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Designing robot-assisted instructional tools to introduce coding concepts to young children

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Abstract

This study aims to develop an educational robot medium as a learning tool for coding among early childhood using a tangible programming approach that aligns with the cognitive and motor development characteristics of children. The development addresses the need for interactive, safe coding learning media capable of integrating foundational skills such as sequencing, pattern recognition, and problem solving. The research employs a research and development (R&D) method, adapting the Borg & Gall model integrated with the Waterfall Model for hardware and software development of the robot. The research process encompasses needs analysis, product design, prototype development, limited trial, revision, field trial, and validation by content and media experts. The results indicate that the developed robot exhibits excellent performance based on black-box testing, with all input-output functions operating consistently, responsively, and safely for early childhood use. Content expert validation yields a feasibility level of 89.3%, whereas media expert validation achieves 90.4%, both categorized as highly feasible. Furthermore, the robot enhances children's engagement and provides concrete learning experiences in understanding basic coding concepts. Thus, this robot medium is deemed effective and feasible for use as a supplementary tool in coding instruction within early childhood education (PAUD) settings, with potential to bolster digital literacy and computational thinking skills from an early age.

Keywords: Educational Robot; Coding; Early Childhood Education.

1. Introduction

The rapid advancement in the field of robotics has propelled the integration of coding and robotics education into early childhood education, extending beyond industry and higher education levels to preschool stages [1][2]. A meta-thematic study reveals that early introduction to coding significantly contributes to children's cognitive and socio-emotional development, encompassing logical thinking, problem-solving, creativity, and preparation for future technological challenges [1]. Furthermore, experimental research demonstrates that the combination of unplugged activities (without digital devices) and educational robotics substantially enhances computer-based coding skills and cognitive abilities, particularly visuospatial skills in preschool children [2]. These findings underscore the importance of introducing fundamental computational and programming concepts from an early age to foster children's readiness in the digital era.

Robotic media have proven to be effective assistive tools in early childhood education, as they present coding concepts in a concrete, visual, and easily comprehensible manner, thereby aligning with children's developmental characteristics [3][4]. Learning robots designed for early childhood typically employ a tangible programming approach, wherein children program the robot's behavior through manipulative activities, such as arranging physical command blocks,

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which facilitate experiential, hands-on learning [3]. This approach enables children to actively explore, play, and learn, while enhancing their engagement and motivation in grasping fundamental programming concepts [4]. The application of tangible programming in educational robots has been widely adopted as a means of active exploration and learning, and it has been demonstrated to be effective in developing computational thinking skills and cognitive abilities in early childhood [3][4].

Observations across various early childhood education (PAUD) institutions reveal that the implementation of coding instruction continues to face limitations in supporting media, resulting in suboptimal development of foundational competencies such as pattern recognition, comprehension of instructional sequencing, and problem solving through iterative experimentation [5][6]. These media constraints hinder the comprehensive attainment of pattern recognition, sequencing, and problem-solving abilities, as most available applications or tools support only one or two aspects rather than integrating all three within a single engaging and interactive medium [5]. Another study affirms that, although tangible coding devices such as Cubetto can facilitate children's understanding of sequencing and cause-effect relationships, media capable of holistically integrating all these competencies in a developmentally appropriate manner remain severely limited in PAUD settings [6]. Therefore, the development of learning media that can combine pattern recognition, instructional sequencing, and problem solving within a single interactive and appealing demonstrative tool is urgently needed to support effective coding education in early childhood.

The development of robot media specifically designed for early childhood is highly essential as a more effective coding learning tool, since such media can assist children in understanding the fundamentals of instructions and command sequencing through concrete and enjoyable play-based activities. Age-appropriate educational robots have been proven capable of fostering basic computational thinking skills, such as sequencing, problem solving, and algorithmic reasoning, which are critical for children's cognitive development. However, a primary challenge in the field persists: the scarcity of coding learning support media that are truly suitable for early childhood, leading to suboptimal achievement of foundational competencies, including pattern recognition, comprehension of instructional sequences, and problem solving. Moreover, existing robot media generally fail to deliver interactive, integrated, and easily comprehensible learning experiences for young children; thus, the development of more innovative and integrated robot media is urgently required to facilitate effective coding instruction in early childhood education (PAUD) settings [7][8].

