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REVIEW ARTICLE

State of the art in movement around a remote point: a review of remote center of motion in robotics

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ABSTRACT The concept of remote center of motion (RCM) is pivotal in a myriad of robotic applications, encompassing areas such as medical robotics, orientation devices, and exoskeletal systems. The efficacy of RCM technology is a determining factor in the success of these robotic domains. This paper offers an exhaustive review of RCM technologies, elaborating on their various methodologies and practical implementations. It delves into the unique characteristics of RCM across different degrees of freedom (DOFs), aiming to distill their fundamental principles. In addition, this paper categorizes RCM approaches into two primary classifications: design based and control based. These are further organized according to their respective DOFs, providing a concise summary of their core methodologies. Building upon the understanding of RCM's versatile capabilities, this paper then transitions to an in-depth exploration of its applications across diverse robotic fields. Concluding this review, we critically analyze the existing research challenges and issues that are inherently present in both RCM methodologies and their applications. This discussion is intended to serve as a guiding framework for future research endeavors and practical deployments in related areas.

KEYWORDS remote center of motion, mechanism, robotics, medical robot, orientation device, exoskeleton

1 Introduction

In many robotic applications, manipulator systems are often required to perform constrained motions to fulfill specific objectives. Among these, the concept of the remote center of motion (RCM) stands out as a widely adopted constraint. Initially conceptualized for minimally invasive surgery (MIS), the RCM principle has found applications across various robotic disciplines owing to its unique motion properties. An RCM is characterized as either rotational or translational movements centered around a distant, fixed point. This concept has been a focal point in both academic and industrial research for more than two decades, reflecting its significance in the field of robotics. The rationale behind the adoption of RCM differs across applications, but it generally revolves around three primary purposes: (a) facilitating movement through an incision or constrained entry point; (b) enabling changes in orientation while maintaining a fixed point of reference; (c) achieving motion mimicry or synchronization of human actions.

The primary and most frequently cited rationale for employing RCM is to facilitate the movement of a manipulator through a surgical incision, particularly in medical robotic systems. This feature is especially critical in the field of MIS, where the ability of a manipulator to perform complex tasks through a small incision is a key technical requirement in minimizing patient discomfort and tissue damage [1,2]. Notable examples include the renowned da Vinci robotic surgery system [3,4], as well as other laparoscopic [5,6] and vitreoretinal surgery robots [7,8]. An RCM enables these MIS manipulators to operate safely within a limited incision space, offering precise control over the RCM point. Several RCM-based MIS robots have been successfully commercialized, and a plethora of innovative RCM methodologies continue to emerge in this field. The second most commonly cited application of RCM is in facilitating orientation changes. Systems utilizing RCM for this purpose typically feature a platform designed to orient around the RCM point. Such devices often employ parallel RCM mechanisms to

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achieve greater stiffness and precision. Applications in this category include needle insertion [9], medical imaging [10], and camera orienting devices [11]. The third key application of RCM is the mimicking or synchronization of movements, particularly those associated with human actions. This application includes human-interactive devices [12] and exoskeleton robots [13]. RCM mechanisms in these applications are designed to replicate the required interaction motions around the RCM point, closely emulating human joint movements. Some studies, particularly those focusing on physical joint constraints, do not fall under the traditional scope of RCM applications. Even though these studies focus on devices move around a center, these works involve robotic wrists and other applications where the motion center coincides with a physical joint, thereby differing in principle, requirements, and objectives from RCM approaches. RCM's unique advantage lies in its ability to operate outside the physical joint center, thus conserving the surrounding space of the motion point, making it ideal for flexible movements in confined spaces. Moreover, RCM mechanisms can passively output motion around a fixed point, offering robustness and safety advantages over other mechanisms in various applications.

This article presents a comprehensive overview of RCM methodologies, which are categorically divided into design-based and control-based strategies. Design-based strategies physically constrain the end-effector to follow an RCM trajectory utilizing specific mechanical configurations, referred to as RCM mechanisms. A notable example of this is the parallelogram RCM mechanism employed by the da Vinci robotic system [3,4]. Conversely, control-based techniques achieve an RCM in serial manipulators through sophisticated control algorithms, as exemplified by the DLR (German Aerospace Center) MIRO robot [14]. The focus of this article is on the diverse approaches employed to realize an RCM, paying particular attention to aspects such as degrees of freedom (DOFs), kinematic structures in design-based strategies, control schemes in control-based strategies, motion characteristics, and performance indices. While previous reviews touched upon RCM, they predominantly center on surgical robotics, discussing RCMs in the context of kinematic requirements for surgery. However, a crucial detail to acknowledge is that RCM, and particularly RCM mechanisms, finds extensive applications beyond surgical robots, spanning various fields of robotics.

By starting from the fundamental principles of an RCM, this article endeavors to provide a thorough review of RCMs, encompassing the methods and applications, objectives, and emerging trends in this field. We aim to furnish a comprehensive reference and enhance understanding for researchers across different disciplines who encounter similar motion requirements in their work.

This article commences with an in-depth exploration of RCM concept, laying a robust mathematical groundwork that encompasses various DOFs in three-dimensional Euclidean space. Subsequent sections methodically examine RCM mechanisms and control algorithms. This review is systematically structured, initially categorizing the DOFs in ascending order and subsequently by the type of mechanism for RCM mechanisms, or by the chronological development of RCM control algorithms. Specific attributes unique to particular RCMs are detailed where necessary. This article also delves into the diverse applications of RCMs across multiple robotic disciplines, highlighting their current uses and potential future developments. The conclusion summarizes key insights and findings from the review, offering a concise summary of the pivotal aspects and implications of RCMs in the broader context of robotics research and application. This comprehensive overview aims not only to inform but also to guide ongoing and future endeavors in the field of RCM and its related technologies.

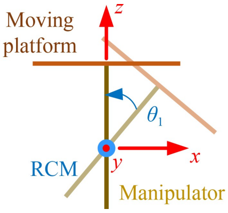
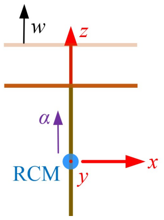
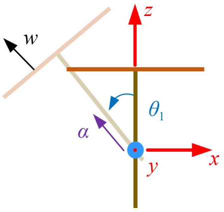
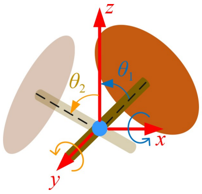
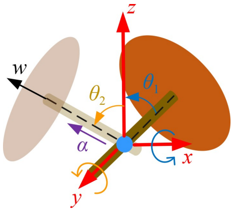
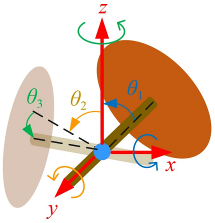
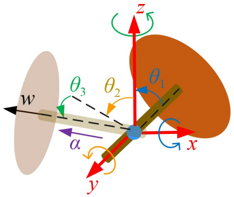
2 Background

This section introduces the concept of an RCM through illustrations and mathematical foundations in three-dimensional space. Some explanations of related academic phrases are provided, thus providing a better understanding of the following reviews.

2.1 RCM concept

An RCM refers to a motion rotating around or translating through a remote stationary point, i.e., an RCM point is the center of rotation or located on the translation line of an end-effector without a physical joint. For example, an end-effector rotates around a stationary point, but the point is not fixed by a physical joint, which represents the end-effector RCM. The RCM point can be located within the geometrical dimensions of the end-effector, meaning that the manipulator passes through the RCM point, or it can be situated outside the geometrical dimensions of the end-effector, which implies that the motion platform does not pass through the RCM point, as shown in Table 1. A rigid body with free movement has six DOFs in three-dimensional Euclidean space, which consists of three rotations and three translations. If a rigid body is constrained by an RCM, then its motion is constrained by the RCM point, and it can have four DOFs at most, which are three rotations around the RCM point and one translation through the RCM point. Various DOF RCM approaches have been studied according to different application demands. Common RCMs include 1R (R represents rotation and T represents translation) for 1-DOF, 2R and 1R1T for 2-DOF, 2R1T and 3R for 3-DOF, and 3R1T for 4-DOF. The RCMs of 1R and 1R1T are planar motions on the two-dimensional plane, and the rest are spatial motions in the three-dimensional space. Their motion illustrations and SE(3) mathematical expressions are displayed in Table 1. The 1T motion is not discussed as an RCM on its own because of its innumerable motion centers on the translational direction. The order of rotation motion in Table 1 is pan, tilt, and spin. Each DOF has a paired set of motions—positive and negative motions—with the reference direction.

Table 1 RCMs with different DOFs

DOF	Motion	Schematic	Mathematical expression[a)]	
			Screw expression	Normal expression
1	1R		$S_1 = \begin{pmatrix} \boldsymbol{y} \\ 0 \end{pmatrix}$	$\boldsymbol{R}(o,\boldsymbol{y}) = \left\{ \begin{bmatrix} e^{\hat{y}\theta_1} & \mathbf{0} \\ \mathbf{0} & 1 \end{bmatrix}, \theta_1 \in [0, 2\pi] \right\}$
	1T		$S_1 = \begin{pmatrix} 0 \\ \boldsymbol{w} \end{pmatrix}$	$\boldsymbol{T}(z) = \left\{ \begin{bmatrix} \mathbf{I} & \alpha \boldsymbol{z} \\ \mathbf{0} & 1 \end{bmatrix}, \alpha \in \mathbb{R} \right\}$
2	1R1T		$\begin{cases} S_1 = \begin{pmatrix} \boldsymbol{y} \\ 0 \end{pmatrix} \\ S_2 = \begin{pmatrix} 0 \\ \boldsymbol{w} \end{pmatrix} \end{cases}$	$\boldsymbol{R}(o,\boldsymbol{y}) \cdot \boldsymbol{T}(z) = \left\{ \begin{bmatrix} e^{\hat{y}\theta_1} & e^{\hat{y}\theta_1} \alpha \boldsymbol{z} \\ \mathbf{0} & 1 \end{bmatrix}, \theta_1 \in [0, 2\pi], \alpha \in \mathbb{R} \right\}$
	2R		$\begin{cases} S_1 = \begin{pmatrix} \boldsymbol{x} \\ 0 \end{pmatrix} \\ S_2 = \begin{pmatrix} \boldsymbol{y} \\ 0 \end{pmatrix} \end{cases}$	$\boldsymbol{R}(o,\boldsymbol{x}) \cdot \boldsymbol{R}(o,\boldsymbol{y}) = \left\{ \begin{bmatrix} e^{\hat{x}\theta_1 + \hat{y}\theta_2} & \mathbf{0} \\ \mathbf{0} & 1 \end{bmatrix}, \theta_1, \theta_2 \in [0, 2\pi] \right\}$
3	2R1T		$\begin{cases} S_1 = \begin{pmatrix} \boldsymbol{x}^{\mathrm{T}} & 0 \end{pmatrix}^{\mathrm{T}} \\ S_2 = \begin{pmatrix} \boldsymbol{y}^{\mathrm{T}} & 0 \end{pmatrix}^{\mathrm{T}} \\ S_3 = \begin{pmatrix} 0 & \boldsymbol{w}^{\mathrm{T}} \end{pmatrix}^{\mathrm{T}} \end{cases}$	$\boldsymbol{R}(o,\boldsymbol{x}) \cdot \boldsymbol{R}(o,\boldsymbol{y}) \cdot \boldsymbol{T}(z) = \left\{ \begin{bmatrix} e^{\hat{x}\theta_1 + \hat{y}\theta_2} & e^{\hat{x}\theta_1 + \hat{y}\theta_2} \alpha \boldsymbol{z} \\ \mathbf{0} & 1 \end{bmatrix}, \theta_1, \theta_2 \in [0, 2\pi], \alpha \in \mathbb{R} \right\}$
	3R		$\begin{cases} S_1 = \begin{pmatrix} \boldsymbol{x}^{\mathrm{T}} & 0 \end{pmatrix}^{\mathrm{T}} \\ S_2 = \begin{pmatrix} \boldsymbol{y}^{\mathrm{T}} & 0 \end{pmatrix}^{\mathrm{T}} \\ S_3 = \begin{pmatrix} \boldsymbol{z}^{\mathrm{T}} & 0 \end{pmatrix}^{\mathrm{T}} \end{cases}$	$\boldsymbol{R}(o,\boldsymbol{x}) \cdot \boldsymbol{R}(o,\boldsymbol{y}) \cdot \boldsymbol{R}(o,\boldsymbol{z}) = \left\{ \begin{bmatrix} e^{\hat{x}\theta_1 + \hat{y}\theta_2 + \hat{z}\theta_3} & \mathbf{0} \\ \mathbf{0} & 1 \end{bmatrix}, \theta_1, \theta_2, \theta_3 \in [0, 2\pi] \right\}$
4	3R1T		$\begin{cases} S_1 = \begin{pmatrix} \boldsymbol{x}^{\mathrm{T}} & 0 \end{pmatrix}^{\mathrm{T}} \\ S_2 = \begin{pmatrix} \boldsymbol{y}^{\mathrm{T}} & 0 \end{pmatrix}^{\mathrm{T}} \\ S_3 = \begin{pmatrix} \boldsymbol{z}^{\mathrm{T}} & 0 \end{pmatrix}^{\mathrm{T}} \\ S_4 = \begin{pmatrix} 0 & \boldsymbol{w}^{\mathrm{T}} \end{pmatrix}^{\mathrm{T}} \end{cases}$	$\boldsymbol{R}(o,\boldsymbol{x}) \cdot \boldsymbol{R}(o,\boldsymbol{y}) \cdot \boldsymbol{R}(o,\boldsymbol{z}) \cdot \boldsymbol{T}(z) = \left\{ \begin{bmatrix} e^{\hat{x}\theta_1 + \hat{y}\theta_2 + \hat{z}\theta_3} & e^{\hat{x}\theta_1 + \hat{y}\theta_2 + \hat{z}\theta_3} \alpha \boldsymbol{z} \\ \mathbf{0} & 1 \end{bmatrix}, \theta_1, \theta_2, \theta_3 \in [0, 2\pi], \alpha \in \mathbb{R} \right\}$

a): $\boldsymbol{S}$ represents a motion screw; $\boldsymbol{R}$ represents the rotation matrix and $\boldsymbol{T}$ represents the translation matrix; $\boldsymbol{x}$, $\boldsymbol{y}$, and $\boldsymbol{z}$ represent the unit vectors in the x-, y-, and z-directions in the world coordinate system, which are $(1, 0, 0)^{\mathrm{T}}$, $(0, 1, 0)^{\mathrm{T}}$, and $(0, 0, 1)^{\mathrm{T}}$, respectively; $\boldsymbol{w}$ represents the unit vector in the w-direction and $\boldsymbol{v}$ represents the unit vector in the v-direction of the object coordinate system in the world coordinate system.

