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Improving Diabetes Education and Metabolic Control in Children Using Social Robots: A Randomized Trial

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Abstract: Robot engagement in healthcare has the potential to alleviate medical personnel workload while improving efficiency in managing various health conditions. This study evaluates the impact of robot-assisted education on knowledge acquisition and metabolic control in children with Type 1 Diabetes Mellitus (T1DM) compared to traditional education methods. A randomized controlled trial was conducted at the pediatric diabetes clinic of the University of Tabuk Medical Center, Saudi Arabia. Thirty children aged 5–15 years with T1DM were randomly divided into two groups: the robot education (intervention) group and the control education group. Both groups participated in six weekly one-hour educational sessions, with the intervention group interacting with a Pepper robot assistant and the control group receiving education from a qualified diabetes educator nurse. Knowledge was assessed using a 12-item questionnaire before and after the intervention, while metabolic control was evaluated through weekly mean home blood glucose measurements and HbA1c levels before and three months post intervention. The intervention group demonstrated a significantly greater improvement in knowledge scores compared to the control group ($p < 0.05$). Weekly mean blood glucose levels were consistently lower in the intervention group throughout the study period ($p < 0.05$ for all samples). Both groups showed a reduction in HbA1c levels after three months, with the intervention group exhibiting a greater mean decrease. The engagement of the Pepper robot in T1DM education for children resulted in improved knowledge acquisition and better metabolic control compared to traditional education methods. This approach may establish a foundation for "learning by interacting with robots" in long-term diabetes management. Further research with larger sample sizes and longer follow-up periods is warranted to confirm these findings and explore the long-term benefits of robot-assisted education in pediatric diabetes care.

Keywords: type 1 diabetes mellitus (T1DM); robot-assisted education; pediatric diabetes management; Pepper robot; knowledge acquisitions; metabolic control

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1. Introduction

Type 1 Diabetes Mellitus (T1DM) is a chronic condition affecting approximately 0.2 million children and adolescents worldwide [1]. Managing T1DM in children presents unique challenges, requiring consistent education and support to maintain optimal glycemic control and prevent complications. The complexity of diabetes management, coupled with factors such as short attention spans, potential feelings of isolation, and the challenge of maintaining consistent motivation for self-care tasks, can make traditional education methods less engaging and effective for children with T1DM.

The management of T1DM extends beyond clinical settings, with home-based care playing a crucial role in long-term health outcomes. Home rehabilitation and continuous education are essential components of effective diabetes management, particularly for children [2]. The COVID-19 pandemic has further emphasized the importance of robust home-based care systems [3]. In this context, innovative solutions that can provide consistent support and education in the home environment are increasingly valuable. Social robots offer a promising avenue for enhancing home rehabilitation and education for children with T1DM, potentially improving adherence to treatment regimens and overall disease management.

Recent advancements in Artificial Intelligence (AI) and robotics have opened new avenues for healthcare management, particularly in chronic conditions like T1DM [4] or asthma [5]. Social robots, a subset of AI technology, have shown promise in various healthcare applications, including patient education and disease management [6–8]. These robots offer an innovative approach to diabetes education and management, potentially improving knowledge retention and treatment adherence [9].

However, while several studies have explored the use of robots in healthcare, their specific application in T1DM education and management for children remains understudied. There is a need for comprehensive research that evaluates the impact of advanced robot-assisted interventions on both knowledge acquisition and metabolic control in pediatric T1DM patients.

This paper aims to evaluate the impact of robot engagement, specifically using the Pepper robot platform, on knowledge acquisition and metabolic control in children with T1DM. Our study contributes to the field through the following:

1. Developing a reliable robot interaction system for T1DM education in children.
2. Investigating the acceptability of the Pepper robot platform among children with T1DM.
3. Validating the efficiency of the developed social robot system compared to traditional education methods through a controlled study.

By addressing these objectives, we seek to fill the gap in understanding how robot-assisted education can enhance T1DM management in pediatric populations, both in clinical settings and as part of home-based care. The findings of this study have the potential to inform future developments in pediatric diabetes care, particularly in the context of home rehabilitation and long-term disease management.

