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OriBot: a novel origami robot creation system to support children's STEAM learning

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Abstract
Origami robots, as novel educational tools and toys, have substantial potential for broad application in children's education. Despite the recent advent of computational origami in the realms of human-computer interaction (HCI) and digital fabrication, children find it challenging to implement design and fabrication processes that leverage computational origami theory. Recognizing this challenge, we developed OriBot—an innovative system for creating origami robots, designed specifically for children aged 5 to 8. This comprehensive system comprises a hardware toolkit and a child-friendly software platform. The software is engineered to guide children through the processes of designing, fabricating, and operating origami robots. We evaluated the efficacy and user experience of the OriBot system by testing it with a sample group of 68 children. The results demonstrated that OriBot effectively facilitates children in the creation of origami robots, augmenting their understanding of robotics. Furthermore, it fosters positive interactions between children and robots while enhancing their engagement and interest in the activity all throughout.

Keywords Origami robot · Children education · STEAM · Robot creation

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1 Introduction

Origami robots, also known as "foldable robots," represent a unique type of robot, primarily designed following the principles of origami art, capable of self-transformation and movement through the mechanisms of folding and unfolding. These robots display high flexibility, robust expandability, cost-efficiency, and a marked level of innovation [1]. Origami robots exemplify a unique interdisciplinary integration of Science, Technology, Engineering, Art, and Mathematics (STEAM). Prior research has indicated that the process of creating origami robots positively impacts the enhancement of children's cognitive abilities, fosters problem-solving skills, and promotes STEAM education [2]. For instance, in the process of creation, children are required to design origami shapes and grasp the functionalities and interrelationships of various components of the robots, thereby augmenting their spatial imagination and logical reasoning skills [3]. Moreover, the design and application scenarios in robot creation can encourage problem-solving, with creativity being stimulated through alterations in design or coding of robots [4, 5].

Despite these educational benefits, the fabrication of origami robots presents several challenges for children. For children in kindergarten to primary school, who are just beginning to understand complex instructions and express their ideas logically but lack a sophisticated conceptualization of computational objects [6, 7], these challenges, along with the cognitive pressure involved, can be formidable. Through a formative investigation involving target children and experts, we identified three core challenges faced by children in the process of creating origami robots: (1) the difficulty of creating origami shapes, (2) the complexity of electronic functions, and (3) the uncertainty in the robot creation process.

To address these challenges, we developed OriBot, a comprehensive system for origami robot creation aimed at children aged 5–8. The system includes a hardware toolkit and software application based on a tablet device. OriBot provides folding guidance for origami shapes, a library of robot roles and customizable functions, and a voice assistant to guide the creative process. We evaluated the efficacy of OriBot through a controlled experiment involving 68 children. The results suggest that OriBot substantially improved the integrity fluency, and expert ratings of the robots, augmented robot knowledge, and increased engagement in the robot fabrication process. However, no significant difference in the level of creativity was observed between the experimental and control groups. Qualitative research indicated similar creative details among both groups in the robot-making process, including organ features, emotions, appearance, and movements. The voice assistant fostered positive child-robot interaction, and OriBot amplified children's confidence and interest in creating origami robots.

This paper primarily contributes through: (1) a formative survey involving children and experts, highlighting how origami robot creation tools can mitigate challenges faced by children in robot creation, and (2) the development and validation of the OriBot system through quantitative and qualitative user research, demonstrating its effectiveness in facilitating children's performance and outcomes in origami robot creation.

The structure of this paper is organized into nine key sections. Section 2 reviews existing research on the educational benefits of origami robots and the challenges faced by children. Section 3 describes the formative study conducted with children and experts to identify key challenges in origami robot creation. Section 4 introduces the OriBot system, detailing its hardware toolkit, software application, and voice assistant. Section 5 outlines the hypotheses guiding our evaluation of OriBot's effectiveness. Section 6 explains the experimental setup and methodology used to assess this efficacy. Section 7 presents the experimental findings through quantitative and qualitative data. Section 8 interprets these results, discussing their implications and suggesting areas for future research. Finally, Sect. 9 summarizes the main contributions of the study and underscores the impact of the OriBot system on children's STEAM learning.

2 Related work

2.1 Exploiting origami robots in child education

Origami robots combine the art of origami with robotics principles, enabling functionalities such as self-folding, self-assembly, and locomotion. These features can improve children's creative cognition and problem-solving skills [8], offering a novel approach for augmenting their cognitive development. Previous research has explored the use of origami in STEAM education, emphasizing its educational benefits [9–12]. Burleson clarified the educational potential of origami to improve spatial visualization, a crucial skill in STEAM education [13]. This study suggested that origami can spark imagination and creativity in children while integrating engineering and mathematical concepts. Aghnia et al. [14] indicated that origami-based game activities could improve children's fine motor skills. Similarly, Afrianti et al. [15] demonstrated that origami structures could enhance students' logical reasoning abilities. Scholars from various disciplines, including psychology, pedagogy, and artificial intelligence, have advocated incorporating robotics into early childhood education [16]. Bers et al. emphasized that digital manipulative tools like programmable blocks and robot kits can make learning an enjoyable experience for children [17]. Their findings showed that these tools can significantly improve a range of cognitive skills, including critical thinking, problem-solving, spatial perception, and logical reasoning. Sony's toio creative robot kit, particularly the "Gesundroid working creatures" theme, exemplifies a biomechanical learning kit with advanced design blueprints and programming technology. In this context, origami robots gain capabilities to "run" and "jump," transforming themselves into dynamic "playmates" for children [18]. While research confirms the educational potential of origami robots, challenges persist, such as the complexity of fabricating these robots, which may pose difficulties for younger children.

2.2 Employing origami robot kits in STEAM education

STEAM education, which amalgamates Science, Technology, Engineering, Arts, and Mathematics, is increasingly popular. Origami robots, which achieve form and functionality through controlled folding [19], integrate materials and machinery through the strategic design of geometric fold lines [20, 21]. These robots serve as valuable educational toys and instructional aids in STEAM education [22–24]. They help students comprehend scientific principles such as the equilibrium of forces and the laws of motion [25, 26], and they impart fundamental technical skills, including programming and mechanical design [25, 26]. By their nature, origami robot kits are powerful interdisciplinary teaching tools [27]. Their use requires integrating knowledge from multiple domains such as science, technology, engineering, arts, and mathematics [28]. The iterative process inherent in working with origami robot kits fosters innovation, critical thinking, and problem-solving skills [29]. The challenges encountered during the design and construction of robots motivate students to persist and refine their solutions to achieve their design objectives [30]. Despite the proven effectiveness of origami robot kits in STEAM education, several limitations remain. These include technical demands on educators, the need for sophisticated school equipment [31], and issues related to instructional time management and student engagement [32]. In sum, while origami robot kits are effective tools for learning and innovation within STEAM education, further research is necessary to address the challenges that may hinder optimal instructional outcomes.

