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TOPICAL REVIEW

A Review of the Research Progress of Orthodontic Archwire Bending Robot for Fixed Appliances

HAN LIU[1], JINGANG JIANG[1], (Senior Member, IEEE), JINGCHAO WANG[2], SHAN ZHOU[2], YONGDE ZHANG[1], (Member, IEEE), AND SINAN LIU[3]

[1]Key Laboratory of Advanced Manufacturing and Intelligent Technology, Ministry of Education, Harbin University of Science and Technology, Harbin 150080, China
[2]Department of Orthodontics, The Second Affiliated Hospital of Harbin Medical University, Harbin 150086, China
[3]Foshan Baikang Robot Technology Company Ltd., Foshan 528225, China

Corresponding author: Yongde Zhang (zhangyd@hrbust.edu.cn)

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ABSTRACT This paper proposes a comprehensive review of orthodontic archwire bending robots for fixed appliances, focusing on their key technologies. Orthodontic archwire bending robots can significantly reduce the workload of orthodontists and enhance the efficiency of orthodontic treatment with compared with the orthodontist's manual bending of orthodontic archwires. Due to the high degree of customization required for orthodontic archwires and the challenge of springback during bending, research on robotic archwire bending has concentrated on developing advanced robotic systems, optimizing archwire bending plans, and implementing springback compensation methods. This paper comprehensively reviews the advancements in design and control of orthodontic archwire bending robots for fixed appliances. It delves into orthodontic archwire bending planning and springback compensation methods, providing a categorized introduction and detailed summaries. Finally, it evaluates and discusses the challenges and future directions of orthodontic archwire bending robots and their core technologies.

INDEX TERMS Orthodontic archwire bending robot, planning methods for bending orthodontic archwires, bending springback compensation method.

I. INTRODUCTION

The earliest report on medical robots dates back to 1988 for needle alignment during neurosurgical biopsy puncture [1]. The medical field has embraced robotics in recent years [2], and dentistry is no exception. Robots are now being used for a variety of procedures, including implantation [3], extraction [4], restoration [5], endodontics [6], orthodontics [7], and maxillofacial surgery [8], [9]. Robots play a role in orthodontics due to their high precision, high efficiency, and high stability. In the filed of dentistry, Orthodontists are able to use robots to achieve the roles such as: measurement of orthodontic forces [10], [11], simulation of tooth movement during orthodontics [12], [13], assist in the fabrication of invisible appliances [14], fixed orthodontic appliances [15], and movable orthodontic appliances [16]. Thus, robots have a vital role to play in the field of orthodontics.

For straightening teeth, orthodontic appliances are the gold standard. These appliances come in three main types: fixed braces [17], invisible orthodontic appliances [18], and removable options [19]. Orthodontists typically rely on fixed braces or clear aligners for active treatment, while removable appliances often play a supportive role in maintaining the final results after treatment is complete [20]. As the wearing of traditional fixed braces would affect the aesthetics, the concept of invisible braces was proposed in 1946 [21], and with the rapid rise of material science and 3D printing technology, invisible braces were introduced into the orthodontic market in 1998 [22]. Due to its material properties and shaping method, invisible braces are automatically processed by robots or other devices combined with 3D printing technology. Invisible aligners are the most favored orthodontic

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appliance of patients because of their aesthetics [23] and comfort [24], but studies have shown that invisible aligners cannot be used when patients need rotational orthodontic treatment [25] and when patients are wearing veneer crowns [26], and therefore, invisible aligners cannot completely replace traditional fixed aligners for the time being [27].

Traditional fixed orthodontic appliances consist of orthodontic brackets and orthodontic wires. When orthodontic wires have placed orthodontic brackets, deformation occurs between the orthodontic wires and brackets, and the orthodontic wires apply orthodontic force to the teeth to restore the deformation so that the teeth will move to the position, which is most suitable for treatment. Different shapes of orthodontic archwires will exert different amounts of orthodontic force on the teeth when the malocclusion of the teeth is certain. Too much orthodontic force may lead to root resorption or tooth loss, while too little orthodontic force may lead to non-movement of the teeth, thus prolonging the treatment time. Since different patients have different malocclusions, the teeth need to be moved in different directions and distances, therefore, different patients need different shapes of orthodontic archwires.

Manually bending orthodontic wires poses several challenges. The super elasticity of the wire causes it to springback after bending, requiring orthodontists to bend it repeatedly. This repeated bending can lead to fatigue fractures and affect the accuracy of the final shape. Additionally, the doctor's experience significantly impacts the precision of the process. For these reasons, researchers have explored using robots to bend orthodontic wires. Studies show that robotic bending offers high precision and efficiency, potentially improving treatment speed and reducing strain on orthodontists [28].

To address the challenges of customizing orthodontic wires and springback during bending, researchers developed two methods: orthodontic archwire bending planning and springback compensation. The planning method allows for designing various wire shapes. It essentially involves taking a straight wire and calculating the precise bend locations, angles, and distances between bends to achieve the doctor's desired final shape. Springback compensation tackles the issue of wires bouncing back after bending. By predicting the springback angle, this method adjusts the initial bending angle to ensure the wire reaches the target shape in a single go, achieving accurate bending.

Dental and orthodontic robots have been discussed as topics [29], [30], [31], as well as a short review of orthodontic archwire bending robots [15], [32], but a systematic summary of orthodontic archwire bending robots and their key technologies has been neglected; therefore, this review is intended to provide a comprehensive and timely reference for the development of orthodontic archwire bending robots and their key technologies.

This paper provides a comprehensive review orthodontic archwire bending robots and their core technologies. It explores the current state of research on orthodontic archwire bending robots, bending planning methods for target orthodontic archwires, and archwire springback compensation methods in the bending process. The mechanism of the orthodontic archwire bending robot and the trajectory planning and control methods are reviewed, and the mechanism types of the orthodontic archwire bending robot are classified into three types: planar, articulated, and Cartesian coordinate. The paper categorizes orthodontic archwire bending robots into three main types based on their movement capabilities: planar, articulated, and Cartesian coordinate. Planar robots bend wires within a single plane, while articulated robots use multi-jointed arms for greater flexibility. Cartesian coordinate robots, meanwhile, utilize a rectangular frame structure for precise movements. There are two main approaches to planning the bending process for target archwires: model-based and model-free. Model-based methods rely on a virtual or physical model of the desired shape, while model-free methods use mathematical calculations. The paper further classifies springback compensation methods based on the archwire material: stainless steel and Nitinol. Stainless steel uses bending compensation, while Nitinol utilizes thermal activation for compensation, as shown in Fig. 1. In the section II of the article, the structures of various types of orthodontic archwire bending robots and their processing capabilities are outlined, and current methods of motion trajectory planning and control of orthodontic archwire bending robots are reviewed. In Section III the principles of the two currently used methods for target archwire planning are highlighted, and relevant research cases are outlined to analyse the advantages and disadvantages of each type of method. In Section IV, two different bending compensation methods for two different materials used in the bending process of archwires are reviewed. Finally, in Section V, the current challenges and future trends of orthodontic archwire bending robots are discussed.

II. ORTHODONTIC ARCHWIRE BENDING ROBOT

The orthodontic archwire bending robot is an essential element of the robotic system, responsible for the manipulation and formation of orthodontic appliances. The formed orthodontic archwires possess an intricate three-dimensional configuration, which challenges the robot's processing capability and serves as a crucial factor in establishing the robot's suitability for replacing the orthodontist in the fabrication of orthodontic appliances. Currently, there exist multiple types of orthodontic archwire bending robots, each possessing distinct processing capabilities. This research categorizes the robots that have been documented into three distinct types: planar bending robots [33], [36], [37], articulated bending robots [38], [39], [40], and Cartesian bending robots [41], [42], [43], [44]. This subsection will provide a detailed description of the structural framework of each robot type, examine the machining capabilities of each type, summarize the strengths and shortcomings of the current robots in each category, and highlight forthcoming design options.