The rest of this paper is organized as follows: Section 2 discusses the recently developed robot-based diabetes management and education systems. In Section 3, the experiment setup is presented, including the design of this study, the participants, and the robot platform. The results obtained from this study are presented and discussed in Section 4, whereas Section 5 summarizes the key findings, interprets the obtained results, and compares the obtained results with recently developed systems. Finally, Section 6 concludes the work presented in this paper and presents several issues that need to be considered in future studies.

2. Related Works

Recent research on social robots in diabetes management for children can be categorized into two main areas: diabetes management systems and diabetes education systems. This section critically examines the existing literature, highlighting the key findings, methodologies, and gaps in the current knowledge.

First, the diabetes management systems are considered: The majority of studies have focused on using robots for diabetes management. Al-Taee et al. [10] investigated the use of NAO robots with 22 participants, reporting the high acceptability of the robot solution. This was further corroborated by another study [11] with a larger sample size of 37, which found an overall acceptability of 86.7%. These studies suggest that children are generally receptive to robot-assisted diabetes management.

Alhmiedat and Alotaibi [12] explored a different platform, the SARA robot, with a small sample of five participants. Despite the limited sample size, they reported a reasonable acceptance rate of 82.2%, indicating that various simple robot platforms may be suitable for this purpose.

Several studies utilized the NAO robot platform for different aspects of diabetes management. Blanson Henkemans et al. [13] reported an increase in diabetes knowledge among 27 participants. Van Der Drift et al. [14] found that children shared more personal experiences in their diaries when interacting with the NAO robot, albeit with a small sample size of six. These studies suggest that robot interaction may enhance engagement and knowledge retention.

Cañamero and Lewis [15] and Kruijff-Korbayová et al. [16] both used NAO robots with sample sizes of 17 and 20, respectively, reporting positive outcomes in terms of social interaction and children's interest in engaging with the robot. This indicates that robots can serve as effective companions in diabetes management.

Robinson et al. [17] conducted a small-scale study with four participants, demonstrating that the NAO robot could help children minimize high-energy food intake and increase their confidence and motivation. Sinoo et al. [18] found that children felt stronger friendship towards the NAO robot in a study with 21 participants.

Second, the diabetes education systems are considered: Fewer studies have focused specifically on robot-assisted diabetes education. Looije et al. [19] used an NAO robot for educational purposes with 17 participants, reporting that children had very positive experiences. Henkemans et al. [20] assessed the effects of personalized robot behaviors on health education using NAO, noting an increment in knowledge among five participants.

While these studies collectively suggest positive outcomes for robot-assisted diabetes management and education, several limitations are evident:

1. The majority of studies used the NAO robot platform, with limited exploration of other robot types.
2. Most research focused on acceptability and engagement, with fewer studies examining concrete health outcomes or long-term impacts.
3. There is a notable lack of controlled studies comparing robot-assisted interventions with traditional methods.
4. The distinction between management and education is often blurred, with many studies incorporating elements of both.

Despite the promising results, there remains a significant gap in understanding how robot-assisted interventions compare to traditional methods in terms of both knowledge acquisition and metabolic control. Most studies have focused on either management or education, but few have combined both aspects in a controlled study with a significant sample size and measurable health outcomes.

Table 1 encapsulates the current landscape of robot-assisted interventions for children with diabetes. While these studies collectively suggest promising outcomes, they also highlight the need for larger-scale, controlled studies that combine both management and education aspects and explore diverse robot platforms. Our study aims to address these gaps through the following:

1. Utilizing the Pepper robot, expanding beyond the commonly used NAO platform. The Pepper robot may be more effective than NAO for interacting with children with T1DM due to its taller, more humanoid design, touch screen interface, advanced sensors, expressive gestures, and superior speech capabilities. These features create stronger emotional connections, personalized interactions, and enhanced engagement, improving educational outcomes for T1DM management [21].
2. Conducting a controlled study comparing robot-assisted education with traditional methods.
3. Measuring both knowledge acquisition and metabolic control outcomes.
4. Including a larger sample size to enhance the reliability and generalizability of findings.

Table 1. A comparison study among the recently developed robot systems for diabetic issues.