The current state of coding education for early childhood indicates that several foundational competencies—such as the ability to comprehend simple instructional sequences (sequencing), recognize patterns (pattern recognition), solve problems through exploratory activities (problem solving), and apply basic logic in play-based tasks—remain suboptimally developed due to limitations in learning media that align with children's developmental characteristics. Experimental studies demonstrate that, although coding interventions can enhance computational thinking skills, including pattern recognition, sequencing, and problem solving, optimal achievement is highly dependent on the availability of interactive and child-friendly media [9]. Furthermore, international literature emphasizes that the primary challenge in developing these competencies is the scarcity of tools or applications truly designed to meet the developmental needs of early childhood, resulting in coding instruction that has yet to fully integrate cognitive, social, and emotional aspects in a balanced manner [10].

The scarcity of interactive supporting media leads early childhood learners to encounter difficulties in comprehending fundamental coding concepts, such as forward and backward commands, direction selection, and the assembly of instruction sequences, as abstract learning processes hinder children's ability to connect instructions with their concrete outcomes [2][6]. Studies indicate that the utilization of tangibly and interactively designed educational robots, such as Cubetto or Bee-Bot, can deliver concrete, engaging, and easily comprehensible learning experiences, thereby facilitating children's understanding of the relationship between instructions and the robot's actual actions. Furthermore, educational robot media have been proven to enhance engagement, collaboration, and computational thinking skills in children through play-based activities aligned with early developmental characteristics. Consequently, the development and application of educational robot media are crucial for overcoming barriers in coding education for early childhood and supporting the optimal attainment of foundational competencies.

This study aims to produce a robot media design suitable for coding instruction in early childhood, evaluate the performance of the robot media in facilitating children's understanding of fundamental coding concepts, and assess the feasibility of the robot media as a supplementary tool in early childhood education (PAUD) settings, consistent with findings that educational robots such as Bee-Bot can enhance engagement, algorithmic comprehension, and enjoyable learning experiences among young children [9]. Learning media are defined as any form of tools, materials, human resources, or events capable of enhancing learners' knowledge, skills, or attitudes; in the context of early childhood, such media serve as a bridge to assist children in capturing, processing, and comprehending information both verbally and nonverbally. Learning media may manifest in concrete forms, including storybooks, cards, images, educational games, and technological devices such as educational robots, tablets, or computers, which have been demonstrated to effectively support the development of computational thinking and sequencing abilities in children [10].

In coding education for early childhood, robot media play a pivotal role by enabling children to learn through physical manipulation, play, and guided exploration, which have been shown to enhance engagement and comprehension of fundamental programming concepts [11][2]. Educational robots are designed to respond to simple instructions provided by children, thereby offering direct experiences of how a command generates tangible actions and assisting children in linking instructions to concrete outcomes. This approach aligns with the principles of tangible programming, wherein programming concepts are embodied through real-world objects that children can touch, arrange, or move, rendering the learning process more meaningful and developmentally appropriate for early childhood [2].

Learning robots for early childhood are generally designed with a high degree of simplicity in terms of form, mechanisms, and interactions, enabling children to comprehend the relationship between instructions and robot behavior without the need to master complex algorithmic concepts [3]. This simplified design facilitates children's natural development of logical thinking, recognition of cause-and-effect relationships, and problem-solving abilities through play-based activities with educational robots. The appropriate development of robot media is crucial for providing engaging and developmentally relevant learning tools that support digital literacy from an early age, as educational robots have been proven effective in fostering computational and algorithmic thinking skills in young children [9].

2. Methods

This study constitutes a research and development (R&D) endeavor that adapts the steps of the Borg and Gall model while integrating them with the Waterfall Model software engineering approach, as the development of robot media for coding instruction in early childhood encompasses two primary domains: educational product development and robotic hardware and software engineering [12]. From a pedagogical perspective, the Borg and Gall model is employed to systematically guide the media development process as a learning product, commencing with needs analysis, design, development, field testing, product revision, and culminating in implementation [13]. Concurrently, the Waterfall Model directs the technical engineering of the robot, encompassing system requirements analysis, device design, implementation, testing, and maintenance; thus, the integration of these two models provides a comprehensive framework for developing effective and rigorously validated educational robot media.

