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A wire-tensioned inclined-joint variable-stiffness linear mechanism balancing flexible-state posture formation and geometrically enhanced locked-state load support

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Abstract

Variable-stiffness linear mechanisms must combine flexible posture formation with reliable load support after locking. This paper presents an Inclined Joint Variable Stiffness Linear Mechanism composed of serial rigid modules with inclined circular contact surfaces and an internal steel wire. Releasing the wire permits continuous relative rotation at the interfaces and three-dimensional posture formation. Tensioning the wire compresses the modules so that interfacial friction and geometric support jointly maintain the posture. A multi-module prototype with an adjustable worm-gear winding mechanism was developed to accommodate posture-dependent changes in wire take-up. A Denavit-Hartenberg-based kinematic model and convex-hull workspace analysis were used to examine the effects of inclination angle and module number and to compare the proposed configuration with an Orthogonal Semicylindrical Joint Mechanism (OSJM). A simplified quasi-static model was established to explain direction-

dependent holding behavior. Module-pair experiments evaluated transverse holding capability and torsional resistance at inclination angles of 30°, 45°, and 60°, and a multi-module experiment examined the relationship between steel wire tension and holding capability. The results show that inclination angle affects posture-forming capability, directional holding capability, and torsional resistance, whereas increasing wire tension improves the holding capability of the assembled mechanism. The proposed configuration therefore provides a practical balance between posture-forming capability and multidirectional load support.

Keywords: *Variable-stiffness mechanism; inclined joint; posture-forming capability; holding capability; torsional resistance; steel wire tension*

I. Introduction

Flexible robotic mechanisms can conform to surrounding objects, absorb disturbances, and operate in confined or irregular environments [1]–[3]. These properties are useful in medical devices, search-and-rescue robots, inspection tools, and manipulators that interact with uncertain environments. However, excessive compliance impairs positioning, posture retention, force transmission, and load support. Achieving deformability and reliable load-supporting capability in one mechanism therefore remains an important challenge.

Variable-stiffness mechanisms [4], [5] address this challenge by switching between a flexible state for posture formation and a locked state for load support. This function is particularly important for line-shaped multi-joint structures that must form three-dimensional postures and then maintain them under external loads. Potential applications include shape-adaptable supports, steerable tubular structures, and flexible robotic arms.

Existing approaches include material-based stiffness modulation, jamming, geometric locking, and friction-based locking. For serial line-shaped mechanisms, internal-tension-element designs are attractive because they are compact and permit continuously adjustable postures. Conventional spherical-joint configurations, however, rely mainly on inter-module friction, which limits their holding capability under large bending and torsional loads.

Introducing geometric support into the joint can improve load resistance beyond that provided by friction alone. Excessive geometric constraint, however, reduces the attainable three-dimensional posture range. The central design problem is therefore to balance locked-state holding capability with flexible-state posture-forming capability.

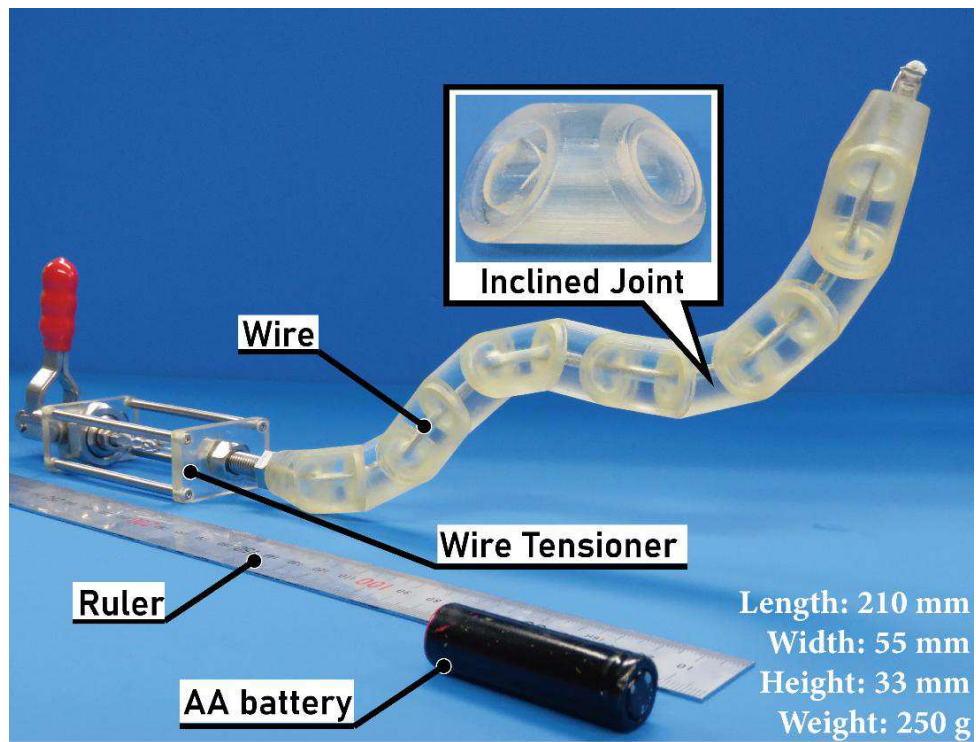


Fig. 1. Prototype of the proposed Inclined Joint Variable Stiffness Linear Mechanism.

To address this problem, this paper investigates the Inclined Joint Variable Stiffness Linear Mechanism shown in Fig. 1. Serial rigid modules with inclined circular contact surfaces are

threaded by a central steel wire. When the wire is slack, adjacent modules rotate continuously about the normals to their contact surfaces, allowing the chain to form different postures. Tensioning the wire compresses the interfaces, so interfacial friction and the inclined-surface geometry jointly resist external loads.

The objective is to obtain high holding capability without sacrificing the three-dimensional posture-forming capability of the serial chain. The mechanism is therefore examined from both kinematic and mechanical perspectives. A serial kinematic model and workspace-based evaluation quantify posture-forming capability for different inclination angles and module numbers. The reachable workspace is also compared with that of an Orthogonal Semicylindrical Joint Mechanism (OSJM), a geometrically constrained reference configuration with strong directional support.

The holding principle is analyzed in terms of steel wire tension, inclined-surface geometry, and external-load direction. Because the inclined contact introduces direction-dependent geometric support, the module pair is evaluated through mechanical analysis and multidirectional holding experiments. Torsional resistance is tested separately, and an assembled multi-module prototype is evaluated under different steel wire tensions to determine their effect on maximum sustainable load.

The main contribution is the systematic evaluation of an inclined-joint architecture that combines frictional locking with geometric support while retaining continuous posture adjustment. Unlike friction-dominated spherical joints, it uses the contact geometry to support load; unlike the strongly constrained OSJM, it preserves a larger posture-forming range.

Kinematic workspace analysis, a direction-dependent holding model, and module-pair and multi-module experiments clarify this balance.

The remainder of this paper is organized as follows. Section II reviews related mechanisms and the design motivation. Sections III-V describe the structure, kinematic model, workspace evaluation, and holding model. Section VI presents the prototype, Section VII reports the experiments, Section VIII discusses the combined results and limitations, and Section IX concludes the paper.

II. Related Work

Variable-stiffness mechanisms are used in soft robots, continuum robots, wearable devices, and medical manipulators to reconcile deformation with force transmission and posture maintenance. Representative approaches include material-based modulation, jamming, geometric locking, and friction-based locking of serial modules.

Material-based variable-stiffness mechanisms change the intrinsic stiffness of the constituent material. Magnetorheological [6]–[8] and electrorheological [9], [10] materials can alter their mechanical properties under magnetic or electric fields. Phase-change materials, such as low-melting-point alloys [11]–[13] and thermally responsive polymers [14], can switch between soft and rigid states through temperature control. These approaches are effective when large stiffness variation is required within a compact volume. However, they generally require external energy input for activation, and their response speed, heat management, material fatigue, and integration complexity must be considered. In addition, material-based stiffness modulation does not always provide a simple mechanical path for supporting large external loads in a slender serial structure.

Jamming-based mechanisms achieve variable stiffness by changing the internal contact state of granular particles or layered sheets. In granular jamming [15]–[17], particles enclosed in a flexible membrane are compressed by vacuum pressure, resulting in increased stiffness through particle-particle contact. In layer jamming [18]–[21], stacked sheets are compressed so that friction between layers resists deformation. These methods are attractive because they can provide continuously variable stiffness while maintaining a soft outer shape. However, vacuum-based systems are limited by the maximum pressure difference available under atmospheric conditions. Their performance also depends strongly on sealing reliability. Damage to the membrane or leakage in the pneumatic system can directly reduce the locked-state load-supporting capability. Positive-pressure variable-stiffness systems [22], [23] can alleviate some sealing issues by arranging rigid elements outside a sealed tube, but their stiffness may still be affected by the elastic restoring force of the pressurized rubber tube.

Geometric locking directly constrains rigid components and can resist large loads with little or no continuous holding energy. Many latching [24] or dog-clutch-like mechanisms [25], however, lock only at discrete positions. This is unsuitable for line-shaped mechanisms that must retain arbitrary, continuously adjusted three-dimensional postures.

Friction-based serial mechanisms compress rigid modules with an internal tensile element [26]–[29]. With the element released, the modules move relative to one another; when it is tensioned, interface friction maintains the posture. The architecture is compact, continuously adjustable, and compatible with a central passage, but locked-state performance depends on the available contact friction.

Spherical Joint variable stiffness Mechanism	Orthogonal Semicylindrical Joint variable stiffness Mechanism(OSJM)	Inclined Joint variable stiffness Mechanism
Variable stiffness achieved ✗ only through inter-module friction ✗ Poor torsional resistance ✓ High overall compliance	High stiffness achieved through inter-module friction and constrained module motion ✓ Strong torsional resistance ✗ Low overall compliance	High stiffness achieved through inter-module friction and constrained module motion ✓ Strong torsional resistance ▲ Moderate overall compliance

Fig. 2. Comparison of three configurations. (a) Spherical-joint configuration. (b) Orthogonal Semicylindrical Joint configuration. (c) Inclined Joint configuration.

