



## Research Article

## Kirigami analogies for parallelogram-based remote-center-of-motion mechanisms

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## ABSTRACT

This paper presents a framework for applying origami-kirigami techniques to design kirigami analogies for remote center-of-motion (RCM) mechanisms, specifically targeting minimally invasive keyhole procedures. The proposed kirigami RCM analogs emulate the motions of existing bar-linkage RCMs, offering advantages in deployability, transportability, and simplified fabrication. A workflow is introduced to transition from initial crease patterns to functional kirigami equivalents, demonstrating the potential for customizability and scalability. Furthermore, a proof-of-concept kirigami RCM under magnetic actuation is presented, showcasing its ability to reduce structural profile during transportation and improve device deployment. Three representative parallelogram-based RCM mechanisms: coupled dual parallelogram, back-drivable, and triple parallelogram, are transformed into kirigami analogs, highlighting the versatility of the design approach. The discussion includes computational modeling, fabrication considerations, and potential applications in MIS robots. This work contributes to the development of compact, deployable, and cost-effective RCM mechanisms for robotic keyhole procedures. This approach can also further facilitate the education of RCM mechanisms and the hands-on demonstration of small-scale RCM concepts.

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## 1. Introduction

## 1.1. Mechanisms for minimally invasive surgery

Minimally invasive surgery (MIS) is a surgical technique that inserts long and thin surgical instruments, such as a laparoscope or endoscopic camera, into the patient's body through small incisions or holes [1]. Performing MIS places a significant burden on the surgeon's dexterity and visuomotor coordination, leading to issues such as hand tremors and limited visual feedback. Surgical robots have been introduced to the field of MIS to assist surgeons in performing surgical procedures by exploiting the complementary strengths of surgeons and robots (Fig. 1A). These robots improve the precision and control of surgical movements, preventing surgeons from fatigue or distractions, and promoting surgical safety [2]. A surgical robotic system typically consists of a master console and a cart positioned beside the patient, which contains surgical manipulators that control a laparoscope

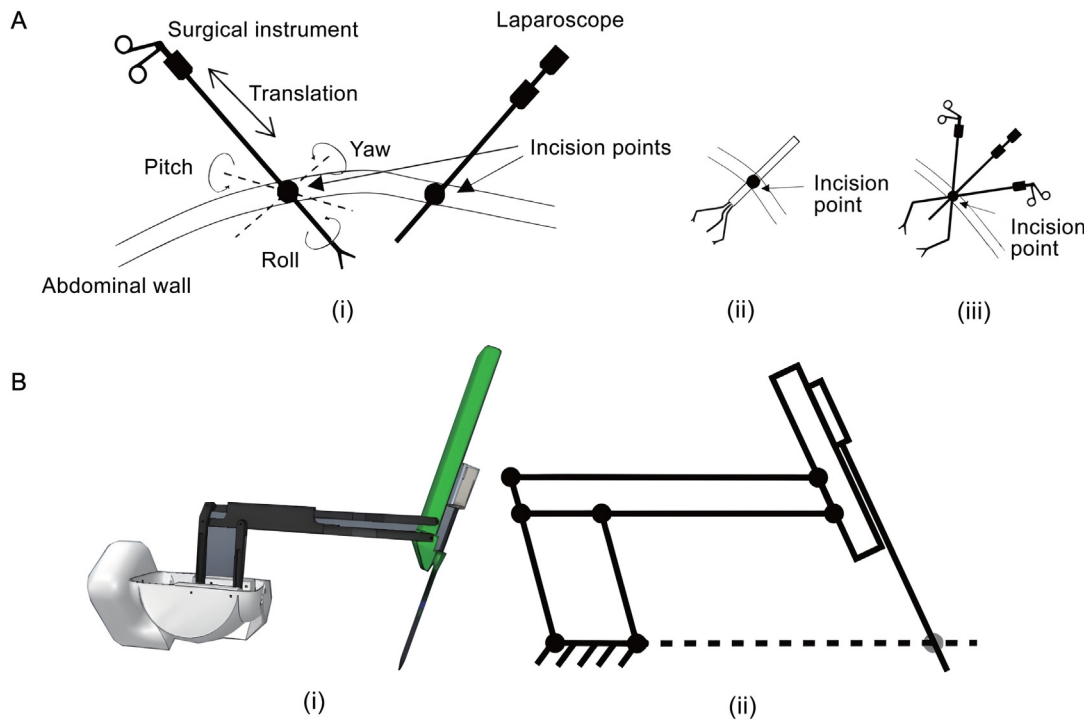
and multiple surgical tools [3]. The manipulation of surgical tools is more precise as hand tremor is reduced, and the clear 3D, magnified, real-time view aids depth perception. A well-known commercialized system is the FDA-approved da Vinci surgical system, the most widely used surgical robot for MIS [4,5].

Surgical robot structures have been developed to address these issues and enhance the effectiveness of minimally invasive surgeries. One structure is the remote center-of-motion (RCM) mechanism, which provides a virtual pivot point for keyhole procedures. However, the mechanical bulk of the mechanism has not been addressed, and its application has been limited to external device deployment. Reconfiguring the device dimension can enable internal deployment of the RCM to complement MIS procedures. Concepts from origami developability, the ability to transform a 2D surface into a 3D structure, were hypothesized to improve the design process of RCM mechanisms. The proposed kirigami RCM aims to reduce the structural profile during transportation, improving device deployment and implementation. The kirigami approach would enable simpler fabrication due to the intrinsic coupling and constraints imposed by facets, resulting in customizability, scalability, and cost reductions. This paper presents origami-kirigami RCM analogies that resemble the motions of existing representative bar-linkage RCMs after review. Various RCM mechanisms demonstrate these kirigami analogies,

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<sup>1</sup> Given his role as Associate Editor of this journal, Hongliang Ren had no involvement in the peer-review of this article and had no access to information regarding its peer-review. This article was handled by Prof. Rui Song.



**Fig. 1.** A. (i) Multi-port procedure with four DOFs required at incision point, (ii) “Y” configuration for single-port procedures (instruments are inserted in a parallel manner), and (iii) “X” configuration for single-port procedures (instruments are inserted in a crossed manner). B. Da Vinci arm: (i) 3D model, and (ii) kinematic diagram in planar motion.

which can further facilitate the education of RCM mechanisms and the hands-on demonstration of small-scale RCM concepts.