2.3 Child-robot interaction

Child-robot interaction is becoming a significant area within robotic research [33], differing from adult-robot interaction due to children's unique cognitive developmental stages [34]. Extensive research on human-machine interaction has revealed that children display social behaviors such as mutual gaze, emotional mirroring, assistive behavior, turn-taking, and information sharing [35]. Studies by Tanaka and Matsuzoe [36] and Tozadore [29] involved integrating educational robots in classrooms to assess their impact on the learning process. Their findings indicated improvements in learning behaviors and increased interest in subjects when children interacted with robots. Studies by Kennedy, Baxter, and Belpaeme [37–39] found that the social behaviors exhibited by robots significantly influenced children's learning outcomes and engagement levels. When robots displayed human-like behavior, children's active participation and effective learning were notably enhanced [40–42]. A study by Belpaeme et al. [43] on long-term child-robot interaction introduced a social-assistant robot into a classroom for two months, significantly improving children's academic performance, particularly in mathematics and literacy [43, 44]. Based on these findings, this study emphasizes the importance of user-friendly, easy-to-operate, and customizable origami robots to ensure a positive and educational interactive experience, thereby enhancing children's engagement in constructing origami robots.

2.4 STEAM learning, STEAM education and children development

In recent years, integrating STEAM education into early childhood learning has garnered significant attention due to its comprehensive developmental potential [45]. STEAM education emphasizes interdisciplinary approaches, encouraging children to develop critical thinking, creativity, and problem-solving skills from a young age [46]. By interweaving science, technology, engineering, arts, and mathematics, STEAM learning transcends traditional educational methodologies, thereby providing children with a broader perspective and a deeper understanding of the world around them [47]. Studies indicate that early exposure to STEAM education can significantly impact cognitive development and foster an enthusiasm for learning [48, 49]. Therefore, tools and programs designed for young learners should be both engaging and appropriately tailored to their developmental stages. Effective STEAM education platforms actively involve children through interactive and collaborative activities, thereby enhancing both their motivation and depth of understanding [50].

In this context, origami emerges as a particularly valuable educational tool. It combines artistic and mathematical thinking [51], thus fostering children's spatial visualization abilities and comprehension of geometric principles [52]. By integrating origami into STEAM education, educators can bridge theoretical knowledge and tangible practice, thereby making the learning experience both specific and enjoyable [53]. The concept of origami robots further enhances the educational value of traditional origami by incorporating technological and engineering principles, thus making the learning process more diverse and challenging. These hybrid educational tools engage children in complex subjects such as robotics, programming, and electronic systems, demonstrating immense educational potential [54, 55]. Furthermore, origami robots promote collaborative problem-solving and innovation, which are indispensable components of effective STEAM education [56–58]. Through interdisciplinary integration and innovative teaching methods like origami robots, STEAM education broadens children's horizons while nurturing their comprehensive abilities and interest in learning. This educational approach helps children achieve holistic development at an early stage, thereby laying a solid foundation for future learning and growth.

3 Formative study

The efficacy of origami robotics in advancing children's STEAM development has been substantiated by existing studies. Nevertheless, several obstacles compromise the experiences of children in design, making, and learning practices involved with origami robots. As a response, we executed a formative study with the following objectives: (1) to discern the challenges that obstruct the process of origami robot creation among children; and (2) to provide design insights that can surmount these challenges.

3.1 Method

We invited 12 children aged 5–8 (M = 9.17, SD = 0.9; 6 females, 6 males) and 6 child educators. Data on their attitudes, opinions, and experiences regarding origami robots were collected through interviews to inform the design of OriBot. First, we conducted an origami robot workshop with these children. Both the children and the 6 child educators were introduced to early prototypes of OriBot. We provided an overview of the OriBot system, demonstrated the creation process of the robots, and showcased various interactive features. Subsequently, the participants were given approximately 1.5 h for free creative exploration and experience with the robots.

A research assistant documented salient aspects of children's behavior and was explicitly directed not to make any suggestive remarks. Each child's entire experience was recorded. We also captured their vocal responses and collected their robot designs. Post-workshop, we facilitated semi-structured interviews with all participants. Children were prompted about the origami robots they constructed and their behaviors as observed by our research assistant. The experts were queried about their understanding of OriBot, their interaction methods, difficulties experienced during origami robot construction, and their suggested resolutions. The interviews with the children lasted between 15 and 20 min (M = 18.00, SD = 2.24), while those with the experts spanned 25–30 min (M = 27.50, SD = 2.06). The researchers noted participants' responses and asked follow-up questions during the interview process. All recordings were transcribed for subsequent analysis. As a token of gratitude, both the participants and experts received a gift worth $10.

All data were collected and analyzed with the consent of the parents. We employed thematic analysis [59] on the recorded videos and interview transcripts. The videos were categorized based on different actions that signified the difficulties children encountered, such as challenges with folding, issues with using electronic components, robot assembly complications, and problems controlling the robot. The interview records were systematically coded to unveil potential reasons for these behaviors and potential solutions. Our aim was to determine if children would face any obstacles or issues with engagement during their creation process, and to expose any unexpected challenges they encountered while making origami robots. Two researchers independently handled the data using NVivo and integrated these insights into broader themes through several rounds of meetings and discussions.