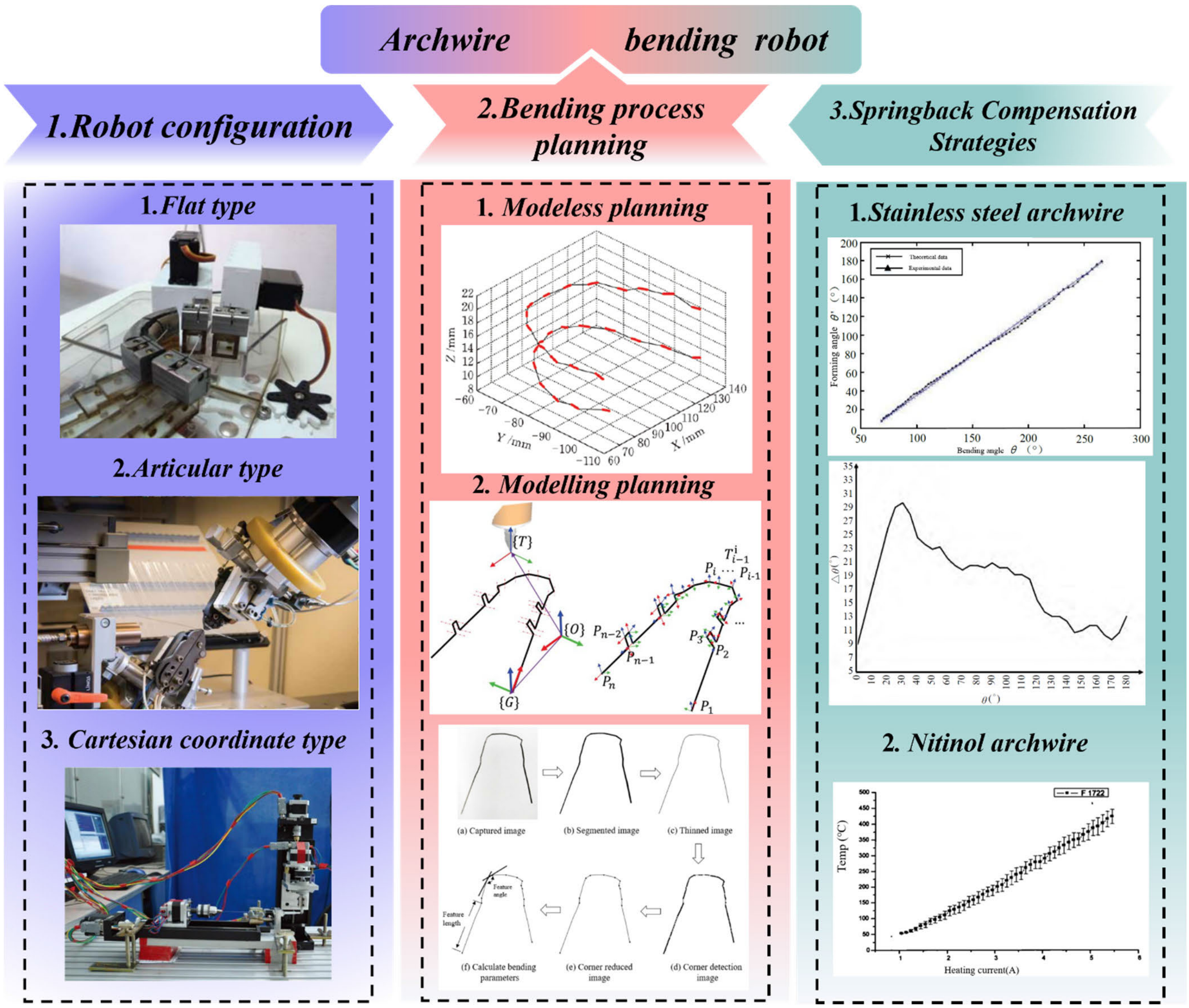

FIGURE 1. Key technologies of orthodontic arch wire bending robots. 1.1 Flat type, "LAMDA" orthodontic archwire bending robot designed by Glbert Reprinted with permission from [33]. Copyright 2011, JCO. 1.2 Articular type, "Suresmile" articulating orthodontic archwire bending robot designed by F. Riemeier et al. Reprinted with permission from [31]. Copyright 2016, Bentham. 1.3 Cartesian coordinate type, Orthodontic archwire bending robot with right-angled coordinates designed by Zhang et al. Reprinted with permission from [7]. Copyright 2014, SAGE. 2.1 Modeless planning, Mathematical modelling of maxillary and mandibular orthodontic archwires by Zhang et al. 2.2.1 Modelling planning for lingual orthodontic archwire realisation by Deng et al. Reprinted with permission from [34]. Copyright 2015, IEEE. 2.2.2 Planning of bending points for orthodontic archwires using image extraction by He et al. Reprinted with permission from [35]. Copyright 2018, IEEE. 3.1 Stainless steel archwire springback prediction model for wire bending. 3.2.1 Stainless steel bow wire overbend angle model 3.2.2 Nitinol bow wire setting temperature model.

Robots can be classified based on their mechanical structure. A planar orthodontic archwire bending robot is one that bends orthodontic archwires in a single plane without converting the bending plane. An articulated orthodontic archwire bending robot is similar to an industrial robotic arm, with multiple rotating joints as the main body. A Cartesian Coordinate Orthodontic Archwire Bending Robot is a robot that uses a rectangular structure to enable linear movement of the end-effector in the X, Y, and Z axes. Please refer to Fig. 2 for a visual representation.

A. PLANAR ORTHODONTIC ARCHWIRE BENDING ROBOT

The first report of an orthodontic archwire bending robot was the design of a robotic orthodontic archwire bending system called the "Bending art system" by H. Fischer-Brandies et al. The system combines an electronic endoscope, bow bending equipment and a computer control system, which manually measures the bow bending data and imports it into the control system, which converts the data and sends commands to the bow bending equipment to complete the bow forming. The main body of the orthodontic archwire bending mechanism in this system is a bending head as shown in Fig. 2(a), which consists of three parts, an outer bending cone that can be transformed into a different direction is provided on the outer side of the bending head, and a guiding cone is provided at the top of the bending head, which is wrapped around the inner torsion cone with a central hole. The advancement and twisting of the archwire can be achieved by the co-ordination of the guide cone and the inner torsion cone, and the bending of the orthodontic archwire is achieved when the outer bending cone moves relative to the direction of the archwire feed. The robot can achieve a bending effect of 6°-54° and a twisting effect of 2°-36° of the archwire with a minimum step of 0.5-0.7 mm [36]. In order to fill the gap in the robotic processing of lingual orthodontic archwires, Alfredo Glbert et al. designed an orthodontic archwire bending assistance system called "LAMDA", which has an end-effector capable of moving in the XY plane to bend lingual orthodontic archwires [33], [45], as shown in Fig. 2b). The team developed the "LAMDA2" lingual orthodontic archwire assisted manufacturing system based on the "LAMDA", as shown in Fig 2c). The drive module of the new generation system has been upgraded from the original 4-motor composition to a 12-motor composition, and the second-generation system achieves bending compensation between the canine and the first molar, as well as between the first molar and the second molar, by increasing the number of end-effector, which enables finer bending [30].

For the planar bending robot its structure is limited, mostly used in a plane to bend the orthodontic archwire, can achieve the first sequence of orthodontic archwire bending needs, but for the first sequence of curves perpendicular to the positional relationship between the special function of the curvature, its processing capacity is insufficient to achieve the geometry of complex special function of curvature bending.

B. ARTICULATING ORTHODONTIC ARCHWIRE BENDING ROBOT

There are two commercially succeed orthodontic archwire bending robots: Ortho-robot and Suresmile. Both robots are articulated and have the ability to bend the initial sequence of labial orthodontic archwires. Additionally, Orthorobot is also capable of bending the first sequence of labial orthodontic archwires [32].

Patents related to the Suresmile robot report that the robot consists primarily of a robotic arm for mobile gripping and bending and a fixed mechanical gripper fixed to a base for clamping the bow wire, with a total of six degrees of freedom. The arm can move and rotate relative to the fixed jaws to complete the bending of the orthodontic archwire [46].

The system is also equipped with a feeding device for the archwire, and a special conveyor belt with grooves is designed to place the unformed archwire in the grooves, so that the conveyor belt advances by one position to make the archwire available to the arm for picking up the archwire when the mobile arm needs a new archwire. Friedrich Riemeier et al. modified the Suresmile system by improving the clamping and bending methods, reducing collisions during bending, and increasing the types of orthodontic wires that can be clamped [38], as shown in Fig 2d).