### 1.2. Remote center-of-motion (RCM) mechanism

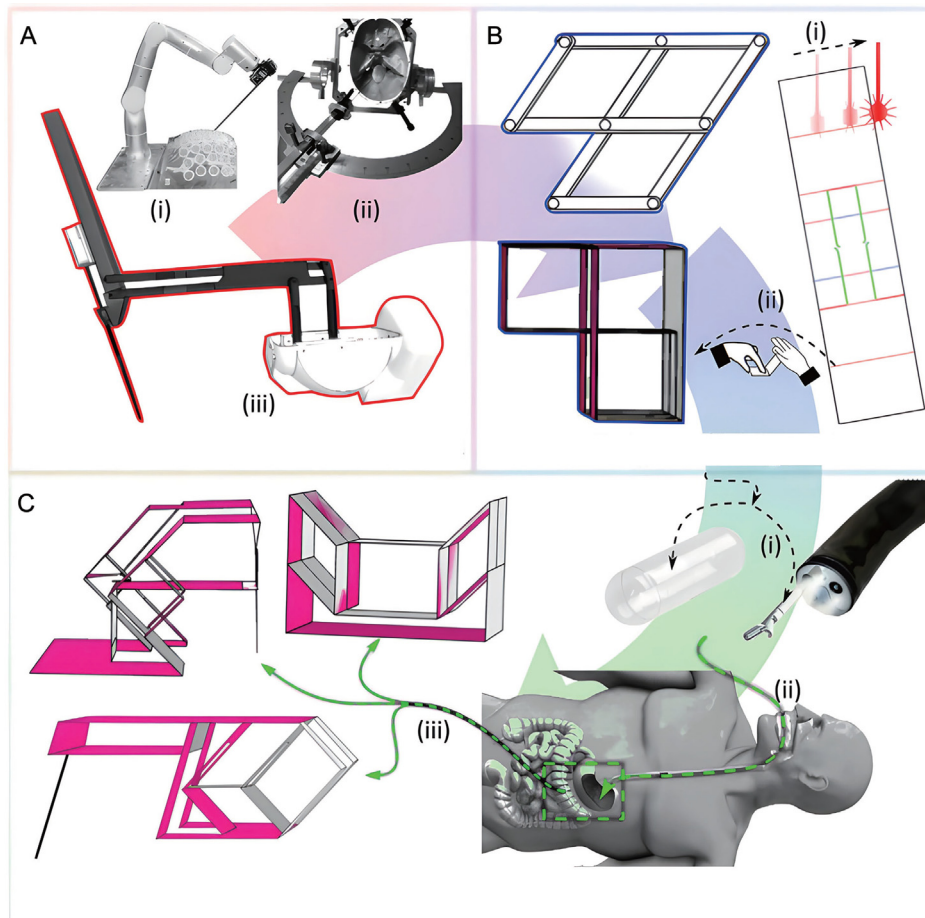
To guarantee the surgical safety of the MIS robots, the surgical instrument that enters the patient’s body must pivot at the incision point (Fig. 1B). This motion constraint suggests four degrees of freedom (DOF) of motion to the surgical tool, including three rotational DOFs centered at the incision point and one translational DOF along the tool axis through the incision point. For a master–slave robotic system, all these constraints can be met by using a RCM mechanism [6], which allows its output link (i.e., the surgical tool) only to rotate about a fixed point distal from itself. The function of an RCM can be achieved using two different approaches. One is to use delicate control algorithms for robot motion to generate a virtual RCM [7], while the other is done through the kinematic constraints of the robot manipulator to create a mechanical RCM [8,9]. Since mechanical RCMs require fewer actuators to achieve the desired motion, they are generally more popular than virtual RCMs in MIS robots. Parallelogram-based RCMs have been adopted in many MIS robots and other surgical robot designs [10]. For example, Hassan et al. [11] designed a complete master–slave telesurgical system with all manipulators utilizing the modified double parallelogram mechanism to achieve RCM. Hadavand et al. [12] proposed a triple-parallelogram robot with an RCM mechanism. Nisar et al. [13] presented a multi-loop parallelogram linkage to offer pitch and translation through the coordinated motion of the mechanism itself. Li et al. [14] proposed a class of two-DOF planar RCM mechanisms that provide pitch and translation DOFs, in which all actuated joints are revolute joints. Li et al. [15] proposed a hybrid RCM mechanism for robotic craniotomy, consisting of two orthogonal parallelogram-based linkages.

### 1.3. Origami, kirigami: definition and benefits

Origami refers to the ancient Japanese art of folding paper, which revolves around crease patterns, where a flat sheet of paper is transformed into the desired structure by folding the crease pattern on the paper [16]. An origami structure has two forms: a flat form and a deployed form. The change between the two forms is achieved through the folding sequence of particular creases. Kirigami refers to the modification of a planar transformation through induced cuts to the laminar structure [17,18]. In this article, kirigami is considered a generalization of origami folding techniques, which also involve cutting techniques. The cuts release the constraints and allow stress concentrations to deform and transform the precursor into specific configurations. The kirigami [16,19] approach aims to achieve a specific 2D to 3D transformation, suggesting that the structure can have a packing configuration that minimizes or optimizes the structural profile for device transportation. An example is the origami water-bomb-based magic ball or the metallic mesh of angioplasty stents [20], which demonstrates the value of a small structural profile for transportation. The shift from conventional bar-hinge fabrication to kirigami also simplifies fabrication due to the facets coupling to each other via the creases [21]. This reduces the need for precise alignment during assembly, which can result in a simpler fabrication process. This makes kirigami fabrication easy for mass production or for the design to be quickly changed to meet different specifications [22].

### 1.4. RCM with origami and kirigami

The integration of origami and kirigami techniques into RCM mechanisms offers several advantages for MIS, including reduced structural profile during transportation, enhanced deployability, and simplified fabrication. The inherent coupling of facets in kirigami designs enables cost-effective mass production and customization, making it suitable for a wide range of surgical applications. Additionally, magnetically steerable techniques [23]



**Fig. 2.** A. Existing Surgical mechanisms have precision requirements such as (i) Serial-arm laparoscopic keyhole access, (ii) guided needle biopsy for soft tissues, (iii) RCM mechanisms in surgical robotic arms. B. The bar hinge mechanism design is transferred to the planar structure, such as with laser patterning. (ii) The planar kirigami can be folded to assemble the functional structure. C. (i) The structures can be miniaturized and packaged into or onto existing devices for (ii) delivery into confined spaces. (iii) Subsequently, these devices can be deployed to function at the target site. Three parallelogram-based RCM Mechanisms are shown.

enable precise actuation and control of kirigami structures, further enhancing their feasibility for robotic surgery. Despite the vast potential and versatility of RCM to solve various robotic MIS challenges, there have been limited attempts to miniaturize and bring the RCM mechanism in vivo. Motivated by Suzuki and Wood's study [24], the objective of this article is to develop an approach to transform traditional parallelogram-based RCM mechanisms into origami-based RCM mechanisms (Fig. 2, Table 1).

This ability enables an origami structure to be transformed from a 2D minimal folding pattern to a larger 3D structure, which has inspired an emerging technology for biomedical devices, such as encapsulants, laparoscopic surgical grippers, micro grippers, and stent-grafts. Particularly, the lightweight and foldable nature of origami has inspired researchers to incorporate it into RCM design for MIS robots. For example, Suzuki and Wood developed a mini-RCM origami that is the size of a tennis ball and weighs 2.4 g [24]. Their mini-RCM is fabricated using the pop-up book microelectromechanical system (MEMS) method, in which materials are deposited in sheets with laser cuts, allowing the sheets to pop up into the required shapes. This method allows for the mass production of small and complex structures. The fabrication approach of "pop-up book MEMS" or "Lamina emergent mechanisms" [25] are essentially a combination of origami and kirigami techniques to achieve the final structure.