3.2 Key findings and design implications

In a semi-structured interview, both children and experts shared their experiences and opinions regarding the process of creating origami robots. The children generally reported difficulties in the paper folding and robot assembly stages, primarily attributing these challenges to a lack of folding techniques and insufficient patience. They also experienced confusion and frustration when dealing with programming and integrating electronic components. The experts, on the other hand, highlighted the inadequacies of the existing instructions, noting that the steps were overly complex. They suggested providing more concise operational guidance and user-friendly programming tools to better assist the children in completing the project. The experts recommended adopting step-by-step instructions and gradually increasing the complexity to ensure that children can incrementally acquire the necessary skills while maintaining their interest. Specifically, they proposed the following three aspects:

Shape Folding. During our experiment, it was observed that children encountered challenges mastering origami techniques, particularly the folding process. Out of all participants, only three children were able to successfully complete an entire origami shape, whereas two children managed to fold recognizable shapes such as an airplane or a boat. Moreover, merely seven children could preserve the integrity of the paper upon the conclusion of the task, while the remaining participants caused some degree of damage to the paper. This was primarily due to the children's unfamiliarity with the folding techniques required for their desired shape. During the construction process, three children required constant guidance from the assistants through hands-on instruction. Based on prior research and our observations, it is clear that there is a need for comprehensive guidance on paper folding techniques, and consideration should be given to substituting the paper with a more appropriate material.

Ambiguity in Process. The construction of origami robots, an endeavor demanding patience and meticulous manipulation, poses significant challenges to children's focus and tenacity. A distinctive lack of thorough guidance and substantial support tends to impede their ability to independently accomplish the task. Our research determined that the participating children exhibited expeditious tendencies during the construction process, alternating between handling origami and hardware, thereby lacking a systematic production strategy. Furthermore, two children abandoned their projects upon encountering difficulties - while one aimlessly roamed the classroom, the other was observed to be desultorily fiddling with a piece of paper and inspecting components. An expert emphasized the critical importance of providing children with structured guidance, insightful tips, and consistent encouragement throughout the execution of a complex, multi-layered project. Drawing from the data and methodology gleaned from our interviews, our goal is to facilitate interaction and proffer guidance, thus actively engaging children in the process of robot creation.

Technological Complexity. It was observed that children frequently grapple with the programming aspect of robotics, particularly those devoid of a programming background. The tasks of controlling origami robots and designing circuits may pose significant challenges. Upon encountering programming difficulties, a select group of participants were able to surmount these obstacles after thoughtful consideration, or by seeking assistance from the teaching assistant. Several participants were left feeling overwhelmed and frustrated. Therefore, in order to alleviate the technological challenges encountered by children during the origami robotics process, it is recommended that basic robot hardware and software solutions be made available. These offerings would serve to not only educate children, but also provide a variety of options from which they could choose.

3.3 Design goals

Grounded in previous studies and the insights gathered from our preliminary survey, we delineate three primary goals for the development of an origami robot creation system:

Goal 1: Generate crease patterns for the origami robot, thereby easing the demand on children's fine motor skills and spatial-visual perception.
Goal 2: Incorporate a voice-assistant feature to guide children through the creative process and foster active engagement.
Goal 3: Provide a variety of origami robot roles and functions to lower the technical barriers for use.

3.4 Learning content

To validate the learning content, we conducted semi-structured interviews with four experts, including two experts in the field of robotics education and two primary school teachers. Overall, the experts expressed a positive and supportive attitude towards our design. However, they provided valuable suggestions for modifying the learning content and activities. One expert recommended removing the complex programming, robot structure, and control concepts, as they may be challenging for children of that age. Instead, the learning content of OriBot should focus on introducing and explaining the functions of simple electronic components, demonstrating various usage scenarios, and teaching origami-making skills. It is also important to highlight the application of origami robots. Additionally, the experts emphasized the significance of play in children's learning and stressed the need to incorporate appropriate games into the learning activities. Based on the recommendations from the experts, we made revisions to the learning content. The revised content prioritizes the following aspects (Table 1):

4 OriBot system

In accordance with the aforementioned three design objectives, we have developed OriBot, a system dedicated to the creation of origami robots. This system encompasses construction guidance, robot shape and function selection, aiming to engage children aged 5–8 in the acquisition of STEAM knowledge. The toolkit also furnishes a variety of electronic components, including but not limited to sound sensors, infrared obstacle avoidance sensors, touch sensors, light sensors, LEDs, and servos. The developmental kit employs a

Table 1 STEAM knowledge content delivered by OriBot

Field	Learning contents
Science	The learning of fundamental scientific principles, which include but are not limited to concepts of geometry, shapes, and structures in addition to understanding forces and movement dynamics.
Technology	The application and utilization of diverse tools such as scissors, glue, computers, printers, and cutters.
Engineering	Designing origami robots made of paper materials integrated with electronic components. Understanding of the key stages involved in the engineering design process, which comprises problem identification, design, construction, and testing.
Art	The creation of origami robots which necessitate skillful and creative folding and shaping techniques. The development of artistic skills is fostered through the decoration and embellishment of these robots.
Mathematics	Mathematical concepts and skills including understanding geometric figures (i.e., squares, triangles), measurements, ratios, and symmetry. It also incorporates learning how to fold paper with precision.

proprietary control board based on ESP-WROOM-32. Despite its compactness and lightweight, this control board integrates Bluetooth 4.2 and WiFi HT40 technologies, as well as a high-performance Tensilica LX6 dual-core processor, equipping it to effectively support children's graphical programming and robotic programming development.

4.1 Hardware toolkit

The hardware toolkit of OriBot provides tangible tools as well as materials for constructing origami robots, chiefly comprising paper materials and an assortment of electronic components. As depicted in Fig. 1, the selection of paper materials was informed by considerations such as toughness, strength, thickness, tactile qualities, foldability, and safety. We elected to use 1 mm thick model paper as the primary material for these origami robots, relying on the paper's natural hue to encourage children's creativity and personal expression through doodling. To ensure the toolkit's user-friendliness, the structure of the control board was reimagined. This redesign intuitively corresponds the sensors to different labeled sockets, thus eliminating the need for children to memorize the pin configurations of the main control board.