2.2 RCM characteristics

In this section, some relevant terminologies for the reviews are introduced, which are used to structure the reviews and discuss the individual methods.

I. Realization types

RCM approaches can be divided into two categories: design-based and control-based strategies. RCM control algorithms are mainly used for surgical robots and are applied in existing commercial serial manipulators. However, RCM mechanisms using design-based strategies have wider applications and have been attracting research attention to realize objectives through different kinematic structures. RCM mechanisms can also be classified as serial or parallel mechanisms based on the arrangement of joints and linkages. A serial mechanism consists of a sequential connection of joints and linkages, whose effector motion is the union of each joint. A parallel mechanism consists of a static platform, a moving platform, and several limbs. The limbs consist of sequential joint and linkage connections, like a serial mechanism, with the static platform at one end and the moving platform on the other end. The motion of the moving platform is the intersection of each limb. In the following section, the studies are reviewed in the order of serial RCM mechanisms, parallel RCM mechanisms, and RCM control algorithms.

II. Degree of freedom

As discussed in Section 2.1, several different RCM DOFs exist. On the basis of the realization type, RCM mechanism studies are reviewed by the DOF number order—1-DOF to 4-DOF. Most RCM control algorithms are developed based on a commercial serial robot. Common commercial robots have at least six DOFs. With the development of human–robot interaction, more redundant commercial robots with 7-DOF have been used for RCMs, and RCM control algorithm studies will be reviewed according to the development and methods.

III. Performance analysis

Despite their many differences in design or control methods, most RCMs seek to achieve similar performance. For the design methods, the common performances of RCM mechanisms include the workspace, which determines the range of motion that the end-effector can reach; the singularity, which determines the forbidden positions that the end-effector cannot reach; the dexterity, which estimates the motion input and output motion relationships; the accuracy, which estimates the true and theoretical RCM position errors; the transmission performance, which estimates the power input and output relationships; the stiffness, which represents the ability to resist deformation due to an external force.

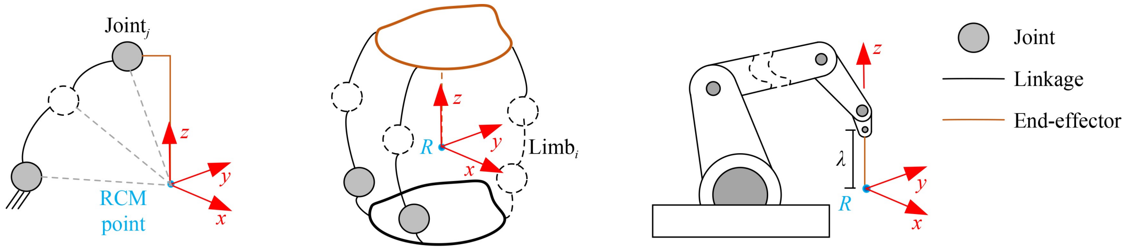
For the control methods, the RCM algorithms also focus on position accuracy to estimate RCM position errors. Although most of the above performances, such as the workspace, singularity, and dexterity, are kinematic performances, the dynamics performances for applications involving human interactions should be considered at the same time for RCM algorithms, such as force accuracy.

3 RCM approaches

This section discusses RCM approaches, starting with serial RCM mechanisms because they are the origin of RCM studies. Then, parallel RCM mechanisms and RCM control algorithms are presented. The RCM approaches are arranged by DOFs for RCM mechanisms and development for RCM control algorithms.

3.1 Serial RCM mechanisms

As shown in Fig. 1, a serial RCM mechanism has at least two types of joints: common joints such as R and P (P represents prismatic) joints and compound joints such as Pa (Pa represents parallelogram) joints. Each joint needs to have independent 1-DOF characteristics and actuation. For a mechanism, the motion relationships can be expressed by the relationships of each joint/limb motion screw system [15]. Screw $\boldsymbol{S}$ is an element in a six-dimensional vector space, while screw system $\mathbb{S}$ is a linear vector subspace. $\mathbb{S}_1 \cap \mathbb{S}_2$ and $\mathbb{S}_1 \cup \mathbb{S}_2$ represent the intersection and union of the screw systems, respectively, and follow the operation method of linear vector subspace. A motion joint could be expressed by a motion screw and a limb could be expressed by a motion screw system. Serial RCM mechanisms satisfy the following relationships:



Serial RCM mechanism Parallel RCM mechanism RCM control algorithm

Fig. 1 Types of remote center of motion approaches.

$$\begin{gathered}\mathbb{S}^{\text{serial-RCM}}_{j\text{-DOF}} = \boldsymbol{S}_{\text{joint-1}} \cup \boldsymbol{S}_{\text{joint-2}} \cup \cdots \cup \boldsymbol{S}_{\text{joint-}j}, \\ j \geqslant 1,\ \boldsymbol{S}_{\text{joint-}j} \subseteq \mathbb{S}^{\text{RCM}}_{\text{1-DOF}},\end{gathered} \tag{1}$$

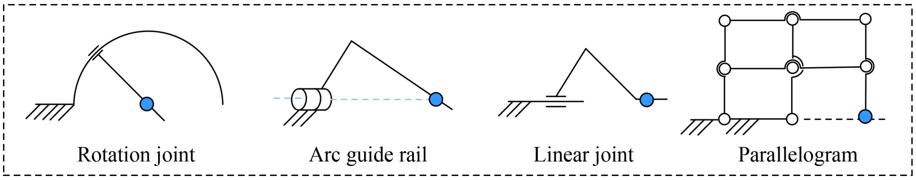
where $\mathbb{S}^{\text{serial-RCM}}_{j\text{-DOF}}$ represents the motion screw system of a serial RCM mechanism with j-DOF and $\boldsymbol{S}_{\text{joint-}j}$ represents the motion screw of the jth joint, which can be a simple joint such as a R or P joint, or a generalized joint such as a Pa joint. $\mathbb{S}^{\text{RCM}}_{\text{1-DOF}}$ represents the motion screw system of a 1-DOF RCM. Equation (1) represents the motion screw system of a serial RCM mechanism, which is the union of all joint motion screws, thus indicating that all joints must move as a 1-DOF RCM. In general, the number of joints in a serial mechanism is the number of DOF.

RCM mechanisms mostly have closed loops; very few are strictly serial mechanisms, and many are hybrid structure mechanisms. A broader definition of serial mechanisms is adopted in this section to better describe and differentiate the design characteristics of various types of RCM mechanisms: RCM motion is generated by the serial connection of each motion joint possessing RCM characteristics. A key feature is that each motion joint has its actuator, which cannot all be placed on the base, distinguishing it from parallel mechanisms. The motion joints with RCM includes three basic types of joints: rotational joints, arc guide rails, linear joints, and generalized joints with 1-DOF RCM motion such as the parallelogram mechanism, as shown in Fig. 2.

The 1R RCM mechanism is widely recognized as the fundamental archetype in RCM mechanism studies. Some research has been conducted on 1R RCM mechanisms, beyond the basic joints that were previously discussed. While these mechanisms may not find direct application in practical scenarios, they are instrumental in providing innovative design methods and conceptual ideas for multi-DOF RCM mechanisms. Notably, those 1-DOF RCM mechanisms exhibit parallel structures; however, they may be generalized joints within serial mechanisms. This section introduces these 1-DOF RCM mechanisms, thereby enriching the understanding of RCM mechanisms.

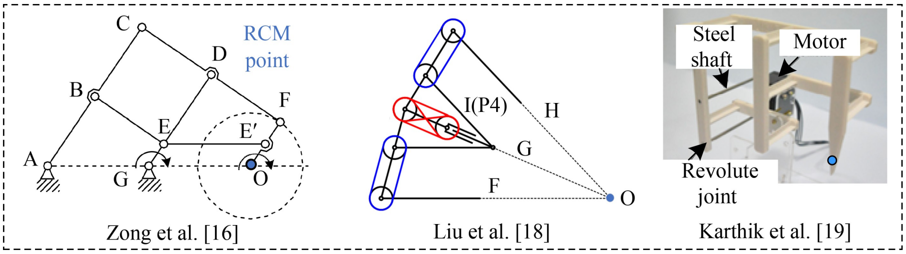
(1) 1-DOF

1R: One-DOF RCM mechanisms are classified into four types by Zong et al. [16]: single-revolute-joint RCM, circular-prismatic-joint RCM, parallelogram-based RCM, and synchronous-transmission-based RCM mechanisms. Two 1-DOF RCM mechanism-type synthesis methods were proposed based on planar virtual center (VC) mechanisms with the RCM point located at the VC point [16], as shown in Fig. 3. Method I combined two VC mechanisms, and Method II added constraint linkages. The methods conveniently construct planar 1-DOF RCM mechanisms, but the premise is that the VC mechanism configurations must be known. Similarly, a 1-DOF RCM mechanism-type synthesis method based on a combination of VC mechanisms was presented [17]. The RCM point was also located at the VC point, and the RCM mechanism volume can be adjusted according to the workspace. However, the RCM mechanisms in Ref. [17] needed a cam mechanism as a joint, thereby reducing the workspace and motion performance. To obtain a smaller footprint, Liu et. al. [18] proposed a 1-DOF cable-driven RCM mechanism (Fig. 3). The cable part consisted of eight links and seven pulleys. Although the cable linkages were complicated, it achieved a 50% to 80% reduction in footprint compared with a parallelogram RCM mechanism. Compliant mechanism theory was applied to RCM design to obtain high-precision micromanipulation for sensitive tissues, such as vitreoretinal surgery. With the replacement of the compliant revolute joints of existing RCM mechanisms, compliant parallelogram RCM mechanisms were proposed [7,19], achieving higher accuracy and a smaller workspace. However, in the field of compliant mechanisms, the reduction of parasitic motions continues to be a challenging issue.



Rotation joint Arc guide rail Linear joint Parallelogram

Fig. 2 Basic joints of serial remote center of motion mechanism.



Zong et al. [16] Liu et al. [18] Karthik et al. [19]

Fig. 3 One-degree of freedom (1R) remote center of motion mechanisms.

(2) Serial 2-DOF

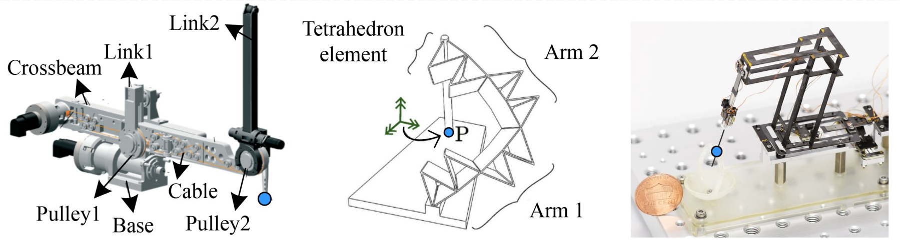
1R1T: A 1R1T RCM mechanism is also a planar mechanism. A 1R1T RCM mechanism can be designed by adding an active prismatic joint to the end-effector of a 1R RCM mechanism, such as part of the da Vinci robot system [4]. However, the active prismatic joint increases the mechanism inertia and reduces the back-drivability [20]. Some planar 1T1R RCM mechanisms have been designed to overcome the shortcomings. The two actuations of most 1T1R RCM mechanisms are fixed on the base, which means they are generalized parallel mechanisms; these will be introduced in Section 3.2.