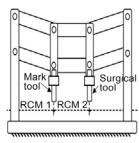
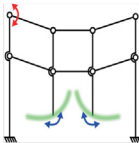
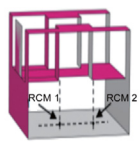
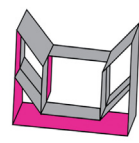
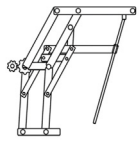
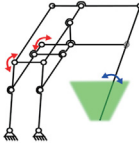


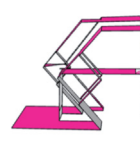
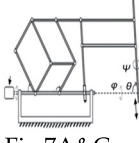
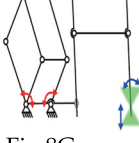
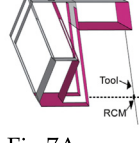

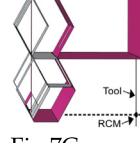
### 1.5. Contributions

RCM mechanism provides a virtual pivot point for keyhole procedures. However, the mechanical bulk of the mechanism has

not been addressed, and its application has been limited to the deployment of external devices. Reconfiguring the device dimension can enable internal deployment of the RCM to complement MIS procedures. Concepts from origami developability, the ability to transform a 2D surface into a 3D structure, was hypothesized to improve the design process of RCM mechanisms. The proposed kirigami RCM aims to reduce the structural profile during transportation, improving device deployment and implementation. The kirigami approach would enable simpler fabrication due to the intrinsic coupling and constraints imposed by facets, resulting in customizability, scalability, and cost reductions. This paper presents origami-kirigami RCM analogies that resemble the motions of existing representative bar-linkage RCMs after review. Various RCM mechanisms demonstrate these kirigami analogies, which can further facilitate the education of RCM mechanisms and the hands-on demonstration of small-scale RCM concepts. Specifically, this paper makes the following contributions:

- A conceptual framework for applying origami-kirigami techniques to design kirigami RCM analogies that resemble the motions of existing bar-linkage RCMs and a workflow starting from initial crease patterns to kirigami equivalents, demonstrates the deployability and transportability in the design.
- Kirigami analogs for different types of parallelogram-based RCMs.
- A proof of concept Kirigami RCM under magnetic actuation.

**Table 1**  
Overview of kirigami analogs for RCM mechanisms.

Bar RCM	Link	Kinematics	Kirigami analogue	Alternative design	Additional considerations
 Fig 4A Bai et al. [28]	 Fig 8E Mirrored arc	 Fig 4A Coupled RCM parallelograms	 Fig 4B		
 Fig 5A Kong et al. [29]	 Fig 8F Downwards cone	 Fig 5A Back- drivable	 Fig 5B	 Fig 6 Iterative	
 Fig 7A&C Gijbels et al. [30]	 Fig 8G Hourglass cone	 Fig 7A Triple Parallelogram	 Fig 7B	 Fig 7C Base- shortening	

## 2. Parallelogram-based RCM precursors

### 2.1. Equivalent parallelogram structures for RCM

Parallelograms are perhaps the most widely adopted design for mechanical RCMs [8]. Fig. 1B shows the kinematic diagram of the da Vinci arm in planar motion [26]. The RCM is a double parallelogram linkage with six links driven by a single motor. For example, Fig. 3A(i) is a traditional double parallelogram, a one DOF RCM mechanism comprised of two coupled parallelogram linkages with two revolute joints at the base. The two parallelograms form two closed kinematic chains that share two edges. This mechanism constrains the movement of the end-link to only rotate around the RCM point. There are redundant constraints in the ABCD loop, which can be eliminated to derive other equivalent configurations as shown in Fig. 3A(iii). The RCM mechanism shown has a single degree of freedom (DOF), which is the pitch motion of the RCM. Four DOFs, three rotational and one translational, are usually required for general MIS applications, such as laparoscopic surgery. As shown in Fig. 3A(ii), a parallelogram-based RCM with four DOFs is typically deployed to perform operations with the RCM (Fig. 3A(ii)).

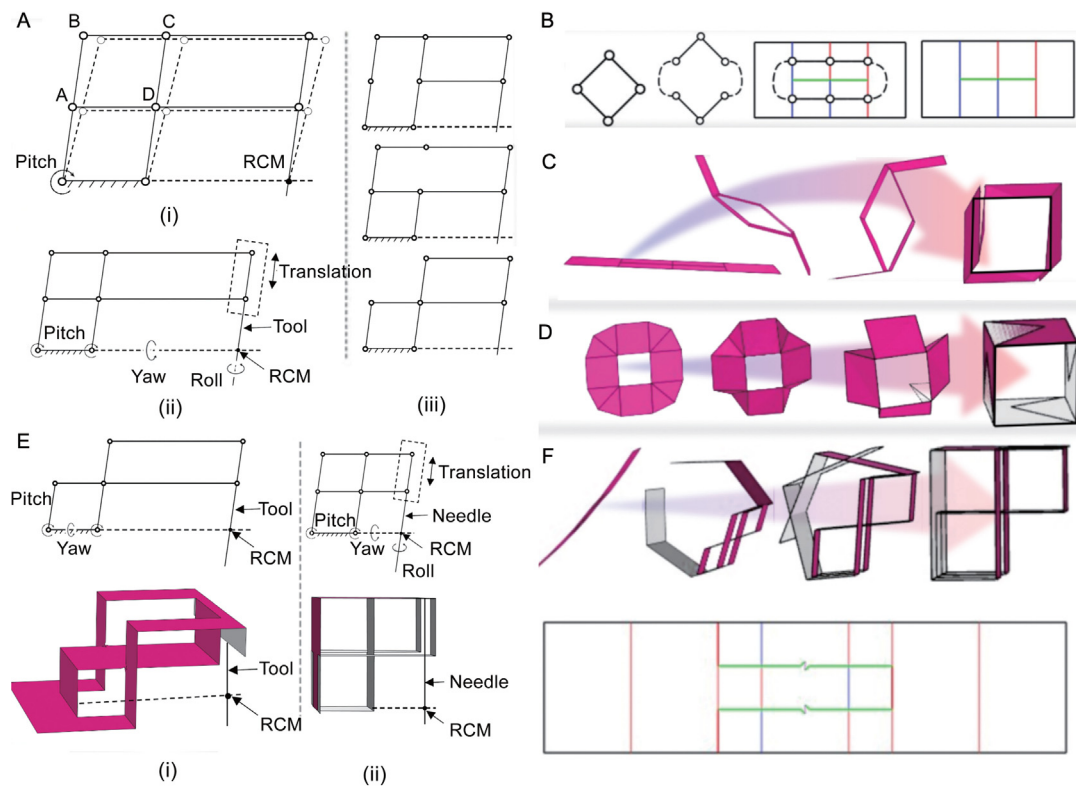
### 2.2. Folding of single parallelogram – closing the loop