A typical configuration in this category is the spherical-joint variable-stiffness mechanism [30], as shown in Fig. 2(a). Because the spherical joint allows multidirectional rotation, the overall mechanism can achieve high compliance and can form various postures. This is a major advantage when the mechanism must be manually shaped or guided through a complex path. However, the same large number of degrees of freedom also limits the holding capability after locking. Since the holding force is generated mainly by friction, the mechanism can slip when subjected to large bending moments or torsional moments. Therefore, although spherical-joint mechanisms are effective in terms of compliance, their holding capability is insufficient for applications requiring stable load support.

To overcome this limitation, joint geometries with additional constraints have been investigated. The Orthogonal Semicylindrical Joint Mechanism (OSJM) [31] is one such example(Fig. 2(b)). In this configuration, semicylindrical joint structures are arranged orthogonally at the front and rear ends of each module. This geometry can strongly constrain motion in a specific direction and provide high holding capability after locking. It can also offer high torsional resistance because the constrained joint surfaces directly support the applied moment. However, this advantage is accompanied by strong anisotropy. The mechanism strongly restricts motion in one direction but provides much lower resistance in the rotatable direction. Moreover, when multiple modules are connected in series, the overall posture-forming capability may become limited, making it difficult to form and lock complex three-dimensional postures.

The design motivation of the inclined-joint mechanism (Fig.2(c)) is based on this trade-off. A variable-stiffness linear mechanism should not simply maximize holding capability by constraining all possible motions. Instead, it should retain sufficient posture-forming capability while introducing sufficient geometric support to improve holding capability after locking. The proposed inclined-joint configuration addresses this requirement by using inclined circular contact surfaces. These surfaces reduce the degrees of freedom of each joint compared with a spherical joint, while still allowing continuous relative rotation between adjacent modules. At the same time, the inclined surfaces generate a structural support component against external loads when the mechanism is locked by wire tension.

This design can be interpreted as an intermediate solution between highly compliant spherical joints and strongly constrained semicylindrical joints. Compared with spherical joints,

the inclined-joint mechanism introduces geometric support in addition to frictional locking, thereby improving the load-supporting capability. Compared with the orthogonal semicylindrical joint configuration, it avoids excessive directional constraint and maintains greater overall posture-forming capability. Therefore, the proposed mechanism is expected to provide a more balanced relationship between posture-forming capability and holding capability.

Based on this design motivation, the trade-off between posture-forming capability and holding capability should be evaluated from both kinematic and mechanical perspectives. In serial variable-stiffness mechanisms with geometrically constrained joints, the joint geometry directly determines both the allowable relative motion between adjacent modules and the mechanical support generated after locking. Therefore, evaluating the holding force alone is not sufficient to characterize the effectiveness of the mechanism. It is also necessary to quantify how the joint structure affects the posture-forming capability of the entire serial mechanism.

For this purpose, this study introduces a workspace-based evaluation method using kinematic modeling. The reachable workspace of the distal end is used as a kinematic index of the posture-forming capability of the mechanism in the flexible state. A larger and more spatially distributed workspace indicates that the mechanism can form a wider range of postures, whereas a smaller or highly restricted workspace indicates stronger kinematic constraint. By comparing the workspace of the inclined-joint configuration with that of the orthogonal semicylindrical joint configuration under comparable geometric conditions, the influence of joint geometry on the posture-forming capability of the mechanism can be quantitatively evaluated.

On the basis of the above considerations, the design requirements of the proposed mechanism are summarized as follows. The mechanism should allow continuous posture formation in the flexible state, improve holding capability beyond that of friction-only spherical-joint mechanisms, avoid excessive geometric constraint that would prevent complex posture formation, and maintain a simple serial modular structure suitable for fabrication and integration. The inclined-joint variable-stiffness linear mechanism is designed to satisfy these requirements by combining frictional locking with geometric support generated by inclined contact surfaces. The following sections describe its structure, kinematic characteristics, holding principle, and experimental performance.

A preliminary study of the proposed mechanism was reported in [32], presenting the basic mechanism design, a static model for a representative loading condition, prototype development, and direction-dependent holding experiments using a 45° inclined-joint module pair. The present article substantially extends that study through DH-based kinematic modeling and workspace-based evaluation of posture-forming capability for different nominal inclination angles and module numbers; kinematic and mechanical comparisons with the Orthogonal Semicylindrical Joint Mechanism (OSJM); generalization of the mechanical analysis to different loading directions and nominal inclination angles; systematic holding and torsional-resistance experiments using module pairs with nominal inclination angles of 30°, 45°, and 60°; and evaluation of the relationship between steel wire tension and the holding capability of the assembled multi-module mechanism. These extensions provide a more comprehensive evaluation of the trade-off between posture-forming capability and load-supporting capability.

III. Structure and Operating Principle

This section describes the structure of the proposed Inclined Joint Variable Stiffness Linear Mechanism, its basic flexible-to-locked switching principle, and a structural issue that arises from the inclined contact surfaces together with its solution.

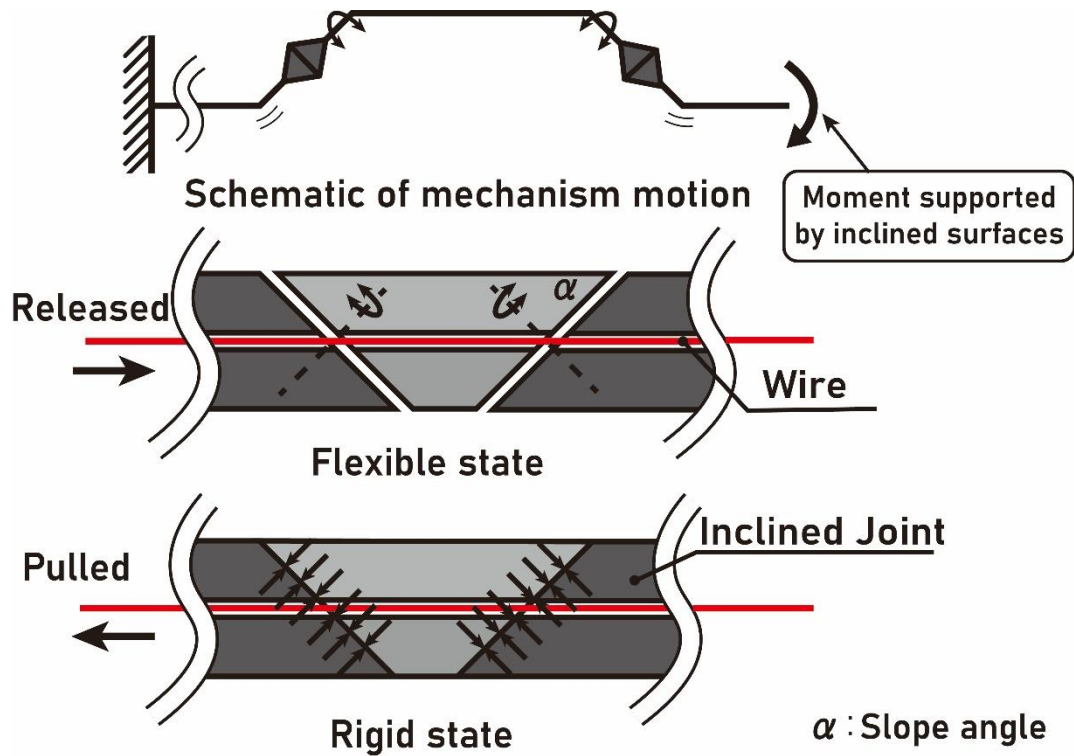


Fig. 3. Principle of stiffness switching in the proposed mechanism.

The proposed mechanism is a serial multi-joint structure designed to combine posture-forming capability with reliable holding. In addition to friction at adjacent interfaces, the inclined contact geometry supplies mechanical support against external loads (Fig.3).

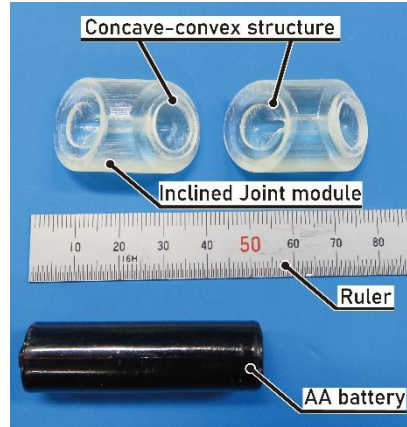


Fig. 4. Structure of the Inclined Joint module.

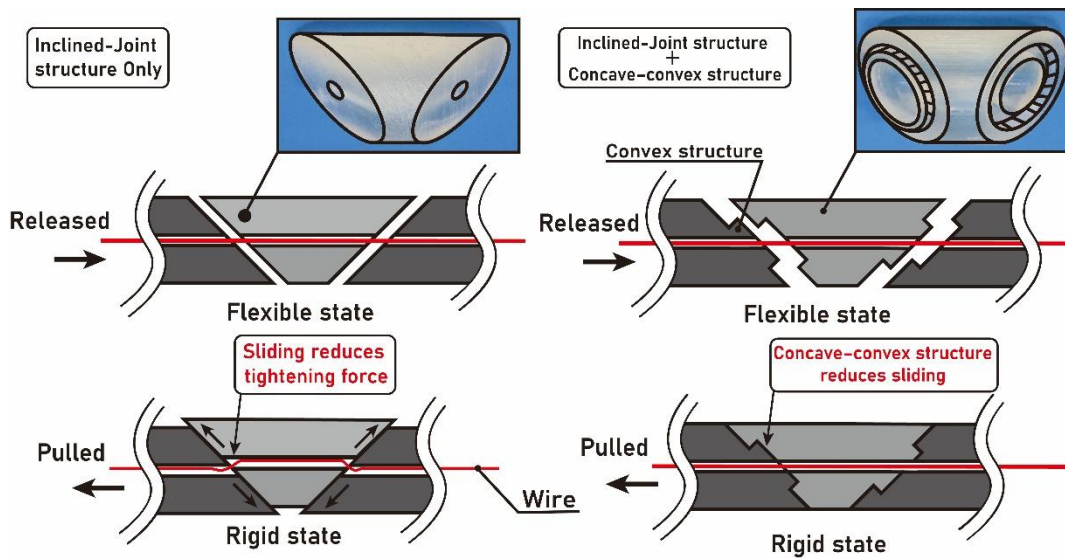


Fig. 5. Schematic comparison of the operating states and sliding behavior of the inclined-joint modules.