2R: The most widely used RCM mechanism is the 2-DOF parallelogram RCM mechanism [21], which is applied in the da Vinci Surgical System, which consists of one revolute joint and one 1-DOF parallelogram compound joint with the axes intersecting at the RCM point. Studies on the performances of 2-DOF parallelogram RCM mechanisms have been conducted, which involved dimensional optimization based on a double space and kinematics accuracy reliability index [22] and an error compensation method combining a kinematic model and neural network [23]. Another famous 2-DOF RCM mechanism with an elegant structure is the RR spherical mechanism [24]. It consists of two revolute joints with the RCM point located at the intersection of two revolute joint axes, which is the simplest structure with the least number of joints and links among 2R and 3R RCM mechanisms. However, the angle between the two revolute joint axes constrains its workspace. A novel RCM mechanism with cables and sliders was proposed by Li et al. [25] with the RCM point located at the intersection of a revolute joint on the base and a prismatic joint on the end-effector, as shown in Fig. 4. The mechanism was optimized using the global condition index after kinematics analysis. Based on a compliant mechanism method, two new spherical flexure joint designs were presented by Rommers et al. [26] (Fig. 4), which can also be regarded as 2-DOF RCM mechanisms. The RCM point is located at the intersection of a trapezoidal blade flexure extension line. Arranging actuations on spherical flexure joints is difficult, which is why they are more suitable for passive RCM mechanisms. With the development of new mechanism design theory, an origami-inspired miniature manipulator with a mass of 2.4 g and a size of 50 mm × 70 mm × 50 mm was proposed for microsurgery by Suzuki and Wood [27] (Fig. 4). A mini-RCM mechanism inspired by the 2-DOF parallelogram RCM mechanism has a similar RCM point located at the line of the base revolute joint axes. The mini-RCM manufacturing was based on pop-up book MEMS technology, which is complex but has high accuracy, thus being suitable for precise microsurgeries. Based on both 1T1R and 2R 2-DOF RCM mechanisms, 3-DOF or 4-DOF RCM mechanisms can be designed easily by adding a prismatic or revolute joint at the end-effector [28].

(3) Serial 3-DOF

2R1T: 2R1T RCM mechanisms usually apply motion around the RCM point with pan, tilt, rotation, and translation along the axis without spin rotation. This type of RCM mechanism is mostly utilized for surgical robots. Li et al. [29] designed an RCM mechanism based on dual orthogonal parallelogram linkages for craniotomies. The RCM point was located at the intersection of a dual orthogonal parallelogram, and a hybrid structure decoupled the three motions, which also increased the mechanism volume and was more suitable for static surgical robots. To enhance safety, Kim et al. [30] presented a 3-DOF passive gravity compensation RCM mechanism that utilized a reduction gearbox and wire cable. Although it had the same structure as a normal parallelogram RCM mechanism, the gravity compensation method guided the RCM mechanism design. For high stiffness, Shim et al. [31] proposed a compact 3-DOF high-rigidity RCM mechanism using linear actuators and gearless-arc guides for bone surgery. Both the linear actuators and gearless-arc guides provided high stiffness, and the RCM point was located at the intersection of the serial gearless-arc guide axes. At the same time, the workspace was limited by the linear actuator and gearless-arc guide ranges.

3R: 3R RCM mechanisms can rotate in all directions around the RCM point. Christensen and Bai [32] presented a spherical RCM mechanism with a double-parallelogram linkage for a shoulder joint exoskeleton, as shown in Fig. 5. The configuration was a basic 1-DOF RCM parallelogram with serial revolute joints on both ends, and the RCM point was located at the intersection



Li et al. [25] Rommers et al. [26] Suzuki et al. [27]

Fig. 4 Serial 2-degree of freedom remote center of motion mechanisms.

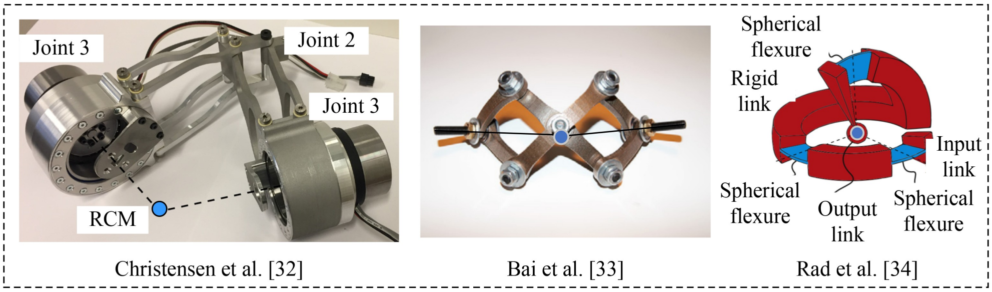
of the revolute joint axes. To obtain the most compact design, they optimized the mechanism, and a scissors shoulder RCM mechanism was proposed for an exoskeleton application [33] (Fig. 5). The compact 3-DOF RCM consisted of revolute joints arranged on a sphere surface, and all revolute joint axes pointed to the center of the sphere, i.e., the RCM point. This device is lightweight, portable, and suitable for wearable robots. On the basis of compliant mechanisms, a novel spherical flexure was investigated using the arc of a circle as the centroidal axis and an annulus sector as a cross section, with the RCM point located at the spherical flexure intersection [34] (Fig.5). The compliant RCM mechanism had superior motion accuracy and lower parasitic motions. However, similar to the compliant RCM mechanisms discussed above, driving it actively was difficult, and it was more suitable for passive joints.

(4) Serial 4-DOF

3R1T: 3R1T RCM mechanisms are full-DOF RCMs. The most common 3R1T 4-DOF RCM mechanisms were proposed by adding serial joints to RCM mechanisms with fewer DOFs. One of the earliest serial RCM mechanisms was proposed in 1993 by Funda et al. [35], as shown in Fig. 6. The RCM mechanism consisted of five serial joints, one revolute joint, two arc guide joints, and one prismatic joint. The RCM point was located at the intersection of the joint axes. Another famous compact mechanism for surgical robotics is the bevel-geared CoBRASurge robotic manipulator designed by Lehman et al. [36]. The mechanism uses gears rather than revolute joints and a serial spherical mechanism linkage to obtain a more compact structure, with the RCM point located at the intersection of the gear center axes [24]. Similar to a serial spherical mechanism, the workspace is limited by the size of the bevel gear. Based on a triple parallelogram linkage, a 4-DOF RCM force-reflective robot was designed for telesurgery systems by Hadavand et al. [12] (Fig. 6). Its RCM point was located at the intersection of the active revolute joint axes and, technically speaking, was a hybrid RCM mechanism. The hybrid design gave the device minimal moving inertia with small errors but, at the same time, a bulky volume. In addition to conventional rigid mechanisms, a variable RCM mechanism was presented using a three-dimensional printing flexible structure by Yoshida et al. [37] (Fig. 6). The flexible structure was manufactured using a polypropylene-like resin material and was driven by pneumatics to control the structure bending radius, which allowed the RCM point to be located in different positions. However, the flexibility also introduced a lower stiffness and higher error.

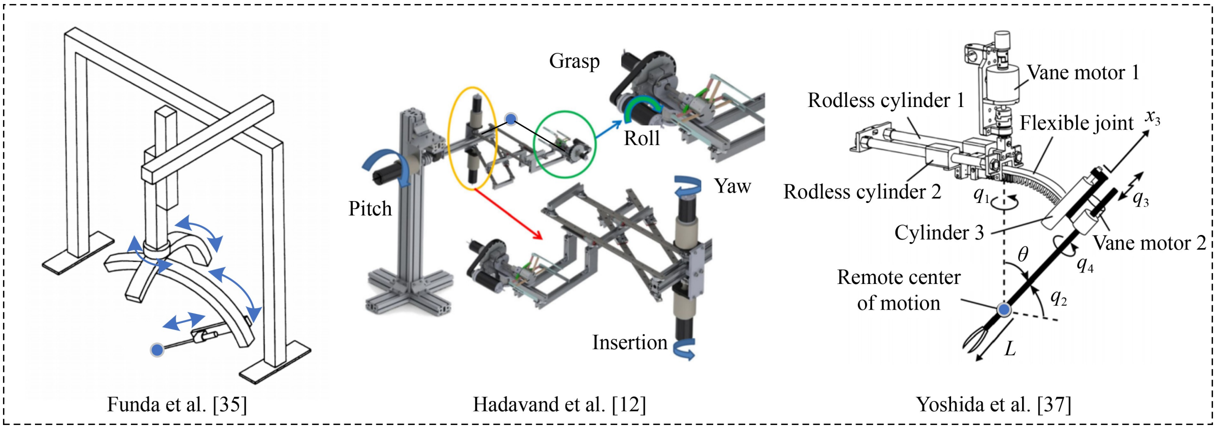
3.2 Parallel RCM mechanisms

As shown in Fig. 1, compared with serial mechanisms, a parallel mechanism has more than one limb and a more



Christensen et al. [32] Bai et al. [33] Rad et al. [34]

Fig. 5 Serial 3-degree of freedom remote center of motion mechanisms.



Funda et al. [35] Hadavand et al. [12] Yoshida et al. [37]

Fig. 6 Serial 4-degree of freedom (3R1T) remote center of motion mechanisms.

complicated structure. Most parallel mechanism actuators are located at the static platform to have less inertia. A parallel RCM mechanism consists of at least two limbs, each of which can be regarded as a serial mechanism and consists of joints in serial. The limb motion screw system is the union of its joint motion screw. It is not required to be an RCM but should contain one. The moving platform is constrained by all limbs and takes the limb motion screw system intersection as the RCM. Parallel RCM mechanisms satisfy the following relationships:

$$\begin{gathered}\mathbb{S}^{\text{parallel-RCM}}_{j\text{-DOF}} = \mathbb{S}_{\text{limb-1}} \cap \mathbb{S}_{\text{limb-2}} \cap \cdots \cap \mathbb{S}_{\text{limb-}i}, \\ j \geqslant 1,\ i \geqslant 2,\ \mathbb{S}_{\text{limb-}i} \supseteq \mathbb{S}^{\text{RCM}}_{j\text{-DOF}},\end{gathered} \tag{2}$$

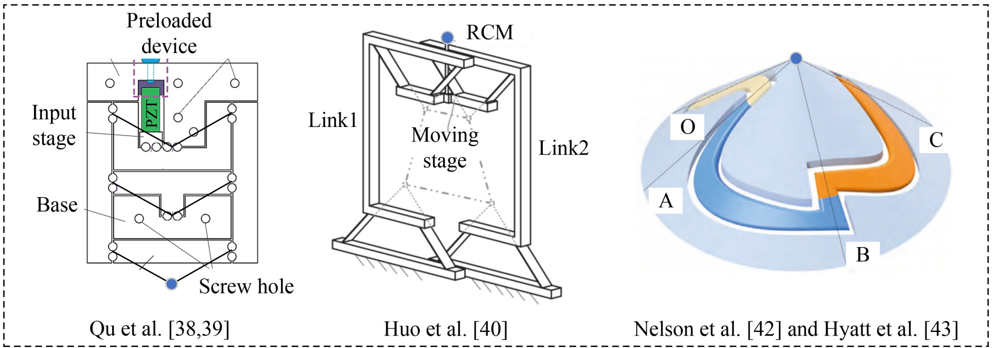
where $\mathbb{S}^{\text{parallel-RCM}}_{j\text{-DOF}}$ represents the moving platform motion screw system of parallel RCM mechanisms with j-DOF, $\mathbb{S}_{\text{limb-}i}$ represents the motion screw system of the ith limb, and $\mathbb{S}^{\text{RCM}}_{j\text{-DOF}}$ represents the motion screw system of a j-DOF RCM. Equation (2) represents the motion screw system of a parallel RCM mechanism as the intersection of all limb motion screw systems, i.e., when the motion screw systems of all limbs contain the same j-DOF RCM, the moving platform of parallel mechanism could move with a j-DOF RCM.

(1) Parallel 1-DOF

1R: Aside from the conventional rigid 1R RCM mechanisms discussed in Section 3.1, other 1R RCM mechanisms are compliant mechanisms designed for high-precision moving stages and accord more with the definition of parallel mechanism. Symmetric double-parallelogram 1R RCM mechanisms based on flexure hinges were designed for application in precision micro/nanomanipulations, as shown in Fig. 7 [38,39]. Two types of compliant RCM mechanisms were designed based on a conventional rigid parallelogram RCM mechanism, and the RCM points are located at the blue point of the equivalent mechanism. The two compliant RCM mechanisms possess a smaller actuation radius and higher rotational precision. The mechanism in Ref. [39] had a larger input displacement because of an output-stiffness enhanced lever amplifier. A family of 1R-compliant RCM mechanisms was proposed based on parasitic motion compensation and cross-spring pivots [40] (Fig.7). The RCM point was located at the instantaneous center of the equivalent trapezoidal four-bar mechanism, and the mechanism achieved great accuracy. For the compliant RCM mechanisms, increasing the output motion and decreasing the parasitic motion are key challenges. A 1R RCM has one application: a remote center-of-compliance device [41], whose constraints are passive and different from the RCMs discussed in this article. With the development of new mechanism theories, a spatial 4R mechanism on a circular cone surface has been studied to propose a new developable mechanism on a developable surface and expand the mechanism design method, whose linkages move around the apex point and can be seen as an RCM [42,43] (Fig.7).