The design, incorporating origami/kirigami, aims to embed the alignment of components into the crease pattern, making fabrication easier. The facet and the crease form a linkage pattern projected onto the planar design (Fig. 3B). For example, we can consider a closed linkage four-bar parallelogram and split it into two (or more) chains. These chains could be branched. The chains are then mapped onto a planar manifold such that the terminal vertices that were split are placed adjacent and can be linked by a collinear crease (collinearity is not necessarily imposed at the

initial folding stage). The following is a kirigami representation of a simple parallelogram (Fig. 3C). There are other alternative crease patterns to remap the hinges to form a similar kirigami parallelogram (Fig. 3D), which rotates the overlapping hinge axis. Fig. 3D highlights the flexibility in design choices, allowing the design to be customized to different functionality or deployment requirements. Compared with the bar-and-pin mechanism (Fig. 3A) to the facet-and-crease (Fig. 3B-D), the facet provides an inherent constraint to couple across multiple creases at different angles through the spatial arrangement of the crease. This is opposed to the bar-hinge, which would require specific fusion between the bars and rotation of the pin axis relative to the bars. The facets also have inherent alignment properties that can facilitate fabrication and assembly. In this work, the crease patterns are described with red lines for mountain folds, blue lines for valley folds, and green lines for kirigami cuts. These designed patterns were created as scalable-vector-graphics in the online origami simulator [27] to generate the origami/kirigami figures.

### 2.3. Extension to RCM equivalents

Given the many variations of an RCM, Fig. 3E-F shows a kirigami RCM mechanism. The kinematics of the mechanism can be concluded as follows: the two parallelogram linkages and the revolute joints form an RCM point. At the same time, the base link can be actuated to construct the yaw motion. The theoretical free range of motion of the pitch angle ranges from  $0^\circ$  to  $180^\circ$  with the ideal position at  $90^\circ$ . Fig. 3E(i) and Fig. 3E(ii) shows two different but equivalent kirigami RCM analogs. The assembly phases and the crease pattern for Fig. 3E(ii) are shown Fig. 3F. Assuming that the needle tip can extend further down from the RCM point, the workspace of the needle tip will be the circumference of the hemisphere. The pitch and yaw DOFs combine to provide a hemispheric workspace centered on the RCM point.



**Fig. 3.** A. The traditional one-DOF parallelogram RCM mechanism combines two parallelogram linkages with two revolute joints at the base. Remove redundant linkages to obtain different configurations of the parallelogram mechanism. B. The projection of a bar hinge onto a kirigami plane. C. Folding assembly of a kirigami analog for a single parallelogram. D. An alternative folding design for an equivalent parallelogram. E. More complex parallelogram assemblies, such as the RCM, can have kirigami analogs. F. The crease pattern and the folding for an RCM kirigami analog.

### 3. Results

#### 3.1. Coupled dual parallelogram RCM

Many other parallelogram-based RCMs with different mechanism topologies can be found in the literature. For example, Bai et al. [28] proposed a parallelogram-based dual-RCM mechanism for teleoperated ophthalmic surgery. By adding a parallelogram to the double parallelogram mechanism, a mechanism with two RCMs and two rotational DOFs can be obtained, as shown in Fig. 4A. One of the dual-RCM tracks the eye movements, while the other is for the pivotal motion of the surgical instrument. The two end effectors allow the penetration depth and location to be tracked in real-time, thus improving the precision of the movements for ophthalmic surgery. The dual-RCM mechanism has a forward and backward tilting angle of  $60^\circ$ , and a rightward and leftward tilting angle of  $45^\circ$ . The range of motion and RCM behavior depend on the parallelogram constraint conditions.

The two parallelograms in the RCM, extreme right and extreme left, are connected by two facets to serially link both parallelograms in the middle. This is the first spatial constraint that serially links the two parallelograms and dictates the type of coupling. The second constraint relation of the two parallelograms can occur in one of two ways. It could be a horizontal constraint, where the case where the RCM point is as shown (Fig. 4A(iii)), where the parallelogram's horizontal facets are constrained to be parallel to each other. The second case occurs when the constraints are on the vertical facets, as shown in Fig. 4B(iii), where the facets perpendicular to the linkage coupling are constrained to be parallel to each other. The coupling allows the two RCM points to become coupled such that the horizontal couplings are in phase, but the vertical couplings are inverted. The inverted coupling can be useful when tracing curved paths.

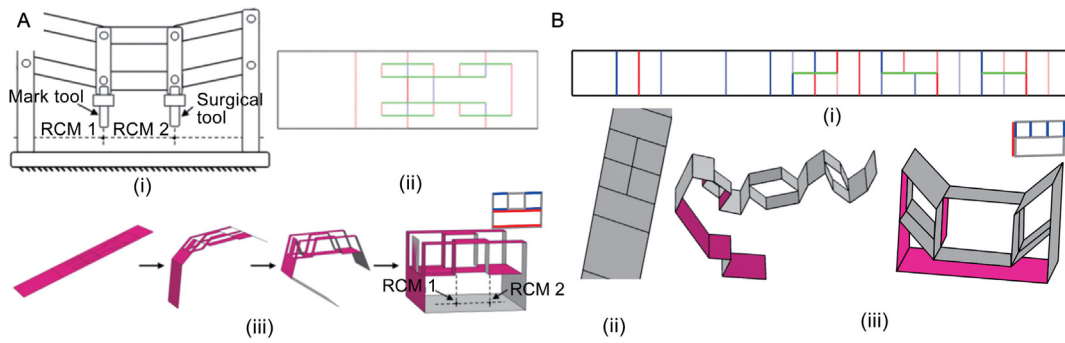
This is different from the horizontal constraint case, where both vertical/horizontal RCM couplings are in phase. Through two different constraint conditions and two different crease patterns (Fig. 4A(ii) & B(ii)), it can be designed to represent the bar-and-pin RCM linkage (Fig. 4A(i)).