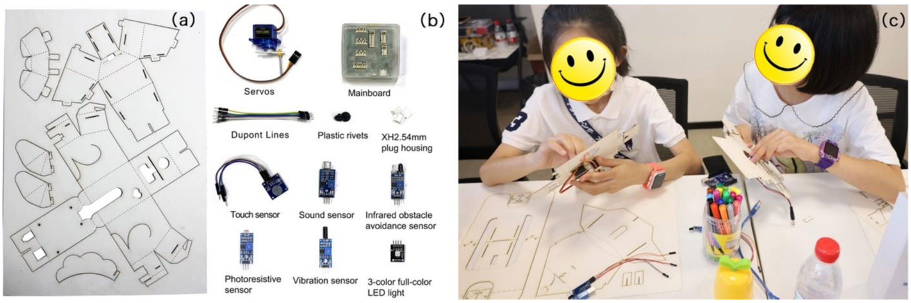

Fig. 1 OriBot Hardware Design. **a** The paper material chosen for the robot; (**b**) Electronic components included in the toolkit; (**c**) The creation scene of the origami robot

4.2 Software

The software, an iPad-based application, offers design, fabrication, interaction, and control of origami robots. With three design goals in mind, OriBot provides the following functions:

4.2.1 Assisted manufacture for origami shapes

Being derived from origami art, origami mathematics proves that any geometry can be theoretically simulated by origami [60]. Paper has emerged as an exemplary medium for prototyping and handcrafting due to its favorable foldability. OriBot features a library of animal roles grounded in the art of origami (Fig. 2a). This role library enables children to explore various options and presents the three-dimensional (3D) model of the chosen role (Fig. 2b). In our efforts to circumvent the complexity children may encounter when crafting origami models, we have integrated origami planarization and paper model expansion algorithms [61] into OriBot. These algorithms possess the capability to transform the selected 3D model into a two-dimensional (2D) plane crease pattern (Fig. 2c). The crease map delineates the positions for folds, cuts, and hollows in the crafting process, thereby serving as a guide for children as they build their shapes. This feature aids children in comprehending the sequence and techniques of folding the origami shapes, effectively alleviating the intricacy associated with manual dexterity and spatial vision in the robot creation process.

4.2.2 Function customization library

To address the engineering challenges associated with creating origami robots specifically targeted at children aged between 5 and 8 years, we have designed a custom library encapsulating the functionalities of origami robots. As shown in Fig. 2d, the OriBot encompasses an array of sensors including those for light, sound, vibration, touch, and infrared, in addition to three distinct modes of locomotion: walking, rotating, and running. Upon selection of a specific functionality module, the system exhibits the respective module's functional description (Fig. 2e). Children are thus given the liberty to select the functionality module for the robot via the software platform, subsequent to which the system generates guiding cues contingent upon the chosen functionality module.

4.2.3 Voice assistant

The majority of software tools developed for children's robots primarily emphasize on the control and interaction of robots during their later stages [62, 63], thereby largely overlooking the production and assembly aspects of origami robots during their initial and intermediary stages. In response, we proposed goal three, adding a voice assistant to OriBot's existing software capabilities. This voice assistant is designed to extend its service through the entire spectrum of the origami robot's lifecycle from early to late stages, primarily to guide children through the sequential steps involved in the creation of an origami robot. For instance, the voice assistant may prompt, "Have you completed the origami assembly?" to encourage children's active involvement in robot construction, and depending on the functional module chosen by the child, might ask questions like, "Have you installed

Fig. 2 OriBot software design. **a** Origami role library; (**b**) 3D model of an origami character; (**c**) The unfolding pattern of an origami model; (**d**) Interface of OriBot function customization library; (**e**) Knowledge introduction to components; (**f**) Interface of voice assistant guidance

an infrared sensor?" (Fig. 2f). The language and tone employed by the voice assistant are tailored to be child-friendly, and each step is conveyed in a manner that is both comprehensible and engaging. The language and vocal intonation employed by the voice assistant are appropriately adapted for children within the targeted age range. Each phase of instruction is presented in an accessible and intuitive manner, enabling children to effectively engage in the process of creating origami robots with the guidance of the voice assistant.

It is important to note that while the voice assistant can provide step-by-step instructions and prompt children with pre-set questions, its ability to respond to children's spontaneous inquiries is limited. The current implementation of the voice assistant relies on a scripted dialogue system, which means it can only offer pre-determined responses and encouragement. However, it is designed to provide positive reinforcement and motivational feedback even when it cannot address specific queries. For example, if a child asks a question beyond the scope of the pre-scripted responses, the voice assistant might respond with phrases such as “That’s a great question! Let’s try to figure it out together,” or “I’m here to help you, keep going!”

4.2.4 Robot interaction and control

OriBot furnishes control functions for the origami robot as depicted in Fig. 3a. Through this game-like control interface, children can use the command buttons on the right to dictate the robot’s movements, facilitating forward and backward movements, as well as to halt the robot. “Bullfight Mode”, selectable by children, is illustrated in Fig. 3b. This mode allows children to engage with the robot by creating obstacles in its path, triggering the robot’s automatic retraction function to evade these obstructions. Concurrently, system prompts will be displayed as portrayed in Fig. 3c. The interaction control of OriBot primarily depends on the robot function modules chosen by the children. Apart from motion control, we also offer a variety of other controls, such as LED control, sound control, and light sensing control, etc.

5 Hypotheses

Goal 1, OriBot aims to mitigate the task complexity of origami creation for children by generating folds for origami models. Goal 2 offers an array of origami robot roles, along with a customization library for diverse functionalities. To validate the achievement of these Goals, we analyzed the integrity and fluency of the children’s fabrication process and the inventive aspect of their robotic creations. Besides, the voice assistant’s interaction method for Goal 3 provides children with fabrication guidance and vocal cues. Based on the aforementioned, we establish the following hypotheses:

Hypothesis 1: OriBot significantly improves the integrity (H1a) and fluency (H1b) of children’s origami robot fabrication.
Hypothesis 2: OriBot significantly enhances the creativity (H2a) and expert rating scores of the robots made by children (H2b).
Hypothesis 3: OriBot significantly increases the robot knowledge (H3a) and engagement (H3b) of the children.

Fig. 3 Control Interfaces of the OriBot. **a** The robot’s motion interface in control mode; (**b**) The interface for bullfighting mode; (**c**) The interface prompt activated when the robot encounters an obstacle

6 Evaluation

To verify these hypotheses, we implemented a controlled experiment involving 68 children, ranging from 5 to 8 years in age. The independent variable was the use of the OriBot system by the experimental group (OriBot Group), whilst the control group (Baseline Group) did not utilize this system. The dependent variables included the integratity, fluency, creativity, expert rating of the origami robots, engagement and knowledge related to robots.

6.1 Participants

We recruited 68 participants aged between 5 and 8 years old (34 females and 34 males). The mean age was 6.44 years old (SD = 1.03). It is noteworthy to mention that these participants were freshly recruited for an evaluative study differentiated from a formative survey. Each participant was a native speaker of the Mandarin language and demonstrated proficiency in the utilization of iPads, corroborated by their exposure to basic electronics coursework. The recruitment process was facilitated through publicizing our requirement on personal social media platforms and disbursing flyers in local primary schools and community centers.