Zhang and Jia [39]. built an orthodontic archwire bending robot using a MOTOMAN UP6 robotic arm, which consists of a MOTOMAN UP6, an end-effector, and an archwire fixation bracket, with one end of the archwire being clamped by the fixation bracket, and the other end of the archwire being clamped by the end-effector for bending. A cylinder, and the clamping drive the end-effector of the robot and releasing of the bow wire by the end-effector is realized by the ejecting and retracting of the cylinder. The clamping jaws of the end-effector are designed with a diamond-shaped notch, which can realize the clamping of both the square wire and the round wire. The researchers carried out bending experiments with Ni-Ti alloy bow wires and achieved the bending of the first sequence of curves of orthodontic bow wires, as shown in Fig. 2h.

When orthodontists bend orthodontic archwires manually, they may use a variety of different types of wire benders. In order to enable the robot to bend orthodontic archwires with a variety of wire benders as well, Xia et al. [40].

Designed a robotic end-effector that can be used in conjunction with a library of wire benders to enable the replacement of wire benders, as shown in Fig. 2e). The robot system as a whole consists of a six-degree-of-freedom articulated robot, end-effector, archwire clamping mechanism, clamp magazine, and archwire pick-and-place frame. At the end of the robot end-effector is configured with a pulley drive mechanism connected to the motor, the other side is connected to the screw mechanism, the wedge-shaped slider is mounted on the screw, the motor rotation is decelerated by the belt drive to transfer the motion to the screw, the screw moves upward with the wedge-shaped slider to push the rollers, so that the pliers can achieve the clamping, the motor reverses the wedge-shaped slider downward movement, the reset springs can be made to open the pliers, and the structure of the end-effector is shown in Fig. 2f). In order to achieve the smooth replacement of mechanical fingers, the team also developed a corresponding clamping tool library, the structure of which is shown in Fig. 2f). The bottom of the clamp library is connected to the motor, when replacing the wire bending clamp, the robot end-effector moves to the de-clamping frame and puts the wire bending clamp into the clamp library, and then moves to the target bending clamp to be replaced and takes it away, when the replacement of the wire bending clamp is completed, the clamp library will re-transfer the empty space to the de-clamping frame. The researchers again attempted the construction of a robotic system using two robotic arms, and the robotic system was able to achieve the bending of the first sequence of curves of the lingual orthodontic archwire, as well as the bending of the two weighted special function curves, the vertical-open curves and the T-shaped curves, as shown in Fig. 2g).

The articulating orthodontic archwire bending robot exhibits exceptional flexibility and is adept at bending

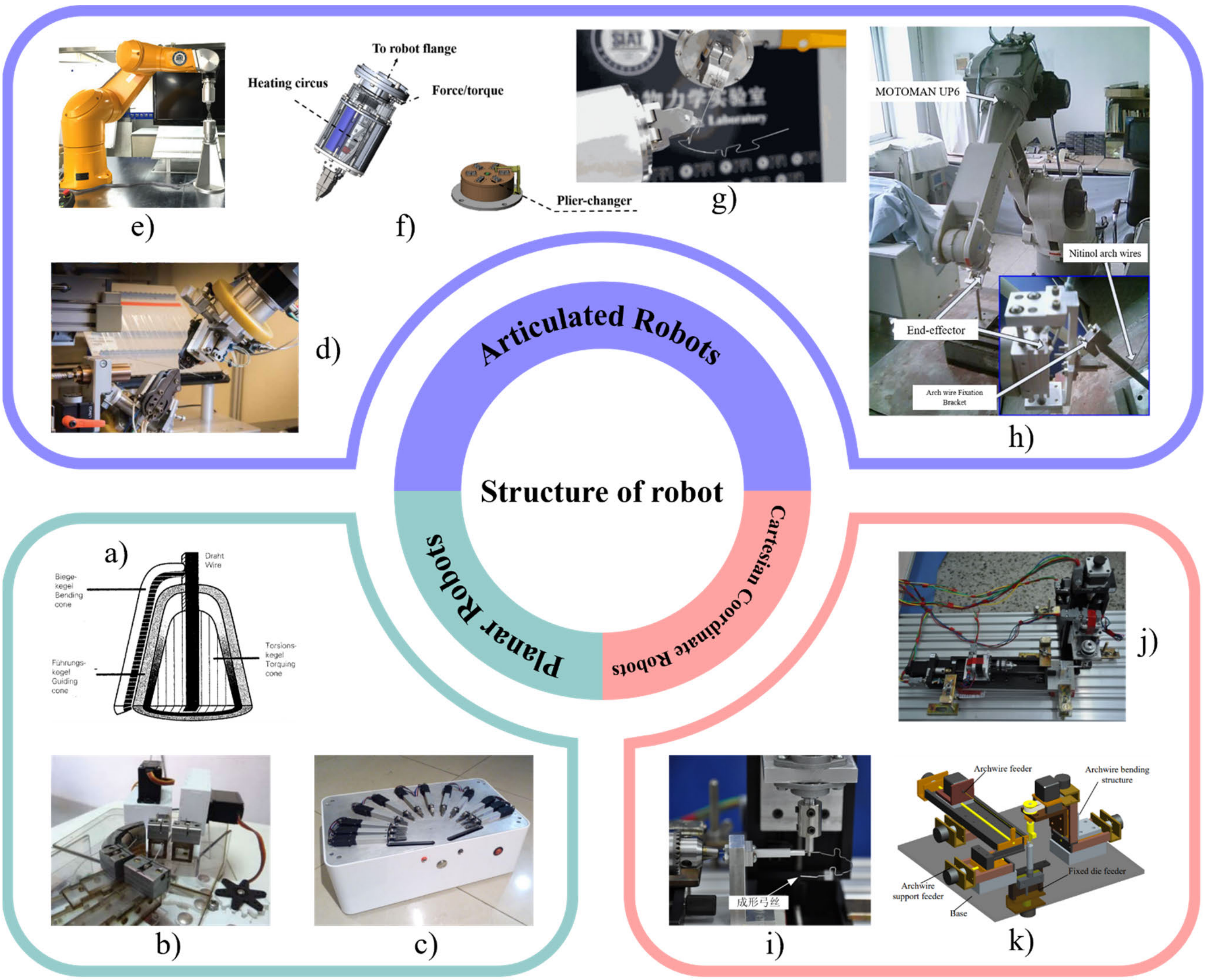

FIGURE 2. Types of orthodontic archwire bending robot structures. a) "BAS" orthodontic archwire bending robot. Reprinted with permission from [36]. Copyright 1996, Springer. b) "LAMDA" orthodontic archwire bending robot. Reprinted with permission from [33]. Copyright 2011, JCO. c) "LAMDA2" orthodontic archwire bending robot. Reprinted with permission from [30]. Copyright 2022, Wolters Kluwer. d) "Suresmile" orthodontic archwire bending robot. Reprinted with permission from [31]. Copyright 2016, Bentham. e) An orthodontic archwire bending robot designed by Deng et al. Reprinted with permission from [34]. Copyright 2015, IEEE. f) Robotic end-effector and clamp library for orthodontic archwire bending designed by Xia et al. Reprinted with permission from [40]. Copyright 2016, IEEE. g) Bending process of orthodontic archwire bending robot designed by Xia et al. h) An orthodontic archwire bending robot based on Motoman UP6 designed by Zhang et al. Reprinted with permission from [39]. Copyright 2009, IEEE. i) The bending process of an orthodontic archwire bending robot designed by Zhang et al. j) An orthodontic archwire bending robot designed by Zhang et al. k) An orthodontic archwire bending robot designed by Jiang et al.

archwires with intricate geometrical configurations, enabling the formation of specialized functional curves. However, it is important to note that this robotic system is associated with higher overall costs and occupies a larger volume.

