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DESIGN OF A RIGIDITY-ADJUSTABLE TENSEGRITY STRUCTURE TO DEVELOP AN EXOSKELETON THAT SUPPORTS KNEE JOINT STABILITY AND MOBILITY IN GAIT

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Abstract

Kinematic compatibility is crucial in wearable walking assistive devices. We aim to design wearable walking assistive devices with high degree of kinematic compatibility by focusing on tensegrity structure, regarded as the basis of the body structure. In this paper, we examined the factors required to design the tensegrity knee joint for wearable walking assistive devices. To support the mobility and stability of the knee joint, we designed a tensegrity joint with a mechanism to change its rigidity by changing the moment of inertia. Experimental results suggest that the mechanism can reduce the structure's rigidity by up to one-third.

Keywords:

Tensegrity, rigidity adjustment mechanism, knee joint, kinematic compatibility, walking assistance

1 INTRODUCTION

The number of people aged sixty-five and over is increasing around the world. With this trend, wearable walking assistive devices have been developed and manufactured for rehabilitation and independence support of the elderly. On such devices, a high degree of kinematic compatibility is crucial [Seguin 2020]. In the natural flexion-extension (FE) motion of the knee joint, the center of rotation shifts. In addition, varus/valgus and internal/external rotation occur with FE of the knee joint in gait [Lafortune 1992]. However, conventional joint exoskeletons have only one axis for simplification, limiting the joint motions [Wang 2014]. This oversimplification increases muscle activity in gait by limiting joint DOF [Hidler 2005]. It also leads to undesirable forces due to misalignment between users and devices. These forces cause discomfort to the user and risk damaging the joint [Mohammad 2011], [Akiyama 2012].

Therefore, several multi-center joints and self-aligning joints have been proposed. These can be divided into two mechanisms: using passive translation [Cai 2011], [Saccares 2016], [Li 2024] and following a predetermined path based on knee joint motion analysis [Ranaweera 2018], [Hong 2023]. The first mechanism has active DOFs to provide power and passive DOFs to follow the knee joint motion [Seguin 2020]. The mechanism naturally adjusts to the individual's biomechanical joint geometry and motions due to kinematic redundancy [Seguin 2020]. On the other hand, it tends to be complex and bulky in structure [Seguin 2020]. In contrast, the second mechanism has simpler and lighter structures [Seguin 2020]. On the other hand, it is nearly impossible for this mechanism to follow the individual motion of the knee joint [Seguin 2020]. Therefore, the authors are working toward designing a new knee exoskeleton having both kinematic redundancy and structural lightness. Focusing on the multi-DOF motion mechanism of the knee joint, we propose an approach based on tensegrity, which can be considered as the basis of the body structure. Tensegrity is "a structural relationship principle in which structural shape is guaranteed by the finitely closed, comprehensively continuous, tensional behaviors of the system and not by the discontinuous and exclusively local compressional member behaviors" [Fuller 1975]. The structure has unique properties such as flexibility, tension propagation function, high specific rigidity and recovery from deformation [Myers 2013], [Liu 2022]. It is generally used for building structures in architecture and robotics [Liu 2022]. In addition, it is known that body structures have properties as tensegrity in recent years [Myers 2013]. In this study, we investigate a design method to apply the tensegrity structure to the knee joint of wearable walking assistive devices. First, we focus on the knee joint function during gait and identify the key elements required for the tensegrity knee joint (TKJ). Second, we discuss the design approaches of TKJ structure. Third, we focus on the rigidity adjustment mechanism and examine specific design methods. Finally, we evaluate the developed structure and discuss future works.

2 DESIGN CONCEPT

2.1 Body and tensegrity

The body structure comprises rigid skeletons and elastic elements including muscles, fascia, tendons, and ligaments. The skeletons support compressive forces, while elastic elements propagate tension. These functions mechanically organize numerous muscles, resulting in mobility and stability of multi-DOF motions. Based on these structural functions, the body structure is understood as tensegrity [Myers 2013]. As shown in Fig. 1, tensegrity consists of tensile members propagating tension and compressive members supporting compressive forces. In the body structure, the elastic elements function as tensile members and the skeleton functions as compressive members. When tensegrity is applied to the body structure, it is specifically called biotensegrity [Nonaka 2016]. Biotensegrity is more dynamic than common tensegrity, since the tensile members including muscles function as actuators.