6.2 Procedure

Pretest. Prior to the main experiment, a pretest was conducted in order to eliminate variability based on the environment. All participants were brought into the same classroom for the pretest. Participants' familiarity with robots and their level of creativity were assessed and they were then randomly assigned to two groups. To evaluate the children's knowledge of robots, a questionnaire consisting of ten questions was developed based on expert advice. Additionally, the Torrance Tests of Creative Thinking (TTCT), a paper-based assessment of creative thinking, was used to measure participants' creativity [64]. To ensure comprehension among the younger participants, a research assistant read each question aloud. It is worth noting that participant demographics, including age, gender, robot knowledge ability, and creativity scores, were balanced across all conditions, as shown in Table 2.

During the Task. One week after making predictions, participants from both the OriBot group and the baseline group attended a basic course on the content related to the study. Following this, participants were individually invited to conduct the study (Fig. 4). A research assistant provided introductions to the experimental materials and tools, such as origami, electronic components, scissors, and other necessary tools. Members of the OriBot group were specifically instructed on how to use the OriBot system and were given a chance to practice. All participants were given the same origami robot creation theme,

Table 2 Participants distribution based on gender, Age, Robot Knowledge scores, and TTCT scores

Group	*N*	ID range	Gender	Age	Robot knowledge scores	TTCT scores
OriBot Group	34	P01-34	F = 15, M = 19	6.38 ± 1.00	3.97 ± 1.53	25.65 ± 5.39
Baseline Group	34	P35-68	F = 19, M = 15	6.50 ± 1.06	4.03 ± 1.44	26.02 ± 4.15

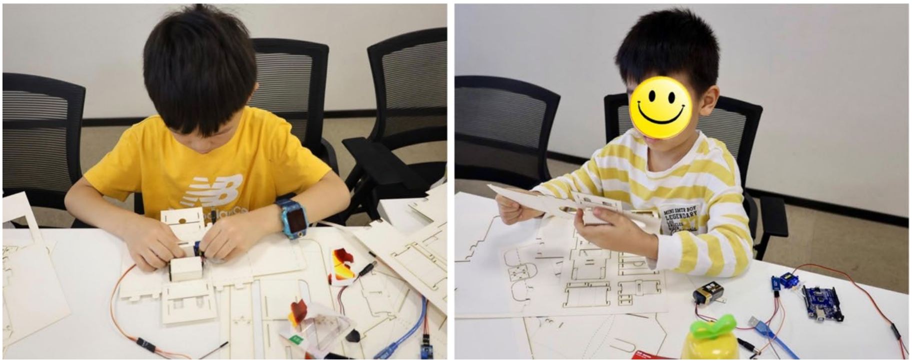

Fig. 4 Children participants were creating origami robots with OriBot in a classroom

which was "Animal Origami Robot." In order to ensure equal difficulty levels for creating an origami robot, we kept the theme fixed and given same time (90 min) to complete their origami robots for both groups. Participants were required to create an origami robot according to the specified conditions. The entire process was recorded with the consent of the child's parents.

Post-Test. Following the completion of the robot construction, participants were asked to complete a questionnaire aimed at evaluating their level of engagement throughout the process. Moreover, children in the OriBot group were engaged in a brief semi-structured interview regarding their user experience and the usability of the system. The interview addressed questions such as "Could OriBot assist you in robot construction?" "Did you encounter any difficulties while building the origami robot using OriBot?" and "Would you consider using OriBot again for creating origami robots?" Each participant received a toy valued at 10 dollars as compensation. Figure 5 illustrates the procedure for one participant.

6.3 Data collection

The study incorporated six primary data collection methods: integrity, fluency, creativity, expert ratings on robots, robot knowledge scores, engagement, and video recordings (Table 3). A comprehensive overview of the data collected and the corresponding measures employed in the evaluation is presented in Table 3. To ensure reliability, two research

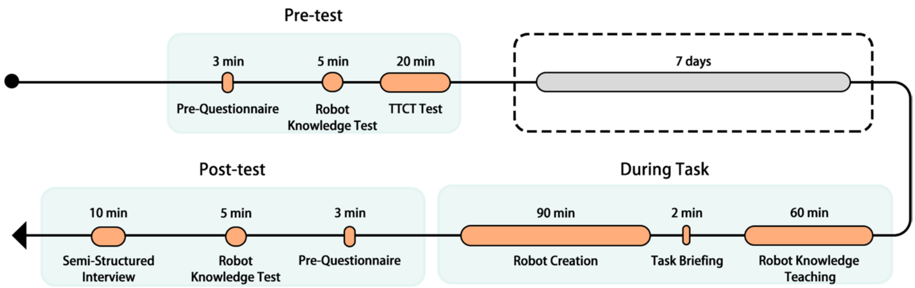

Fig. 5 The flow chart for one participant

Table 3 Summary of the collected data and the parameters used in the evaluation

Data	Measure	Description
Fabrication Process	Integrity	Integrity was measured based on the extent to which the robot fulfilled the task requirements, including origami shape, hardware utilization, software interaction, and adherence to the design theme.
	Fluency	The number of pauses and requests for assistance were considered as indicators of fluency.
Robot Creativity	Creativity	Robot creativity was assessed by quantifying the total number of themes and ideas observed in the children's robot creations [65].
	Expert Ratings on Robots	Expert ratings on children's robot creations were performed under Amabile's [66] consensual creativity assessment technique.
Robot Knowledge Test	Robot Knowledge Scores	A set of 10 multiple-choice questions pertaining to robot knowledge was administered.
Engagement Questionnaires	Giggle Gauge Instrument	Giggle Gauge self-report instrument [67] assesses children's engagement in seven terms of perceptions (Aesthetic and sensory appeal, Challenge, Endurability, Feedback, Interest, Novelty, Perceived user control) on a 4-point scale.
Video Recordings	Open Coding and Affinity Diagramming	Three researchers frst coded key clips individually and met to achieve consensus [59]. The codes were then discussed by the research team and arranged into themes [68].