(a) in the inclined-joint-only structure, wire tension induces relative sliding along the inclined contact surfaces, causing the steel wire to contact the inner wall of the module hole and reducing the effective wire tension; (b) the addition of the concave-convex anti-sliding structure suppresses relative sliding while preserving flexibility in the released state, thereby improving locking in the tensioned state.

The Inclined Joint Variable Stiffness Linear Mechanism consists mainly of two parts: an inclined-joint module section and a wire-tensioning section. The inclined-joint module has a geometry similar to an obliquely cut cylinder (Fig.4). The boundary of the inclined contact surface is designed as a true circle, so that a constant contact condition can be maintained

between adjacent modules during relative rotation. A through-hole is provided at the center of each module for the steel wire to pass through.

Two types of modules are used in the mechanism. The first type has inclined contact surfaces at both ends and is used as the main intermediate module of the mechanism. The second type has an inclined contact surface on only one side and is used as the terminal module at both ends of the mechanism. These modules are connected in series by a steel wire passing through their central holes, thereby forming the complete linear mechanism.

When the steel wire is slack, adjacent modules can rotate relative to each other along the inclined circular contact surfaces. As a result, the entire mechanism can deform flexibly and form various postures. When the steel wire is tensioned, the modules are compressed against each other, and the current posture is maintained. In this locked state, the mechanism obtains high holding capability through the combined effect of frictional locking at the contact interfaces and geometric support generated by the inclined surfaces.

In this type of line-shaped variable-stiffness mechanism, steel wire tension is a key parameter governing the locked-state holding capability. However, unlike spherical modules, modules with inclined contact surfaces generate a force component perpendicular to the central axis when the steel wire is tensioned. This force component causes adjacent modules to slide along the inclined surfaces. As a result, the inner wall of the module hole may eventually come into contact with the steel wire, as shown in Fig. 5(a). Although the modules do not separate because they remain connected by the internal steel wire, this contact between the module hole and the steel wire significantly reduces the effective wire tension available for locking and reduces the

overall holding capability. Therefore, the contact structure of the module must be improved in order to suppress this displacement as much as possible.

To solve this problem, a flat protrusion is introduced at one end of the module, and a matching recess is introduced at the other end. These concave-convex features are designed to be concentric with the inclined circular contact surface, as shown in Fig. 5(b). By mechanically constraining the outward sliding tendency between adjacent modules, this structure enables the modules to rotate more stably about the axis normal to the inclined surface. At the same time, it allows a larger proportion of the steel wire tension to be effectively used for inter-module locking. As a result, the proposed concave-convex structure improves the stability of the inclined-joint module and improves the holding capability of the overall mechanism.

IV. Kinematic Modeling and Workspace Evaluation

This section quantitatively evaluates the posture-forming capability of the proposed inclined-joint mechanism in its flexible state. Serial kinematic models were developed for inclined-joint configurations with nominal inclination angles of 30° , 45° , and 60° as well as for the Orthogonal Semicylindrical Joint Mechanism (OSJM). The reachable positions of the distal end were calculated through forward kinematics, and the convex-hull volume of the sampled point cloud was used as a quantitative index of workspace size. The effects of the joint geometry, nominal inclination angle, and number of modules on the posture-forming capability of the mechanisms were then evaluated.

A. DH-Based Kinematic Model and Evaluation Method

To quantitatively evaluate the posture-forming capability of the inclined-joint configuration and the Orthogonal Semicylindrical Joint Mechanism (OSJM), both mechanisms were modeled

as serial kinematic chains. Inclined-joint configurations with nominal inclination angles of 30°, 45°, and 60° were considered. For each configuration, the number of modules was varied from two to six. The analysis focuses on the flexible state, in which the internal steel wire is released and relative motion is permitted between adjacent modules.

According to the Denavit–Hartenberg convention, a coordinate frame Σ_i was assigned to each module joint. The z_i -axis was aligned with the rotational axis of the corresponding joint, the x_i -axis was defined along the common normal between adjacent joint axes, and the y_i -axis was determined by the right-hand rule. The homogeneous transformation from Σ_{i-1} to Σ_i is expressed as:

$${}^{i-1}\mathbf{T}_i = \begin{bmatrix} \cos \theta_i & -\sin \theta_i \cos \alpha_i & \sin \theta_i \sin \alpha_i & a_i \cos \theta_i \\ \sin \theta_i & \cos \theta_i \cos \alpha_i & -\cos \theta_i \sin \alpha_i & a_i \sin \theta_i \\ 0 & \sin \alpha_i & \cos \alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

where a_i , d_i , and α_i are the DH parameters determined by the module geometry, and θ_i is the joint angle. The joint angle is written as

$$\theta_i = q_i + \theta_{i,0}$$

where q_i is the joint variable and $\theta_{i,0}$ is the initial angular offset determined by the assembled configuration.

In the inclined-joint configuration, the rotational axis of each joint is normal to the inclined contact surface. When the nominal inclination angle of the contact surface is denoted by α , the inclination of the rotational axis relative to the module axis is

$$\beta = 90^\circ - \alpha$$

Accordingly, nominal inclination angles of 30°, 45°, and 60° correspond to rotational-axis inclination angles of 60°, 45°, and 30° respectively. These geometric relationships were incorporated into the DH parameters of the corresponding serial models.

For an n -module mechanism, the transformation from the base frame to the final module frame is obtained by sequentially multiplying the transformation matrices:

$${}^0\mathbf{T}_n(q) = {}^0\mathbf{T}_1(q_1){}^1\mathbf{T}_2(q_2) \cdots {}^{n-1}\mathbf{T}_n(q_n)$$

When the fixed terminal offset is included, the transformation of the distal end is expressed as

$${}^0\mathbf{T}_E(q) = {}^0\mathbf{T}_n(q){}^n\mathbf{T}_E$$

where ${}^nT_E$ represents the fixed transformation from the final module frame to the distal end. The distal-end position is obtained from the translational component of the transformation matrix:

$$p_E(q) = \begin{bmatrix} x_E(q) \\ y_E(q) \\ z_E(q) \end{bmatrix} = \text{trans}({}^0T_E(q))$$

A base azimuthal rotation was introduced separately and was allowed to vary over a full 360° range for all configurations. This eliminates the influence of the initial azimuthal orientation on the calculated workspace.

For the inclined-joint configurations, each module joint was allowed to complete a full rotation about the normal to its inclined contact surface:

$$q_i \in [0, 2\pi), \quad i = 1, 2, \dots, n$$

For the OSJM, relative motion at every module joint was restricted by the convex–concave semicylindrical contact geometry. The allowable angular range of each OSJM module joint was set to

$$q_i \in [-45^\circ, 45^\circ], \quad i = 1, 2, \dots, n$$

The number of modules was set to

$$n = 2, 3, 4, 5, 6$$

The corresponding straight lengths of the mechanisms were 35, 55, 75, 95, and 115 mm, respectively. For a given number of modules, the three inclined-joint configurations and the OSJM had the same total length and the same distal-end definition. Therefore, their workspace volumes could be directly compared under identical dimensional conditions.

The joint variables were sampled within their allowable ranges, and the distal-end position was calculated for each sampled posture using the forward kinematic model. The resulting set of distal-end positions P was used to approximate the reachable workspace. The envelope volume of the workspace was evaluated using the convex hull of the sampled point cloud:

$$V_{\text{hull}} = \text{Volume}(\text{ConvHull}(P))$$

For configurations with the same number of modules, the original convex-hull volume V_{hull} was used directly because their total lengths were identical. When comparing mechanisms with different numbers of modules, the total length also changed. Therefore, the workspace volume was normalized by the cube of the straight mechanism length:

$$V_{\text{norm}} = \frac{V_{\text{hull}}}{L_{\text{total}}^3}$$

The normalized volume permits comparison across module numbers while reducing the effect of mechanism scale.

Self-collision between modules, collision with the surrounding environment, elastic deformation of the modules, and restrictions caused by the actual steel wire path were not considered in the kinematic analysis. Therefore, the calculated workspace represents the fundamental geometric mobility of each configuration rather than the complete reachable workspace of the physical prototype. In addition, because the convex hull may include concave regions and internal voids that are not actually reachable, V_{hull} was used as a consistent comparative index of workspace size.

B. Representative Four-Module Comparison

The reachable workspaces of the four configurations were first compared using representative four-module models. The straight length of each model was 75 mm, and the same distal-end definition and workspace evaluation procedure were used. Fig. 6 shows the sampled workspaces of the 30 °, 45 °, and 60 ° inclined-joint configurations and the OSJM.