The adapted Borg and Gall R&D stages encompass: (1) needs analysis, involving the identification of coding learning requirements, curriculum review in early childhood education (PAUD), observation of ongoing instructional practices, and evaluation of limitations in available media; (2) planning, which includes formulating development objectives, specifying targeted competencies, drafting initial robot media specifications, and designing validation instruments; (3) initial product development, comprising robot design, interaction mechanisms, prototype construction, and user guidance; (4) preliminary testing with a small group of young children to assess usability and content appropriateness; (5) product revision based on preliminary testing outcomes; (6) main field testing in larger classroom groups to measure media effectiveness; and (7) operational revision to yield a deployment-ready product.

Concurrently, the technical development process of the robot adheres to the Waterfall Model, comprising: (1) system requirements analysis, encompassing sensor types, actuators, command logic, and safety considerations; (2) system design, including the physical design of the robot, logic flow diagrams for coding, electronic circuitry, and user interface; (3) implementation, involving the construction of the robot, microcontroller programming, and integration of input modules; (4) functional and safety testing; (5) distribution through field trials; and (6) maintenance, in the form of bug fixes and performance enhancements. The integration of the two models is achieved by aligning the Borg and Gall stages with the Waterfall process—for instance, combining educational needs analysis with technical requirements analysis, synchronizing prototype development with technical implementation, and integrating educational trials with the robot's testing and deployment phases. Thus, this combined-model approach enables the development of robot media that are not only pedagogically effective but also technically reliable.

2.1. Time, Location, Data Collection, and Data Analysis

This research was conducted at Algoland Academy and the Robotics Engineering Laboratory of the Electronics Engineering Study Program, Faculty of Engineering, during the period from September to December 2025. The object of the study was a robot-based learning medium developed as a tool for teaching coding to early childhood learners, while the research subjects comprised early childhood education (PAUD) content experts, educational technology experts, robotics engineering experts, instructors at Algoland Academy, and early childhood learners aged 5–6 years as the end users.

Data were collected using several techniques, namely: (1) classroom observation employing a non-participatory observation approach to examine children's responses during interaction with the robot, their level of engagement, and the ease of use of the medium; (2) questionnaires utilizing a four-point Likert scale administered to experts and instructors to assess the pedagogical, technical, and accessibility aspects of the robot medium; and (3) a checklist to evaluate the mechanical and electronic functions of the robot in accordance with established standards for the development of educational devices. The instruments employed consisted of an observation guideline, expert validation questionnaires, user response questionnaires, and a robot functionality testing checklist.

The data analysis technique employed was quantitative descriptive analysis to determine the feasibility level of the developed robot media based on expert assessments and user responses. Questionnaire scores were calculated using weighted Likert-scale values and subsequently converted into feasibility categories. Observation and checklist results were analysed to complement the qualitative assessment regarding aspects of ease of use, safety, and the suitability of the media with the developmental characteristics of early childhood.

To conclude the feasibility level of the developed robot media, a curve distribution analysis was employed to establish feasibility score intervals. The feasibility level of the media was classified into four categories, as presented in Table 2.

Table 1 Feasibility Interval of Robot Media for Coding Learning

Interval Skor	Kategori Kelayakan
$\bar{X} + 1{,}5\ SB < x \leq \bar{X} + 3\ SB$	Sangat Layak
$\bar{X} < x \leq \bar{X} + 1{,}5\ SB$	Layak
$\bar{X} - 1{,}5\ SB < x \leq \bar{X}$	Tidak Layak
$\bar{X} - 3\ SB < x \leq \bar{X} - 1{,}5\ SB$	Sangat Tidak Layak

The conversion of the media robot feasibility score into percentage form is performed using the following formula:

$$\text{Kelayakan (\%)} = \frac{\text{Skor rata-rata}}{\text{Skor maksimum}} \times 100\%$$

This formula is used to interpret the feasibility level of a robotic medium based on the assessment results from experts and users, thereby indicating whether the robotic medium has met the pedagogical, technical, and functional feasibility criteria as a learning tool for introducing coding to early childhood learners.

3. Results and discussion

3.1. Learning media design

Referring to Figure 1, this educational robot consists of several main components that support coding learning for early childhood children.