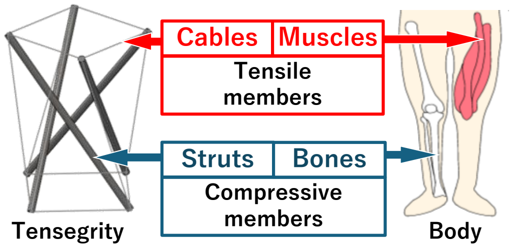


Fig. 1: Comparison of tensegrity and body composition.

The authors' group have investigated how to utilize tensegrity structures for motion assistance focusing on the similarity between body and tensegrity [Wakashima 2023]. As shown in Fig. 2, a spine-inspired tensegrity structure was constructed to support the entire body when standing upright. This structure has no actuator and supports the body passively. Our members walked in normal condition and carrying heavy objects condition with two structures attached to the front and another two to the back of the body. The results imply that the structures support loads while flexibly following the body motions. They also imply that the structures apply force to the body by exerting restoring force when deforming with body motions.

Fig. 2: The proposed tensegrity basic structure and the motions performed with the tensegrity structure attached to the body.

2.2 Application to the knee joint

Based on prior research mentioned above, tensegrity structure is newly applied to an exoskeleton for the knee joint in this paper. The following functions are expected when the tensegrity structure is applied to the knee joint exoskeleton.

1. Follow the natural motion of the knee joint

Tensegrity structures have redundant DOF and deform flexibly in response to external forces such as compression, tension, bending, and torsion. Thus, they can flexibly adjust to knee joint motions.

2. Support the knee joint stability

Tensegrity structures have high specific stiffness by compressive members to support compressive forces. Therefore, it can increase the stability of the knee joint despite its lightweight structure.

3. Exert force by the elasticity of the tensile members

Tensegrity structures have the property of returning to their initial shape. Therefore, when the structure bends with the flexion of the knee joint, it exerts force in the direction of extension to return to its initial shape. This force comes from the elasticity of the tensile members and can be used as an assist torque for the knee joint instead of using motors.

In other prior studies, a bionic ankle tensegrity exoskeleton by Wei et al. [Wei 2023] and a foot-based wearable assist mechanism by Sun et al. [Sun 2022] have been proposed as lower limb exoskeleton designs using tensegrity structure. The former introduced a mathematical analytical model for designing an ankle exoskeleton based on biotensegrity. The latter proposed a structure that supports postural coordination at the metatarsophalangeal joint and enhances gait smoothness by leveraging the flexibility and deformation recovery properties of tensegrity.

In contrast, this study focuses on designing knee joint exoskeleton. The knee joint exhibits significant flexion during the swing phase and maintains stability during the stance phase. To assist these, TKJ must act as a flexible structure during the initial swing and transition to a rigid structure during the terminal swing and stance phases. Therefore, a new mechanism is needed for the TKJ to adjust its structural rigidity according to the gait cycle. In this paper, we develop a mechanism to adjust the rigidity of joint-type tensegrity structures.

3 METHOD

3.1 Geometry of the structure

In this study, the TKJ was based on the joint model proposed by Tom Flemons as it resembles a rotational joint like the knee and is easier to attach than a spherical model [Flemons 2018]. As shown in Fig. 3, this model consists of two prismatic units, the top unit and the bottom unit, linked so that their bases overlap. The unit is a four-strut prism with its upper base twisted 45° clockwise to the lower base when viewed from above. It consists of twelve tensile members and four compressive members. The tensile members are located on the edges, while the compressive members connect the vertices of the lower base and the upper base in a rightward direction. This TKJ model has a higher DOF per unit than the spine-based structure used in our previous study. Thus, the model can be deformed on a large scale, allowing larger ranges of motion with fewer units. Therefore, it is suitable for the exoskeletons for the parts having a large range of motion, such as the knee joint. Fig. 4 shows the bending and torsion of the model. As shown in Fig. 3, the tensile members that form the top, side, and bottom surfaces of the unit are referred to as Top Tensile Members (TTM), Side Tensile Members (STM), and Bottom Tensile Members (BTM). When connecting the top and bottom units, the tips of the top unit compressive members are linked to the midpoint of the bottom unit TTM.