C. CARTESIAN ORTHODONTIC ARCHWIRE BENDING ROBOT

Jiang et al [41]. focused on the use of a Cartesian Coordinate type robot to complete the bending of orthodontic archwires and designed a five-degree-of-freedom orthodontic archwire bending robot using a rectangular structure, as shown in Fig. 2j). The robot mainly consists of a base, an orthodontic archwire feeding mechanism, an orthodontic archwire rotation mechanism, an orthodontic archwire clamping and supporting mechanism, and an orthodontic archwire bending mould [42]. The main body of the robot is a right-angle coordinate type, using the screw nut mechanism as the robot's mobile carrier, the two mobile carriers are equipped with a bow wire clamping and support mechanism and bending mould, bending moulds using a two-finger structure of orthodontic bows to achieve bending around the shape of the bows, the bow wire clamping and support mechanism of the design of a smaller diameter can reduce the bow wire bending process of the interference problem, as well as the bow wire fluttering. The researchers carried out bending experiments of Australian and stainless steel square wires using a robot, and the experimental results showed that the robot was able to achieve the bending of the first sequence of curvature and vertical curvature of the orthodontic archwires. The error range of the orthodontic archwires for each geometrical feature was 4.6%-10.5% as shown in Fig. 2i). Aiming at the problem that the stiffness of the orthodontic archwire is low and prone to slip and warp during the bending process of this robot, Jiang et al. improved its structure and designed an eight-degree-of-freedom robot, in which a support and blocking mechanism was added to improve the stiffness of the orthodontic archwire in the bending process, preventing the archwire from shifting during bending, and completing the dynamics simulation of the whole machine [43], as shown in Fig. 2k).

The main body of the orthodontic archwire bending robot designed by Alfredo Glbert et al. is a gantry-type frame, through which the horizontal movement of the end-effector along the X, Y, and Z axes can be realised, and the archwire clamping mechanism adjacent to the end-effector can realise the fixation and clamping of the archwire, which is driven by the side pulleys to make the archwire realise the rotational movement. A motor connected to the spindle is mounted on the base of the mechanism, which enables the vertical movement of the clamping mechanism with a stroke of 35 mm along the Z-axis direction, and the bending of the orthodontic archwire is realized by the cooperation between the clamping mechanism and the end-effector, and the bending angle of the wires can reach up to 180° [44].

Cartesian coordinate robots possess a straightforward design, exhibit stable movement, and demand less control compared to articulated coordinate robots. However, the trade-off for these advantages is a reduced level of flexibility, as these robots employ a rigid rectangular structure that may not be capable of executing tasks involving intricate curved shapes.

D. OTHER CONFIGURATIONS OF ORTHODONTIC ARCHWIRE BENDING ROBOTS

In addition to the above three cases, researchers have also designed robots using other configurations. Song et al. [47] designed an orthodontic archwire bending device similar to a tube bending device, which mainly consists of a wire feeding device, a bending device, and a cutting device. Wire feeding device has a number of rotating rollers as well as a guiding section, and the horizontal movement of the archwire in the guiding space is realized by the rotation of the rotating rollers. The bending device comprises a fixed portion and a bending portion for clamping and bending orthodontic archwires, respectively, and the bending portion can be rotated in a circumferential direction or moved in one direction to achieve bending of the archwires. The cutting device employs three blades feeding simultaneously from three directions to the center to cut off the orthodontic archwire that has completed bending into shape, which can theoretically achieve continuous bending of the archwire.

According to this section, among the three types of robots, the planar orthodontic archwire bending robots have some limitations in their ability to process orthodontic archwires compared to the other two types, and they appear to be incapable of bending special functional curves. However, compared with the other two types of robots, the planar orthodontic archwire bending robot only needs to carry out the two actions of wire feeding and bending, and does not need to change and adjust the position of the orthodontic archwire, so it has a higher efficiency and precision for the bending of the first sequence of orthodontic archwire curvature. The articulated orthodontic archwire bending robot is more flexible than the other two types and is capable of bending the first sequence of orthodontic archwires and some special functional curves, but this configuration has the disadvantages of redundant degrees of freedom, large size, and high cost. The flexibility and bending capacity of the Cartesian Coordinate Orthodontic Archwire Bending Robot lies between the two, and it is capable of bending the first sequence of orthodontic archwires as well as some of the special function curves. It is clear that the degree of flexibility of the robot is directly proportional to the bending capacity, and the degrees of freedom and the processing capacity of each robot that has performed bending experiments are summarized in Table 1.

The number of degrees of freedom has a direct impact on the robot's processing capacity. In order to mitigate the issue of redundancy in the robot's degrees of freedom while ensuring its processing capabilities, Han et al. [48]. introduced a novel design approach for the robot configuration, employing bionic design principles. This approach aims to determine the necessary degrees of freedom for orthodontists to manually bend orthodontic archwires and different types of special functional curves. The analysis involves iteratively examining each result and combining them to determine the specific type and quantity of degrees of freedom required for the robot to possess optimal processing capabilities. Following this, the primary framework of the robot is devised to consist of the wire bending mechanism and the wire feeding mechanism. The degrees of freedom obtained are then appropriately distributed between the two mechanisms to finalize the design of the robot's structure, in accordance with the mechanism. The method allows for the creation of robot structures that have specific machining capabilities and solves the issue of unnecessary degrees of freedom.

E. MOTION TRAJECTORY PLANNING AND CONTROL OF AN ORTHODONTIC ARCHWIRE BENDING ROBOT

The motion trajectory planning of the orthodontic archwire bending robot is one of the important research contents for the robot to realize orthodontic archwire bending [49]. Haiyan et al. [50] ocused on calculating the precise joint angles needed for the robotic arm to bend the archwire at each designated point.

They ensured these angles wouldn't cause the arm to move outside its designated workspace and used them to plan the optimal path for bending the archwire.

The robotic arm of the orthodontic archwire bending robot system set up by Xia et al. has to undertake four tasks: wire picking, wire releasing, fixation and bending. The researchers established a planner for the orthodontic bowline bending robot based on the RRT fast expanding random tree algorithm and collision detection algorithm, planned multiple collision-free motion paths through random sampling strategy, and solved the optimal paths through cost estimation of the paths, and finally smoothed the paths to achieve the collision-free path planning in the robotic machining process [34].

For the control method of orthodontic archwire bending robot, Zhang et al. concluded that the motion mode of orthodontic archwire bending robot belongs to point-to-point hybrid motion, and the traditional acceleration and deceleration motion control method is not applicable to this mode. To reduce the shock and vibration during the bow wire bending process and improve the bending processing accuracy. A segmented self-adjusting acceleration-deceleration strategy based on a three-segment pure S acceleration-deceleration curve, a five-segment acceleration-deceleration curve, and a modified acceleration-deceleration curve displacement is proposed. By judging the length of the orthodontic archwire feeding distance, different acceleration-deceleration curves were selected to reduce the impact during robot motion and improve the stability of the robot during motion [51].

In order to improve the bending precision of orthodontic archwires, Deng and Liu used force sensors to monitor the reverse force of orthodontic archwires on the bending clamp during the bending process, and judged whether the orthodontic archwire springback was over by detecting the reverse force, and at the same time, detected and compensated the bending angle, so as to realise the precise bending control of orthodontic archwires [52].

Currently, there are fewer studies on the motion trajectory planning and control methods of orthodontic archwire bending robots, and most of the orthodontic archwire bending robots use open-loop control mode to bend orthodontic archwires, which leads to a decrease in the precision of orthodontic archwire shaping, whereas closed-loop control of the robots through the use of various types of sensors can significantly improve the precision of the bending process. In the process of orthodontic bow wire bending, the robot needs to carry out continuous bending action in a narrow space, which may lead to the collision between the orthodontic bow wire and the robot or the entanglement between the orthodontic bow wire and the robot end-effector, thus affecting the bending accuracy of the orthodontic bow wire, which

TABLE 1. Summary of the characteristics of fixed orthodontic processing robots in various type.

Robot Type	Year	Robot Name	Robotic Degrees of Freedom	Processing Capacity	Processing Type	Literature
Flat Type	1996	BAS	3	Bending and twisting of the first sequence of curves	Labial	[36]
	2011	LAMDA	2	Bending of the first sequence of curves	Lingual	[33, 45]
	2012	LAMDA2	2	Bending of the first sequence of curves	Lingual	[30]
Articular Type	2004	Suresmile	6	Bending of the first sequence of curves	Labial	[32, 38, 46]
	-	Ortho-Robot	6	Bending of the first sequence of curves	Labial and Lingual	[32]
	2010	OABR	6	Bending of the first sequence of curves	Labial	[39]
	2014	ROAP	6	Bending of the first sequence of curves, vertical curve and T-shaped curve	Lingual	[40]
Cartesian Coordinate Type	2013	OABR	5	Bending of the first sequence of curves and vertical curve	Labial	[41, 42]

can be avoided by the reasonable robot motion trajectory planning.