#### 3.2. Back-drivable RCM

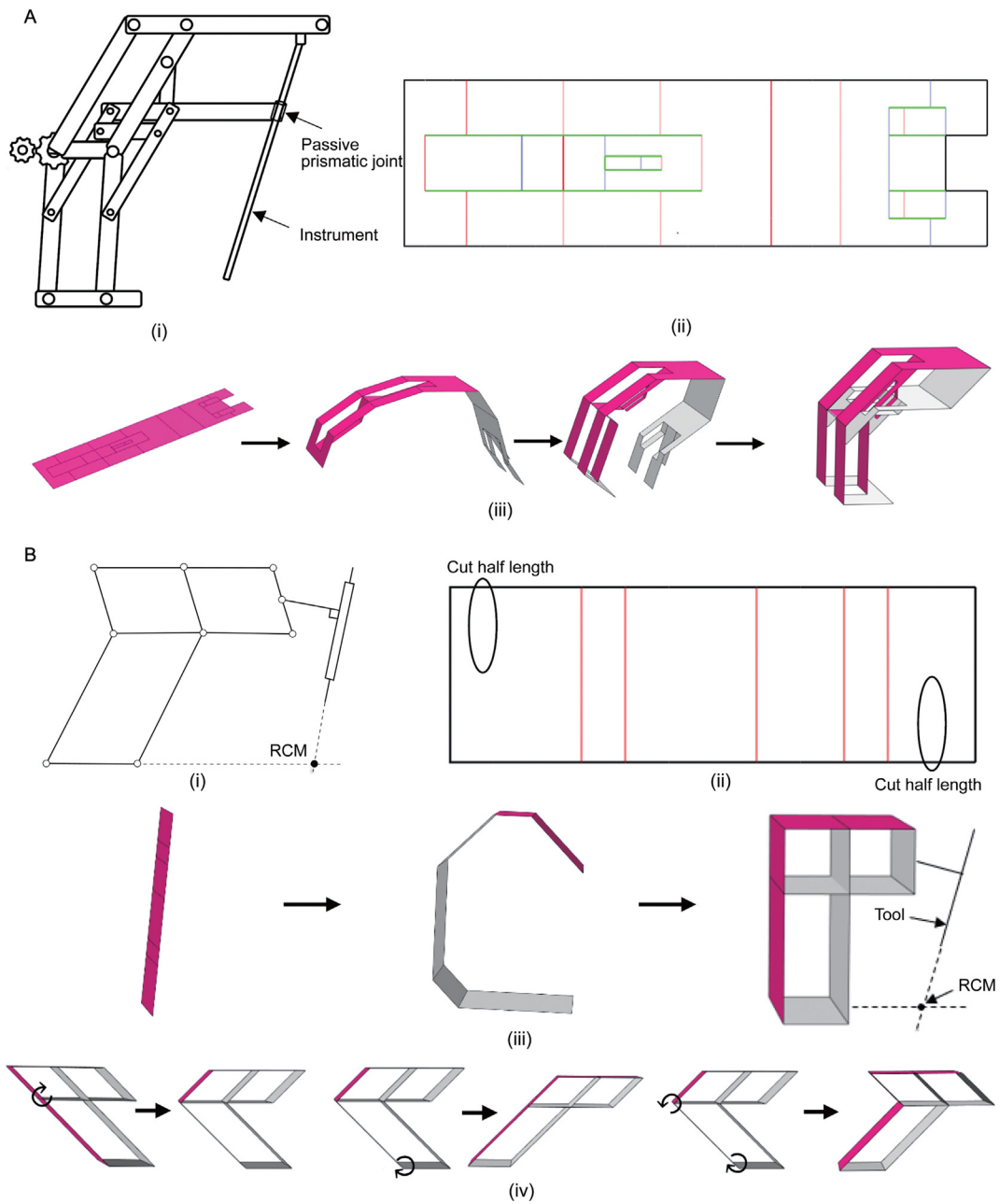
Kong et al. [29] proposed a two-DOF planar RCM mechanism to enhance the back-drivability of the existing planar RCM mechanism, where an active prismatic joint is needed to move the surgical instrument in a linear motion. The revised mechanism has a passive prismatic joint as shown in Fig. 5A. This passive prismatic joint is easier to implement than an active one and can be used to guide surgical instrument movements, similar to the function of a trocar. The origami kirigami representation is shown in Fig. 5A(ii) & A(iii). Shown in Fig. 5B, one simplified RCM mechanism can achieve the back drivability of the needle tip. It is a mechanically constrained structure that utilizes two parallelogram linkages and revolute joints to form an RCM point. Specifically, the attached surgical instrument or needle has the RCM point that depends serially on both parallelograms. The mechanism has two independent degrees of freedom (Fig. 5B(iii)), and the combination of the two parallelograms can generate different RCM motions as shown in Fig. 5B(iv).

#### 3.3. Tuning design parameters

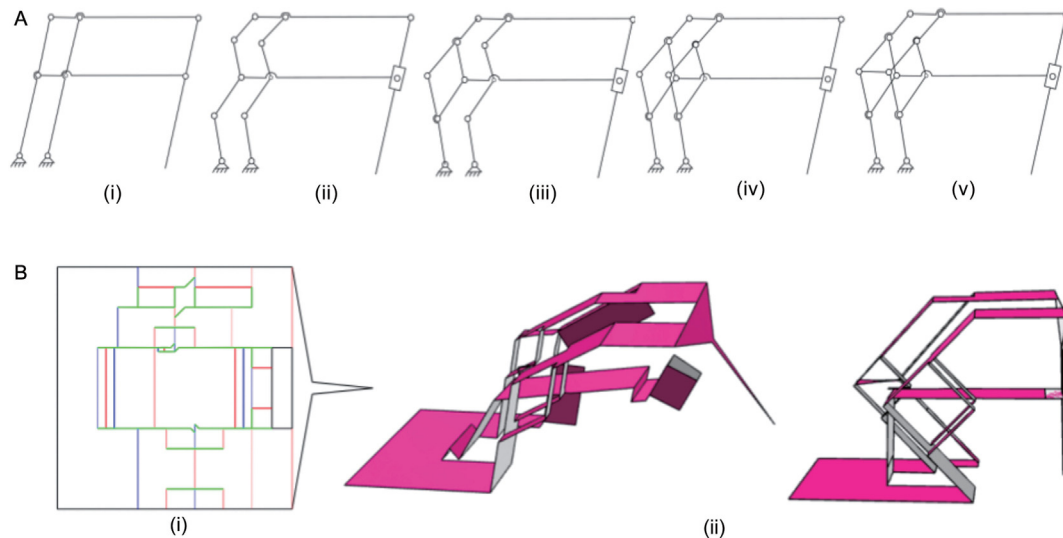
There is an increase in the mechanical complexity from a parallelogram-based RCM (Fig. 3F) toward a back-drivable RCM (Fig. 5). To build up this mechanical complexity, the bar-and-pin mechanism can be iteratively modified by adding, subtracting or modifying previous linkages (Fig. 6A). Using a similar approach,



**Fig. 4.** A. Dual parallelgram RCM couples two parallelgrams, and RCM points to a single actuation input. B. Vertically constrained dual parallelgram RCM.



**Fig. 5.** A. A back drivable RCM mechanism. (i) Schematic diagram. (ii) Crease pattern. (iii) Various fold percentages of kirigami analogs. B. Origami/kirigami representations of a simplified 2 parallelgram RCM mechanism. (i) Schematic. (ii) Crease pattern. (iii) Kirigami analogs. (iv) The additional degree of freedom allowing back drivability.