The overlapping surface of the bottom surfaces of the two units formed by this linkage is called the linking surface.

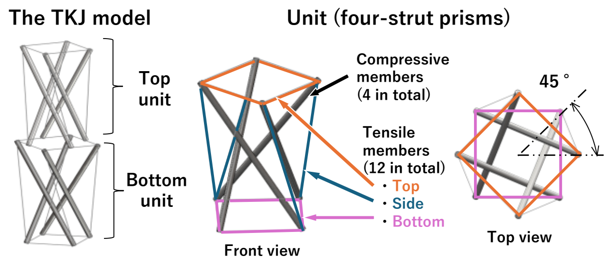


Fig. 3: The TKJ model configurations.

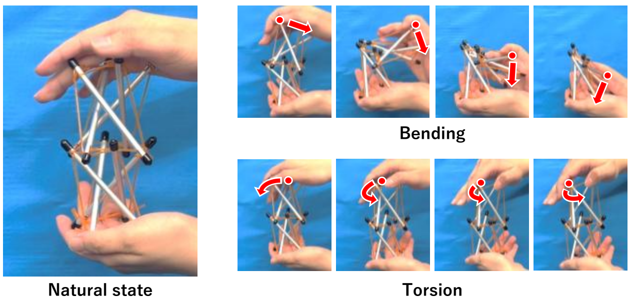


Fig. 4: The deformation of the TKJ model.

3.2 Rigidity of the structure and methods of adjusting its rigidity

The spring constant of the tensile members has a significant influence on the properties of TKJ. In this study, the rigidity of TKJ assists leg swing at terminal swing and increases the stability of the knee joint during the stance phase. Therefore, it is necessary to achieve the required rigidity by combining the spring constants of the tensile members. To achieve this, we investigated the influence of the spring constants of tensile members on the structural bending rigidity by simulation using the NASA Tensegrity Robotics Toolkit (NTRT) [NASA 2024]. In particular, we focused on the influence of the spring constants of the TTM of the bottom unit (TTM-BU) and the STM of the top unit (STM-TU), which both connect to the linking point.

Additionally, we studied the method to change the rigidity of TKJ according to gait. There are two methods to change the rigidity of the tensegrity structure proposed by Zappetti et al. in robotics. One is by changing the properties of the tensile members [Zappetti 2020] and the other is by increasing the contact points of the compressive members [Zappetti 2021]. In the former, variable rigidity cables made of a low-melting-point alloy are used as tensile members. The cable's spring constants change when an electric current is applied and heated, resulting in a change in the rigidity of the structure. The latter has a mechanism whereby the length of the tensile members can be varied using an actuator. This mechanism shortens the length of the tensile members between the units, bringing the compressive members into contact with each other. It creates new constraint points between the units and increases the rigidity of the structure. When TKJ is designed with these methods, the former requires heating and cooling equipment to achieve a response speed corresponding to gait. The latter causes a 45° torsion of the TKJ model and requires structures or devices to absorb the restoring forces.

Based on the above, this study proposes a new method of adjusting the rigidity of the TKJ model. The rigidity adjustment should be achieved with compact devices to improve wearable comfort. Therefore, this study focuses on the moment of inertia of the structure. As shown in Fig. 5, in the TKJ model, the moment of inertia of the linking surface changes when the linking points move. It simultaneously changes the bending rigidity of the structure. By utilizing this property, the bending rigidity of the structure could be changed only by the mechanism of moving the linking points.