The most important parameter for orthodontic archwire bending is the bending angle of the orthodontic archwire. A depth camera can be used to monitor the process of robotic bending of orthodontic archwires, identify the bending angle in real time and judge whether the desired angle is reached, and when the desired angle is not reached, the second bending process is taken to compensate for this, so as to realise the closed-loop control of the robot in orthodontic archwire bending, and to improve the precision of the robot in bending the orthodontic archwires. The robot can be controlled in closed loop to improve the precision of the robot bending orthodontic archwires.

III. METHODS OF PLANNING THE BENDING OF ORTHODONTIC ARCHWIRES

Orthodontic archwire hand bending is a qualitative procedure in which the orthodontist manually bends a specific orthodontic archwire according to the patient's dental structure. The bent archwire is then compared to a teeth model, and necessary adjustments are made to the orthodontic archwire. The qualitative bending approach is appropriate for manual bending, but not for robotic applications. Consequently, the process of using robots to bend orthodontic archwires necessitates precise design of the desired orthodontic archwires. In the present study, researchers have employed various quantitative techniques to plan the target orthodontic archwires. This paper categorizes the different planning methods based on whether a model is used or not, and further divides them into two categories: modeless planning and modeled planning, as illustrated in Fig 3. This section will present the concepts of each method type and the characteristics.

A. MODELESS PLANNING METHODS OF ORTHODONTIC ARCHWIRES

The primary distinction between modeless planning approaches and modeling planning methods lies in the fact that modeless planning necessitates the prior establishment of a well-founded model of the target orthodontic archwires, which is then followed by the planning of the position of robotic bending points. This subsection presents the modeling techniques for several modeless planning approaches and the planning of the position of robotic bending points.

A acceptable orthodontic archwire model should have the shape of a healthy arch to allow the teeth to be moved into a reasonable position. In previous studies, many scholars proposed mathematical models of dental arch morphology to facilitate orthodontic treatment of teeth, using hanging chain curves [53], [54], [55], polynomials [55], [56], [57], [58], Beta functions [58], [59], spline curves [60], [61], Fourier series [62], power functions [58], and elliptic equations [54] to express the shape of the human dental arch. Asian dental arch morphology is better in line with the power function model, as Zhang et al.'s research revealed [63], [64]. Afterwards, Haiyan et al. [50]. employed a power function to model orthodontic archwires, adjusting the model's size based on the breadth and length of the arch to accommodate a range of mouth shapes. In order to plan the model's bending points, the researchers divided the model into multiple parts using the stationary points associated with the function's monotonicity, the inflection points associated with the graph's concave direction, and the points where the first-order derivatives do not exist as the demarcation points. They then determined the locations of the bending points in each part and, using the maximum amount of spacing in the y-axis direction as a criterion, determined the positions of the robot's bending points in accordance with the precision required for orthodontic archwires.

Zhang and Jiang [65]. proposed a segmented power function model with canine and molar abduction curves based on the power function model. Straight line segments were used to model the canine and molar teeth, while the other parts separated by the two were still modeled using a power function, as shown in Fig 3a) and 3b). Fig 3c) and 3d) show two potential bending point planning techniques for this model: the incremental method and the finite point spreading method. The incremental technique divides the archwire model into numerous equal divisions in the x-axis direction, connects the equal points, utilizes strings instead of arc segments, and checks the longitudinal axis error values to see if correctness is attained [66], [67]. The finite point spreading approach locates the bending point by bending it between a finite number of key points. The start and end points of canine and molar abduction bends were used as key points, and the key points were connected using chords rather than arc segments, and the difference between the area enclosed by the chord and the arc was used to determine whether accuracy was achieved [51], [68], [69]. The researchers then compared the incremental technique to the finite point spreading method, concluding that the latter beats the former in terms of search efficiency and algorithmic time consumption [70].

Zhang and Jiang et al. advocated employing marker points to create a more accurate orthodontic archwire model. Using both sides of the orthodontic bracket grooves as marking points (Fig. 3e), a mathematical model of the orthodontic archwire was built using Bezier curves with straight line segments (Figs. 3f) and 3g). At the same time, mathematical models for some of the special functional curves, as well as an interaction model between the special functional curves and the position of the orthodontic archwire, were created [68], [71], [72]. The researchers also apply the concept of a finite point spreading approach in the bending point search algorithm of this model, with the search region being each Bezier curve section [73].

This method involves mathematically modeling the idealized orthodontic archwire and then using a search algorithm to discover the placement of the bending points. The method can achieve automatic planning through computer programming and calculations to improve efficiency, but it is important to determine whether the mathematical model of

TABLE 2. Orthodontic archwire modeling summary.

Year	Research worker	Model	Influencing factors considered	Literature number
2010	Du	$y=\alpha x^{\beta}$	Modeling orthodontic archwires according to the shape of the dental arch	[50]
2011	Zhang	$\begin{cases} y=\alpha_1\cdot x^{\beta_1} & x\in[0,x_1] \\ y=\alpha_2\cdot x^{\beta_2} & x\in[x_2,x_3] \\ y=\alpha_3\cdot x^{\beta_3} & x\in[x_4,x_5] \\ y=y_2+\frac{(y_3-y_2)(x-x_2)}{(x_3-x_2)} & x\in[x_1,x_2] \\ y=y_3+\frac{(y_4-y_3)(x-x_3)}{(x_4-x_3)} & x\in[x_3,x_4] \end{cases}$	The special shape of the position of the canines and molars in the orthodontic archwire is taken into account	[65]
2017	Zhang and Jiang	$\begin{cases} P(t)=P_0(1-t)^3+3P_1(1-t)^2+3P_2t^2(1-t)+P_3t^3 \\ \frac{x-x_1}{x_2-x_1}=\frac{y-y_1}{y_2-y_1}=\frac{z-z_1}{z_2-z_1} \\ \frac{x-x_3}{x_4-x_3}=\frac{y-y_3}{y_4-y_3}=\frac{z-z_3}{z_4-z_3} \end{cases}$	Complex cases of malocclusion and three-dimensional modeling of orthodontic archwires were considered	[71-73]

the orthodontic archwires created is standard and accurate, as well as whether the characteristics of the current orthodontic archwire models are summarized in Table 2.

B. MODEL PLANNING METHODS OF ORTHODONTIC ARCHWIRES

This study categorizes the techniques for planning orthodontic arch wire bending using virtual and solid models into model planning approaches. The following section provides an overview of the many types of model planning methods.

Deng et al. [34], [40] used software to design the final shape of the orthodontic archwire (see Fig. 3h). They created a virtual model and treated the archwire as a series of connected straight segments (Fig. 3i). Each segment's endpoint became a bend point, where the actual bending would begin. By analyzing these segments and the desired final shape, they determined the direction and angle of each bend, enabling precise planning of the archwire as shown in Fig. 3j.

Furthermore, certain researchers have employed tangible models of orthodontic archwires to strategize the manipulation of orthodontic archwires by means of an image recognition technique, in addition to the aforementioned virtual modeling approaches. He and his colleagues employed a single pair of cameras to record photos of orthodontic archwires. They then utilized the Otsu threshold segmentation and flood fill approach to extract the arch contours from the images. Subsequently, they employed corner detection on the derived contours to determine the precise positions of all bending points. Afterwards, the slope-based corner filtering method is applied to all the acquired bending points in order to extract the useful bending points.

Subsequently, the bending parameters, such as the bending angle, are calculated based on these useful bending points to finalize the bending planning [35]. This process is illustrated in Fig 3k) and 3l). Chen et al. introduced a method for selecting the bending point of an archwire using contour localization and binocular vision. The process involves correcting the stereo image, identifying the orthodontic archwire skeleton, and extracting the bending point using a multilayer contour detection method [74]. This can be seen in Fig 3m) and 3n).