Research Study	Target Function	Robot Platform	Sample Size	Obtained Results
[10]	Diabetes management	NAO	22	High acceptability of NAO robot solution
[11]	Diabetes management	NAO	37	Overall acceptability of 86.7%
[12]	Diabetes management	SARA	5	Reasonable acceptance rate of 82.2%
[13]	Diabetes management	ALIZ-E	9	Children could benefit from social robots motivation
[14]	Diabetes management	NAO	6	Children shared more personal experiences in diary and their relationship with the NAO robot
[15]	Diabetes management	NAO	17	An engaging social interaction partner
[16]	Diabetes management	NAO	20	A high interest in children in engaging with the robot
[17]	Diabetes management	NAO	4	The robot could help diabetic children to minimize their high-energy food and drink intake and increase their confidence and motivation
[18]	Diabetes management	NAO	21	Children felt stronger friendship towards the NAO robot
[19]	Educational	NAO	17	Children had very positive experience
[20]	Diabetes management	NAO	27	An increase in diabetes knowledge

By addressing these aspects, our research seeks to provide a more comprehensive understanding of the potential of social robots in T1DM management and education for children.

3. Methods

3.1. Study Design

This study employed a randomized controlled trial design to evaluate the impact of robot-assisted education on knowledge acquisition and metabolic control in children with Type 1 Diabetes Mellitus (T1DM). This study was conducted at the pediatric diabetes clinic of the Medical Center, University of Tabuk, Saudi Arabia, between 1 September 2023 and 31 November 2023. The experimental setup for the control group is presented in Figure 1A, whereas Figure 1B depicts the experimental setup for the robot group. Both areas consist of a diabetic child, a parent (mother, father, or both), and an observer. However, the control testbed area includes a nurse educator, whereas the intervention testbed area includes a Pepper robot platform.

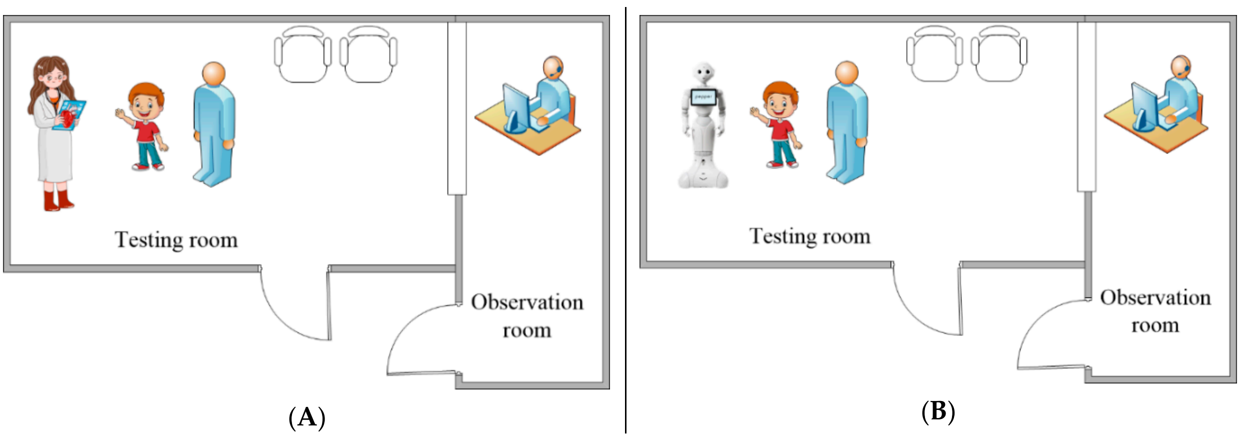

Figure 1. Setup for the testbed area: (**A**) the control testbed area and (**B**) the robot testbed area.

3.2. Participants

Children aged 5–15 years with T1DM were eligible for inclusion. The inclusion criteria were as follows: confirmed diagnosis of T1DM, disease duration within the first year after diagnosis, Saudi nationality, and having educated, cooperative parents. The exclusion criteria included the following: non-Saudi participants, Type 2 diabetes or other types of diabetes, diabetes with other associated autoimmune or chronic disorders, and those with incomplete data.

A total of 30 participants were recruited and randomly assigned to either the robot education (intervention) group (n = 15) or the control education group (n = 15). The adopted methodology for this study is presented in Figure 2, starting from the enrolment stage, then collecting the last HBA1C and knowledge assessment test which is presented in Appendix A, starting the education stage, and finally performing the knowledge test and HBA1C test. The questions of the knowledge assessment test have been obtained from [22].