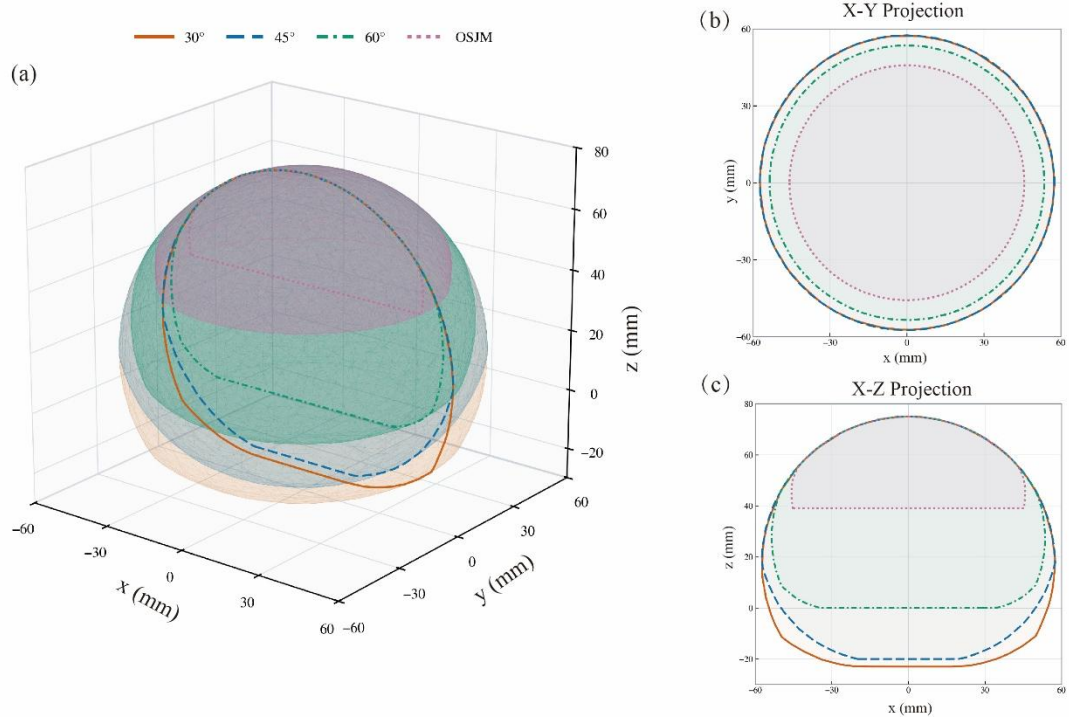


Fig. 6. Reachable workspaces of the representative four-module configurations. (a) three-dimensional workspace envelopes; (b) X-Y projections; (c) X-Z projections.

The inclined-joint configurations generated larger spatial envelopes than the OSJM. Among the three inclined-joint configurations, the workspace became smaller as the nominal inclination angle increased. The 30° configuration generated the largest workspace, followed by the 45° and 60° configurations, whereas the OSJM exhibited the most restricted workspace.

Table 1 summarizes the convex-hull volumes of the representative four-module models.

Table 1 Comparison of convex-hull workspace volumes of four-module inclined-joint configurations. and the OSJM

Configuration	Nominal inclination angle	$V_{\text{hull}}(\text{cm}^3)$	Ratio to OSJM
Inclined joint	30°	730.346	4.41
Inclined joint	45°	661.589	3.99
Inclined joint	60°	500.804	3.02
OSJM	—	165.663	1.00

The workspace volume of the 30° inclined-joint configuration was approximately 4.41 times that of the OSJM. The corresponding ratios for the 45° and 60° configurations were approximately 3.99 and 3.02, respectively. Thus, all three inclined-joint configurations provided substantially larger reachable workspaces than the OSJM under the same module number and total length.

The smaller workspace of the OSJM results from the limited angular range of its module joints. Although the orthogonal arrangement of the semicylindrical joints permits bending in alternating directions, each module joint is restricted to $\pm 45^\circ$. In contrast, each inclined joint can continuously rotate about the normal to its contact surface, allowing a larger number of combinations of module orientations.

The comparison also confirms that inclination angle affects flexible-state posture-forming capability. Within the investigated range, decreasing the nominal inclination angle increased the reachable workspace.

C. Effects of Inclination Angle and Module Number

To examine whether the tendency observed in the four-module comparison was maintained for different serial-chain lengths, the workspace analysis was extended to mechanisms consisting of two to six modules. Because the straight mechanism length increased with the number of modules, the normalized workspace volume V_{norm} was used for this comparison. Fig. 7 shows the relationship between module number and normalized workspace volume for the three inclined-joint configurations and the OSJM.

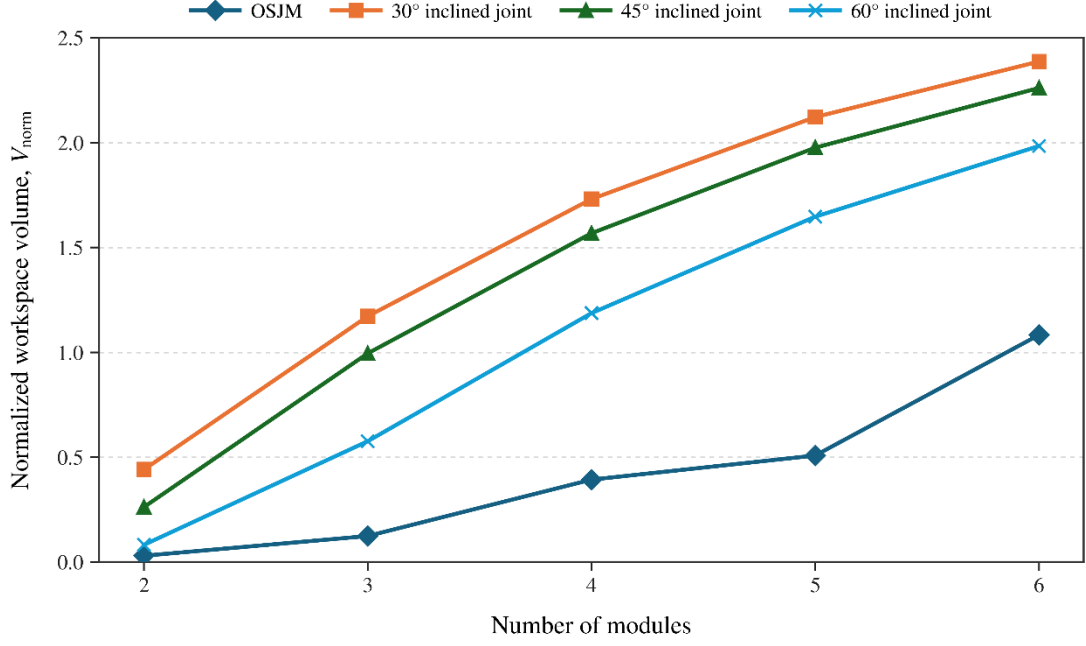


Fig. 7. Effect of module number on the normalized workspace volume.

For all four configurations, normalized workspace volume increased with module number. Because the volume was normalized by the cube of total length, the increase reflects the additional combinations of joint rotations rather than scale alone.

The ordering remained unchanged over the full range:

$$V_{30^\circ} > V_{45^\circ} > V_{60^\circ} > V_{OSJM}$$

Thus, the relationship observed in the representative four-module comparison was also maintained for mechanisms consisting of two, three, five, and six modules. The 30° inclined-joint configuration consistently generated the largest normalized workspace, whereas the OSJM generated the smallest.

The difference among the three inclined-joint configurations became smaller as the number of modules increased. For the two-module models, the normalized workspace volume of the 30° configuration was approximately 1.69 times that of the 45° configuration, whereas this ratio decreased to approximately 1.06 for the six-module models. Similarly, the normalized

volume of the 60° configuration increased from approximately 31% of the 45° value for two modules to approximately 88% for six modules.

This tendency suggests that the influence of the geometry of an individual joint is particularly pronounced in short serial chains. As the number of modules increases, the greater number of possible joint-angle combinations partially reduces the difference in the overall workspace caused by the nominal inclination angle. Nevertheless, even for the six-module models, the normalized workspace volumes of the 30° , 45° , and 60° inclined-joint configurations remained approximately 2.20, 2.09, and 1.83 times that of the OSJM, respectively.

In summary, smaller nominal inclination angles produced larger workspaces under the investigated conditions, and increasing module number enlarged the normalized workspace for every configuration. The inclined-joint mechanisms consistently retained a larger flexible-state posture range than the OSJM.

V. Quasi-Static Holding Model under Transverse Loading

In the locked state, steel wire tension generates interface compression and friction, while the inclined contact geometry provides additional support against external loads. Holding capability therefore arises from both frictional locking and geometric support.

The simplified quasi-static model developed here isolates the geometric support responsible for the directional variation observed in module-pair tests. Friction, local deformation, roughness, clearance, and detailed pressure distribution are omitted; the model is intended to explain directional trends rather than predict the absolute maximum force.

The external load is applied at the distal end within the transverse plane. An apparent inclination angle defined for each loading plane allows the maximum sustainable load to be expressed as a function of loading direction.

A. Definition of the Transverse Loading Direction

The module axis is defined as the X-axis. Accordingly, the transverse plane at the distal end of the module pair is defined as the Y-Z plane. The direction of the external load within this transverse plane is represented by the angle φ .

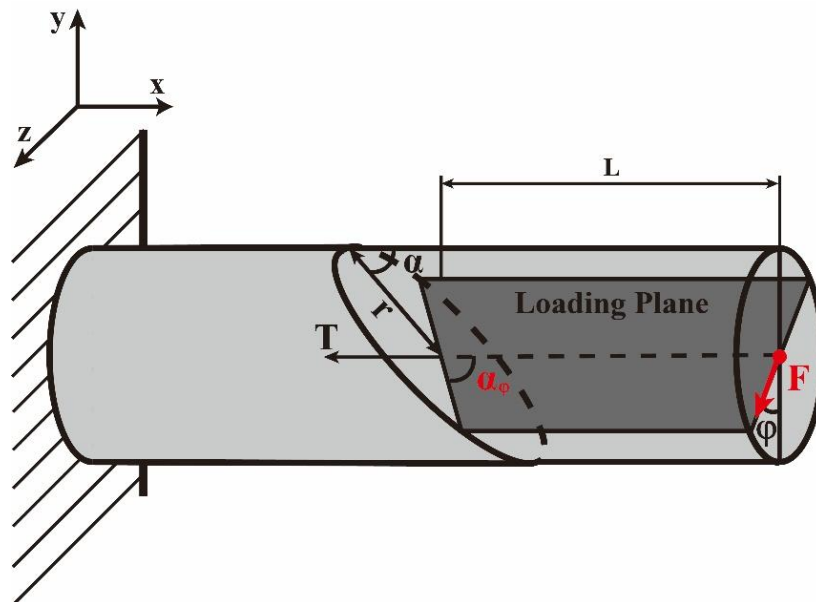


Fig. 8. Geometric framework for quasi-static holding analysis under an arbitrary transverse load.