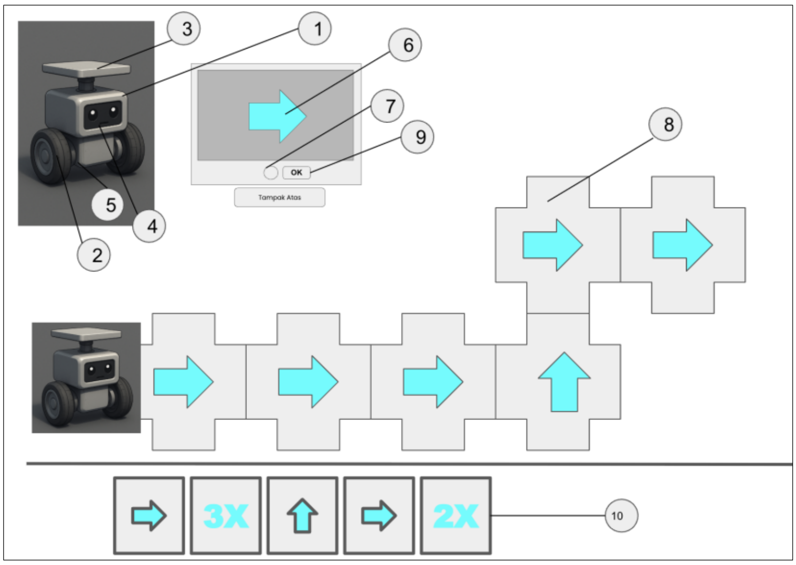

Figure 1 illustrates the primary components of an educational robot designed for interactive learning.

The robot body (No. 1) serves as the main structural framework, providing robust support and integration for all other subsystems, including motors, sensors, and the touchscreen display. The robot wheels (No. 2) enable locomotion and are driven by DC motors functioning as actuators, which execute movement commands derived from the programmed instructions. The upper touchscreen display (No. 3) acts as an intuitive human–machine interface, allowing children to directly interact with the system by dragging and arranging visual programming blocks to construct and modify command sequences that control the robot's behavior. The interactive robotic face (No. 4) incorporates an LED matrix capable of displaying various facial expressions and operational states, thereby delivering engaging visual feedback to young users throughout the learning process. The actuation system (No. 5) relies on DC motors that precisely translate coded instructions received from the touchscreen into physical motion. The coding interface (No. 6), presented on the display, features a block-based visual programming environment that introduces fundamental computational thinking and programming concepts in an accessible and enjoyable manner suitable for children. Finally, the mode-switching button (No. 7) enables users to toggle between distinct operational states, such as editing the program and executing the assembled command sequence, facilitating seamless transitions during educational activities.

Robot Path (No. 8): This path represents the route or trajectory that the robot will follow based on the programmed instructions. Children can determine the robot's path or direction of movement by arranging a sequence of coding blocks. OK Button – Program/Coding Mode Lock (No. 9): This button is used to lock the programming mode once the children have finished composing the code. Upon pressing the OK button, the robot immediately begins executing the programmed commands. Coding Sequence Arrangement Area to Be Compiled by Children (No. 10): This section consists of a series of command blocks that children arrange and organize on the touchscreen interface. Children can edit these visual programming blocks to create a specific sequence of robot movements, such as moving forward, backward, turning, or repeating certain actions.

Referring to Figure 4, the flowchart illustrates the sequential steps performed by children in controlling the robot. First, the device is powered on by activating the robot through a physical button or the touchscreen interface to initiate the coding setup. Next, learning and training occur as children program the robot's movements by arranging command blocks on the screen according to their intended sequence. The children then categorize and organize the commands, classifying and sequencing robot motion instructions—such as forward movement or turning—using a visual block-based interface. Finally, upon completion of the command sequence, the robot detects the finalized program and executes it, utilizing its motors and sensors to move precisely in accordance with the provided instructions.

Executing a robot simulation is a process in which children can test the commands they have created within a visual programming interface and directly observe the robot's physical response to those commands. The process begins when children access the Touchscreen (No. 3), which serves as the primary interface for assembling command blocks. On this screen, children are presented with a visual coding environment comprising various command blocks (e.g., blocks instructing the robot to move forward, turn, or repeat actions). They then select and arrange the Coding Sequence Arrangement Area (No. 10) on the touchscreen. For instance, children may choose command blocks to direct the robot to move forward, turn left, or turn right. Additionally, they can incorporate repetition blocks such as "3X" or "2X" (No. 8) to execute repeated movements, such as "move forward three times" or "turn twice."