The model planning approach relies on the obtained target model, which exhibits superior accuracy in comparison to the modeless planning method. However, the process of acquiring a virtual or physical model of the target orthodontic archwire is a crucial matter that requires investigation. Utilizing software for virtual orthodontic treatment planning and generating virtual models of orthodontic archwires is a viable method. However, it is crucial to investigate how to assess the rationality of the planned orthodontic pathways and the effectiveness of the resulting orthodontic archwire models for successful treatment. In regards to the modeless planning method, constructing a precise model is a necessary requirement for logical planning. Inadequate planning of orthodontic archwire bending can result in interference, collisions, and other issues during the bending process. This directly impacts the accuracy of the orthodontic archwires and reduces the efficiency of the robot. Therefore, enhancing the rationality of the planning of orthodontic archwire bending and improving the accuracy of the orthodontic archwire model are crucial aspects in the advancement of the orthodontic archwire bending robotic system.

IV. ORTHODONTIC ARCHWIRE BENDING SPRINGBACK COMPENSATION METHOD

During the process of bending orthodontic archwires, the archwire contains both elastic and plastic deformation

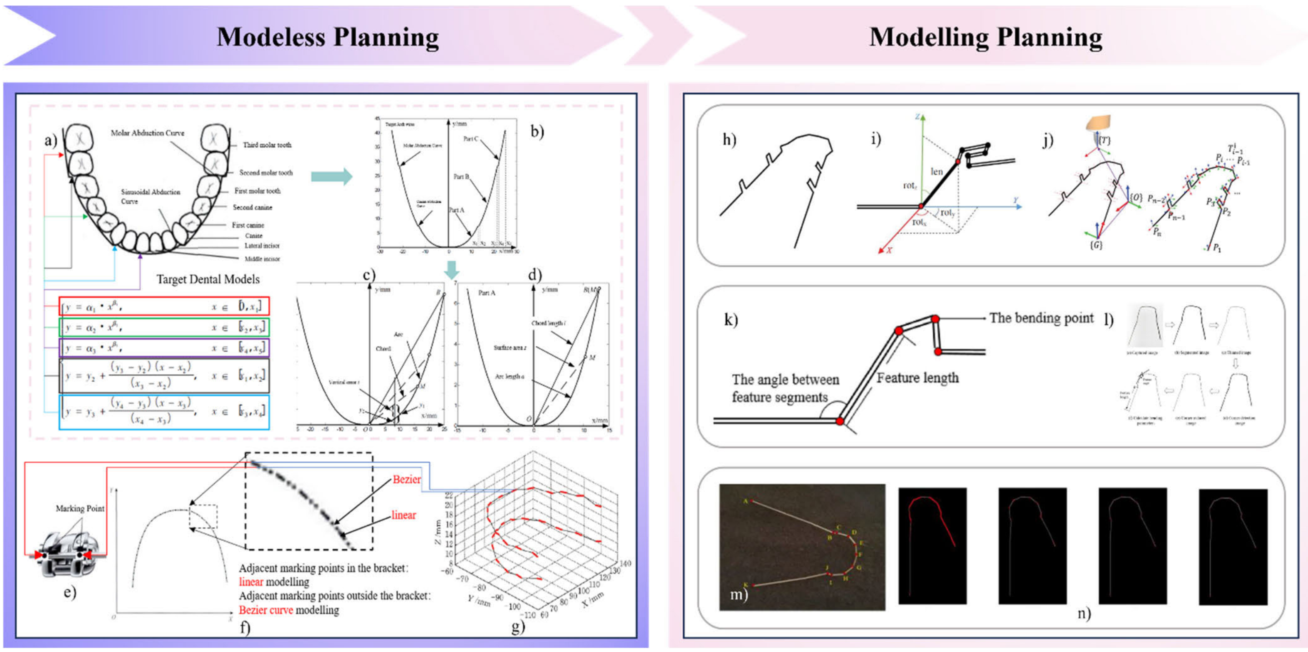

FIGURE 3. Planning of orthodontic archwire bending. a) Segmental power function modelling process for orthodontic archwires proposed by Zhang et al. b) Segmental power function modelling of orthodontic archwires. c) An incremental approach to planning orthodontic archwire bending. d) Planning of orthodontic archwire bending by the finite point spreading method. e) Orthodontic archwire modelling marking points. f) An orthodontic archwire segmentation model based on marker points. g) Orthodontic archwire effect model. h) Virtual model of target orthodontic archwires by Deng et al. Reprinted with permission from [34]. Copyright 2015, IEEE. i) Principles of orthodontic archwire bending point planning by Deng et al. Reprinted with permission from [34]. Copyright 2015, IEEE. j) Modelling planning for lingual orthodontic archwire realization by Deng et al. Reprinted with permission from [34]. Copyright 2015, IEEE. k) Orthodontic archwire bending point selection principles and bending distance, bending angle calculation methods by He et al. Reprinted with permission from [35]. Copyright 2018, IEEE. l) Planning of bending points for orthodontic archwires using image extraction by He et al. Reprinted with permission from [35]. Copyright 2018, IEEE. m) Solid model of target orthodontic archwires with bending point extraction results by Chen et al. Reprinted with permission from [74]. Copyright 2022, IEEE. n) Target orthodontic archwire bending points by Chen et al. Reprinted with permission from [74]. Copyright 2022, IEEE.

regions [75]. When the bending force is removed, the elastic deformation region will return to its original shape. This phenomenon is known as the springback phenomenon of orthodontic archwires [76]. The springback effect of the archwire directly results in the inability of the bent archwire to achieve the desired geometric shape, rendering it ineffective for orthodontic treatment. Additionally, this may cause the archwire to interfere or collide with the clamp during the bending process, thereby compromising the accuracy of the final shape. In order to achieve precise shaping of orthodontic archwires, numerous researchers have conducted extensive studies on the issue of archwire springback. They primarily employ experimental methods to comprehend the mechanical properties of various materials, analyze various influencing factors, and compensate for the bending process, all with the aim of achieving accurate shaping. This research specifically examines studies pertaining to the management of archwire springback in the two primary types of archwires used in orthodontic treat: stainless steel archwires and nickel-titanium alloy archwires [77].

A. STAINLESS STEEL ARCHWIRE SPRINGBACK COMPENSATION STUDY FOR WIRE BENDING

Several factors influence the angle at which the stainless steel archwire springback during the bending operation. The latest research indicates that the primary parameters that have an impact are the curvature's bending radius [78], [79], the bending angle [80], [81], [82], the location of the neutral layer [67], [83], and the wire diameter's dimensions [79]. This portion presents a comprehensive analysis of pertinent studies investigating the elements influencing stainless steel bow wires and the methods for making compensation.

Turke, K.S. et al. conducted a study on the springback properties of circular cross-section archwires. The experimental findings revealed a correlation between the amount of archwire springback and torque. Specifically, higher torque resulted in a decrease in archwire springback, while a larger radius of the bending curvature led to an increase in spring back [78].

Zhang et al. employed MSC. Marc finite element analysis software to examine the flexural properties of four different types of archwires: nickel-titanium alloy, β-titanium alloy, Australian stainless steel, and domestically produced stainless steel. The findings revealed a sequential decrease in archwire springback among the four orthodontic arch wires, with the angle of archwire springback increasing proportionally to the bending angle [80]. The researchers conducted theoretical calculations, finite element analyses, and bending tests on circular Nitinol archwires, square stainless steel archwires, and circular Australian stainless steel archwires.

They applied the theory of large deformations and found that the archwire springback angle increases as the bending angle increases [81], [82].

Jiang et al. conducted a study to address the issue of the orthodontic archwire springback and its impact on the accuracy of the archwire formation. They analyzed the springback characteristics of Australian stainless steel archwire and considered the displacement of the neutral layer and the bending force arm during the bending process. Based on their analysis, they developed a theoretical model for the springback of the Australian stainless steel archwire. To validate their model, they conducted experiments using a wire bending robot. The results showed that their model achieved an error rate of less than 15% for all item parameters of orthodontic archwires [83]. The researchers also examined how the movement of the stress-strain neutral layer of the orthodontic archwire during bending affects the springback of the archwire. They proposed a model for calculating the springback of orthodontic archwires with rectangular cross-section. To verify the model, they used a bending robot for bending and found that the errors in the parameters of the archwire were reduced from 22.46% and 10.23% to 11.35% and 6.13%. The improved accuracy of the model was significant [84]. The researchers analyzed the impact of two specific situations that occur in the archwire during the bending process, taking into account the robot's structural characteristics. They developed a model to explain how the stainless steel square archwire springback when it experiences slip and warp. Through experimentation, they confirmed that considering the effects of slip and warp can enhance the precision of archwire bending [85].