For an arbitrary loading direction φ , a two-dimensional loading plane can be defined by the module axis and the current external-load direction. The effective geometric support point at the holding limit is assumed to lie within this loading plane. In this plane, the original inclined surface appears as a projected inclined line. Consequently, the inclination angle used in the quasi-static analysis is not necessarily the nominal inclination angle α , but rather the apparent inclination angle in the current loading plane, denoted by α_φ .

B. Apparent Inclination Angle and Holding Model

The apparent inclination angle α_φ is obtained from the geometric projection of the original inclined surface onto the current loading plane, as illustrated in Fig. 8. Its sine and cosine are expressed as

$$\sin \alpha_\varphi = \frac{\sin \alpha}{\sqrt{\sin^2 \alpha + \cos^2 \alpha \cos^2 \varphi}}$$

$$\cos \alpha_\varphi = \frac{\cos \alpha \cos \varphi}{\sqrt{\sin^2 \alpha + \cos^2 \alpha \cos^2 \varphi}}$$

Here, $\cos \alpha_\varphi$ is treated as a signed quantity. Its sign represents the direction of the axial projection of the inclined surface in the current loading plane and changes with the transverse loading direction φ .

The fundamental relationship of the model is

$$\text{Maximum sustainable transverse load} = \frac{\text{Resisting moment generated by the wire tension}}{\text{Moment arm of the external load}}$$

The holding limit is defined as the critical state immediately before relative rotation, sliding, or separation begins between the locked modules. In the two-dimensional loading plane corresponding to φ , the wire tension T generates a resisting moment through the inclined geometry. The effective moment arm of the wire tension about the geometric support point is approximated as

$$r \sin \alpha_\varphi$$

where r is the radius of the circular inclined contact surface. The resisting moment generated by the wire tension is therefore expressed as

$$M_T(\varphi) = Tr \sin \alpha_\varphi$$

The external load F produces an overturning moment about the same effective geometric support point. Its effective moment arm is expressed as

$$L - r \cos \alpha_\varphi$$

where L is the distance from the center of the circular inclined contact surface to the external-load application point. The overturning moment generated by the external load is therefore

$$M_F(\varphi) = F(L - r \cos \alpha_\varphi)$$

At the holding limit, the resisting moment generated by the wire tension balances the overturning moment generated by the external load. The maximum sustainable external load in the transverse loading direction φ is therefore obtained as

$$F_{max}(\varphi) = \frac{Tr \sin \alpha_\varphi}{L - r \cos \alpha_\varphi}$$

This expression indicates that the maximum sustainable load varies with the transverse loading direction φ . When the loading direction changes, the apparent inclination angle α_φ in the corresponding loading plane also changes. Consequently, both the resisting moment arm of the wire tension and the effective moment arm of the external load vary with the loading direction.

The proposed quasi-static model describes the geometric support contribution of the inclined joint under transverse end-face loading. The model indicates that the maximum sustainable external load is governed by the balance between the resisting moment generated by the wire tension and the overturning moment generated by the external load. Increasing the wire tension T , increasing the effective contact radius r , or reducing the distance L between the contact

region and the external-load application point can improve the holding capability. The inclination angle α should be designed by considering both the holding performance in the locked state and the posture-forming capability in the flexible state.

The model explicitly represents only geometric support. Actual holding additionally includes friction, side-wall contact, local deformation, surface condition, and contact area. Therefore, this model is primarily used to investigate the origin of the direction-dependent load-bearing capability of the inclined-joint mechanism and to provide a preliminary explanation of how variations in the nominal inclination angle affect its load-bearing capability.

VI. Prototype Development

A. Module Fabrication and Assembly

A multi-module prototype was fabricated to verify switching between flexible and locked states and to examine the posture-dependent wire take-up required by the serial chain.

Intermediate modules have inclined contacts at both ends; terminal modules have one inclined and one perpendicular end. All modules were printed in AR-M2 resin using an AGILISTA system (Keyence, Japan), and a 2 mm-diameter steel wire passed through their central holes.

During assembly, the first terminal module, the intermediate modules, and the final terminal module were threaded sequentially onto the fixed wire while each protrusion-recess pair was engaged. The free wire end was then connected to the tensioner, allowing free relative rotation when released and interface compression when tensioned.

B. Posture-Dependent Wire Take-Up and Adjustable Tensioning Mechanism

Joint rotation changes the wire path through the modules. Relative to the aligned reference posture, bent configurations and postures involving several rotated joints generally require more take-up before all interfaces are sufficiently compressed.

The initial toggle-clamp tensioner (Fig. 1) confirmed basic flexible-to-locked switching but provided an essentially fixed stroke. Limited adjustment through the hollow screw could not reliably lock some complex postures.

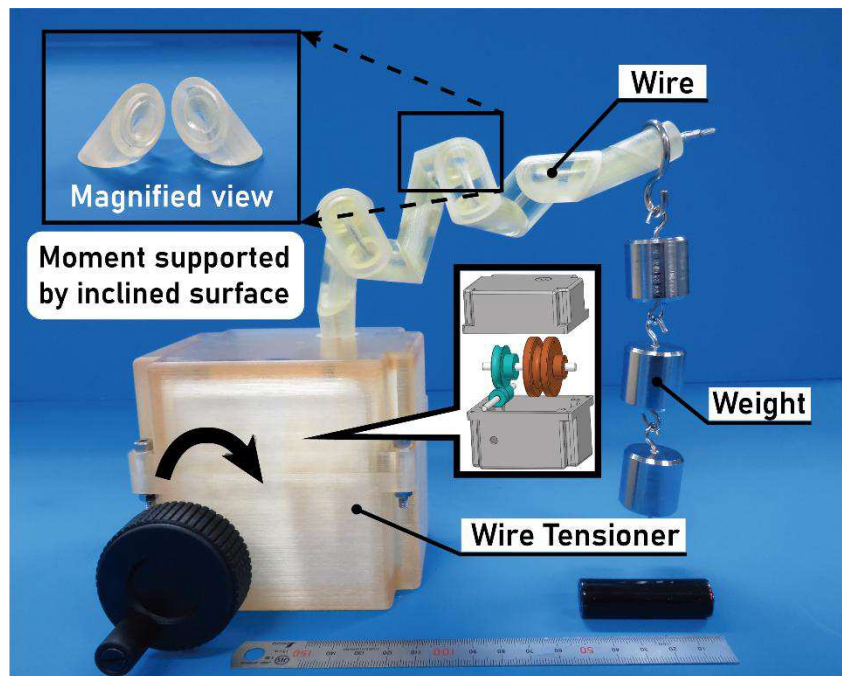


Fig. 9. Prototype with an adjustable steel wire take-up length using a worm gear tensioning mechanism.

An adjustable worm-gear winding mechanism was therefore developed (Fig. 9). A handwheel drives a worm, worm wheel, and coaxial roller to wind or release the steel wire gradually. The mechanism continuously adjusts take-up to the current posture, and worm self-locking suppresses reverse rotation under wire tension. It thereby accommodates different postures, although winding displacement alone does not directly measure the compression at each interface. The parameters of the improved prototype are summarized in Table 2.

Table 2 Prototype specifications.

Specification	Value
Overall dimensions (L×W×H)	109×86×101 [mm]
Assembly mass	860 g
Module slanted-face diameter	21.21 mm
Module slant angle	45°
Number of modules	15
Module material	AR-M2

VII. Experimental Evaluation

A. Direction-Dependent Holding Capability of Module Pairs

1) Experimental Setup and Evaluation Method

To evaluate the holding capability of different module-pair configurations under transverse end-face loading, quasi-static loading experiments were conducted using a simplified specimen consisting of a single pair of modules. Three inclined-joint module pairs with nominal inclination angles of 30°, 45°, and 60°, respectively, and one Orthogonal Semicylindrical Joint Mechanism (OSJM) module pair were evaluated.

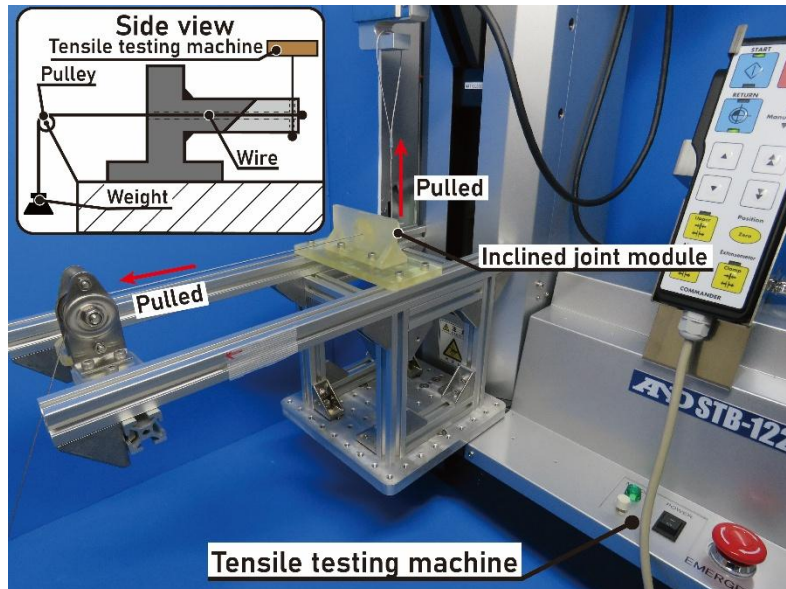


Fig. 10. Experimental setup for the directional holding-force tests of the inclined-joint and OSJM

module pairs.