Each arranged command is immediately visualized in the Coding Display (No. 6), providing a clear, real-time representation of the programmed sequence. Once the command blocks have been fully composed, children can press the Mode Button (No. 7) to switch to simulation mode. This mode enables seamless transition between editing the command blocks and executing the assembled program. In simulation mode, the robot promptly initiates execution of the entered instructions, allowing children to observe the direct correlation between their visual programming and the robot's corresponding physical movements.

Once the command sequence has been assembled and is ready for testing, children can press the OK Button (No. 9) to lock the editing mode and initiate the simulation. This button serves to confirm that the programmed instructions are finalized and ready for execution, while simultaneously activating the motors and sensors connected to the Robot Actuator (No. 5). Upon pressing the OK button, the robot immediately commences movement in accordance with the previously arranged command sequence. The Robot Actuator Utilizing DC Motors (No. 5) drives the wheels to execute designated commands, such as forward motion, reverse motion, or turning, precisely as specified in the program. The robot adheres to the predefined Robot Path (No. 8), following the directional trajectory established within the coded instructions. Encoder Sensors and Motion Detection Sensors continuously monitor and regulate the robot's locomotion, ensuring trajectory accuracy, enabling obstacle avoidance, and facilitating adaptive adjustments to movement based on real-time environmental conditions or predefined parameters.

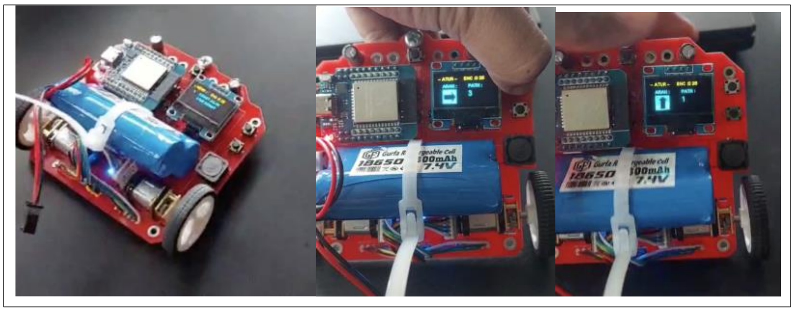

Figure 2 Executing the Program on the Educational Robot

During the simulation, the robot provides visual feedback through its interactive facial display utilizing LEDs (No. 4). The LEDs on the robot's face convey status information or emotional responses corresponding to the currently executed commands, such as displaying specific expressions or colors when a command is successfully completed. In cases where the robot is unable to execute a command or an error exists in the command sequence, children receive corrective feedback directly on the touchscreen interface, enabling them to identify and rectify programming mistakes.

Following the execution of the simulation, children can evaluate the outcomes and determine whether modifications to the command sequence are required. They are able to edit the previously arranged command blocks by repositioning existing blocks, inserting new commands, or removing unnecessary ones, thereby refining the robot's behavior. This iterative process may be repeated multiple times, facilitating a deeper understanding of programming logic and fundamental coding concepts among the children.

Through these structured steps, the robot simulation offers children a practical and engaging approach to learning coding, allowing them to immediately observe the consequences of their programmed instructions and interact with the robot in an enjoyable manner. Furthermore, the simulation promotes experimentation and trial-and-error learning, which significantly enhances children's comprehension of logical sequencing and procedural thinking in programming.

3.2. Performance of the Robot-Based Learning Media

The performance of the robot-based learning medium for coding education was evaluated through a comprehensive series of tests, encompassing black-box testing, sensor and actuator calibration, motion command responsiveness, and robot movement assessment during learning activities. These tests were conducted to ensure that the robot could execute coding instructions consistently, safely, and in full accordance with the interaction design specifically developed for early childhood learners.

The performance test results covered the robot’s ability to respond to basic instructions (forward, backward, and turning), accuracy of movement along simple trajectories, device stability during use by children, and congruence between commanded inputs and actual motion outputs. Overall, the outcomes of the robot medium’s performance evaluation are presented in the subsequent section to illustrate the level of reliability and effectiveness of the robot as an educational tool for teaching coding.