**Fig. 6.** A back drivable RCM mechanism. A. Iteration approach to modify an RCM to have a back-drivable design. B. Kirigami analog of a back-drivable RCM. (i) Crease pattern. (ii) Analog.

an existing RCM pattern (Fig. 6B) can be built into an equivalent mechanism [29] of Fig. 6A(v) exhibiting the back drivability (Fig. 5A). In Fig. 6A(ii), the parallelograms are split to allow the additional degree of freedom to flatten, in addition to the existing rotation. This additional vertical motion was coupled via an additional linkage (Fig. 6A(iii) & (iv)) and these two linkages were further coupled together in Fig. 6A(v). Similarly, the parameters for the crease pattern design is iteratively adjusted to build the RCM analog (Fig. 6B). This iterative buildup of complexity, allows a more systematic approach to modification of crease design and makes subsequent design iterations easier.

### 3.4. Triple parallelogram

As shown in Fig. 7A, Gijbels et al. [30] proposed a two-degree-of-freedom planar RCM mechanism using a triple parallelogram linkage to construct the linear degree of freedom at the base of the mechanism. The fundamental unit of this RCM is a triple parallelogram with 2 degrees of freedom after applying constraints. Each parallelogram shares a facet with the other two. This overcomes the issues of a large end effector caused by attaching a linear actuator at the end effector, which prohibited the manipulator from vitreoretinal procedures that required the end effector to be compact and maneuverable in constrained spaces. The triple parallelogram mechanism is similar to the above design (Fig. 5A) with the aim of shifting the translations of the RCM point to the rear of the structure. The fundamental unit of the triple parallelogram could be achieved with a different design, Fig. 7B(i) & (ii) compared with Fig. 7A(ii) & (iii); The approach of Fig. 7B simplifies alignments during assembly and allow modularity into higher order structures. Comparing Fig. 7A(iii), the formation of the triple parallelogram requires careful alignment with distal facets, while the design in Fig. 7B only requires selective flat folding between adjacent facets. Due to the inherent coupling in the approach of Fig. 7B, modularity and assembly of multiple parallelograms can be achieved.

### 3.5. Shortening base profile

Achieving the translation motion through the design of the rear mechanism results in a larger operational space relative to the conventional counterpart of one degree of freedom. Nisar

et al. [13] further improved on this limitation in [31] by proposing an RCM mechanism design, as shown in Fig. 7C(i), that has the same kinematic performance and size, but with a smaller operational space. The improved design has 1.6 times smaller footprint, which refers to the space requirements for set up and operation. The RCM mechanism requires the smallest operational space compared to Fig. 7A(i), while its kinematic performance is not adversely affected. The fundamental approach to achieving the new design was the use of a base-shortening approach by stacking parallelograms. This increases the complexity of the crease pattern design (Fig. 7C(ii) & (iii)), which could be simplified with other designs, such as Fig. 7B.

The kirigami RCM analog, similarly does not depend on actuators attached at the end effector for translation motion, thus allowing for a compact distal end and better operational performance. The prismatic portion could be approached in a similar manner to Fig. 6B. In addition, the foldability of the analog promotes the device transportability and ease of use in confined spaces.

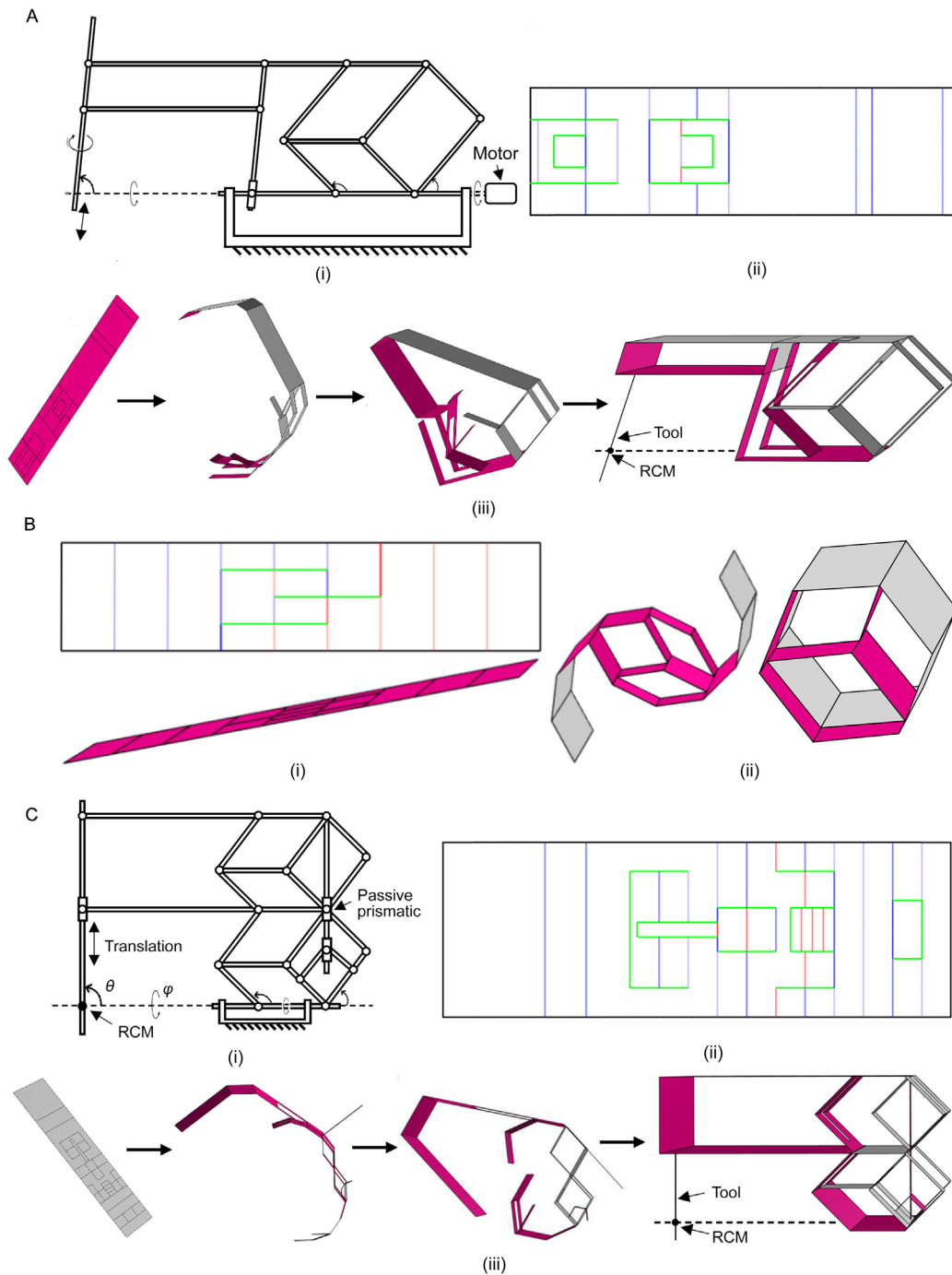
### 3.6. Proof-of-concept kirigami RCM under magnetic actuation (RCMMA)

The proof-of-concept kirigami RCM under magnetic actuation (RCMMA) is designed to demonstrate the deployability and functionality of the proposed mechanism, based on our earlier work of magnetically steerable serial and parallel structures [23].