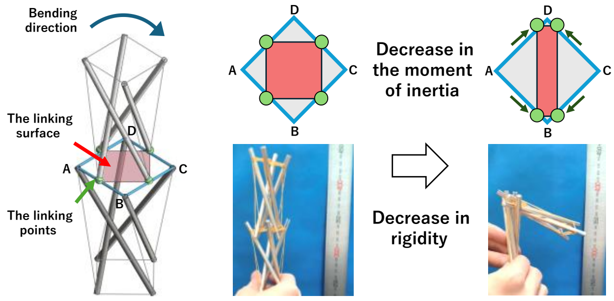


Fig. 5: Change in the rigidity of the TKJ model due to the change in the moment of inertia of the linking surface (In this figure, the moment of inertia of the linking surfaces is changed by pressing the bottom unit by hand.).

4 DESIGN AND IMPLEMENTATION

4.1 Required specifications

The requirements for TKJ are (1) small and light enough to be attached to the knee joint, (2) flexible enough during the initial swing, (3) rigid enough during the terminal swing and stance phase, and (4) quick enough in rigidity adjustment. Numerical targets for these requirements were set for the prototype TKJ device as follows.

1. Dimensions and weight

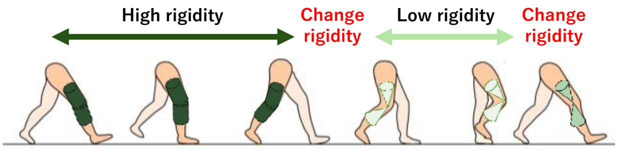
The dimensions of one unit of TKJ are defined as 60 × 60 × 100 mm. Since the minimum knee joint width of elderly Japanese women is 93 mm [AIST 1991], the width of the structure would be less than two-thirds of the knee joint width. The overall weight of the TKJ device is defined to be less than 1.0 kg per side.

2. Structural rigidity

TKJ is defined to exert a torque of 3.12 Nm when flexed by 20°. The bending moment applied to the knee joint is max when the knee joint flexes approximately 20° during the loading response [Perry 2010]. The bending moment is 0.52 Nm/kg when walking at 80 m/min [Perry 2010]. Therefore, if the body weight is 60 kg, the knee joint bending moment is 31.2 Nm. Based on the above, the torque of the structure is defined to be approximately 10% of the knee joint load torque. 10% was set as the first stepped target, taking account the rigidity of the preliminarily fabricated structure and the spring constant of the tensile material utilized for it.

3. Speed of rigidity adjustment

Considering the function of the knee joint in gait, the rigidity of TKJ should be changed during the pre-swing and terminal swing. The gait speed of a typical adult is 114 steps/min, so one cycle takes 1.05 s [Perry 2010]. As shown in Fig. 6, the initial swing accounts for approximately 12% of the gait cycle and the terminal swing for approximately 13% [Perry 2010], so these phases last for 0.13 s and 0.14 s. Therefore, to adjust the rigidity during these phases, the structure must be able to change its rigidity for 0.13 s.



Stance phase				Swing phase		
Loading response	Mid stance	Terminal stance	Pre-swing	Initial swing	Mid swing	Terminal swing
12%	19%	19%	12%	13%	12%	13%

Fig. 6: The proportion of each phase in the gait cycle and the change in the rigidity of TKJ.

4.2 Rigidity

To satisfy the target rigidity of the structure, the spring constants of tensile members are discussed. First, NTRT is used to verify the influence of the combination of spring constants of TTM-BU and STM-TU, both connected to the linking points. Simulations were conducted under the following conditions: the spring constant of the target tensile members was increased by 10 N/cm from 10 N/cm to 50 N/cm, while the other was set to 50 N/cm.