Fig. 10 shows the setup. One module was fixed, and a tensile testing machine (STB-1225S, Instron, Japan) loaded the other. Suspended weights applied an approximately constant steel wire tension throughout loading, limiting changes in the locking condition.

For the inclined-joint pairs, load was applied in the transverse plane at

$$\varphi = 0^\circ, 45^\circ, 90^\circ, 135^\circ, 180^\circ$$

The desired direction was obtained by changing the specimen mounting orientation because the testing machine loaded only along its actuation axis. The OSJM was tested in its representative rotatable (0°) and geometrically constrained (90°) directions.

Experimental conditions:

- 1) Loading direction: $0^\circ, 45^\circ, 90^\circ, 135^\circ, 180^\circ$.
- 2) Hanging weight: 2 kg ($T \approx 19.6\text{ N}$).
- 3) Wire diameter: 2 mm.
- 4) Inclined angle of the module: $\alpha = 30^\circ, 45^\circ, 60^\circ$.
- 5) Radius of the inclined circular surface of the module: $r = 10.6\text{ mm}$.
- 6) Center-to-center distance between the two end faces of a single module: $L = 17.5\text{ mm}$.
- 7) Tensile speed: 20 mm/min.
- 8) Length of the module pair: 40 mm.

All specimens used the same wire tension, loading speed, overall length, axial distance from the module end face to the circular-surface center, and contact-surface diameter. The OSJM also incorporated comparable protrusion-recess features to maintain consistent test conditions.

After the prescribed wire tension locked the pair, the external load was increased until the measured force dropped abruptly. The preceding peak was defined as the maximum holding

force and marked the onset of appreciable relative motion. Each condition was tested five times; results are reported as means with standard-deviation error bars.

2) Effect of Inclination Angle and Comparison with the Quasi-Static Model

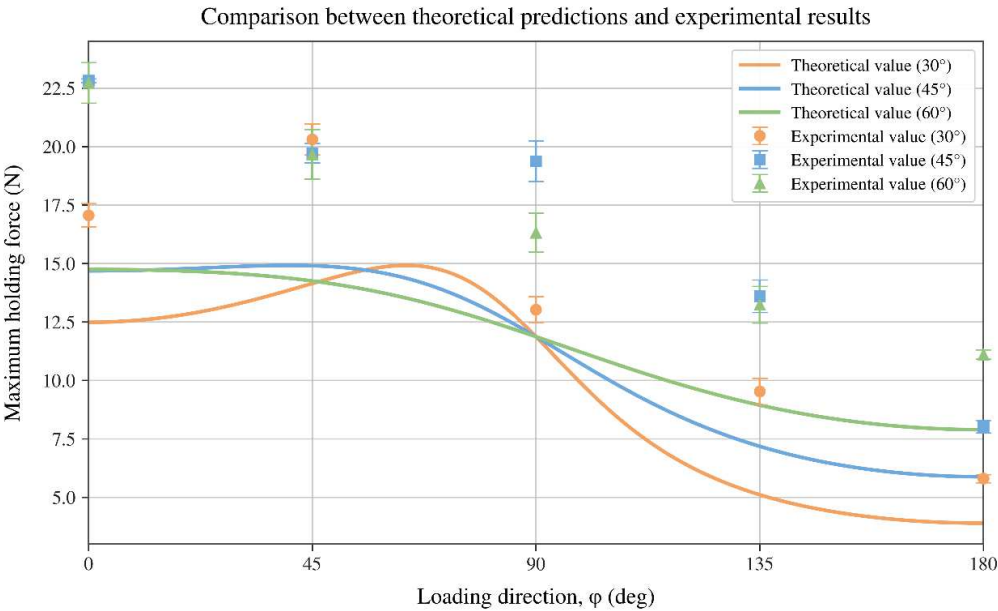


Fig. 11. Predicted and experimental direction-dependent maximum holding forces.

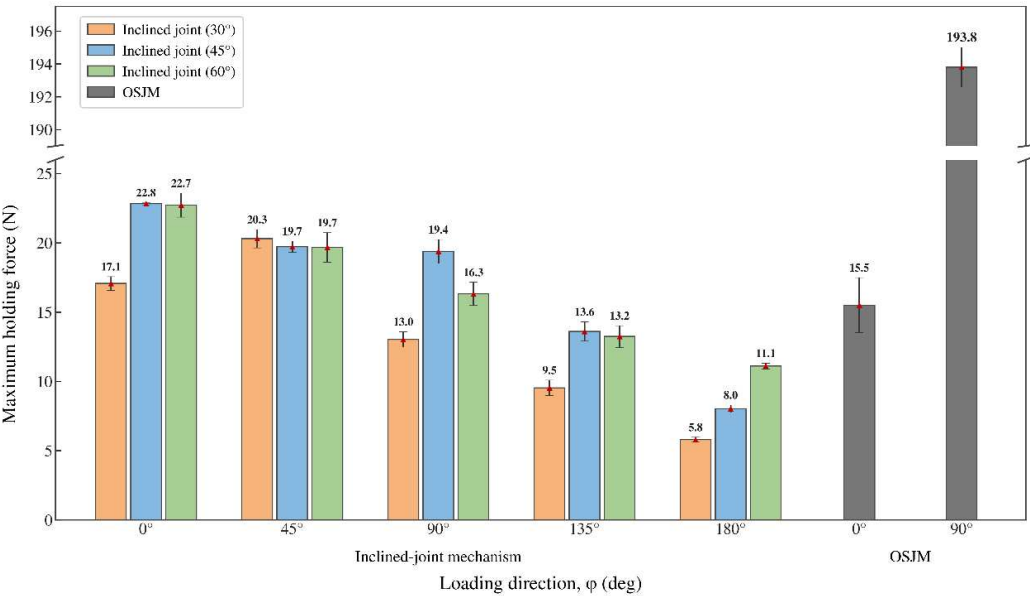


Fig. 12. Experimental comparison of direction-dependent maximum holding forces.

Fig. 11 compares the experimentally measured maximum holding forces with the predictions of the quasi-static geometric model for inclined-joint module pairs with inclination angles of

30°, 45°, and 60°. The experimental results are represented by discrete markers with error bars, whereas the continuous curves represent the geometry-only predictions obtained using the model proposed in Section V.

Model parameters were taken directly from specimen dimensions and test conditions, without fitting, to evaluate whether the geometry-only model reproduced the observed directional trends.

As shown in Fig. 11, the maximum holding force was significantly affected by both the loading direction and the nominal inclination angle. In particular, the module pair with an inclination angle of 30° exhibited a non-monotonic directional response. The experimental results showed that the maximum holding force in the 45° loading direction was higher than that in the 0° direction, after which the holding force decreased as the loading direction approached 180°. The quasi-static geometric model predicted the same initial increase followed by a decrease.

This non-monotonic behavior results from the competing variations of the two effective moment arms in the model. As the loading direction φ increases, the effective resisting moment arm generated by the steel wire tension,

$$r \sin \alpha_{\varphi}$$

gradually increases. At the same time, the effective overturning moment arm of the external load,

$$L - r \cos \alpha_{\varphi}$$

also increases. For the 30° module, the beneficial effect of the increase in the resisting moment arm dominates over the relatively small loading-direction range, causing the predicted maximum holding force to initially increase. As the loading direction increases further, the effect of the increasing external-load moment arm becomes dominant, resulting in a gradual decrease in the maximum holding force. For the present geometric parameters, the model predicts that the geometry-only holding force reaches its maximum at a loading direction of approximately 64°. In the experiments, the holding force at 45° was higher than that at 0°, supporting the intermediate-loading-direction peak predicted by the model.

For the module pair with an inclination angle of 45°, the theoretical prediction varied only slightly in the low-loading-angle range and then gradually decreased as the loading direction approached 180°. The experimental results similarly exhibited an overall decreasing tendency toward 180°, although the measured maximum occurred in the 0° direction. For the module pair with an inclination angle of 60°, both the model and the experimental results exhibited a more continuous decrease from 0° to 180°. These results indicate that the nominal inclination angle affects not only the absolute magnitude of the maximum holding force, but also the shape of its directional response and the loading direction corresponding to the maximum holding capability.

As also shown in Fig. 11, the three theoretical curves intersect at

$$\varphi = 90^\circ$$

At this loading direction, the apparent inclination angle satisfies

$$\sin \alpha_\varphi = 1 \quad \cos \alpha_\varphi = 0$$

and the geometry-only prediction becomes

$$F_{geom}(90^\circ) = \frac{Tr}{L}$$

which is independent of the nominal inclination angle α . In contrast, the experimental results at 90° remained dependent on the nominal inclination angle. This difference indicates that, in this loading direction, the holding behavior of the actual module pair includes additional contributions associated with the contact state between the modules.

Predictions were generally below the measured maxima because the experiment also included interfacial friction, side-wall contact of the mating features, local deformation, and assembly effects. The model therefore provides a geometric baseline, whereas the measurements represent total holding capability.

Despite the differences in absolute magnitude between the model predictions and the experimental results, the model captured several important directional characteristics observed in the experiments. In particular, it reproduced the non-monotonic response of the 30° module and predicted that increasing the inclination angle improves the holding capability near the 135° and 180° loading directions. These results demonstrate that the proposed quasi-static model provides a mechanical interpretation of how the inclination angle and loading direction influence the geometric contribution to the holding capability of the module pair.