#### 3.6.1. RCMMA design

The RCMMA is fabricated by coating a preprogrammed crease and cut pattern on a foldable template material (such as paper or flexible metal oxides like graphene oxide templated platinum) with a magnetic elastomer. The magnetic elastomer is a suspension of NdFeB microparticles (5  $\mu\text{m}$ ) in a curable silicon elastomer with a mass ratio of 1:1:4 (Silicone part A:Silicone part B:magnetic powder).

The structure is folded and magnetized in a static magnetic field (1.1 T) to program the magnetic orientations into the folded domains. The folding during magnetization allows for the alignment of magnetic domains based on the crease geometry. The backbone template (e.g., paper) provides anisotropy and rigidity, enabling more discrete motions and force transmission compared to pure magnetic elastomers. The Young's modulus of pure paper



**Fig. 7.** A. Proposed triple parallelgram RCM mechanism (i) two DOFs planar RCM mechanism, using a triple parallelgram linkage. (ii) Crease pattern. (iii) Kirigami RCM analogs with varying percentages of fold. B. A different triple parallelgram design that focuses on fabrication ease. (i) Crease pattern. (ii) Analog. C. A design modification to reduce the footprint of triple parallelgram RCMs by 1.6 times smaller. (i) Mechanism; (ii) Crease pattern; (iii) Analog.

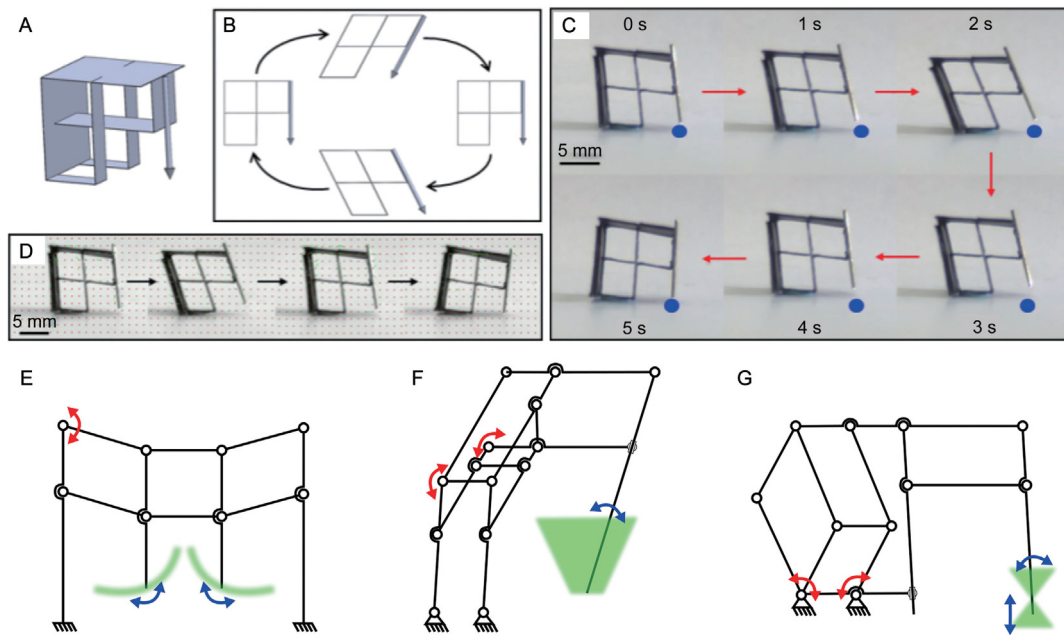
was measured to be 190 MPa, while magnetic elastomers have a Young's modulus of 0.03 MPa. The Young's modulus of the paper-magnetic-elastomer composites is around 150 MPa.

### 3.6.2. Actuation mechanism

RCMMA Actuation is achieved through tetherless magnetic interactions with an external magnetic field. An external magnetic source (e.g., a rotating permanent magnet) induces forces and torques on the programmed magnetic domains. The external permanent magnet (EPM) was a 25 mm N52 NdFeB cube from Titian Magnetics. The EPM had a remanence of around 1.2 T.

The RCM structure is anchored at the base, and the rear plane of the RCM structure is magnetized. Rotations in an external magnet coupled with the rotations of the magnetized plane cause the RCM structure to rock forward and backward while preserving the RCM point (Fig. 8, Supplementary video). The magnetic structures were shown to achieve optimal magnetic coupling with the external magnet when a distance of 5–10 mm was maintained.

This RCMMA mechanism ensures that the RCM point remains isolated, which is crucial for applications requiring tool insertion and manipulation past sensitive barriers. The ability to fully collapse the structure into a flat form ( $\geq 90\%$  volume reduction when folded) enhances its transportability and deployability.



**Fig. 8.** Magnetic Remote Center of Motion. A. A computer-aided design represents the remote center of motion (RCM) parallel structure. The entire structure is made from a single plane where the pattern was generated with kirigami cuts and origami folds. B. The range of motion for the RCM structure is shown where the actuation is driven by changes in the applied magnetic field. C. Representative frames from the actuation where the blue dot indicates the RCM point. D. Optic flow field for the RCM motion. Contrasting with the kinematics of more complex RCM mechanisms; E. Coupled parallelograms RCM. F. Back-drivable RCM. G. Triple parallelogram RCM.

### 3.6.3. Results and potential applications

Experimental results validate the performance of the Kirigami RCMMA. With dimensions of 10 mm width and 10 mm height, the mechanism achieves a rotational angle of up to 33°. The experimental testing confirms its ability to navigate complex anatomical structures with reduced unreachable cavities. The RCM prototype could apply a force of around 120 mN at the RCM tip. This demonstrates the effectiveness of the design and actuation mechanism in real-world applications, particularly in medical procedures where precision and control are paramount.

RCM structures are adept at tool insertion and manipulation of an RCM point. The RCM point allows structures near that point to become isolated, which is helpful in situations where we need to insert tools or manipulate objects past a sensitive barrier, such as in minimally invasive surgeries. Due to the fabrication approach, the structure can be fully collapsed into a flat structure, which could have benefits in transportability and deployability. Origami structures can also be built into the joint segments to act as a limiter on the range of motion to restrict rotations about the RCM point.

## 4. Discussion

This work explored kirigami analogs for RCM mechanisms (Table 1). An approach to resemble existing RCMs into kirigami equivalents demonstrates the foldability of the mechanism and the versatility of the design. The concept was demonstrated through three different types of parallelogram-based RCMs, bringing the benefits of origami and kirigami to RCM mechanisms.

### 4.1. Joints and hinges analogs

#### 4.1.1. Pin joint

This work presented three different ways to convert the pin joint into a crease hinge, showing a design approach to generate equivalent kinematic kirigami analogs. In the simplest case (Fig.