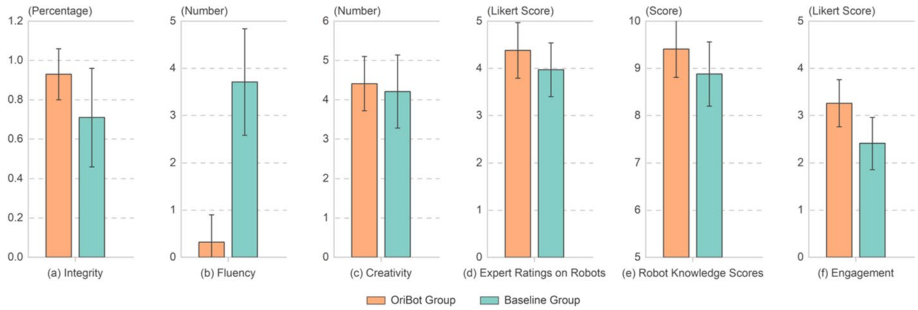

Fig. 6 Bar charts illustrate the data distribution of **a** integrity, (**b**) fluency, (**c**) creativity, (**d**) expert ratings on robots, (**e**) robot knowledge scores, and (**f**) engagement

Table 4 The statistical metrics on participants' performance, where the Manwhitney U test p-values (*: $p<.050$, **: $p<.010$, * * *: $p<.001$) are reported

Metrics	Distribution(M ± SD)		Statistics		Hypotheses
	OriBot Group	Baseline Group	Z	p	
Integrity	0.93 ± 0.13	0.71 ± 0.25	-3.879	0.001***	H1a accepted
Fluency	0.32 ± 0.58	3.71 ± 1.13	-7.207	0.001***	H1b accepted
Creativity	4.41 ± 0.69	4.21 ± 0.93	-1.169	0.242	H2a rejected
Expert Ratings on Robots	4.38 ± 0.59	3.97 ± 0.57	-2.768	0.006**	H2b accepted
Robot Knowledge Scores	9.41 ± 0.60	8.88 ± 0.68	-3.113	0.002**	H3a accepted
Engagement	3.26 ± 0.50	2.41 ± 0.55	-5.244	0.001***	H3b accepted

assistants initially coded 10% of the data (7 participants chosen at random using a random number generator) and met to establish consistency before independently coding the entire dataset. An inter-coder reliability analysis was conducted, resulting in an impressive inter-coder consistency rate exceeding 90%.

7 Results

7.1 Quantitative analysis

In this study, we obtained measurements for quantitative analysis from six indicators. To visually represent the data distribution for each dimension of the indicators, bar charts were utilized. Figure 6 displays the bar charts illustrating the data distribution. Additionally, we employed the Mann-Whitney U test to analyze the differences between the OriBot group and the Baseline group (Table 4).

Integrity. Figure 6 illustrates the comparison between the OriBot group and the control group in terms of integrity. The OriBot group (M = 0.93, SD = 0.13) achieved a higher score than the control group (M = 0.71, SD = 0.25) in factors such as origami shape, hardware usage, software interaction, and design theme using the OriBot system. The Mann-Whitney U test result demonstrates a significant difference between the two groups (Z = -3.879, $p = .001^{***}$). These findings support the hypothesis that the use of OriBot significantly enhances the integrity of children's origami robot creations (H1a).

Fluency. During the construction of origami robots, both the frequency of pauses and instances of requests for assistance were recorded for the OriBot and baseline groups. It was observed that the OriBot group (M = 0.32, SD = 0.58) had a significantly lower mean pause frequency than the baseline group (M = 3.71, SD = 1.13), as depicted in Fig. 6. This marked difference was statistically significant (Z = -7.207, $p = .001^{***}$). Thus, the inference can be drawn that with the introduction of OriBot, the children's fabrication process becomes smoother, their confidence in decision-making is reinforced. Consequently, it can be concluded that the hypothesis proposing a significant improvement in the fluency of children's origami robot fabrication due to OriBot (H1b) is accepted.

Creativity. We recorded the total number of themes and ideas produced by the OriBot group and baseline group. Although the Origami group (M = 4.41, SD = 0.69) produced slightly more themes and ideas than the baseline group (M = 4.21, SD = 0.93), the difference between the two groups was not significant (Z = -1.169, $p = .242$). Thus, the hypothesis that OriBot significantly enhances the creativity of children's origami robots (H2a) is unsupported.

Expert Rating on Robots. Following both experiments, we utilized Amabile's Consensual Assessment Technique to assess the robotic creations made by the children. The OriBot group achieved an average score of 4.38 (SD = 0.59), which was substantially higher (Z = -2.768, $p = .006^{**}$) than the baseline group's average score of 3.97 (SD = 0.57). Hence, we accept the hypothesis (H2b) that OriBot significantly enhances the expert evaluation of robots.

Robot Knowledge Scores. To gain deeper insights into children's mastery of robot-related knowledge, we scored their robot knowledge after the experiment. The Origami group (Mean = 9.41, Standard Deviation = 0.60) displayed a superior performance as compared to the baseline group (Mean = 8.88, Standard Deviation = 0.68). The test results show a significant difference (Z = -3.113, $p = .002^{***}$). This indicates that after creating origami robots using OriBot, children's understanding and grasp of robot related knowledge such as electronic components, sensors, and circuit building significantly improved. Therefore, the hypothesis that OriBot significantly improves children's robot-related knowledge (H3a) is accepted.

Engagement. Children's engagement was assessed utilizing the Giggle Gauge self-report instrument. As depicted in Fig. 7, the Origami group yielded a higher score (M = 3.26, SD = 0.50) compared to the baseline group (M = 2.41, SD = 0.55). A notable difference between the two groups was confirmed via the Mann-Whitney U test (Z = -5.244, $p = .001^{***}$). This disparity may be attributed to various factors including the children's familiarity with OriBot, their interest orientation, the complexity of the task, among others. Consequently, the hypothesis that OriBot significantly augments children's engagement in the origami robot creation process (H3b) is accepted.