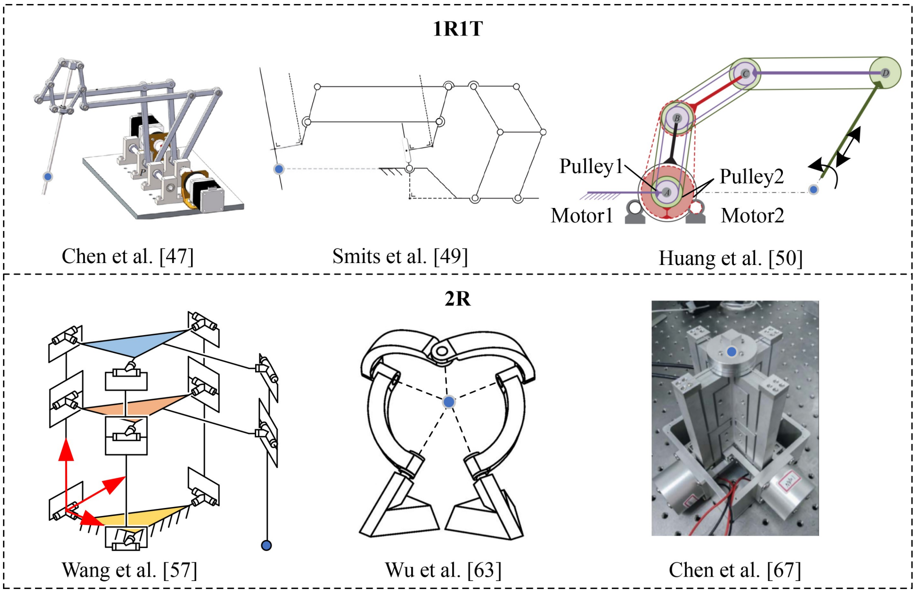
(2) Parallel 2-DOF

1R1T: 1T1R RCM mechanisms are planar motion mechanisms (Fig. 8). Most 1T1R RCM mechanisms were proposed with two actuations fixed on a base to avoid adding an active prismatic joint to the end-effector to obtain better performance. Typical studies to solve the problem based on adding constraint linkages involved type synthesis methods using virtual parallelograms [20], using a pantograph mechanism [44], based on dual-triangular linkages to reduce the occupied space [45], based on multi parallelograms [46], inspired by a Peaucellier–Lipkin straight-line linkage with straightforward kinematics [47], coupling parallelogram and linear motion mechanisms [48], and using dual parallelograms [49]. Although the constrained linkage methods have various forms, their RCM points are all located at the axis of two revolution joints fixed on a base. The design process of various forms requires in-depth knowledge and inspiration from researchers. RCM mechanisms that add constraint linkages have complex structures with more links and joints. With the use of a cable transmission without prismatic joints, a 1T1R RCM mechanism was proposed with fewer linkages and joints, which provided a large workspace and low collision risk [50]. Some studies were conducted on performance aside from design methods. The singularity and kinematic performance of a generalized 1T1R double-parallelogram RCM mechanism were investigated using a Jacobian matrix [51]. An RCM



Qu et al. [38,39] Huo et al. [40] Nelson et al. [42] and Hyatt et al. [43]

Fig. 7 Parallel 1-degree of freedom (1R) remote center of motion mechanisms.



Chen et al. [47] Smits et al. [49] Huang et al. [50]

Wang et al. [57] Wu et al. [63] Chen et al. [67]

Fig. 8 Parallel 2-degree of freedom remote of center motion mechanisms.

mechanism was optimized to yield maximum manipulability and desired translational motion with the smallest size [52].

2R: The earliest proposed 2R parallel RCM mechanism was the PantoScope for force reflection in 1997 with two limbs—an RPaR-RRRRR (one limb consisting of a revolute joint, a parallelogram joint and a revolute joint in serial; the other limb consists of five revolute joints in serial), with the RCM point located at the intersection of the two revolute joint axes fixed on the base [53]. The PantoScope had a simple structure, and along with a parallelogram mechanism, it inspired the design of other parallel RCM mechanisms with two limbs. Li et al. [54] designed a URR-UPR (one limb consisting of a universal joint and two revolute joints; the other limb consisting of a universal joint, a prismatic joint, and a revolute joint) RCM mechanism, which could be developed into a 4-DOF compact hybrid robotics wrist by adding serial joints to meet various MIS demands. Realpe et al. [55] proposed an RPaRRC-RPaR (C: column joint) RCM tensegrity mechanism, which could be reconfigured and perform decoupled stiffness modulation. Wang et al. [56] designed a metamorphic RCM mechanism with UPaR–UPa limbs and analyzed it using a constrained screw multiset, which had three motion branches with 2-, 1-, and 1-DOF RCMs. The actuations of these 2-DOF RCM mechanisms with two limbs were always the two revolute joints fixed on a base, and their workspace was almost symmetrical. Their RCM points were always located at the intersection of axes of revolute joints fixed on the base. Not only 2-DOF RCM mechanisms but most RCM mechanisms, both serial and parallel, must locate the RCM point at the intersection of revolute joint axes fixed on a base or as actuations. The constraint must consider specific robot design and deployment for practical applications to avoid collision, especially for complex MIS. To overcome the RCM point position constraint, Wang et al. [57] analyzed basic planar parallelogram mechanism using screw theory to clarify the RCM principle and proposed a 2-DOF RCM mechanism by mapping the structure of a planar parallelogram to spatial mechanism based on a 3-UU parallel mechanism (Fig. 8). The RCM point could be located at any position by reshaping the linkages without constraints. On the basis of this principle, Wang et al. [58] proposed a family of 2-DOF RCM mechanisms, and a new type of synthesis method by coupling two 2-DOF translation parallel mechanisms with a spherical workspace and redundant linkages by multiple 2-DOF RCM mechanisms with RCM points being able to be located at any position could be generated. As for the 2-DOF parallel RCM mechanisms with the simplest structure, another famous type of 2-DOF RCM mechanism has been developed, namely, the 5R spherical mechanism, which was initially designed for a force-reflecting manipulator with spherical rotation motion, not as an RCM [59,60]. It rotated on a spherical surface and around the center of a sphere, which satisfied the RCM definition. Many studies have been conducted on 5R spherical mechanisms regarding workspace, singularity, decoupled actuation, and motion/force transmission to obtain better performance [61–65]. However, a common 5R spherical RCM mechanism issue is that the workspace is limited by the revolute joint angle and the RCM points must be located at the intersection of all revolute joints inside the mechanism. A new parallel RCM mechanism for an ear and facial surgical application was proposed, coupling a parallelogram RCM mechanism and a spherical mechanism [66]. The decoupled RCM mechanism could deploy the actuation on the base and locate the RCM point outside the mechanism, which gave it a lower inertia and more flexibility for the application. For the compliant parallel 2R RCM mechanism, a 2-DOF large-range compliant RCM stage with input/output decoupling was presented based on an *n* pseudo-rigid-body-model method and compliance matrix method, as shown in Fig. 8 [67].

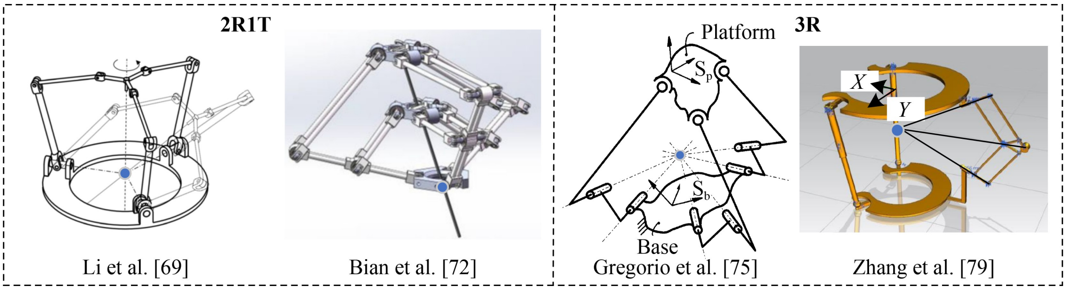
(3) Parallel 3-DOF

2R1T: A 2R1T RCM mechanism can be designed by adding a prismatic joint in series, such as the RRRP-RR spherical RCM mechanism for bone cutting, which was designed by adding a prismatic joint to a 5R spherical mechanism [68], whose RCM point was located at the intersection of revolute joints. The serial-parallel mechanism method is convenient for designing a new mechanism that satisfies DOF requirements but was limited by the characteristics of existing mechanisms. In addition, some new parallel mechanisms were proposed. Li et al. [69] proposed a family of RCM mechanisms with two and three limbs based on intersecting motion planes, including 1-, 2-, and 3-DOF RCM mechanisms (Fig. 9). With the use of a similar three-limb structure [69], Zhang et al. [70] proposed a 2-CRRR-CRR mechanism and optimized the motion/force transmission. The two types of RCM mechanisms had relatively simple and symmetrical structures, and the RCM points of two types were located at the intersection of three fixed revolute joints in three limbs. For most parallel RCM mechanisms, the number of actuations was equal to the DOFs and had one fixed RCM point. Zhao et al. [71] designed a 3-UPU RCM mechanism and utilized redundant actuators to realize multiple RCM points and solve the singular problem. Aside from the normal structure parallel mechanisms, the generalized structure parallel RCM mechanism was proposed by Bian et al. [72] (Fig. 9). The class of spatial 3-DOF RCM mechanisms was designed by using a double-delta mechanism with multi sub-loops, and the RCM point was located at the center of the static platform. Its structure was symmetrical, but the excessive number of universal joints might limit the workspace.

3R: Most 3R mechanisms are also well known as parallel wrists, such as the Argos 3-RPaS mechanism [73], the well-known agile eye 3-RRRR mechanism [11,74], a non-overconstrained spherical parallel manipulator 3-RRS mechanism [75] (Fig. 9), and a reconfigurable 3-RRR spherical RCM mechanism for robotic-assisted craniotomy [76,77]. Kong and Gosselin [78] proposed a synthesis of 3-DOF spherical parallel manipulators. The 3R spherical wrist mechanisms had the following common characteristics: three limbs, only revolute joints (or universal joints or sphere joints consisting of revolute joints), and RCM points located at the intersection of actuator axes. A 3R RCM mechanism can also be designed by adding another constraint limb in series on a 2R RCM mechanism, such as the 2RPaPaR+UPS mechanism for remote ultrasound imaging [10], in which the two RPaPaR limbs constrained the end-effector to rotate with pitch and yaw and the UPS limb constrained the end-effector to rotate with roll. With the addition of a pantograph as an RPaR constrained to 2UPS limbs, an asymmetric RCM mechanism with an RCM point located at the intersection of R-Pa-R joint axes was designed for hip joint assistance [79], in which the moving platform moved as RCM was constrained by an RPaR limb and was driven by two UPS limbs, as shown in Fig. 9. The two types of RCM mechanisms were designed based on the addition of the UPS limb because the UPS limb imposed no constraint to the platform with full 6-DOF motion and could drive the platform with a high-stiffness linear actuator. With the use of passive constraint limb, other wrist joints were designed, such as 2-UPS+1U for humanoid robots [80]. However, the joints rotated around the physical universal joint of the passive 1U limb, which had a similar rotation motion as RCM but not RCM strictly. Such wrist mechanisms were introduced in more detail in Ref. [81].

(4) Parallel 4-DOF

3R1T: As early as 2005, a class of 4-DOF RCM mechanisms was proposed by Zoppi et al. [82], which consisted of 4-5R, four limbs and only revolute joints, where RCM points were located at the intersection of four fixed revolute joint axes. The class of 4-DOF RCM mechanisms had a simple and symmetrical structure, but the forward and inverse kinematics were not simple and the actuator was coupled. Another 4-DOF RCM mechanism with RRRP-2RRRUU limbs was designed by Kuo and Dai [83] to decouple the motion (Fig. 10). Its RCM point was also located at the intersection of fixed revolute joint axes. However, its 4-DOF motions were



Li et al. [69] Bian et al. [72] Gregorio et al. [75] Zhang et al. [79]

Fig. 9 Parallel 3-degree of freedom remote center of motion mechanisms.

decoupled and could be controlled by one corresponding actuator, which simplified the complexity of control. One of the simple design methods for 4-DOF RCM mechanisms was to add serial joints on the parallel RCM mechanisms with fewer DOF to generate serial-parallel mechanisms. By adding an active revolute on the end-effector of the existing 2R1T RCM mechanism [72], Beira et al. [84] designed a 4-DOF hybrid RCM mechanism. The RCM point position of RCM mechanisms generated by adding serial joints was the same as the former parallel RCM mechanisms. Aside from redesigning the existing RCM mechanisms, Cao et al. [85] designed a 2-RAr (Ar represents an arc guide joint) parallel RCM mechanism and integrated it into a 4-DOF RCM mechanism by adding serial revolute and prismatic joints, whose RCM points were located at the center of arc guide joints, as shown in Fig. 10. Although the 2-RAr RCM mechanism had a simple structure, its workspace was limited by the length of the arc guide joint, and the two actuation joints on the end-effector might increase the inertia. The 4-DOF parallel RCM mechanism with the simplest structure was proposed by Chen et al. [86] (Fig. 10). The RCM mechanism with two limbs consisted of 2URRH, and its RCM point was located at the intersection of two fixed revolute joint axes. To control the RCM mechanism, Chen et al. [86] designed a new decoupled 2-DOF wrist actuations for each limb, which was compact and simplified the complexity of control.