As shown in Fig. 7, it confirmed that the bending rigidity of the structure increases with the rise of the spring constant of both TTM-BU and STM-TU respectively. It also confirmed that in the condition where the spring constant of TTM-BU rose, the rate of rigidity increase was higher than in the condition where the spring constant in STM-TU rose. In addition to this, as the elongation of STM-TU allows the linking points to move, the force required for rigidity adjustment increases when the spring constant of STM-TU rises. Therefore, we use a material with a high spring constant for TTM-BU to increase the rigidity of the structure. On the other hand, we use a material with a lower spring constant for STM-TU. It increases the rigidity of the structure while reducing the force required for rigidity adjustment. By the above policy and in consideration of the workability of the material, a steel wire is used for TTM-BU, and a urethane tube (estimated to be around 550 N/cm), which is more elastic than a steel wire, is used for STM-TU.

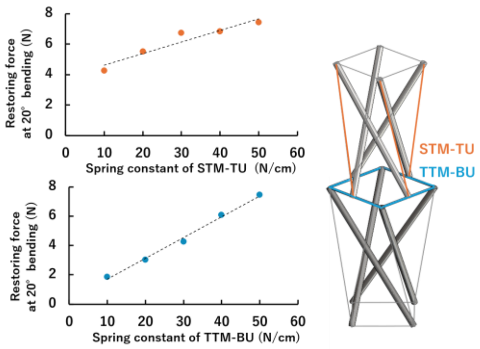


Fig. 7: Relationship between the spring constant of tensile members and the force required to bend the structure.

4.3 Rigidity adjustment mechanism

As shown in Fig. 8, and 9, the prototype TKJ device consists of a tensegrity structure, upper and lower attachments, and a rigidity adjustment mechanism. The top and bottom attachments enable the structure to be mounted to the joint model used in the experiments described below. The dimensions of the overall prototype TKJ device are 130 × 120 × 320 mm, and the mass is 560 g. The rigidity adjustment mechanism consists of a servomotor, a frame to embed the servomotor, a disk that rotates with the servomotor, and a disk frame.

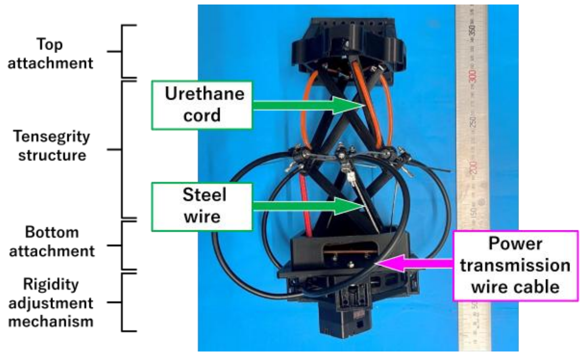


Fig. 8: The overview of the prototype TKJ device.

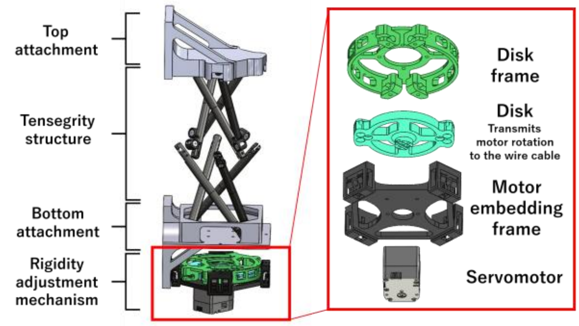


Fig. 9: The composition of the TKJ device.

Fig. 10 shows power transmission wire cables between the mechanism and the tensegrity structure. The endpoints of the wire cables on the mechanism side are fixed on the disk, while those of the structure side are fixed to the linking point through the tips of the bottom unit compressive members. As shown in Fig. 11, when the wires are wound up along the circumference of the disk by the motor rotation, the linking points are pulled towards the tips of the bottom unit compressive members. When the motor rotates backward, the wires are pushed out and the linking points are also pushed away from the tips of the compressive members.