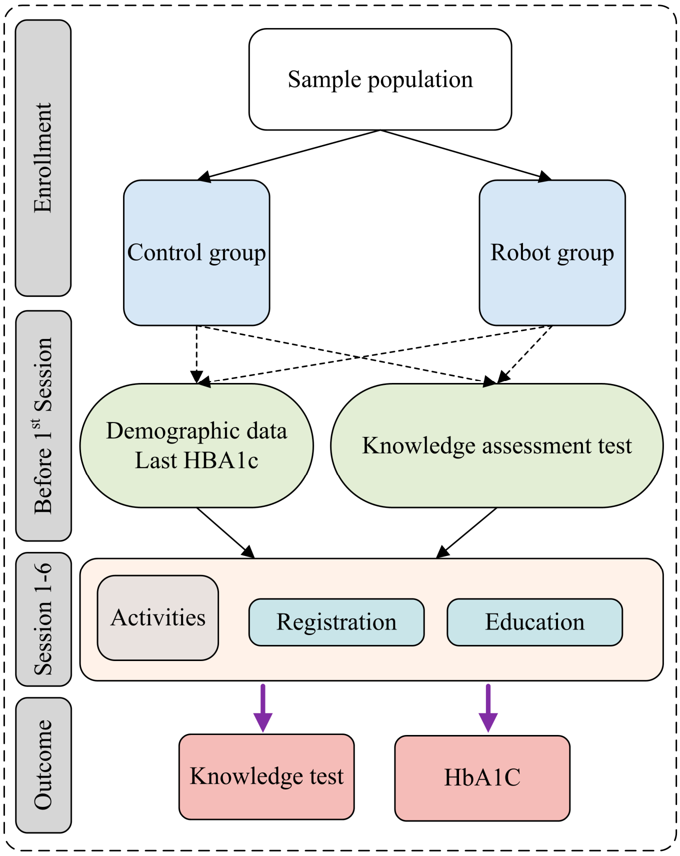

Figure 2. The adopted study methodology.

The age distributions for the two groups are presented in Figure 3, where the average age of the children in the control group was equal to 8 years old, and the average age of the children in the intervention (robot) group was equal to 9 years old. On the other hand, participants were categorized based on the time since their initial T1DM diagnosis, as depicted in Figure 4. Four categories were established: 1–3 months, 3–6 months, 6–9 months, and 9–12 months post diagnosis. This categorization allows for the analysis of how the duration of T1DM might influence the effectiveness of the educational intervention. The figure illustrates the distribution of participants across these categories for both the intervention and control groups.

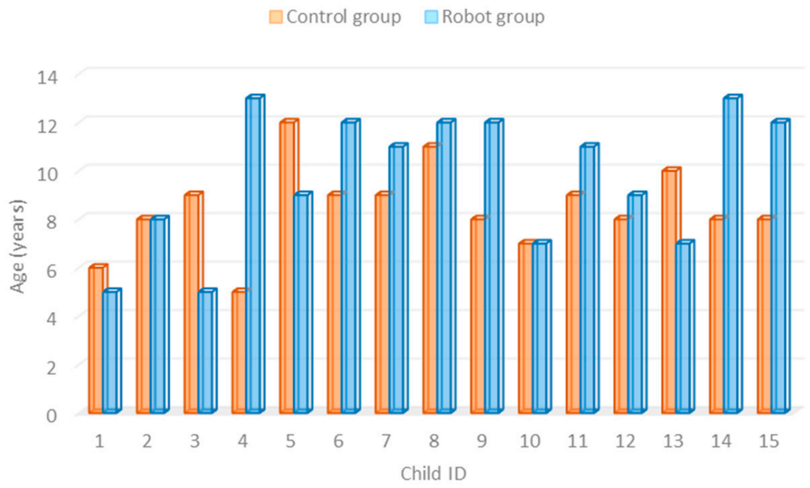

Figure 3. The age distribution of children who were involved in this study.