For both serial and parallel RCM mechanisms, different DOFs present distinct advantages and disadvantages. One-DOF mechanisms have a relatively simple structure, but they are often unable to operate independently and are usually used as part of multi-DOF RCM mechanisms. Two-DOF RCM mechanisms are divided into two types: 1T1R and 2R. 1T1R allows planar motion and is limited to planar operations, while 2R can only make directional adjustments. In the case of 3-DOF RCM mechanisms, the 1T2R mechanism can essentially meet the needs of minimally invasive medical surgery applications, and the 3R mechanism is more suitable for simulating the movements of hip and wrist joints. Four-DOF RCM mechanisms can meet the requirements of all applications, but they often involve more drivers and are larger in size.

3.3 RCM control algorithms

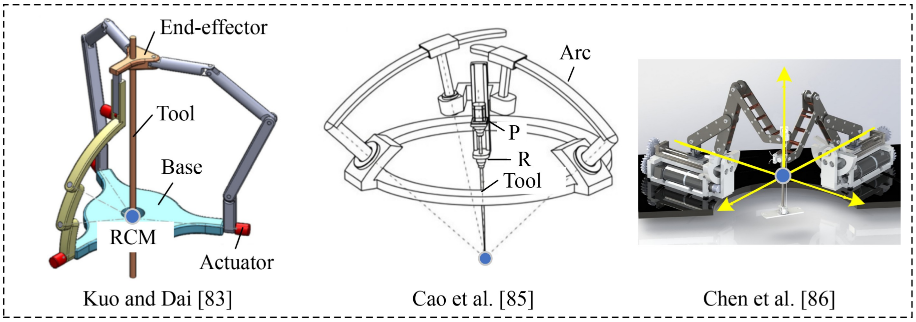
Generally, design-based RCM strategies are safer and more widely used for different applications. RCM mechanisms can maintain the RCM without additional control and have been applied for MIS robots [2,27], orientation devices [10,74], and exoskeleton robots [13,79]. However, control-based RCM strategies have been studied for application in MIS robots only. Most control-based RCM strategies are used in commercial serial robots, which are more flexible, durable, economical, and space-efficient solutions [87,88]. However, compared with design-based strategies, the control-based RCM strategy uses objects and applications that are less variable. Therefore, this review, which introduces generalized RCM methods and applications, discusses studies on control-based RCM strategies to focus on the developments of methods rather than on the details of control derivations.

The motion of a point on a serial robot can be expressed by the Jacobian between it and the joint motions. The following equation is satisfied to realize the RCM constraint, as shown in Fig. 1 [87]:

$$\dot{\boldsymbol{p}}_{\mathrm{RCM}} = \boldsymbol{J}_{\mathrm{RCM}}(\boldsymbol{q},\lambda)\begin{pmatrix}\dot{\boldsymbol{q}}\\ \dot{\lambda}\end{pmatrix} = \mathbf{0}, \tag{3}$$

where $\dot{\boldsymbol{p}}_{\mathrm{RCM}} \in \mathbb{R}^3$ is the RCM point in the three-dimensional Cartesian space, $\boldsymbol{J}_{\mathrm{RCM}}$ is the Jacobian matrix from the joints to the RCM point controlled by the RCM algorithms, $\boldsymbol{q}$ is the joint parameter vector, and λ is the RCM position parameter for the serial robot. Equation (3) shows that under the RCM algorithms, the Cartesian coordinate of the RCM point on the robot must be static.

Initially, the end-effector motion is constrained to pass through the RCM point, considering purely from the perspective of robotic arm kinematics. Existing control algorithms to realize RCM constraints formulate the desired motion as a set of tasks solved as a constrained quadratic optimization [89]. Subsequently, studies improved the RCM constraint control. For example, Aghakhani et al. [87] proposed a new RCM constraint formalization to control the end link to take rotations around the RCM point and translation along its axis

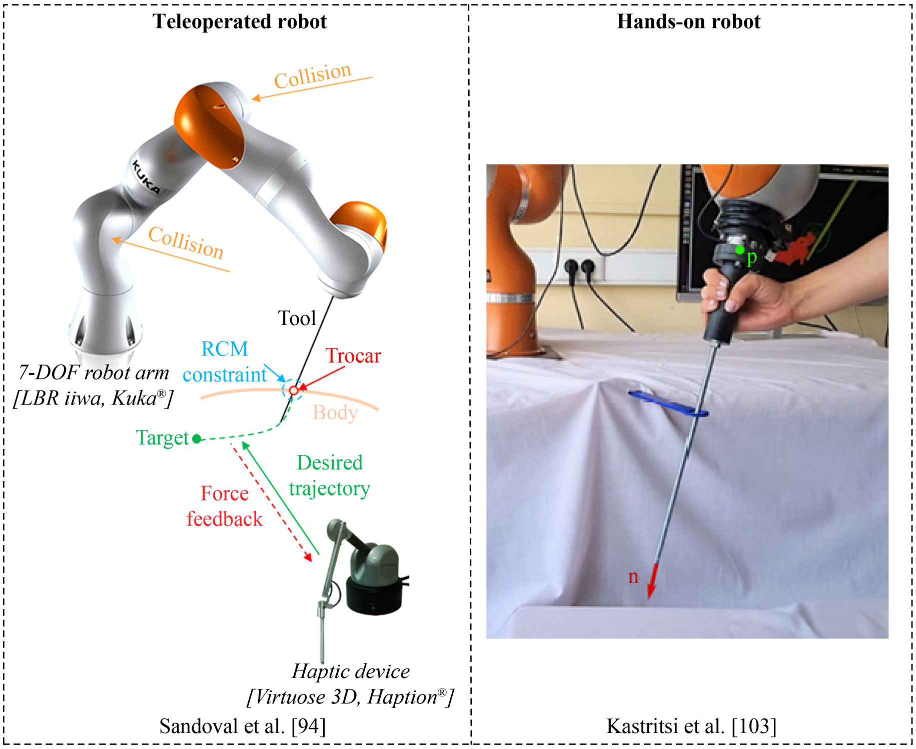


Kuo and Dai [83] Cao et al. [85] Chen et al. [86]

Fig. 10 Parallel 4-degree of freedom (3R1T) remote center of motion mechanisms.

requiring only the insertion position. With the development of serial robots, more control-based RCM strategy studies for redundant serial robots have been conducted because of added flexibility. With surgeon acceptance in the early 2000s taken into consideration, the Cartesian kinematic control of a 7-DOF robot was presented to enable a surgeon to perform open surgery, and the algorithm built an observer for Cartesian velocity control [90]. Compared with 6-DOF robots, redundant DOF robots have more DOFs than a full 4-DOF RCM, thus ensuring variable robot motion that can address different requirements. Locke and Patel [91] presented an isotropy-based kinematic optimization method for RCM location, which was tested on PA10-7C (a 7-DOF robot). Considering accidental incision movement, Pham et al. [92] presented a novel framework for the compensation of a moving RCM point and verified it by using an 8-DOF industrial robot.

With the advancement of collaborative robotics technology, research has begun on RCM algorithms in human–robot collaboration (HRC). As one of the most successful commercial serial redundant robots, KUKA LWR4+ (or iiwa) is a good test platform for MIS robots with RCM constraint control in laboratories. To improve the manipulability of the surgical tip and maintain the RCM, Su et al. [93] proposed an optimization control and validated it using KUKA LWR4+, which used the first degree of redundancy to achieve the RCM constraint and adopted the second degree for manipulability optimization. With the development of HRC, operator actions on robots have been considered in RCM constraint methods. Two main operation types were studied with the RCM constraint on KUKA LWR4+. One is teleoperated surgery, which involves surgeons operating haptic devices to control the end-effector by using master–slave control. Another is hands-on surgery, which involves surgeons holding the end-effector to operate, which is a form of HRC control. Teleoperated surgery robots are studied widely now because controlling robots by using haptic devices to identify operation intentions is easy. Sandoval et al. [94] proposed a generalized framework with a strict priority torque controller for a teleoperated MIS robot (Fig.11), in which the priority was the tool-tip trajectory in the task space and the second and third priorities were the RCM constraint and the joint compliance in the null space, respectively. To allow medical staff and robots to work in a shared workspace and consider their contact with each other, Sandoval et al. [95] proposed a control framework at the torque level through a null-space compliance control. Then, Su et al. [96] proposed a safety-enhanced collaborative control framework with the robot's elbow being able to move freely using the KUKA LWR 4+ robot and Sigma 7 master device. On the basis of previous studies, Su et al. [97–100] conducted further research for a teleoperated MIS robot with an RCM constraint, such as an improved HRC control for accuracy and computation efficiency, an Internet of Things-based


Teleoperated robot

Sandoval et al. [94]

Hands-on robot

Kastritsi et al. [103]

Fig. 11 Control-based remote center of motion strategies.

HRC control scheme to improve accuracy, a bilateral teleoperation control to ensure the RCM constraint while providing haptic feedback safely, and an optimized whole-body hierarchical impedance controller to maintain the RCM constraint in a dynamical environment. As for hands-on MIS robots, surgeons can hold the robot end-effector to perform surgeries just like traditional MIS, which provides easier acceptance and a slower learning curve for surgeons [101]. Kastritsi and Doulgeri [102] proposed a target admittance model in the joint space to impose an RCM for a hands-on MIS robot, which required only the measurements of human force and a forward robot kinematic model. Then, to increase the safety of non-surgical regions, they proposed a passive admittance controller to guarantee that the end-effector would not enter forbidden regions and move through an RCM at the same time, as shown in Fig. 11 [103].

With the development of modern control theory in recent years, machine learning represented by neural networks has been used in control-based RCM strategies to develop nonlinear models of MIS robots with RCM constraints and human operation, such as an accelerated finite-time convergent neural network [104], improved recurrent network [105], recurrent neural network (RNN)-based metaheuristic approach [106], gradient-based neural network [107], incorporating model predictive control with fuzzy approximation [108], accelerated dual neural network [109], improved incremental radial basis function network [110], bioinspired network [88], model-based RNN [111], and fuzzy approximation-based task-space control [112]. In addition, some control studies in which the RCM was not the main research target have been conducted, such as those on maximum end-effector accuracy and dexterity [113] and transferring manipulation skills from humans to humanoid robots using teaching by demonstration [114]; these works are not discussed in detail here.

3.4 Summary

Sections 3.1 and 3.2 discussed design-based strategy RCM approaches, which are divided into serial RCM mechanisms and parallel mechanisms by DOF. Section 3.3 discussed control-based strategy RCM approaches. On the basis of all RCM approaches, the RCM studies are presented in Fig.12 according to their timeline. The serial RCM mechanism was the earliest research object. In the 1990s, the concept of RCM was proposed by Russel Taylor, and Funda et al. [35] proposed the earliest serial RCM mechanism. However, from 1993 to 2005, few studies were conducted on different RCM approaches. The pioneering works [6,21] inspired succeeding studies. As for the parallel RCM mechanisms during this period, the spherical mechanism was proposed in 1994 [74]. Although the above-mentioned mechanisms have the same motions as RCM, they were studied only as spherical mechanisms. In 2006, Lum et al. [24] designed a new serial RCM mechanism inspired by spherical mechanisms, and studies on serial RCM mechanisms started to increase by combining with other classic mechanisms. In 2011, Beira et al. [84] proposed the parallel RCM mechanism based on the delta mechanism, which was also proposed by their lab. From then on, the study of parallel RCM became a highlight. Numerous studies proposed variable configurations. The design methods became flexible and inspired by some other mechanism theory. The structures of RCM mechanisms became more complex and brought different performance features. With the development of a compliant mechanism, theory was also applied to RCM mechanisms. Qu et al. [38] proposed the parallel compliant RCM mechanism in 2014, and Parvari et al. [34] proposed the serial compliant RCM mechanism in 2016. In recent years, the research thinking pertaining to RCM mechanisms is to simplify complex structures by using

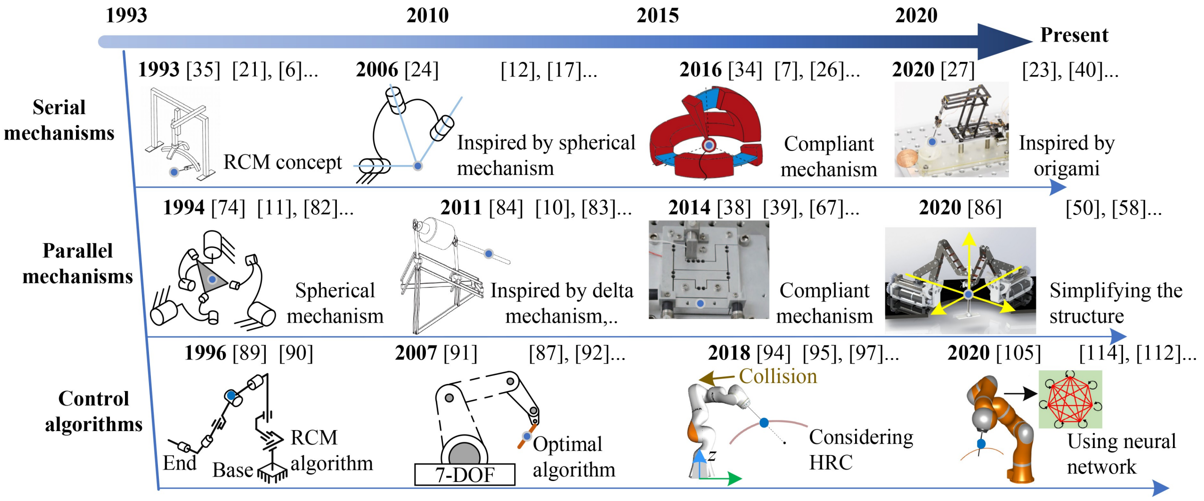


Fig. 12 Timeline of remote center of motion approaches.

new mechanism methods. In 2020, Suzuki and Wood [27] designed a mini RCM mechanism with high accuracy by using origami, and Chen et al. [86] designed a parallel RCM mechanism with a simple structure by using a coupled actuation module. Parallel mechanisms have variable configurations, which is why they have been outnumbering serial RCM mechanisms over the years.

