticity of the wires. Elasticity of the wires have difficulty to be adopted in the simulation environment.

4. Conclusion

In this research, RoM of the light weight and multi DoF bionic wrist was increased by optimizing the design variables. Through the simulation process of the joint, kinematics of the tendency of ligament and tendon path points was analyzed. Path points of wires were optimized to maximize RoM of the joint. The increased RoM has been evaluated through the experiment with the testbed. From the result of this research, it has been found that the ligament and tendon path points largely affect to RoM of the ellipsoid joint.

Acknowledgement

This research was supported by the convergence technology development program for bionic arm through the National Research Foundation of Korea(NRF) funded by the Ministry of Science, ICT &Future Plannig (No. NRF-2015M3C1B2052820). This work was supported by the National Research Foundation of Korea(NRF) Grant funded by the Korean Government (MSIP) (No. NRF-2016R1A5A1938472).

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