7.2 Qualitative analysis

Our qualitative analysis revealed three major themes in the creation process of the participants:

Fig. 7 Origami robots created by participants. **a** A cow robot created by P13, featuring drawn-on eyes; (**b**) A dog robot created by P26, decorated with floral designs and puppy stickers; (**c**) Robots created by children using the OriBot system

7.2.1 The creation details of origami robots

Our research revealed parallels between the OriBot group and the baseline group in terms of detail in children's origami robot creation. Primary similarities were observed in four key areas: organ attributes (including eyes and mouth), emotions (manifested as smiles), physical appearance (such as clothing and buttons), and actions (like walking and rotating). As illustrated in Fig. 8, participant P13 crafted a cow robot and adorned

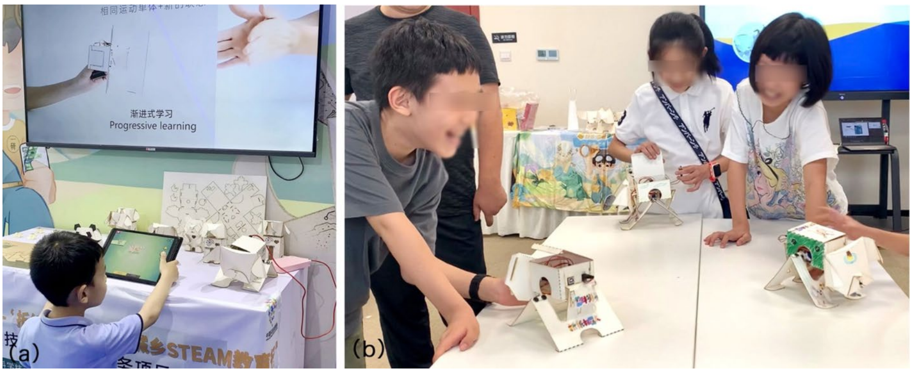

Fig. 8 **a** Children utilizing the OriBot software platform to interact with robots; (**b**) Participants spontaneously displaying and discussing their origami robots upon completion of the test

it with eyes (Fig. 7a), whereas participant P26 fashioned a dog robot, embellishing the robot's body with floral patterns and puppy stickers (Fig. 7b). Though there was variability in the overall completeness of the robots, they universally incorporated organ attributes and details of physical appearance. Further observation revealed that during the origami process, the OriBot group's children acquired and mastered numerous origami techniques, including but not limited to folding, cutting, and flipping. They were not only capable of adhering to crease marks for assembly but also exhibited the capability for free-form innovation, thereby inventing their own origami methodologies.

7.2.2 Positive interaction in children's origami robot making

The voice assistant plays a vital role in fostering positive child-robot interaction. In comparison to traditional origami activities, children displayed a genuine willingness and engaged in dialogue with the robots. An example of this interaction is when P19 posed questions or expressed confusion about origami to the voice assistant during the production process. Despite the robot's inability to answer all of their inquiries, it provided encouraging feedback and accompanied them throughout each origami task. As a result of this interaction, the children's curiosity and involvement in constructing origami robots were heightened. Throughout the production process, children may encounter various difficulties and frustrations. However, through interaction and guidance from the voice assistant, they not only learn how to confront and overcome these obstacles but also develop patience and perseverance. This is evidenced by the frequent use of positive phrases like "thank you" and "I'll try again" in response to the voice assistant. The OriBot robot guides children in creating origami robots in a friendly manner, allowing them to learn while being entertained and enjoying the learning process. This positive attitude towards learning and the habit of persistence will undoubtedly have a positive impact on their future educational endeavors.

7.2.3 Children's confidence and interest in origami robot making

Based on the feedback received from the children, it is evident that they thoroughly enjoyed interacting with the OriBot system, which consequently sparked their desire to use it again. This indicates that activities related to the creation of the OriBot origami robots have the ability to stimulate children's interest, a critical driver for their continued exploration and learning. Notably, the children expressed confidence in their ability to construct origami robots. Confidence plays a pivotal role in motivating individuals to overcome challenges, embrace novelty, and persist even in the face of potential failure. This sense of confidence may have emerged from their successful completion of the robot-making task with the assistance of the OriBot system, leading them to believe in their capabilities to tackle similar challenges. Furthermore, the OriBot system's provision of a simple and easily understandable user interface, along with step-by-step guidance, significantly alleviated the perceived difficulty of creating the robots, thereby creating a relaxed and comfortable environment for the children during use. This pressure-free environment could have contributed to enhanced learning outcomes and greater participation, ultimately fostering a willingness to participate again.

8 Discussion

8.1 OriBot's performance in creativity

In examining creativity, we observe that the difference between the OriBot group and the baseline group is not statistically significant. This phenomenon can be analyzed from the perspective of two essential standards for measuring creativity:

Firstly, drawing on Daniel Kahneman's work on fast and slow thinking [69], children primarily rely on rapid thinking abilities in a short time frame. This ability requires them to quickly retrieve information and experiences from memory, constructing creative images in their minds. Rapid thinking often depends on intuition and external stimuli [70]. For children with limited knowledge reserves, fully utilizing fast thinking creativity becomes challenging when external information is scarce.

Secondly, to ensure the experiment's controllability and minimize interference from variables such as prior experience, the participating children were introduced to origami robots for the first time. Their cognitive processes were still at an initial stage, with most of their time spent on attaining fundamental cognition of the robot. This situation somewhat confined their capability for slow thinking, which is characterized by deeper, more reflective processing. With increased learning time, children develop a more profound understanding of the robot's manufacturing requirements and procedures. Consequently, their brains can draw from a broader pool of experiences and knowledge, enabling more personalized and profound creativity through slow thinking.

Additionally, it is essential to consider whether the study assessed "productivity" rather than "creativity" due to the structured process provided by OriBot. While the OriBot system aims to guide children through the creation process, it may inadvertently homogenize the outcomes, thus affecting the measurement of creativity. This finding aligns with prior research suggesting that while guided systems improve productivity and technical understanding, they sometimes limit the exploration that fosters raw creativity [71].

To better support the development of children's creativity, we should focus on innovative software design within the OriBot system, incorporating functions capable of stimulating children's inspiration. For instance, we could offer a variety of creative tasks and introduce interactive stories and role-playing elements, allowing children to participate in storylines while sparking their innovative thinking. On the hardware material front, we could incorporate more universal forms of modular origami, encouraging children to freely explore different combinations and ideas. This approach can contribute to cultivating their problem-solving skills, imagination, and both fast and slow thinking processes inherent to creativity.

8.2 The assistance and guidance features of OriBot

We found that children in the OriBot group received guidance and prompts from the voice assistant throughout the process of constructing the robot, rendering their experience more seamless compared to the control group. The systematic guidance offered presently encompasses key stages such as character selection, origami construction, introduction to sensor functions, robot assembly, and robot control, thereby providing extensive support throughout the entirety of the robot creation process. The feedback received from the children suggests that the OriBot system effectively mitigates the complexities and challenges they encounter during the creative process, thereby enhancing their success rate and escalating their enthusiasm and self-assurance in crafting origami robots. However, there are limitations to OriBot's voice assistant as it does not currently support comprehensive intelligent interactions with children. Despite it being capable of responding to children's inquiries, the scope of its assistance is confined to the aforementioned six features, and it is unable to deliver precise feedback for every query.