RCM algorithms are another development route. The earliest RCM constraint algorithm was proposed in 1996 [89]. For the next 20 years, some optimal RCM algorithms were proposed, such as Ref. [91]. In 2018, Sandoval et al. [94] proposed a generalized control frame for commercial redundant robots considering the RCM constraint, teleoperation, and robot collision with humans, which first introduced HRC in RCM algorithms. In 2020, Li et al. [104] used machine learning in RCM algorithms first, and machine learning for RCM became another research highlight. Aside from RCM approaches, RCM applications in variable fields are also a research highlight, which will be discussed in Section 4.

As shown in Tables 2 and 3, RCM mechanisms can also be classified by the fundamental structures with different characteristics. Control-based strategy RCM approaches can be classified according to whether they include human–robot interactions, which can be applied in different scenarios.

Parallelogram structures, which are renowned for their adaptability, are the most extensively studied and employed foundational elements in RCM mechanism design. As identified by Ref. [57], the core principle of a parallelogram involves constructing synchronized rotating linkages through the use of redundant connections. This design philosophy has been fundamental in the development of various RCM mechanisms, including serial [12,21,29,30,32,33,45,47,51,52] and parallel mechanisms [10,53–57,72,79,84]. Beyond individual mechanisms, a spectrum of synthesis methods based on parallelograms [16,17,20,44,46,58] has been proposed, facilitating the creation of diverse RCM mechanisms with analogous structures. However, the complexity and variability of the connecting linkages in parallelogram-based RCM mechanisms need to be considered carefully in practical applications. For instance, in the case of 2R parallel RCM mechanisms, designs based on parallelograms can vary significantly, such as those documented in Refs. [53,55,57] with their respective link and joint counts. Such variations need careful attention to avoid mechanical interference. Similarly, the 5R spherical parallel mechanism, which comprises only four links and five joints [60], demonstrates the potential of variable structures to introduce unique benefits, such as decoupled motion [55] or unconstrained RCM point position [57].

Synchronized belt/cable/gear RCM mechanisms share a fundamental principle with parallelograms, synchronizing linkages in rotational motion, but with fewer linkages and more compact forms. However, their simplicity results in fewer DOFs, limiting their suitability for complex designs [18,25,50].

Conversely, RCM mechanisms designed based on arc guides offer a different approach. Unlike linear guides, arc guides enable the rotational motion of the slider around the arc’s center, potentially serving as the RCM point. Despite their high stiffness, arc guides’ voluminous nature, governed by their length, limits their motion range [31]. Consequently, arc guide-based RCM mechanisms find prevalent use in bone surgery, ensuring precision in drilling or milling [85].

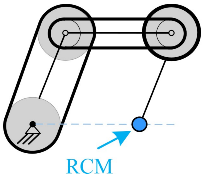
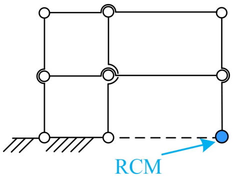
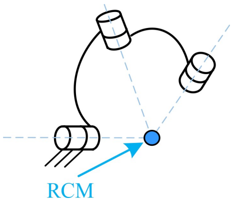
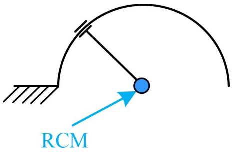
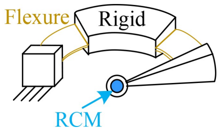
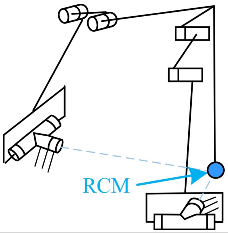
Another prominent category of RCM mechanisms features designs based on spherical/wrist mechanisms, encompassing all-revolute joint configurations for both serial [24,28,36,115] and parallel mechanisms [11,48,49, 59–65,68,73–77] (including the type synthesis method [78]). These mechanisms typically exhibit a relatively simple, often symmetrical structure. However, a common constraint across spherical/wrist mechanisms is the intersection of all revolute joint axes at a single point, namely, the RCM point, as exemplified by the works of Lum et al. [24], the 3-DOF serial mechanism developed by Castro et al. [33], the 4-DOF serial mechanism developed by Lehman et al. [36], the 2-DOF parallel mechanism developed by Ouerfelli and Kumar [60], the 3-DOF parallel mechanism developed by Gosselin et al. [11], and the 4-DOF parallel mechanism developed by Zoppi et al. [82]. This design constraint must be carefully considered in the desired workspace.

RCM mechanisms based on limb constraints represent a unique approach that is exclusive to parallel RCM mechanisms, as they require at least two limbs to restrict the end-effector’s motion. Various parallel RCM mechanisms [70,71,83,86] and type synthesis methods [69,82] have been proposed based on limb constraints. The diversity of limb constraint designs allows for a wide range of RCM mechanism structures. Nevertheless, designing mechanisms based on limb constraints can be challenging, often drawing inspiration from various limb motions.

Compliant and soft mechanisms have been hot research topics in recent years. Some RCM mechanisms have been designed using methods based on compliant joints, including serial mechanisms [7,26,27,34,37], parallel mechanisms [38,39,42,43,67,116], and type synthesis methods [40]. This type of RCM mechanism does not consist of conventional joints, and their motions are produced by the deformation of a compliant part. They can have a smaller size and higher stiffness and accuracy, which may make them more widely applied in the future.

Control-based strategy RCM approaches are mainly studied and used for commercial serial robots. The approaches can be classified into two types: whether they include human–robot interactions. First, control-based strategy RCM approaches were proposed to solve the RCM constraint control problem without considering

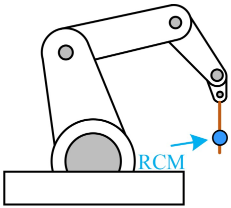
Table 2 Design-based RCM approaches

Type	Fundamental	Kinematic sketch	Reference					
			1R	1R1T	2R	2R1T	3R	3R1T
Serial	Synchronized belt/cable/gear		[18]	[50]	[25], [73]a)			
	Parallelogram		[16, 17]b)	[20, 44, 46]a),b), [45, 47, 51, 52]a)	[21], [53–57]a), [58]a),b)	[29, 30], [72]a)	[10, 79]a), [32, 33]	[12], [84]a)
	Spherical/wrist mechanism			[48, 49]a)	[24], [59–65]a)	[36], [68]a)	[11,73–77]a), [78]a),b)	[28, 115]
Parallel	Arc guide				[85]a)	[31]		
	Compliant joint		[7, 19], [38, 39]a), [40]a),b)		[26,27], [42, 43, 67]a)		[34], [116]a)	[37]
	Limb constraint					[69]a),b), [70, 71]a)		[82]a),b), [83, 86]a)

a): References represent parallel mechanisms.

b): References represent not only one mechanism but also a synthesis method type of a class of mechanisms.

Table 3 Control-based RCM approaches

Fundamental	Kinematic sketch	Reference	
		RCM constraint	RCM with HRC
Serial commercial robot		[88–93, 104–113, 117]	[90, 94–100, 102, 103, 114]

human–robot interactions. Some control laws and algorithms were studied to constrain the end-effector to move through the RCM point with more accuracy [88–93, 104–113,117]. On the other hand, with the development of surgical robotics, an increasing number of operator actions should be considered in control loops. HRC has become an important problem in control-based RCM approaches. Therefore, many recent studies have been conducted on RCMs with HRC to achieve safety and accuracy [94–100,102,103,114].

Most RCM studies also include performance analyses of the proposed methods in Table 4. For RCM mechanisms, almost all RCM mechanism studies would analyze the workspace and singularity, which are the most important performance metrics and the fundamentals for mechanism utilization. Also related to mechanism space, some studies researched the space occupied by mechanisms themselves or going through by the links to ensure that the mechanisms occupy less space, with volume [17,25,52] and footprint [18,45] being the key performance metrics. Accuracy is another important performance metric, especially in MIS, to prevent incidental collisions with small incisions. Most position errors of the RCM mechanism are associated with manufacturing and assembling accuracy, which may be stable after the complete production. The stiffness of the compliant mechanisms is then subjected to analyses. The dexterity and motion/force transmission were evaluated to assess the motion performance in the workspace. These factors are the first targets in optimizing the performance of a mechanism, aside from being subjected to analyses. The following studies proposed dexterity optimization methods [11,22,24,25,29,51,52,68,76,77] and motion/force transmission optimization methods [63,70]. Some studies also proposed optimization methods for the workspace [60], volume [52], and accuracy [22,23]. For the RCM control algorithms, almost all studies measured the accuracy of RCM point positions on the serial manipulators to prove the validity of the RCM control. For the RCM control algorithms with HRC, some studies [97–100] measured the accuracy of interaction force to ensure the precision and safety of operations.

4 RCM applications

RCM applications are discussed in this section. As mentioned in the introduction, an RCM is used for three purposes: first, moving through an incision; second, changing orientations; third, mimicking or synchronizing motions. These are also the three main abilities of RCMs. In particular, RCMs have three main application fields: medical robots, orientation devices, and exoskeleton robots. In terms of RCM approaches, RCM mechanisms are the most widely used for three main reasons in the three application fields. Most RCM control algorithms are proposed to allow medical robots to move through an incision. The approaches, ability, and application (3A) fields of RCM are presented in Fig. 13, and the specific applications in each field are subsequently discussed.4.1 Medical Robotics

(1) Minimally invasive surgery

MIS requires a surgical end-effector to move through an incision and perform complicated operations. For MIS, the RCM points are located at the incision position, as shown in Fig. 14. The earliest and most famous MIS robot is the da Vinci system, which was developed for laparoscopic surgery based on a parallelogram RCM mechanism, followed by the Zeus system, which uses two passive revolute joints intersecting at one point [4]. Raven-II is an open MIS robot platform for collaborative research based on open standard software, which has been studied by seven universities and uses a two-link spherical mechanism to realize RCM [5]. In addition to the mechanisms, teleoperation and hands-on operation for laparoscopic surgery using RCM control algorithms have been developed and used in commercial robots for laparoscopic surgery [97]. Eye surgery requires accurate and complicated RCM operations because of the small incision and delicate issues. A master–slave robotics system was realized based on an arc-guided 4-DOF RCM mechanism for vitreoretinal surgery [118] and a defined parallelogram RCM with a guide screw for retinal vascular bypass surgery [8], which increases the motion accuracy. A compliant RCM mechanism is another method to increase vitreoretinal surgery accuracy [19]. A

Table 4 RCM performance

Strategy	Performance metric	Reference	
		Analysis or measurement	Optimization
Design-based	Workspace	[12, 17, 31–33, 38–40, 45, 47–51, 53, 54, 56, 57, 60, 61, 67, 72, 79, 82–86]	[60]
	Singularity	[10, 25, 32, 50, 53, 54, 56, 57, 60, 62, 64, 65, 70, 71, 79, 82-84, 86]	
	Volume	[17, 25]	[52]
	Footprint	[18, 45]	
	Accuracy	[7, 19, 22, 23, 27, 31, 37–40, 45, 47, 50, 67, 86]	[22, 23]
	Stiffness	[26, 31, 34, 37–40, 67, 116]	
	Dexterity	[12, 22, 24, 25, 32, 33, 54, 60, 74]	[11, 22, 24, 25, 29, 51, 52, 68, 76, 77]
	Motion/force transmission	[48, 62, 71]	[63, 70]
Control-based	Position accuracy	[87, 89–100, 102, 103]	
	Force accuracy	[97–100]	