3) Comparison with the Orthogonal Semicylindrical Joint Mechanism

To further clarify the holding characteristics of the inclined-joint configuration, its experimental results were compared with those of an OSJM module pair. As shown in Fig. 12, the figure presents the maximum holding forces of the inclined-joint module pairs with

inclination angles of 30° , 45° , and 60° under five loading directions, together with the experimental results of the OSJM in the 0° and 90° directions.

For the OSJM, the 0° direction corresponds to its representative rotatable direction, whereas the 90° direction corresponds to the direction in which relative motion is strongly constrained by the orthogonal semicylindrical geometry. As shown in Fig. 12, the maximum holding force of the OSJM was approximately 15.5 N in the 0° direction. In contrast, it increased to approximately 193.8 N in the 90° geometrically constrained direction. This substantial difference indicates that the OSJM exhibits pronounced directional anisotropy and provides strong structural support in its constrained direction.

None of the three inclined-joint module pairs achieved the extremely high holding force exhibited by the OSJM in its 90° constrained direction. Nevertheless, the inclined-joint module pairs maintained a certain level of holding capability in all five transverse end-face loading directions investigated. In addition, changing the nominal inclination angle altered the directions of relatively high and low holding capability. In particular, increasing the inclination angle improved the holding capability near the 135° and 180° loading directions.

Together with the workspace results in Section IV, these tests distinguish the two design strategies. The OSJM favors strong support in a specified direction, whereas the inclined joint favors useful holding across several directions while retaining greater flexible-state mobility.

B. Torsional Resistance of Module Pairs

1) Experimental Setup and Evaluation Method

To investigate the effect of the inclination angle on the torsional resistance of inclined-joint module pairs, torsional loading tests were conducted using module pairs with inclination angles

of 30°, 45°, and 60°. For comparison, an Orthogonal Semicylindrical Joint Mechanism (OSJM) module pair was also tested under the same conditions.

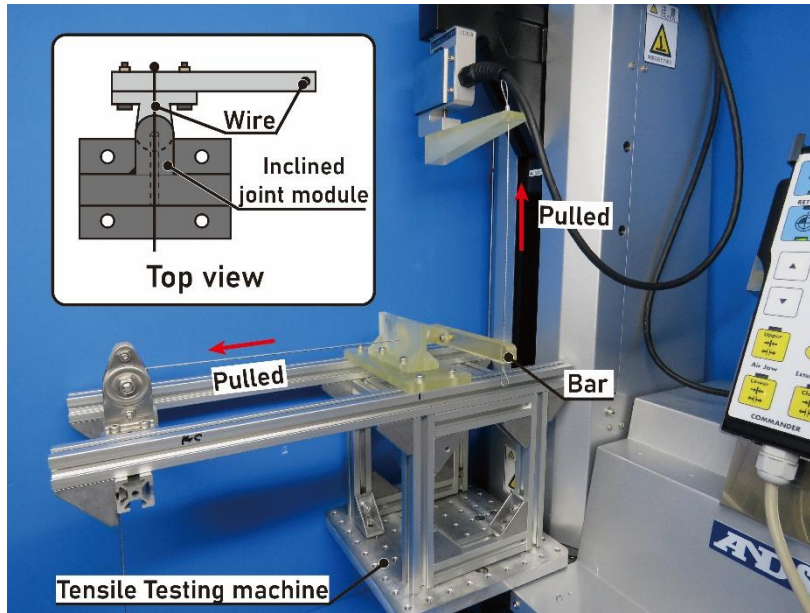


Fig. 13. Experimental setup for torsional-resistance measurements of the inclined-joint and OSJM

module pairs.

In this experiment, torsional resistance was defined as torque about the central through-hole axis, which coincides with the steel wire axis in the straight configuration. One module was fixed and a 90 mm loading bar was attached to the other (Fig. 13). A wire at the bar tip remained parallel to the tensile direction so that the measured force generated torque about the central axis.

The experimental conditions were as follows:

- 1) Hanging weight: 2 kg, ($T \approx 19.6 \text{ N}$).
- 2) Loading-bar length: 90 mm.
- 3) Internal steel-wire diameter: 2 mm.
- 4) Tensile speed: 20 mm/min.
- 5) Module-pair length: 40 mm.

Torque was calculated from tensile force and the 90 mm arm. Initial displacement offsets were corrected to reduce the effect of loading-system slack before the five torque-displacement curves for each configuration were averaged.

The maximum value within the tested displacement range was defined as the maximum measured resisting torque because not every configuration exhibited a distinct post-peak decrease. Means and standard deviations were calculated from five trials.

2) Torsional Test Results and Discussion

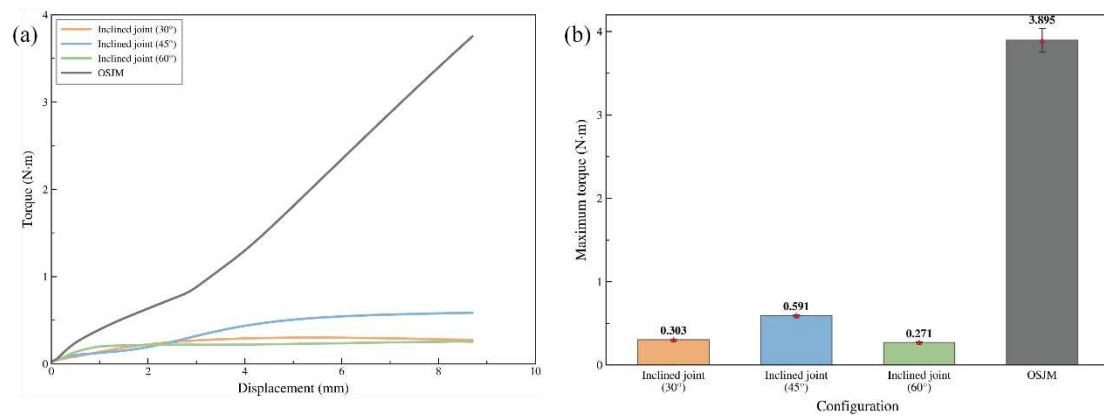


Fig. 14. Torsional-resistance comparison of inclined-joint and OSJM module pairs. (a) mean torque-displacement curves; (b) mean maximum resisting torques.

Fig. 14(a) shows the torque-displacement curves of the inclined-joint module pairs with inclination angles of 30°, 45°, and 60°, together with that of the OSJM module pair. The resisting torque of the 30° module pair gradually increased to a distinct peak and subsequently decreased. The resisting torque of the 45° module pair increased over most of the tested displacement range without exhibiting a pronounced post-peak reduction. The 60° module pair exhibited a relatively rapid initial increase in resisting torque, followed by a region of more gradual change. By contrast, the resisting torque of the OSJM module pair increased continuously throughout the tested displacement range and reached a substantially higher level

than those of the inclined-joint module pairs, with no evident peak or plateau before the end of loading.

As summarized in Fig. 14(b), the maximum resisting torques, averaged over five trials for each configuration, were 0.303, 0.591, 0.271, and 3.895 N·m for the 30°, 45°, and 60° inclined-joint module pairs and the OSJM module pair, respectively; the error bars represent one standard deviation. Among the inclined-joint configurations, these results indicate that torsional resistance does not vary monotonically with the nominal inclination angle. The maximum resisting torque of the OSJM module pair was approximately 6.6 times that of the 45° inclined-joint module pair, which exhibited the highest value among the three inclined-joint configurations. This pronounced difference is consistent with the directional holding tests and supports the interpretation that the orthogonal semicylindrical contacts of the OSJM strongly restrict rotation about the steel-wire axis, thereby providing substantially greater torsional resistance in its constrained direction.

C. Relationship between Assembled-Mechanism Holding Capability and Steel Wire Tension

1) Experimental Setup and Evaluation Method

Multi-module tests examined the effect of steel wire tension on holding capability (Fig. 15). After the mechanism was locked, a tensile testing machine loaded its distal end. The posture and loading direction were kept identical because holding capability is direction dependent.

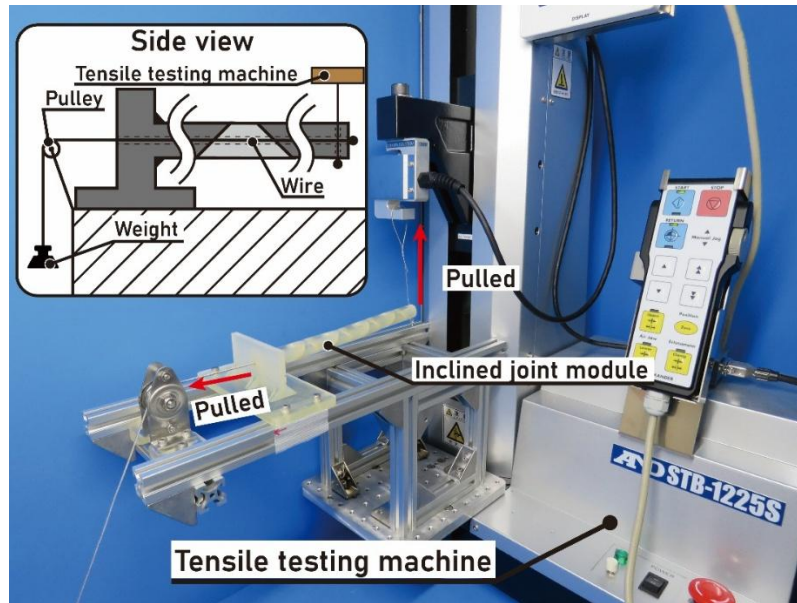


Fig. 15. Experimental setup for multi-module holding-capability tests.

The steel-wire tension was adjusted by changing the mass of the hanging weight. The experimental conditions were as follows:

- 1) Steel-wire tension: applied using hanging weights of 1, 2, 3, 4, 5, and 6 kgf.
- 2) Internal steel-wire diameter: 2 mm.
- 3) Inclined angle of the module: 45° .
- 4) Radius of the inclined circular contact surface: 10.6 mm.
- 5) Tensile speed: 20 mm/min.
- 6) Overall length of the mechanism: 195 mm.
- 7) Total number of modules: 10

For each trial, the peak immediately before the abrupt load drop was defined as maximum holding force, marking loss of the stable locked state. Five trials were conducted at each tension; means deviations were used for analysis.