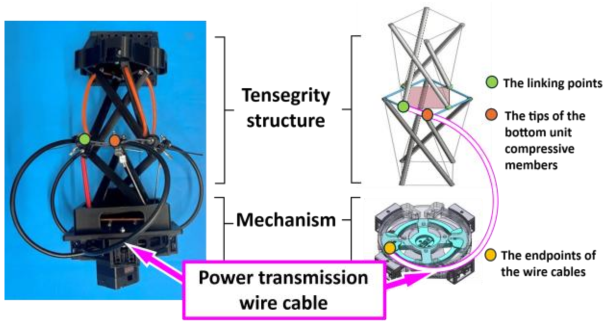


Fig. 10: Power transmission paths with wire cables.

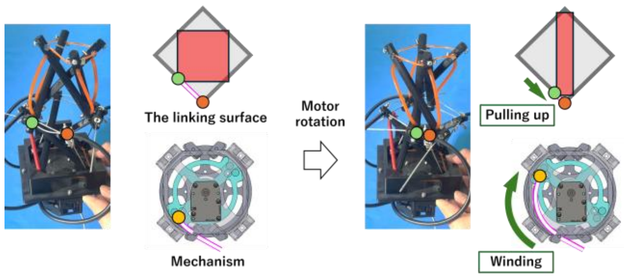


Fig. 11: Movement of the linking point with the rotation of the motor.

There are four wire cables in total, connected to each of the four linking points. When the motor rotates, two of the wire cables are pushed out while the other two are wound up.

This causes the respective linking points to move and the moment of inertia of the linking surface to change, as shown in Fig. 12. The moment of inertia *I* is obtained by $I = b \times h^3/12$ where *b* is the width and *h* is the height. In this mechanism design, the linking surfaces vary from $h = 50\sqrt{2}$ mm and $b = 10\sqrt{2}$ mm to $h = 50\sqrt{2}$ mm and $b = 50\sqrt{2}$ mm, allowing a rigidity reduction of one twenty-fifth.

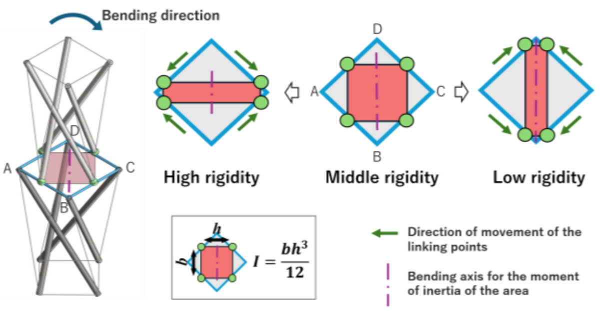


Fig. 12: Movement of linking points and change in the moment of inertia of the linking surface.

In this mechanism, four wire cables move along the circumference of the disk. Therefore, when these paths are set so that they do not overlap, the movable range of the disk is less than 90°. Hence it is defined to transition from low to high rigidity when the servomotor rotates by 60°, allowing room for that range of movement. In this case, the rotation speed of the servomotor required to change rigidity in 0.13 s is approximately 79 rpm. Thus, a high-power, compact servo motor is built into the mechanism (Kondo Kagaku, KRS-5032HV ICS, 125 rpm, 2.19 Nm). After the prototype was developed, the time required for the structure to transition from low to high rigidity was measured. The motor was actuated using an internal encoder. The results indicated that the structure transitioned from low to high rigidity in an average of 0.12 s over three trials, meeting the criterion of 0.13 s

4.4 Procedure

The relationship between the flexion angle and the restoring torque of the prototype TKJ device is investigated using a joint model. In this experiment, torque measurements were conducted in a quasi-static condition, assuming that inertia in a dynamic condition considering walking motion can be practically ignored due to the lightweight structure. The experimental system is shown in Fig. 13. The prototype TKJ device, which is extended fully and in its natural state is mounted to the one-axis joint model. The flexion angle of the joint is measured by the potentiometer (Tocos, TCQ96A02, Mechanical angle: 300° ±5°, Independent linearity: ±2% Max) attached to the rotation axis of the joint model. The restoring torque of the structure is calculated from the force acting tangentially to the joint model measured by the load cell (Sensor and Control Company Limited, SC301A-100kg, Rated Capacity: 100 kg, Linearity Error: ±0.03 %R.O) embedded at a distance of 300 mm from the rotation axis. The flexion of the joint model is performed manually by the experimenter, holding the grips fixed to the load cells. Only the flexion movement is measured, as the force with which the experimenter holds the grip affects the results in the extension movement. Measurements are taken three times in each high, medium, and low rigidity conditions. The rigidity of the structure changes by controlling the servomotors using a motor driver via a computer.