3.2.1. Black Box Testing

Black box testing was employed to evaluate the functionality of each input and output component in the educational robot medium developed for introducing coding concepts to early childhood learners. This testing approach aimed to verify that all command buttons, sensors, motion mechanisms, and robot responses performed in accordance with the intended design, without examining the internal code or program structure. The robot medium was deemed fully functional when every input command—whether delivered via directional buttons, command cards, or other interactive modules—consistently produced the expected, accurate, and safe output suitable for use by young children.

The black box testing was conducted by robotics engineering experts along with selected end-users, including teachers and children serving as testers, to ensure that the robot medium was truly reliable, effective, and appropriate for implementation in early childhood coding learning activities.

Table 2 Results of Black Box Testing on the Coding Robot Learning Media

No.	Tested Function	Input / User Action	Expected Output	Test Result	Remarks
1	Forward Button	Child presses the “↑” button	Robot moves forward by 1 step	Passed	As designed
2	Backward Button	Child presses the “↓” button	Robot moves backward by 1 step	Passed	As designed
3	Left Button	Child presses the “←” button	Robot rotates 90° to the left	Passed	Consistent
4	Right Button	Child presses the “→” button	Robot rotates 90° to the right	Passed	Consistent
5	Command Combination	Sequence: ↑ → ↑	Robot moves forward → right → forward	Passed	No delay observed
6	Command Card Reading	“FORWARD” card is placed on the reader	Robot moves forward by 1 step	Passed	RFID sensor responds quickly
7	Obstacle Sensor	Object approached within 10 cm	Robot stops or avoids the obstacle	Passed	Sensor performs well
8	Reset Button	Child presses the reset button	Robot returns to initial position	Passed	System stable
9	Movement Speed	Forward command executed	Constant speed (0.5 m/s)	Passed	Speed remains consistent
10	System Stability	Robot operated continuously for 10 minutes	No errors occur in movement	Passed	System highly stable

3.2.2. Validation by Subject Matter Experts

The feasibility assessment of the coding robot learning media was conducted by three expert validators: an Early Childhood Education (PAUD) Expert, an Educational Technology Expert, and a Children's Educational Robotics Expert. Each validator evaluated 20 indicators encompassing content, pedagogical, and technical aspects. A 5-point Likert scale (ranging from 1 to 5) was employed for scoring. The maximum total score was 100 (20 indicators × 5 points), while the minimum score was 20. The final feasibility category was determined based on the mean score, as follows: a mean score of ≥ 4.21 was classified as Highly Feasible, a mean score of 3.41–4.20 was classified as Feasible, and a mean score below 3.41 was categorized as Moderately Feasible or Not Feasible.

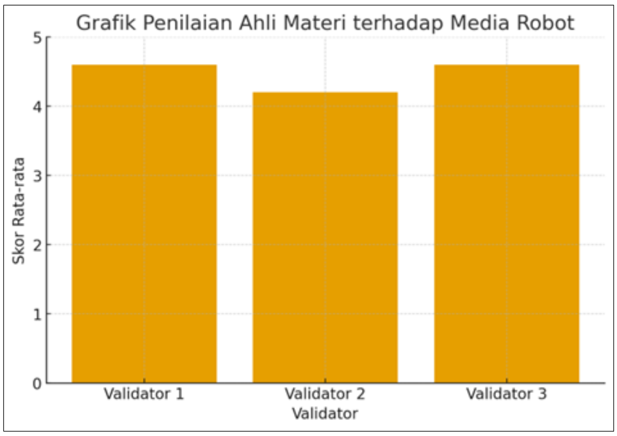

Figure 3 Material Expert Assessment Graph

Based on the evaluation conducted by three material experts encompassing three primary aspects—content, pedagogical, and technical—the graph indicates that the coding robot learning medium achieved a very high level of feasibility. Validator 1 (Early Childhood Education Expert) assigned a total score of 92, Validator 2 (Educational Technology Expert) assigned a total score of 84, and Validator 3 (Educational Robotics Expert for Children) assigned a total score of 92. The average feasibility score obtained was 89.3, equivalent to 89.3%, placing the robot medium in the "highly feasible" category for implementation in coding instruction for early childhood learners. These results confirm that the robot medium fully satisfies the required criteria in terms of content appropriateness with children's developmental stages, accuracy of pedagogical approaches, as well as technical safety and device reliability.