Kono and Kikuchi [79]. conducted a study to determine the theoretical bending angle and the actual forming angle of stainless steel and cobalt-chromium alloy archwires. They also developed a model to compensate for the springback of the archwire, considering factors such as the wire diameter and the bending radius of curvature. Deng et al. introduced a technique for compensating for rebound in the use of model prediction. This method involves detecting the springback state of the archwire while simultaneously using force sensors to measure the force on the pincer. When the force reaches zero, it indicates the end of the archwire rebound. The technique then determines whether the current forming angle meets the standard. If it does not, the archwire is bent further until the forming angle reaches the desired standard. This approach effectively controls the error of the special function curves within a range of ± 1mm [52], [86].

To address the issue of archwire springback in stainless steel, the primary approach is to employ a model that can forecast the angle of springback. This model takes into account the angle of bending to ensure precise angular forming. The accuracy of the model relies heavily on the modeling process, which considers various factors that influence springback. Table 3 provides a summary of the current models used for springback compensation, taking into account the factors and the associated error.

B. STUDY ON SPRINGBACK COMPENSATION IN HEAT TREATMENT OF Ni-Ti ALLOY ARCHWIRES

In orthodontics, Nitinol most widely usable material for archwires due to its exceptional resistance to corrosion and remarkable super-elasticity. The exceptional elasticity of Nitinol renders it highly resistant to deformation through cold bending. Attempting to bend the Nitinol archwire through cold bending may lead to the deterioration of its mechanical properties. However, Nitinol, being a memory alloy, can be shaped through the application of heat treatment [87], [88]. During the transition from the previous century to the current one, numerous scholars conducted experimental research on the impact of heat treatment on the mechanical characteristics of Ni-Ti alloy bow wires. The findings indicate that bending Ni-Ti alloy bow wires during heat treatment can permanently alter their shape without significantly impacting their super elasticity [89], [90], [91], [92], [93], [94], [95], [96], [97], [98]. This article presents a comprehensive overview of the existing techniques used for heat treatment of nickel-titanium alloy bow wires. It also outlines the merits and drawbacks associated with each method.

The initial heat treatment and shaping of nickel-titanium orthodontic archwires were conducted using either melting furnaces [99] or vacuum furnaces [100]. These furnaces have

TABLE 3. Summary of a study on rebound compensation modeling for orthodontic archwire bending.

Year	Research worker	Material properties applicable to the model	Influencing factors considered	Model error	Literature number
2015	Jiang	Australian stainless steel wire with a cross-section diameter of 0.38mm	Neutral layer movement and bending force arm length	Less than 15 %	[83]
2016	Deng	0.017*0.022inch stainless steel bow wire	-	5%	[52, 86]
2017	Jiang	0.44*0.54mm Stainless Steel Square Wire	Neutral layer shifts in stress and strain	6.13%-11.35%	[84]
2018	Jiang	0.16*0.16inch stainless steel square wire	Two special cases of slip and warp	-	[85]

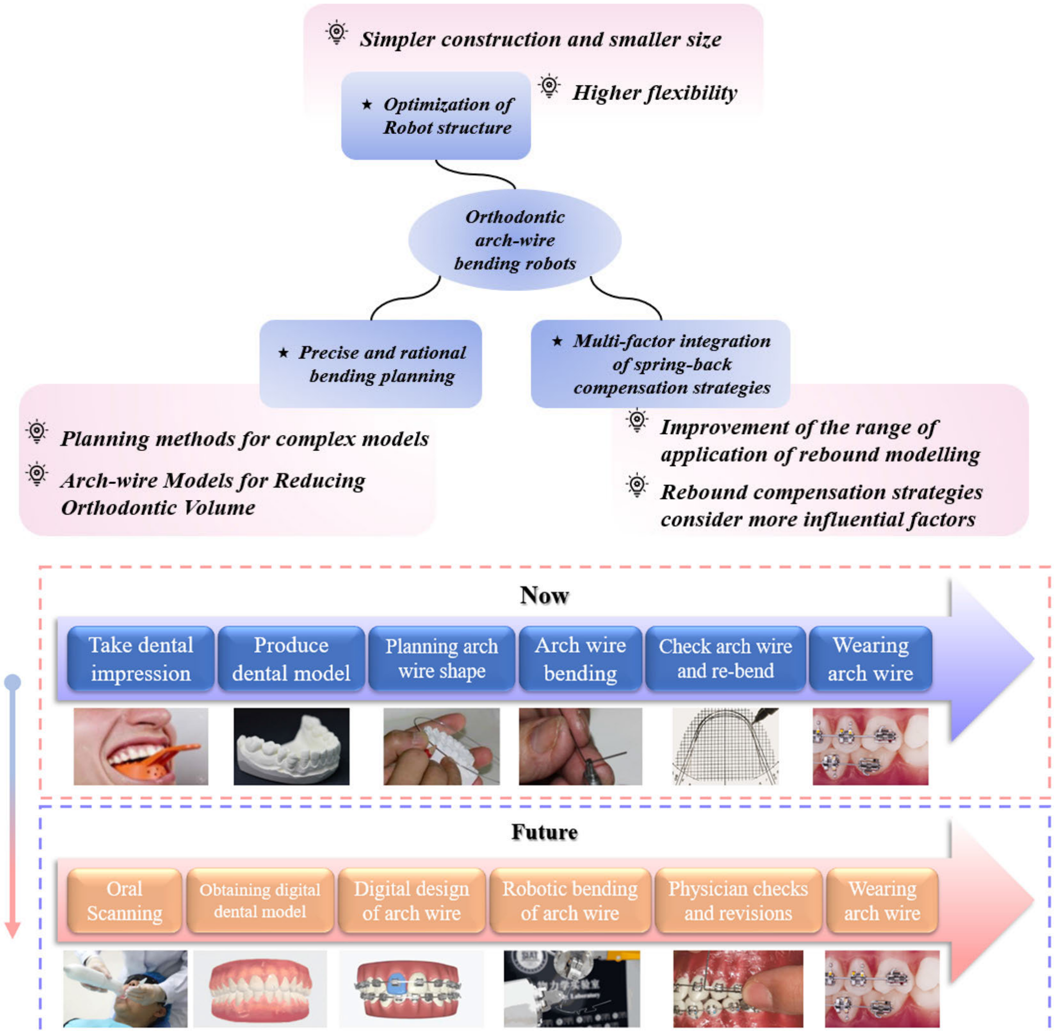

FIGURE 4. Future trends of orthodontic archwire bending robotic system and comparison of traditional orthodontic treatment process and robot-assisted orthodontic treatment process.

the capability to heat the archwires as a whole unit, but they lack precise temperature control. Therefore, Miura et al. introduced a heat treatment technique called the direct resistance heat treatment method (DERHT) for Ni-Ti alloy bow wires. This technique employs pliers to secure the bow wire segments that need to be heated. These segments are then electrified to create the desired heating and shape. Additionally, scientists have discovered that reducing the diameter of the archwire decreases the amount of electric current needed to permanently shape it. This method does not impact the mechanical characteristics of the archwire. Furthermore, heating and shaping specific segments of the archwire leads to the best hyper-elasticity of the orthodontic archwire on each individual tooth [101].

TOMY has enhanced the safety protocols of the DERHT process by incorporating a control panel that allows for precise adjustment of current intensity and heat levels, in addition to integrating necessary sensors. While operating the equipment, the machine delivers an electric current to the bow wire in order to perform heat treatment. This occurs only when the two pliers securely grip the bow wire and position it on top of the sensors. Additionally, it is possible to control the activation and deactivation of the current using a foot pedal [102], [103].

In order to understand the practicality of heating Nitinol orthodontic archwires, Yufeng et al. [104], [105]. conducted numerous tests to measure the temperatures achieved by various archwire models at varying levels of electric current. They then established the current-temperature relationships for each archwire model. The control circuit in this approach has the capability to autonomously establish the duration of the heat treatment after the archwire model is determined, and subsequently terminate the power supply upon completion. Xia et al [106].'s method enables real-time temperature detection and feedback during the archwire heating process. It adjusts the output current value based on the feedback information to regulate the archwire's heating temperature. This establishes a closed-loop control network for precise control of archwire heating.