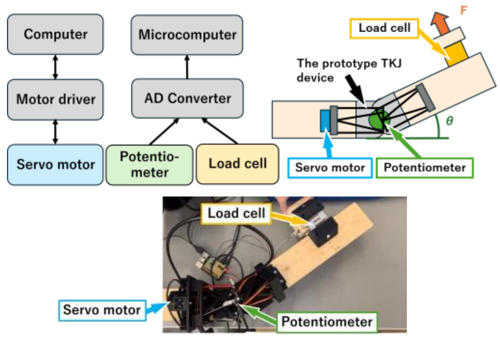


Fig. 13: Measurement system of the relationship between the flexion angle and the restoring torque of the prototype TKJ device.

4.5 Result

Fig. 14 shows the relationship between the flexion angle and the structure restoring torque. The data of structural restoring torque is smoothed by a 5-period moving average. At a flexion angle of 20°, a restoring torque is 3.16 Nm on average for high rigidity and 1.09 Nm for low rigidity. In the measurements of high rigidity and medium rigidity, torque was observed even at a flexion angle of 0 degrees. This is considered to be influenced by the hysteresis at the connection between tension members and compression members in the structure, as the experiments were conducted continuously under conditions from low rigidity to high rigidity.

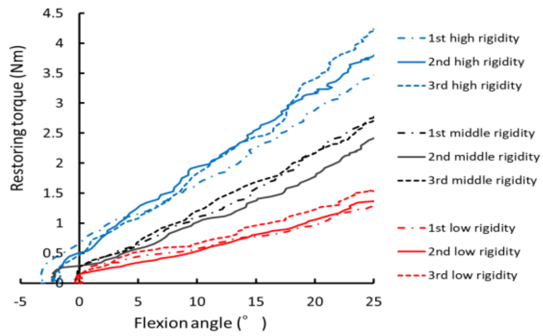


Fig. 14: Relationship between flexion angle and structure restoring torque.

4.6 Discussion

Experiment results indicate that when flexed at 20°, the structure in a highly rigid state achieved a restoring torque equivalent to about 10% of the knee joint torque in the gait, which was set as the target. It suggests that the structure may be able to support walking by applying force and contribute to knee joint stability during the stance phase. It is also confirmed that the bending rigidity of the structure can be reduced up to one-third by the rigidity adjustment mechanism, from 3.16 Nm to 1.09 Nm at 20° flexion. It suggests that the structure may be able to support knee joint mobility during the swing phase.

Regarding the rigidity reduction rate, the prototype TKJ achieved a maximum rigidity reduction of approximately one-third. In contrast, the ideal rigidity reduction rate is one twenty-fifth. The gap between the ideal and experimental rates can be attributed to the linking points not reaching their intended positions. One potential cause of this is the friction between the wires and cables in the power transmission path. Additionally, friction between the tensile members of the linking surface and the linking points may also contribute to this issue. To achieve a higher rigidity reduction rate, it is necessary to design a power transmission path and linking method with less friction.

5 CONCLUSION

In this study, we designed a rigidity adjustable tensegrity structure as a first step to design a tensegrity knee joint exoskeleton, aiming to realize wearable walking assistive devices with high kinematic compatibility. The proposed mechanism adjusts the structural rigidity by moving the linking points to change the moment of inertia of the linking surface. Experimental results suggest that structural rigidity can be reduced by up to one-third. Owing to this mechanism, the proposed TKJ can increase its rigidity in terminal swing and decrease it in pre-swing. Our future work will focus on the integration of this mechanism into a gait-assistive orthosis and the evaluation of its effect on gait.

6 ACKNOWLEDGMENTS

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