3.2.3. Validation by Media Experts

The feasibility evaluation of the coding robot learning media was conducted by three expert validators: a Learning Media Expert, a Child Robotics Technology Expert, and an Educational Product Design Expert. Each validator assessed 24 indicators encompassing the physical design of the media, robot functionality, safety features, child–robot interaction, visual presentation, and alignment of the media with intended learning objectives. The assessment employed a Likert scale ranging from 1 to 5, resulting in a maximum total score of 120 (24 indicators × 5) and a minimum score of 24. The average score from each validator served as the basis for determining the feasibility category, in which a mean score of ≥ 4.21 is classified as Highly Feasible, scores between 3.41 and 4.20 are classified as Feasible, while scores below this range fall into the categories of Moderately Feasible, Less Feasible, or Not Feasible, in accordance with the predefined classification criteria established in the media validation instrument.

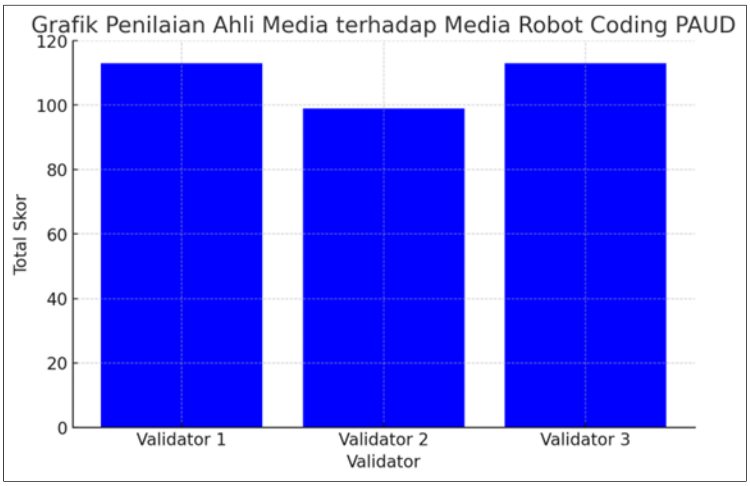

Figure 4 Media Expert Assessment Graph

Based on the evaluation conducted by three media experts assessing aspects of physical design, functionality, safety, child–robot interaction, visual display quality, and alignment with learning objectives, the results indicate that the feasibility level of the coding robot learning media falls within the Highly Feasible category. Validator 1 (Learning Media

Expert) assigned a total score of 113, Validator 2 (Child Robotics Technology Expert) assigned a total score of 99, and Validator 3 (Educational Product Design Expert) assigned a total score of 113. The average feasibility score obtained was 108.3, corresponding to an overall mean of 4.52 (equivalent to 90.4%). This outcome confirms that the robot learning media is classified as highly feasible for use as an instructional tool in introducing basic coding concepts to early childhood learners. These findings affirm that the robot satisfactorily meets established feasibility standards in terms of physical design quality, functional reliability, user safety, effectiveness of child–robot interaction, and congruence with the intended learning outcomes for foundational coding education in young children.

4. Conclusion

This study has successfully developed an educational robot medium specifically designed to facilitate coding instruction for early childhood learners through an interactive, safe, and developmentally appropriate tangible programming approach. The development outcomes demonstrate that the robot medium effectively provides concrete and engaging learning experiences, thereby enabling young children to more effectively comprehend fundamental coding concepts such as sequencing, pattern recognition, and problem-solving. Feasibility evaluations conducted by content experts and media experts indicate that the robot medium falls within the highly feasible category for implementation in early childhood education (PAUD) settings, achieving an average score of 89.3% from content experts and 90.4% from media experts. These findings confirm that the content design, pedagogical approach, technical implementation, and safety features fully comply with established standards for early childhood learning media. Results from black-box testing further reveal that all robot functions—including responses to basic commands, movement accuracy, system stability, and sensor responsiveness—operate consistently and in complete accordance with the original design specifications. The robot successfully executes child-provided coding instructions without errors, rendering it highly suitable as an experiential and exploratory learning tool. The developed robot medium has been proven effective in enhancing children’s engagement, facilitating meaningful learning experiences, and fostering the development of computational thinking skills from an early age. Consequently, this educational robot represents a promising innovative alternative capable of enriching coding education in early childhood settings (PAUD) and better preparing young learners to address the challenges of digital literacy in an increasingly technology-driven era.

Compliance with ethical standards

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Disclosure of conflict of interest

No conflict of interest to be disclosed.

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