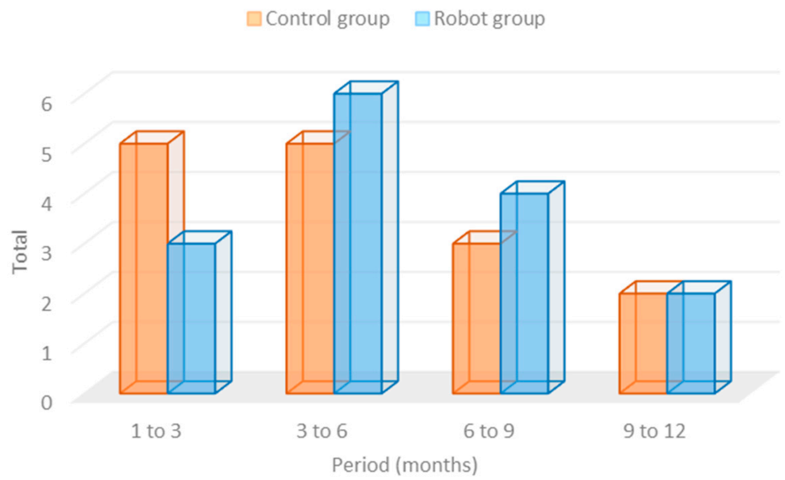

Figure 4. Distribution of time since T1DM diagnosis among participants.

3.3. Robot Platform and Intervention Group

The intervention group received education from a Pepper robot platform, chosen for its high acceptability rate among children [23]. Pepper is a 120 cm tall humanoid robot designed for human interaction, capable of perceiving its environment using touch, distance, vision, and voice sensors, Figure 5. The Pepper robot was located in the medical center at the University of Tabuk.

A robot application for the Pepper platform was developed for the purpose of allowing the robot to interact with diabetic children, where we employed the Python SDK and NAOQi OS 2.8.7 to accomplish this task. The robot platform was implemented using the Choregraphe development environment. Choregraphe is a development environment for Pepper and NAO robots, and it offers a reliable method for developing a robot application that contains services, dialogs, and robot behaviors.

The developed robot platform relied on Python 2.7 to obtain data from Pepper's sensors, process the received data, and control the Pepper robot accordingly. In addition, JavaScript language was employed to develop an application for the Pepper robot's tablet. Both Python and JavaScript environments were combined in a single robot application to provide a reliable interaction system for the Pepper robot.

For the purpose of developing an effective human–robot interaction approach, a set of packages and tools were adopted, and a number of functions were developed. These functions enabled Pepper to interact dynamically with the children during educational sessions, as shown in Figure 6. The developed robot education system for children with T1DM integrated several packages and tools, as follows:

- NAOqi motion: this package allows the Pepper robot to move and perform animations through a communication link with the physical actuators (head, arms, and legs).
- NAOqi audio: using this package, the developed application can access Pepper's loudspeaker and microphones.
- NAOqi vision: this package allows for communication with the physical RGB and RGB-D cameras in order to process and analyze the received captured frames.
- NAOqi people detection: this is used to analyze the emotional aspects of people facing the robot.
- NAOqi sensors: this package is mainly employed to access onboard sensors including obstacle avoidance, infrared, touch, and sonar.

Figure 5. Pepper robot platform in the clinic.

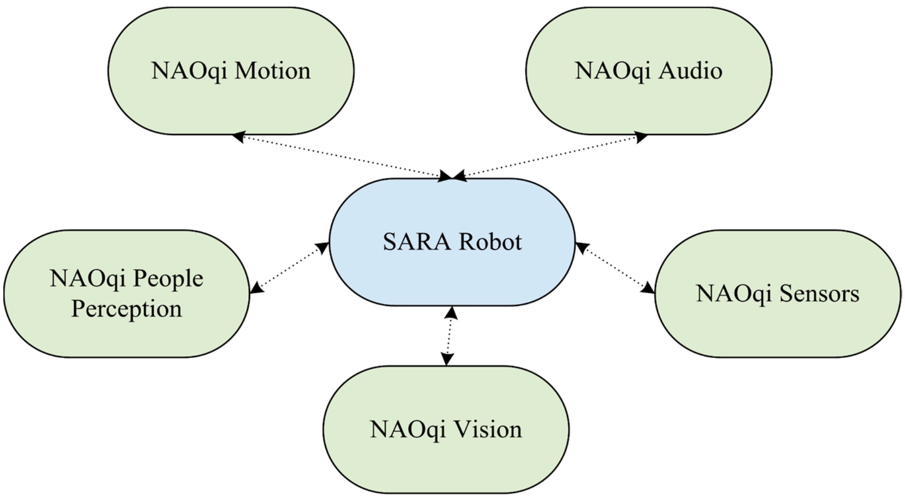

Figure 6. The main developed functions for the education robot system.