2) Experimental Results and Discussion

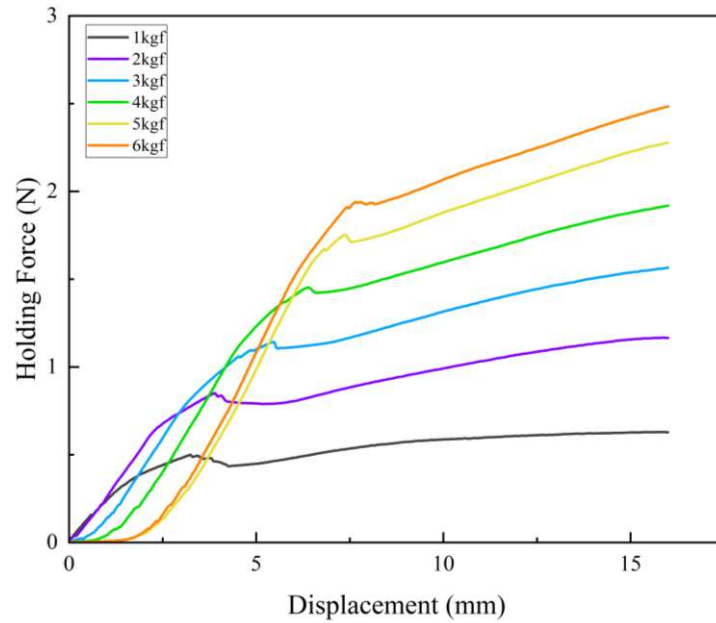


Fig. 16. Holding force curves under different steel wire tension.

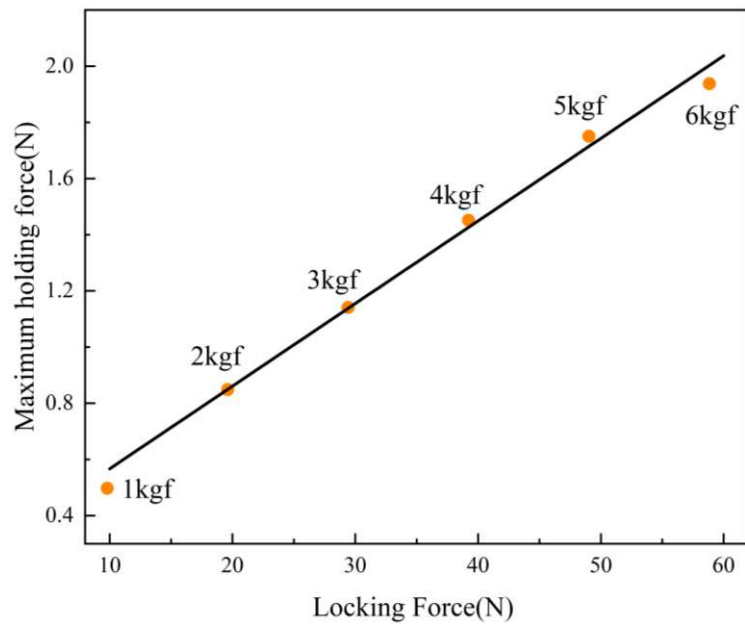


Fig. 17. Relationship between steel wire tension and maximum holding force.

Fig. 16 shows that both the sustained load and the peak immediately before failure increased with steel wire tension.

As shown in Fig. 17, the maximum holding forces measured under hanging weights of 1, 2, 3, 4, 5, and 6 kgf were approximately 0.497, 0.848, 1.141, 1.451, 1.750, and 1.937 N, respectively. The maximum holding force increased monotonically with the steel wire tension over the investigated range.

Linear regression of the experimental data yielded

$$F_{max} = 0.273 + 0.0294T,$$

with a coefficient of determination of $R^2 = 0.992$, where both F_{max} and T are expressed in newtons. This result indicates that the maximum holding force of the assembled mechanism increased approximately linearly with the steel wire tension within the tested range. The empirical relationship obtained in this experiment can serve as a practical reference for selecting the steel wire tension required to resist a specified external load under the tested posture and loading direction.

VIII. Discussion

The combined kinematic and mechanical results show that the nominal inclination angle α affects both the posture-forming capability of the mechanism in the flexible state and its load-supporting characteristics in the locked state. However, these performance indices do not exhibit the same dependence on the inclination angle. Among the three configurations investigated, the 30° configuration consistently generated the largest workspace, whereas the 45° module pair exhibited the highest torsional resistance. Increasing the inclination angle also improved the holding capability near the 135° and 180° loading directions, but reduced the overall workspace. Therefore, the nominal inclination angle is a coupled design parameter governing posture-forming capability, directional holding capability, and torsional resistance,

and it cannot be selected on the basis of a single performance index. A smaller inclination angle is advantageous when a wide posture-forming range is required. Among the tested configurations, the 45° configuration is preferable when torsional resistance is prioritized, whereas a larger inclination angle may be beneficial when greater holding capability under opposite-side loading is required. Accordingly, the inclination angle should be selected by considering both the required posture range and the expected loading directions.

The influence of the nominal inclination angle on the workspace decreased as the number of modules increased. The ratio of the normalized workspace volume of the 30° configuration to that of the 45° configuration decreased from approximately 1.69 for the two-module models to approximately 1.06 for the six-module models. This result indicates that the geometry of an individual joint has a stronger influence on the posture-forming capability of a short serial chain, whereas the increasing number of possible joint configurations in a longer chain partially compensates for the workspace difference caused by the inclination angle. Therefore, for mechanisms containing a relatively large number of modules, greater emphasis may be placed on the locked-state mechanical performance when selecting the inclination angle. In contrast, the OSJM exhibited the smallest normalized workspace for all investigated module numbers, while its maximum holding force in the constrained direction reached approximately 193.8 N. Its maximum measured torsional resisting moment was approximately 3.895 N·m, which was 6.6 times that of the 45° inclined-joint module pair. These results demonstrate that strong geometric constraint can substantially improve load-supporting capability in a specific direction, but simultaneously restrict the posture-forming range. The inclined-joint configuration instead

retains continuous rotational freedom at each joint and therefore achieves a different balance between geometric support and overall posture-forming capability.

For the assembled mechanism, maximum holding force increased approximately linearly with applied steel wire tension under the tested posture and direction. End tension, however, need not equal interface compression: bending changes the wire path, and wall contact and friction can cause losses and nonuniform joint forces. The worm-gear device accommodates take-up variations, but winding displacement alone does not determine the locked-state force. The measured relationship is therefore limited to the tested configuration, and direct tension sensing is preferable for control and state evaluation.

Several limitations remain. Convex hulls can include unreachable concavities or voids and therefore serve only as comparative workspace indices; self-collision and the physical wire path were neglected. Module-pair tests do not capture serial-chain tension losses or joint interactions. Finally, because several torsional curves lacked a post-peak decrease, the reported torques are maximum measured values rather than confirmed ultimate capacities.

IX. Conclusion and Future Work

This study developed an Inclined Joint Variable Stiffness Linear Mechanism that combines interfacial friction with geometric support. Releasing the steel wire permits continuous joint rotation and posture formation; tensioning it locks the serial modules. The design was evaluated using DH-based workspace analysis, a direction-dependent quasi-static model, an adjustable worm-gear tensioner, and module-pair and multi-module experiments.

The workspace analysis showed that, under identical module numbers and total mechanism lengths, the 30°, 45°, and 60° inclined-joint configurations all generated larger workspaces than

the OSJM. The 30° configuration consistently produced the largest workspace, although the differences among the three inclined-joint configurations gradually decreased as the number of modules increased. The holding-force experiments demonstrated that the nominal inclination angle affected both the magnitude and directional distribution of the maximum holding force, while the quasi-static model reproduced the non-monotonic directional response observed for the 30° module pair. Torsional resistance did not vary monotonically with the inclination angle, and the 45° module pair exhibited the highest torsional resistance among the three inclined-joint configurations. Although the OSJM provided substantially greater holding and torsional resistance in its geometrically constrained direction, its workspace was also more severely restricted. In addition, under the posture and loading direction examined in this study, the maximum holding force of the assembled mechanism increased approximately linearly with the steel wire tension. These results indicate that the nominal inclination angle is a coupled design parameter affecting posture-forming capability, directional holding capability, and torsional resistance of the mechanism. They also show that the inclined-joint configuration achieves a different balance between posture-forming capability and load-supporting capability from that of a strongly constrained joint configuration.

Future work will incorporate self-collision and the physical wire path into the kinematic model and experimentally validate reachable workspaces. The holding model will be extended to friction, side-wall contact, deformation, and clearance. A motorized tensioner with direct tension sensing and closed-loop control will support multi-module tests under arbitrary three-dimensional postures, dynamic and repeated loads, and larger torsional displacements. These

data will enable multi-objective optimization of inclination angle, module geometry, and tension conditions for specific applications.

List of abbreviations

DH Denavit–Hartenberg

OSJM Orthogonal Semicylindrical Joint Mechanism

Declarations

Availability of data and materials

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

SY conceived and designed the study, developed the proposed mechanism, performed the modeling and experiments, analyzed the results, and drafted the manuscript. KA provided technical guidance on the DH-based kinematic modeling and workspace evaluation and reviewed and revised the manuscript. SM, MW, and KT provided guidance on the overall research direction, and reviewed and revised the manuscript. All authors read and approved the final manuscript.

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tool was not used to generate research ideas, experimental data, data analyses, or scientific conclusions. All AI-assisted revisions were carefully reviewed and verified by the authors, who take full responsibility for the final content of the manuscript.

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