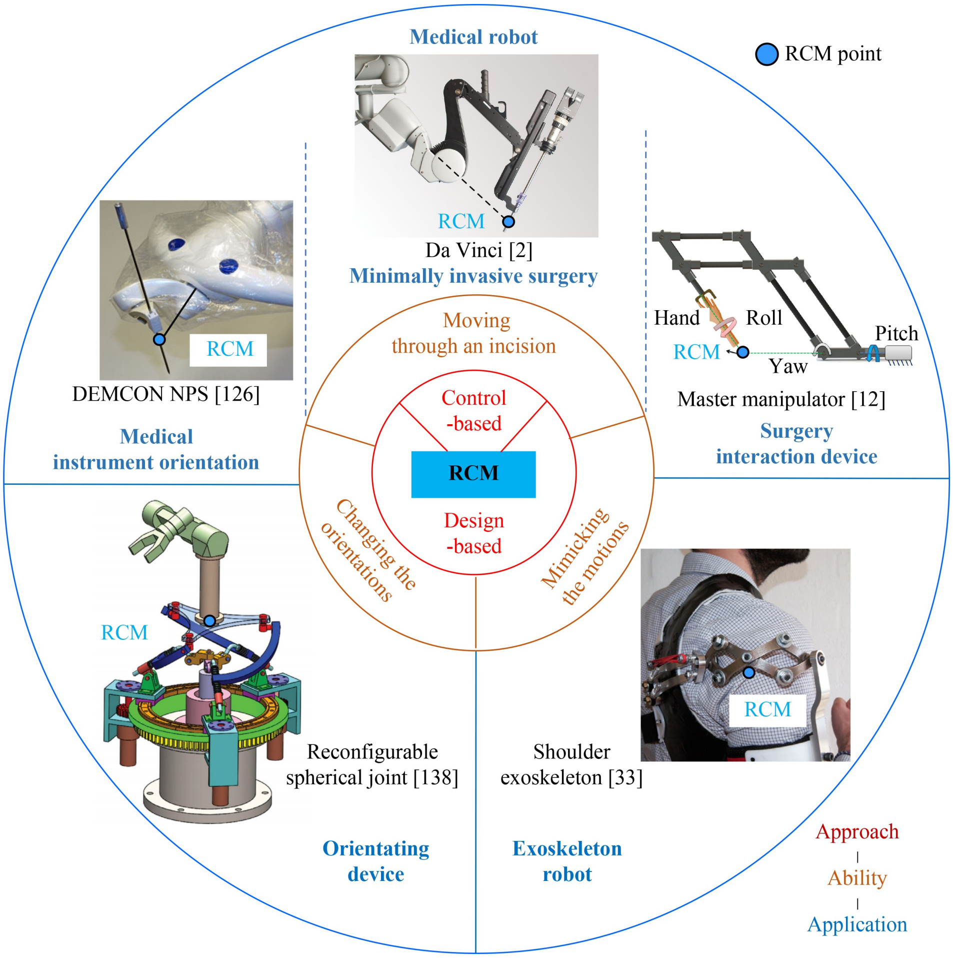


Fig. 13 RCMs are most widely applied in medical robots. An RCM can be applied to different subfields in medical robots and in MIS because of its ability to move through an incision, in medical instrument orientation because of changing orientations, and in surgery interaction devices because of synchronizing motions.

miniature manipulator for teleoperated microsurgery was inspired by origami based on a parallelogram RCM mechanism, whose compact, simple structure facilitates manufacture, to further reduce the volume and increase the accuracy [27]. RCMs are also applied in other surgeries, such as endometrial regeneration surgery robots based on robust RCM constraints [119], ear and sinus surgery based on parallelogram RCM mechanisms [120], and knee arthroplasty based on spherical RCM mechanisms [121].

(2) Medical instrument orientation

Unlike in MIS, some medical instruments need to orient in the right direction, which is an RCM ability as a wrist mechanism. For medical instrument orientation, RCM points are located at the rotation center of the medical instrument, which is often the endpoint (Fig. 15). Medical instruments with an RCM can be divided into two types: surgical instruments and examination instruments. Surgical instruments may cause damage to tissues and require an RCM to orient in the right direction and aim the focus. As early as 1993, although the RCM concept was not mentioned, a needle insertion manipulator used an arc guide to orientate around a point [9]. Then, some needle insertion manipulators with smaller, lighter, and more compact bodies were developed based on different RCM approaches, such as a modular percutaneous procedure robot [122] and radiological intervention robot [123] based on a synchronized belt RCM mechanism, robotic needle guidance based on a double-ring spherical mechanism [124], a lumbar puncture robot based on a parallelogram RCM mechanism [125], and DEMCON NPS for CT-guided percutaneous needle placement based on a spherical RCM mechanism [126]. Similar to needle insertion, a hair-implanting device was designed based on a spherical RCM mechanism with gravity compensation [127]. A parallel wrist for robotic trauma microsurgery was proposed using a parallel spherical mechanism [128]. For craniotomy, a surgical robot using a spherical parallel RCM mechanism to orient and drill as needed was designed because of the high stiffness of parallel mechanisms [68]. Similar to bone surgery, a robot to guide the orientation of the drilling axis toward the target and against the drilling motion was developed based on

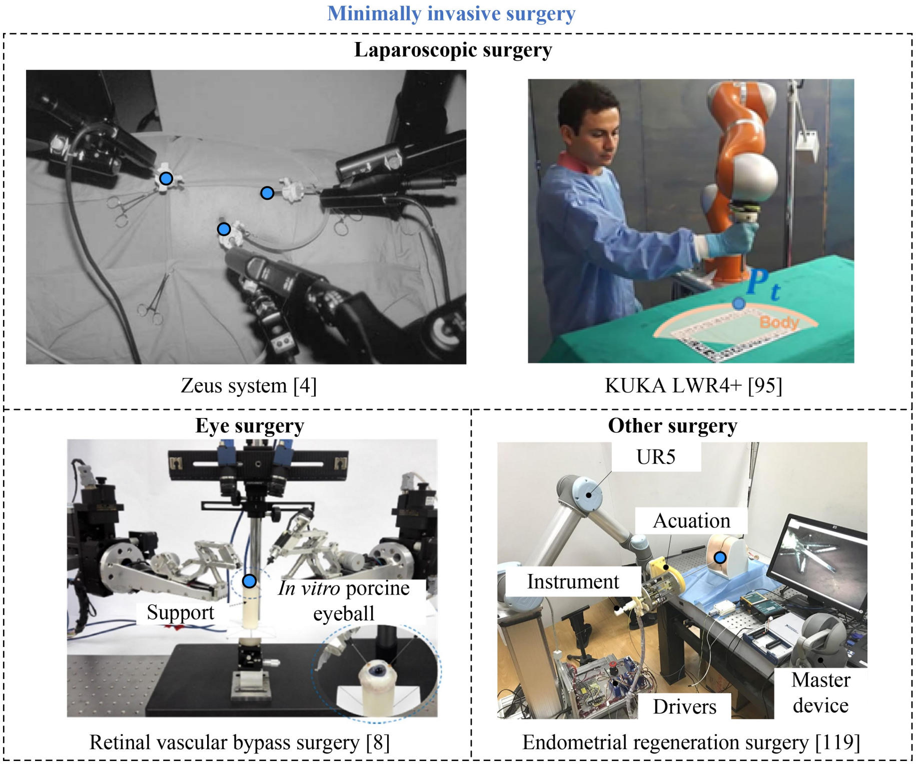


Fig. 14 Remote center of motion applications in minimally invasive surgery.

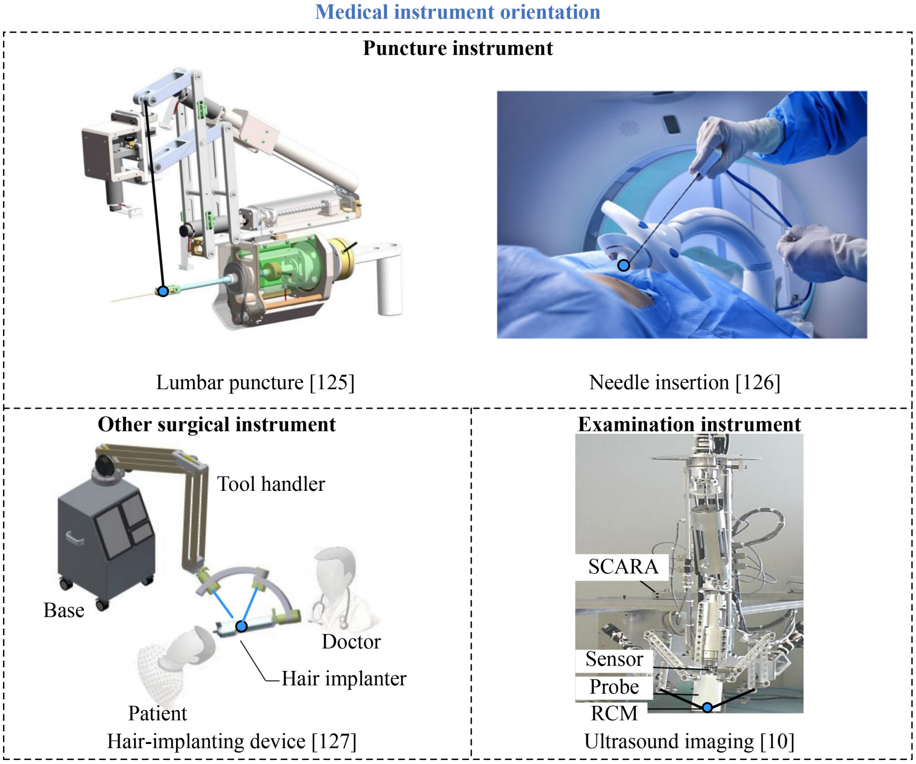


Fig. 15 Remote center of motion applications in medical instrument orientation.

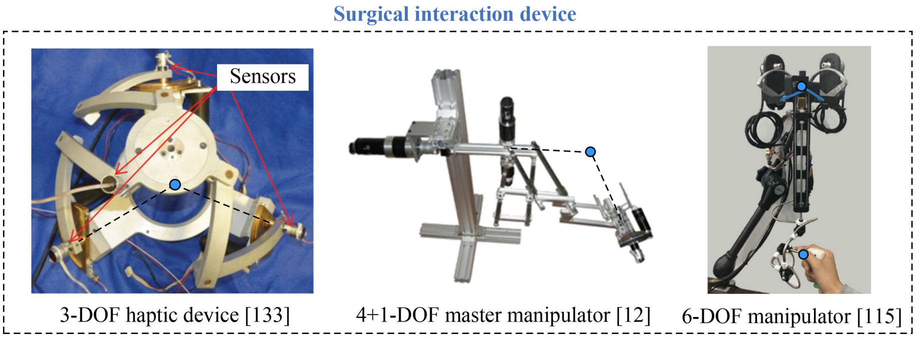
an arc guide with high resolution and rigidity [31]. A 5-DOF neurosurgery robot was developed based on two decoupled RCM mechanisms in series to position and orient a drill for craniotomy and brain tumor biopsy surgeries [129]. For the same surgery, different robots use an RCM for different reasons [121]. An RCM can be used to enable drilling through a small incision. For knee arthroplasty, a semiactive robot named Stanmore Sculptor was developed to orient ball milling around the center of a ball burr, which was also the RCM point, based on a spherical RCM mechanism [130]. Examination instructions should not cause damage to tissues. Robotic wrists for remote ultrasound imaging were developed based on RCM mechanisms [10,76]. Owing to the recent outbreak of the respiratory virus pandemic, a swab sampling robot was developed based on a synchronized belt RCM mechanism [131] and RCM control [132] to orient the swab.

(3) Surgery interaction devices

An RCM can mimic motion and can be applied in surgical interactions because it is similar to the wrist of the human hand, and the motion of a MIS instrument is also constrained by an RCM (Fig. 16). For this application, RCM points are always located at two types of points. One is the rotation center similar to a slave end-effector, and the other is the center of the human wrist, which moves simultaneously. For teleoperation applications, a 3-DOF haptic device was proposed based on a redundant actuated 3-RRR spherical RCM mechanism [133]. With the translation and grasp DOFs taken into consideration, a 4+1-DOF force reflective haptic system was developed based on a triple parallelogram RCM mechanism with minimal moving inertia [12]. A full 6-DOF haptic can also be presented by combining an RCM, such as a 6-DOF master manipulator based on combining the position arm with a spherical RCM mechanism [115]. Haptic devices based on RCM mechanisms can be used in not only surgery interaction devices but also in all haptic fields; such devices include the SHeDe 3-DOF haptic device based on a parallel spherical RCM mechanism [134] and a 6-DOF haptic device based on a delta mechanism with three translation DOFs and a spherical RCM mechanism with three rotation DOFs [135].

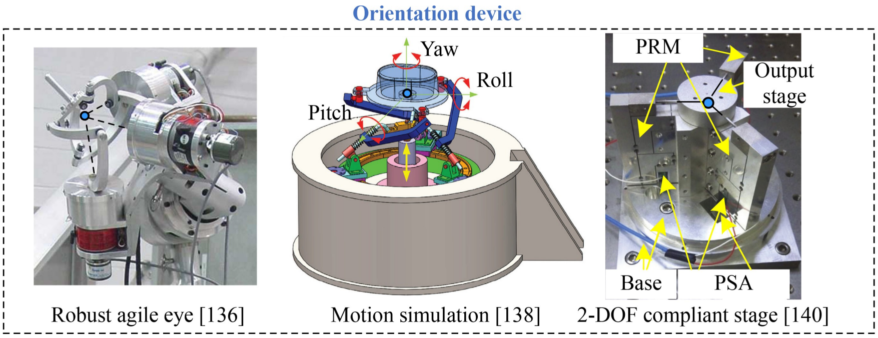
4.1 Orientation device

Orientation devices are not only needed by surgical instruments. An RCM was used for variable types of orientation devices, and the RCM points are located at the rotation center as needed (Fig. 17). The famous Agile Eye spherical RCM mechanism was developed for orienting a camera based on a 3-RRR parallel spherical mechanism [11]. Another well-known orientating mechanism is Argos, which is based on a parallel synchronized belt RCM mechanism [73]. The design of most wrist RCM mechanisms was inspired by Refs. [136–138]. A review on spherical parallel mechanisms introduced these devices in more detail [139]. In addition to rigid



3-DOF haptic device [133]
4+1-DOF master manipulator [12]
6-DOF manipulator [115]

Fig. 16 Remote center of motion applications in surgical interaction device.