All of the aforementioned techniques are heating mechanisms and approaches that operate autonomously from the robotic system. The "Suresmile" and "LAMDA" robotic systems both include an orthodontic archwire heating device that can heat and shape the wires while they are being bent by the robots. The "LAMDA" robotic system has the ability to elevate the temperature of Ni-Ti archwires to 600°F for a specific duration, enabling them to be flexed without compromising their internal metallic structure [31], [45].

Currently, the research on heat treatment and shaping of Ni-Ti alloy archwire primarily emphasizes the safety and convenience of processing. However, the author argues that while safety remains a priority, the focus should shift towards controlling the processing temperature. This control is necessary to ensure the proper shaping of the Ni-Ti alloy archwire while also maintaining its desired elasticity. By achieving this, the bent orthodontic archwire can effectively provide the necessary elasticity for orthopedic treatment, ultimately improving the efficiency of the treatment process.

V. CONCLUSION AND FUTURE TRENDS

To address the issues of strong personalization of orthodontic archwires and high forming accuracy requirements, the design of an orthodontic archwire bending robot, planning of orthodontic archwire bending, and compensation of orthodontic archwire springback were carried out in order to inhibit the bending archwire springback of orthodontic archwires and obtain orthodontic archwires with high forming precision. This paper discusses the research and development process of orthodontic archwire bending robotic systems. It also introduces the structure types of orthodontic archwire bending robots, orthodontic archwire bending planning, and the current state of research on orthodontic archwire springback compensation methods.

Researchers have dedicated significant effort to studying orthodontic archwire-bending robots, leading to advancements in intelligent orthodontics and notable progress. Several challenging processing capabilities have been effectively accomplished, including the capacity to manipulate intricate geometries, such as T-shaped curves, and the ability to limit the mistake in orthodontic archwire springback to within 5 percent after bending. After conducting a thorough analysis of existing research findings, we have discussed and evaluated the future development direction and challenges of the orthodontic archwire bending robotic system. Based on this, we have identified several areas for future in-depth research, as depicted in Fig 4. These research ideas offer potential avenues for further advancing the orthodontic archwire bending robotic system. Additionally, we have compared the traditional orthodontic treatment process with the robot-assisted orthodontic treatment process and envisioned the future of robot-assisted treatment.

A. STRUCTURAL OPTIMIZATION OF AN ORTHODONTIC ARCHWIRE BENDING ROBOT

The central component of the orthodontic archwire bending system is the robot itself, responsible for manipulating the wires. This paper classifies these robots into three main types based on their design: planar, articulated, and Cartesian coordinate. Each type is built differently and offers unique capabilities. For example, planar robots boast a simple design, small size, and impressive agility. However, their tool (end-effector) is limited to movement within a single plane, hindering their flexibility and making complex bending tasks challenging. In contrast, robots built around a 6-degree-of-freedom articulated arm offer much greater flexibility. This increased flexibility enhances the robot's processing abilities and helps prevent interference during the bending process. Optimizing robot structure remains a critical area of research in orthodontic archwire bending robots.

B. ACCURATE AND RATIONAL BENDING PLANNING

Both modeless and modeled planning methods for designing orthodontic archwire bends have drawbacks. Modeless methods often rely on templates based on "ideal" arches, which may not be suitable for every patient. Research into creating personalized archwires with minimal treatment time is a promising area. Current planning methods primarily focus on the initial stages of treatment. However, there's a need for more sophisticated methods that can handle wires with unique bends and complex shapes. Improving the logic and accuracy of the planning process is essential for efficient and precise robotic bending. Ultimately, the goal is to develop planning methods that are universal and applicable to a wider range of patients.

C. MULTI-FACTOR INTEGRATION OF SPRINGBACK COMPENSATION STRATEGIES

Prior studies have examined the elements that affect bending rebound and have sought to build a rebound compensation model based on the rebound mechanism. However, the majority of these studies have focused on a single-factor model. The factors that influence bending rebound are intricate and intricate. To enhance the precision of the model's prediction, it is necessary to integrate multiple factors and establish a rebound compensation model that takes into account various influencing aspects. This will not only improve the accuracy of the model's predictions but also expand its applicability. Investigating the variables influencing rebound will be a crucial area of study. Previous research has explored factors affecting bending rebound and attempted to create compensation models based on the rebound mechanism. However, most studies have focused on models considering only one factor at a time. In reality, bending rebound is influenced by a complex interplay of factors. To improve the accuracy of these models, we need to consider multiple factors simultaneously. Building a multi-factorial rebound compensation model would not only enhance prediction accuracy but also broaden its applicability to a wider range of scenarios. Investigating the variables that influence rebound remains a crucial area of future research.

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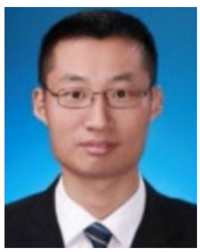
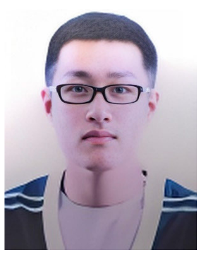
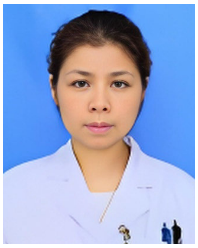
HAN LIU was born in Heilongjiang, China, in 1999. He received the B.Sc. degree in mechatronic engineering from Harbin University of Science and Technology, Harbin, Heilongjiang, in 2022, where he is currently pursuing the M.S. degree in mechatronic engineering. His research interests include medical robots, minimally invasive interventional robots, and dental robots.



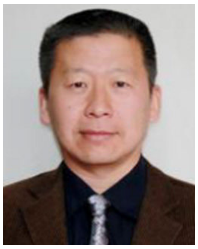
JINGANG JIANG (Senior Member, IEEE) received the B.Sc., M.Sc., and Ph.D. degrees from Harbin University of Science and Technology, in 2005, 2008, and 2013, respectively. Currently, he is a Professor and a Doctoral Supervisor with Harbin University of Science and Technology. His main research interests include medical robots and biomimetic robots.



JINGCHAO WANG was born in Harbin, China, in 1993. He received the B.Sc. and M.Sc. degrees in stomatology from Harbin Medical University, in 2016 and 2020, respectively. He interned at The First Affiliated Hospital of Harbin Medical University, from 2013 to 2016. From 2017 to 2020, he studied at the Department of Orthodontics, The Second Affiliated Hospital of Harbin Medical University, and engaged in research on invisible orthodontics without brackets. His current research interest includes orthodontic biomechanics.



SHAN ZHOU was born in Heilongjiang, China, in 1973. She received the bachelor's, M.Sc., and Ph.D. degrees in stomatology from Harbin Medical University, in 1996, 2004, and 2012, respectively. From 2009 to 2012, she was the Deputy Director of the Orthodontics Department, The Second Affiliated Hospital of Harbin Medical University. She has been the Director of the Orthodontics Department, since 2012, where she was promoted as a Professor, in 2019, and a Doctoral Supervisor, in 2022. Her current research interests include orthodontic tooth movement and orthodontic biomechanics



YONGDE ZHANG (Member, IEEE) was born in Jilin, China, in 1965. He received the B.S. degree in mechanical engineering and the M.S. and Ph.D. degrees in mechanical engineering from Harbin Institute of Technology, Harbin, Heilongjiang, China, in 1988, 1993, and 1999, respectively. From 1999 to 2001, he was an Associate Researcher with the Automation Research Center, City University of Hong Kong. In 2004, he was a Researcher with the Computer-Assisted Interventional Medicine Laboratory, Nanyang Technological University, Singapore. From 2004 to 2006, he was a Visiting Scholar with the University of Rochester Medical Center. Since 2007, he has been a Professor and a Doctoral Supervisor with the School of Mechanical Power Engineering and Robotics and the Engineering Research Center, Harbin University of Science and Technology. His current research interests include medical robots, education robots, and biomimetics.

SINAN LIU was born in Qiqihar, Heilongjiang, China, in 1997. He received the B.S. and M.S. degrees in mechatronics engineering from Harbin Institute of Technology, Harbin, China, in 2015 and 2023, respectively. His research interests include medical robotics, puncture robotics, and dental robotics.