3B) when the two joints have only a single-facet constraint relationship. This design was demonstrated and can be observed in Fig. 4B and Fig. 7B. When a pin joint links two bars, this work proposed two different approaches to design the analog. The most commonly used design is shown in Fig. 3F, the kink in the green lines. This approach has the simplest fabrication and assembly, but the size of the coupling crease and the stiffness of the material must be well-designed to avoid yield stresses. This design was demonstrated and can be observed in Fig. 6B. A second design (Fig. 5B) requires more complex fabrication in alignment and adhesion, but could provide a stronger hinge with the redundant material. These two designs are non-exhaustive and there could be different optimizations for the crease analogs for different designs. This design was demonstrated and can be observed in Fig. 5, Fig. 4A and Fig. 7A&C.

#### 4.1.2. Prismatic slide

In this work, the focus has been on the analog design of the pin joint and the prismatic sliding joint has only been roughly explored in Fig. 6B and it remains an open question whether the kirigami analogs would have similar benefits or whether the design of the crease pattern would be optimal. This would be a potential area for future research.

### 4.2. Limitations

#### 4.2.1. Fabrication

The fabrication of kirigami RCM mechanisms involves selecting materials with appropriate stiffness and flexibility to ensure reliable folding and deployment. The crease patterns are optimized to achieve the desired bending and rotational motions while minimizing stress concentration. Experimental testing is performed to validate the system's reliability and performance, ensuring its feasibility for practical applications in MIS. Still, there are several practical challenges in fabricating, folding/expanding, selecting parameters for desired stiffness, and ensuring system

reliability of the proposed kirigami RCM mechanisms. The laminar fabrication approach also has constraints, as the thickness of the panels could be a consideration for flat foldability. Typical sample thicknesses tested were around 0.4 mm for composites, though pure paper/elastomer could be thinner (0.1–0.2 mm). Additionally, achieving specific stiffness anisotropy often requires different materials, thicknesses, or geometries.

One limitation in the Kirigami RCM analogs is that folding is still required to assemble the functional mechanism. Rearrangements of projected crease components mean that additional material may need to be removed or folded in the fabrication step. Rearrangements of projected crease components may necessitate additional material removal or folding steps during the fabrication process. This adds complexity to the manufacturing process beyond simply creating the 2D pattern. The laminar fabrication approach is also challenging, as not all materials can be folded to create a crease. To introduce stiffness anisotropy, different materials, material thickness, or geometry have to be considered. Introducing stiffness anisotropy requires careful consideration of different materials, material thicknesses, or geometric designs within the kirigami structure. Achieving specific and reliable hinge and facet stiffness can be complex. Additionally, the thickness of the panels could be a consideration for flat foldability. The stiffness of the thin and large facets could also be a limitation in providing the required constraints during folding, as the constraints for facet flexure may result in poor component alignment.

#### 4.2.2. Folding/packing and expansion/deployability

Similar to fabrication, folding is essential for assembling the functional RCM. For internal deployment in MIS, the folded mechanism needs to be reliably expanded or deployed at the target site. This highlights the benefit of designs achieving high volume reduction by 90% demonstrated by the proof-of-concept RCMMA. Just as the crease pattern has to accommodate for assembly, packing/deployment and function, the actuators would also have to have the same requirements. For each desired degree of freedom, an actuator component has to be associated. An increase in the complexity of functional demands on the RCM would also require similar actuators to drive the mechanism. The implementation of actuators would be the subject of future work. Still, one possible approach could be the use of magnetic actuation [23] to drive these RCM analogs (Fig. 8, Supplementary video).

#### 4.2.3. Parameter selection for desired stiffness

Material selection, thickness, and geometry are factors influencing the stiffness of the kirigami RCM. Precisely tuning these parameters to achieve the desired stiffness for different parts of the mechanism (e.g., hinges vs. facets) is a significant challenge. The design of the crease patterns also plays a crucial role in the overall stiffness and flexibility of the structure. The angles, lengths, and arrangements of creases dictate the folding behavior and the resulting stiffness in the deployed state. As shown by material characterization, Young's moduli can vary significantly, from 0.03 MPa for pure magnetic elastomer to 190 MPa for paper, with composites around 150 MPa.

#### 4.2.4. System reliability

The reliability of the kirigami RCM mechanism would depend on the durability of the folded hinges under repeated actuation. The material properties and the design of the crease (e.g., avoiding yield stresses) are critical for long-term reliability. Component alignment, which can be affected by facet flexure during folding, is crucial for the kinematic accuracy and reliability of the RCM motion. Poor alignment could lead to deviations from the intended remote center of motion.

### 4.3. Future work

#### 4.3.1. Field test and applications

The near-future focus of this work would be to test these structures on a smaller scale and integrate them with the appropriate actuator systems. This would allow the three analogs presented in this work to be tested in the field, such as for surgical tool applications.

#### 4.3.2. Joint complexity

To extend the scope of this work, future kirigami analogs could consider other RCM mechanisms with more complex structures. For example, joints with multiple degrees of freedom instead of a single pin joint. Complex non-planar RCMs, such as spherical RCMs, could also be interesting in future work. Most of the facets function as fixed spatial constraints to align the hinge axes; Facets with complex behavior exhibiting partial constraints, such as multi-stability, could be used to create complex RCM structures with multiple RCM points.

### 4.4. Conclusion

Minimally invasive surgery, while offering benefits through small incisions, presents challenges due to the significant demands on a surgeon's dexterity and visuomotor coordination, potentially leading to hand tremors and limited vision feedback. Surgical robots incorporating RCM mechanisms have been developed to address these limitations by providing a virtual pivot point for keyhole procedures. However, a significant drawback of existing mechanical RCMs is their structural bulk, which has limited their application primarily to external device deployment. To overcome this limitation, this paper hypothesizes that concepts from origami developability, the transformation of a 2D surface into a 3D structure, can significantly improve the design process of RCM mechanisms (Table 1). The proposed kirigami RCM aims to reduce the structural profile during transportation, thereby improving device deployment and implementation, potentially enabling internal deployment to further complement MIS procedures. The integration of a kirigami approach is also expected to lead to simpler fabrication due to the intrinsic coupling and constraints between facets. This simplification can translate into enhanced customizability, scalability, and potential cost reductions. This paper presents origami-kirigami analogies for parallelogram-based RCM mechanisms. Through a review of existing representative bar-linkage RCMs, various mechanisms are shown to exhibit these kirigami analogies. This novel approach can further facilitate the education of RCM mechanisms and the hands-on demonstration of small-scale RCM concepts.

### CRediT authorship contribution statement

**Bok Seng Yeow:** Formal analysis, Conceptualization. **Alex Wang:** Writing – original draft, Formal analysis, Conceptualization, Visualization, Data curation. **Chin-Hsing Kuo:** Writing – review & editing, Methodology. **Hongliang Ren:** Writing – review & editing, Resources, Investigation, Supervision, Project administration, Conceptualization.

### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Supplementary data

Supplementary material related to this article can be found online at <https://doi.org/10.1016/j.birob.2025.100251>.

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