Robust agile eye [136]
Motion simulation [138]
2-DOF compliant stage [140]

Fig. 17 Remote center of motion applications in orientation device.

orientation devices, many micro positioning devices were proposed using a compliant RCM because of better accuracy. Qu et al. [38,39] proposed a 1-DOF compliant RCM stage for precision active parallel alignment to eliminate harmful lateral displacement. The compliant RCM stage was based on flexure hinges and driven by a piezoelectric actuator. On the basis of a compliant parallelogram RCM, Chen et al. [67] and Qu et al. [140] made further efforts and proposed a 2-DOF compliant RCM micro-positioning stage with three compliant limbs and four limbs.

4.2 Exoskeleton robot

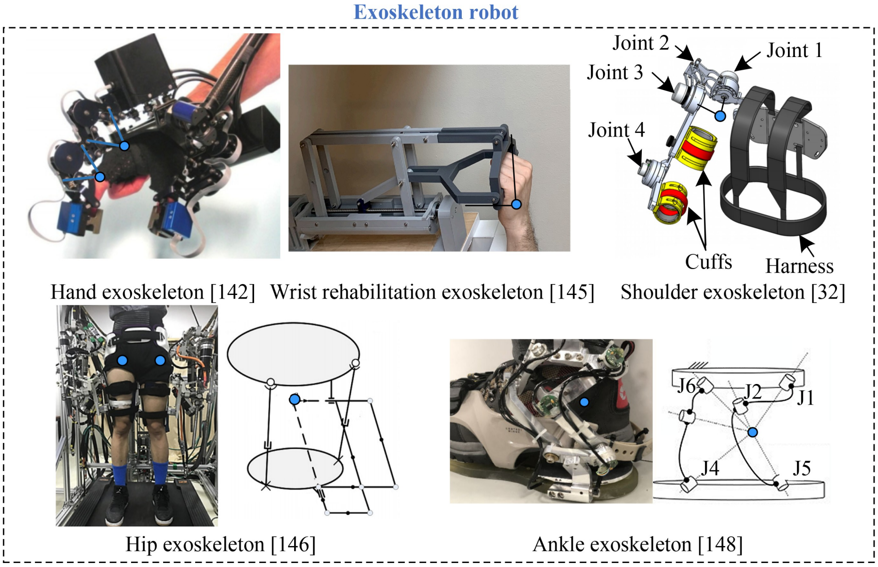
An exoskeleton robot is a type of HRC system and can be divided into rehabilitation exoskeletons and assisted exoskeletons. Both types of exoskeleton robots can be worn on the human body and move with the motions of humans. The motions of humans are generated by human joints, which are the phalangeal, wrist, elbow, shoulder, hip, knee, and ankle joints from the upper to the lower body. Human joints can be regarded as motion joints, such as a revolute joint for the phalangeal, elbow, and knee joints; a universal joint for the ankle joint; a spherical joint for the wrist, shoulder, and hip joints. To adapt to humans better, an exoskeleton robot should move with the motions of humans and remotely, thus requiring an RCM. The RCM points for exoskeleton robots are located at the center of human joints (Fig. 18). On the basis of a parallelogram RCM mechanism for two main phalangeal joints of each figure, hand exoskeleton robots were designed for haptic hands [141,142]. Based on a spherical RCM mechanism for wrist joints, a compact wrist rehabilitation robot was developed with an assist-as-needed controller and misalignment adaptation [143,144]. For wrist joints, a portable wrist rehabilitation robot was proposed based on a parallelogram RCM mechanism, and a portable, low-cost 3D-printed prototype was presented [145]. Christensen and Bai [32] and Castro et al. [33] developed two types of shoulder exoskeleton robots based on a parallelogram RCM mechanism and a spherical RCM mechanism. The commercial upper-body rehabilitation exoskeleton Harmony used a spherical RCM mechanism for the shoulder part to match motions [13]. Based on a parallelogram RCM mechanism, a hip rehabilitation exoskeleton was designed, and its human-centered adaptive control was established [79,146]. An RCM mechanism was also used in ankle exoskeletons such as the multifunctional ankle exoskeleton for mobility enhancement based on a parallelogram RCM mechanism [147] and the ACE-Ankle military ankle exoskeleton based on a spherical RCM mechanism [148]. In addition to exoskeleton robots, RCM approaches can be applied to the wrist and shoulder of a robot arm to mimic human motion [149], which are generally regarded as a robotic wrist and reviewed in detail in [81].

5 Discussion

Despite significant advancements in RCM research, several areas and issues need to be investigated further.

(1) Control versus mechanism

The RCM mechanism and the RCM control algorithm represent two distinct methodologies for achieving an RCM. A critical prerequisite for an RCM control algorithm is that the robot must possess more DOFs than the RCM itself requires. Consequently, most RCM control algorithms are tailored for 6-DOF and 7-DOF



Hand exoskeleton [142] Wrist rehabilitation exoskeleton [145] Shoulder exoskeleton [32]

Hip exoskeleton [146] Ankle exoskeleton [148]

Fig. 18 Remote center of motion applications in exoskeleton robot.

commercial serial robots, which have sufficient redundant DOFs to adhere to RCM constraints. Using a redundant commercial robot for MIS is advantageous; it not only conforms to RCM movement but also mitigates potential collisions between the operator and the robot due to the additional joints [97]. However, these control algorithms are predominantly developed with a focus on MIS. For other applications, such as orientation devices and exoskeletons, a simpler structure is often preferable, and redundant DOFs may introduce unnecessary complexity. Thus, control-based strategies tend to concentrate on more generalized and cost-effective methods for controlling serial robots with RCM in specific applications such as MIS. As indicated in Table 3, research on control-based strategies is divided into two directions: one aims to realize RCM in serial robots through new control algorithms grounded in modern control theory [104–112], and the other extends beyond mere RCM realization to encompass additional MIS requirements such as instrument placement optimization [113] and specialized robot systems for specific surgical procedures [119]. In contrast, design-based strategies emphasize the development of versatile structures to cater to advanced applications. Research in this domain also diverges into two primary threads. One focuses on the enhancement of existing mechanisms for specific uses, exemplified by the adaptation of parallelogram mechanisms for wrist rehabilitation [145] and swab sampling [131]. The other is directed toward the invention of novel mechanisms integrated with cutting-edge theoretical concepts. These mechanisms include the development of origami mechanisms for heightened precision [27], generalized parallel mechanisms with an unconstrained RCM point [58], reconfigurable mechanisms with multi-RCM DOFs [56], and flexure joints with more compact structures [26] to provide better performance and adaptability.

(2) Rigid versus compliant

The evolving landscape of robotics research is witnessing a significant shift from traditional rigid robots toward compliant or soft robotics, particularly in applications involving human interaction. In the context of RCM control algorithms, the rigidity of robots manifests in the interactions between the RCM point and the environment, and between the robot and the operator. During MIS, various factors such as the patient's unintentional movements or respiratory motions can alter the incision position, subsequently impacting the RCM point. Similarly, potential collisions between the operator and the robot may also influence the RCM point. In such scenarios, robots equipped with a compliant RCM point could enhance safety and operability. However, incorporating compliance into the control algorithms increases their complexity.

On the mechanism side, beyond merely having a compliant RCM point, the entire mechanism may embody compliance. Such compliant mechanisms typically utilize flexure joints instead of conventional rigid joints. This shift toward compliance offers several advantages, including reduced mechanism size, lighter weight, and improved accuracy. However, the design and analysis of compliant mechanisms present a more intricate challenge. The evaluation of such mechanisms, encompassing kinematics, dynamics, and stiffness aspects, tends to be nonlinear and considerably more complex. This ongoing research trend toward compliance in both RCM control algorithms and mechanisms underscores the need for innovative approaches that balance the benefits of compliance with the complexities it introduces. As the field progresses, developing streamlined methods for analyzing and implementing compliant RCM systems remain a critical area of focus.

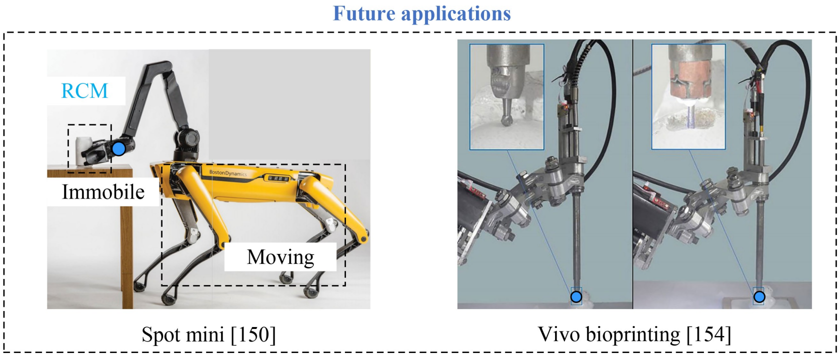
(3) Application versus research

The foregoing discussion highlights significant disparities between practical applications and theoretical research in the realm of RCM technologies. More straightforward RCM approaches are typically employed in real-world applications. Nonetheless, the field has witnessed the development of numerous innovative RCM mechanisms, each characterized by diverse structures and functionalities. The majority of RCM mechanisms that are currently used, particularly in applications, are grounded in either parallelogram or spherical RCM designs and are known for their simplicity. This simplicity is advantageous because it eases the system's design, analysis, and control processes when an RCM is required. Future research in RCM design could pivot toward formulating a wider array of RCM approaches with varied structural configurations to meet diverse application needs.

Concurrently, research on RCM applications might increasingly concentrate on functional realization (Fig. 19). For instance, RCM control has been effectively implemented in the robotic arm of the quadruped robot, Spot Mini, to maintain the end-effector's position stationary [150]. Moreover, the application of RCM mechanisms is exhibiting growing potential in stereotactic technology, particularly in 3D printing, where they can precisely control the orientation of the print head [151,152]. Beyond conventional 3D printing, RCM mechanisms have also been leveraged in the pioneering field of *in vivo* bioprinting [153,154], which broadens the therapeutic horizon for tissue injuries and the applications of RCM technology. Such advancements underscore the versatile potential of RCM mechanisms, marking a significant stride in both research and practical implementations.

6 Conclusions

This paper conducted an exhaustive review of RCM technologies, with a primary emphasis on dissecting the


Future applications

Spot mini [150]

Vivo bioprinting [154]

Fig. 19 Future remote center of motion applications.

myriad RCM approaches and their diverse applications in the field of robotics. RCM kinematics were examined in detail and categorized based on their DOFs and distinct methodologies. The two principal categories of RCM approaches, namely, RCM mechanisms, and RCM control algorithms, were meticulously analyzed, offering a comprehensive insight into their current state and evolution. Furthermore, this paper delved into the recent advancements in RCM applications, specifically in the domains of medical robotics, orientation devices, and exoskeletons, providing a granular analysis of their development and implications. This work engaged in a critical discussion on the various research challenges and practical considerations that emerge in the implementation and sustained utilization of RCMs in these fields. The breadth of applications for RCMs, as a critical form of constrained motion, underscores the significance of this review. This review serves not only as an informative compendium for those currently engaged in the field but also as an invaluable resource to guide and inform future research endeavors. By synthesizing the current knowledge and identifying areas for further investigation, this paper aims to catalyze the continued advancement and innovative application of RCM technologies in robotics and beyond.

Nomenclature

Abbreviations

Ar	Arc guide joint
DOF	Degree of freedom
HRC	Human–robot collaboration
MIS	Minimally invasive surgery
P	Prismatic
Pa	Parallelogram
R	Rotation
U	Universal
RCM	Remote center of motion
RNN	Recurrent neural network
T	Translation
VC	Virtual center

Variables

$\boldsymbol{J}_{\mathrm{RCM}}$	Jacobian matrix from the joints to the RCM point controlled by the RCM algorithms
$\dot{\boldsymbol{p}}_{\mathrm{RCM}}$	RCM point in the three-dimensional Cartesian space
$\boldsymbol{q}$	Joint parameter vector
$\boldsymbol{S}$	Screw in a six-dimensional
$\boldsymbol{S}_{\mathrm{joint}\text{-}j}$	Motion screw of the jth joint
$\boldsymbol{v}$	Unit vector in the v-direction
$\boldsymbol{w}$	Unit vector in the w-direction
$\boldsymbol{x}$	Unit vector in the x-direction in the world coordinate system
$\boldsymbol{y}$	Unit vector in the y-direction in the world coordinate system
$\boldsymbol{z}$	Unit vector in the z-direction in the world coordinate system
λ	RCM position parameter for the serial robot

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