8.3 OriBot's extensibility and applications

OriBot, while initially designed for children aged 5 to 8, has significant potential for adaptation to broader age groups. For older children and teenagers, the system can be enhanced with more advanced design tools, coding interfaces, and modular electronics, facilitating a deeper understanding of robotics and programming. This extension could be particularly beneficial in educational settings such as middle and high school curricula, after-school programs, and competitive robotics clubs, providing a progressive learning path from basic origami to complex robotic systems.

Beyond traditional classrooms, OriBot can be integrated into diverse educational environments, including museums, libraries, and community centers. These settings can host interactive exhibits, workshops, and lending programs, making STEAM education more accessible and engaging for children and their families. Additionally, OriBot's adaptability makes it a valuable tool in special education, where it can be customized to support various learning styles and therapeutic needs, enhancing cognitive and motor skills through interactive, hands-on activities.

Commercially, OriBot can appeal to hobbyists, maker communities, and families looking for enriching collaborative activities. It can be marketed as a family bonding tool or utilized in maker spaces and DIY robotics clubs to foster creativity and innovation. Future enhancements such as augmented reality for real-time instructions, IoT integration for smart interactions, and expanded content libraries can further increase OriBot's applicability and user engagement, ensuring its continued relevance and impact in both educational and recreational contexts.

8.4 Limitation and future work

The current version of OriBot has limitations that can be addressed to improve its overall effectiveness and impact. The role library, offering only 16 animal figures, restricts children's creative possibilities. Expanding this library to include a variety of shapes, themes, and 3D models would enhance creative expression. Additionally, the existing origami unfolding algorithm struggles with complex designs, indicating a need for further development to handle more intricate structures and challenge children with higher-order thinking tasks.

The study's limited sample size and controlled setting restrict our understanding of OriBot's real-world applicability. Future research should involve larger sample sizes and be conducted in authentic classroom environments to gather comprehensive insights into its educational impact. Another limitation of the current study is the absence of a power analysis, which is essential for determining the sample size needed to detect an effect with a given level of confidence. Future research should include a power analysis to ensure that the study is appropriately powered to support meaningful conclusions. Additionally, while OriBot's voice assistant is beneficial, it currently lacks the ability to provide precise and contextually aware feedback for every query, limiting the depth of interaction and guidance it offers. Addressing these limitations is crucial for fully realizing OriBot's potential in enhancing children's STEAM learning experiences.

Given the encouraging results and insightful feedback from the initial deployment of OriBot, we identify several innovative avenues for future work to enhance the system's capabilities and educational impact.

AI-powered Oribot design. To address key limitations of the OriBot system, we propose integrating advanced AI technologies to enhance its capabilities. Firstly, AI-generated models like GANs and VAEs will be utilized to expand the role library, providing children with a vast and dynamically growing selection of origami designs, thus broadening creative opportunities. Secondly, reinforcement learning (RL) will be employed to optimize the folding sequences of complex 3D designs, improving the system's efficiency and usability. Lastly, advanced natural language processing (NLP) techniques will be incorporated to develop a sophisticated voice assistant capable of understanding and responding to a broader range of children's questions, offering personalized guidance, and fostering engaging, educational interactions.

Classroom integration and large-scale trials. To evaluate OriBot's efficacy in real-world educational settings, it is imperative to conduct large-scale classroom-based studies. Collaborating with educational institutions, we aim to deploy OriBot in diverse school environments. This will enable us to gather comprehensive feedback, assess the system's impact on STEAM learning outcomes, and refine the product based on authentic classroom interactions and educator insights.

Accessibility and inclusivity enhancements. Ensuring that OriBot is accessible to all children, including those with disabilities, is crucial. Future iterations of the system will incorporate universal design principles and AI-driven accessibility features. For instance, image recognition and gesture-based interfaces can assist children with motor impairments, while text-to-speech and speech-to-text functionalities can support those with visual or auditory challenges.

Cross-cultural applicability and multilingual support. Recognizing the global potential of OriBot, we plan to incorporate multilingual support and culturally diverse content. AI translation tools and cross-cultural design principles will be employed to ensure that children from different regions and linguistic backgrounds can equally benefit from the system.

By integrating these advanced AI technologies and approaches, our future development of OriBot aims to create a more robust, adaptive, and inclusive tool that significantly enhances STEAM learning through the engaging and educational process of origami robot creation.

9 Conclusion

In our study, we presented OriBot, a novel system designed to facilitate the creation of origami robots by children aged 5 to 8 years. Following an initial formative investigation, which incorporated workshops and interviews, we identified the specific challenges encountered by children during the origami robot creation process and established key design goals to address these challenges. OriBot was developed with three primary assistance functions: (1) Assistance in the construction of origami shapes for origami robots. Provided detailed, step-by-step instructions for folding origami shapes essential for robot creation. (2) A library for role selection and function customization of origami robots. Offered various character options and customization features to help children personalize their robots. (3) A voice assistant to guide through the manufacturing process. Ensured continuous, interactive support across essential stages such as character selection, origami construction, sensor introduction, robot assembly, and control.

Our controlled evaluations, with 68 participating children, substantiated that OriBot significantly enhanced the children's engagement and learning of STEAM skills while nurturing their interest in origami robots. Children in the OriBot group benefitted from a more seamless and supportive experience as compared to the control group, due to the system's comprehensive guidance and assistance features.

Despite these successes, our findings also indicate room for further improvements. Although the OriBot system's current functionalities are robust, the voice assistant feature is limited to guiding key stages and lacks comprehensive intelligent interaction capabilities. Future enhancements will focus on broadening the interaction scope, providing more detailed and precise feedback to children's queries, and conducting longitudinal studies to evaluate the system's long-term impact on children's learning and creativity. By addressing these enhancements, we aim to further fortify OriBot's role in supporting children's STEAM education and inspiring their creative explorations in origami robot creation.

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Data availability The authors confirm that all data generated or analysed during this study are included in this published article. Furthermore, primary and secondary sources and data supporting the findings of this study were all publicly available at the time of submission.

Declarations

Competing interest The authors declared that they have no conflict of interest.

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