The robot was programmed to perform various interactive functions, including greeting the child, asking about their name and status, shaking hands, dancing, hugging, and mimicking animals. Figure 7 presents the Pepper robot interacting with a diabetic child and her mother.

Figure 7. A diabetic child with her mother interacting with the Pepper robot.

A Python SDK is available to communicate with the Pepper robot's sensors and actuators. Therefore, we developed several Python-based functions to communicate with sensors through the adoption of Pepper's sensor API to obtain data from microphones and cameras and the distance to objects surrounding the Pepper robot.

Moreover, several functions were implemented to control the Pepper robot's actuators (animation and movement) through communication with actuators using the actuator API. In addition, a GUI was implemented to allow the child to interact with the robot and to display several productive pictures; this GUI application was implemented using JavaScript and initiated using Python SDK. The Pepper JavaScript SDK allows for the Pepper robot's animation and speech to be shown. Figure 8 presents the software architecture for the developed Pepper robot application.

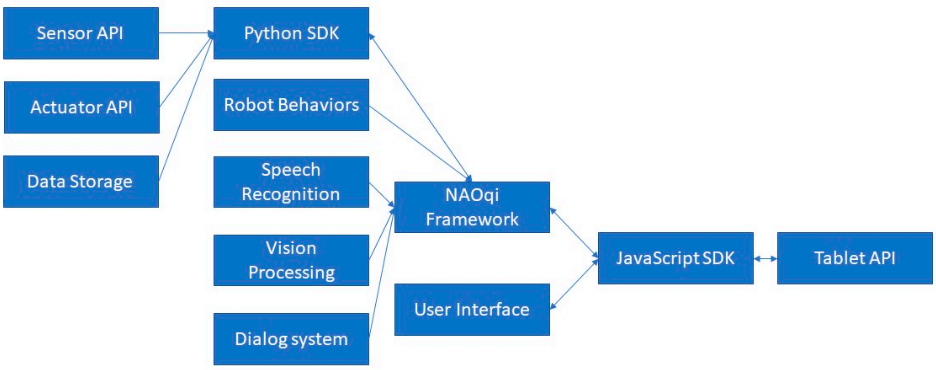

Figure 8. The developed application for the Pepper robot.

3.4. Control Group

The control group received traditional education from a qualified diabetes educator nurse, following the same session structure and content as the intervention group, Figure 1A.

For both groups, the robot platform and the educator nurse were required to deliver educational content through a series of six weekly one-hour sessions. Each session included the following:

- Five minutes for registering mean blood glucose data from the previous week.
- Five minutes of entertainment and games.
- In total, 30–40 min of diabetes education presentation.

All interactions were conducted in Arabic, the first language of all participants.

3.5. Data Collection

Data were collected at baseline and after the six-week intervention period. Measures included the following:

1. Demographic and control data.
2. Knowledge assessment: a 12-item multiple-choice questionnaire developed by diabetes educators and reviewed by consultants.
3. Metabolic control: weekly mean home blood glucose measurements and HbA1c levels.
4. Parent and child perceptions: questionnaires on the acceptability and perceived effectiveness of the education program.

The nature of our intervention, which compared robot-assisted education to traditional human-led education, made full participant blinding unfeasible. However, to minimize potential bias, outcome assessors evaluating the knowledge questionnaires and analyzing HbA1c results were blinded to group allocation. We acknowledge this limitation and address strategies to mitigate it in our discussion of future research directions.

3.6. Data Analysis

Data were analyzed using SPSS version 22.0. Descriptive statistics were used for demographic data. Comparisons between groups were made using *t*-tests for continuous variables and chi-square tests for categorical variables. Repeated-measures ANOVA was used to assess changes in knowledge scores and metabolic control over time. A p-value < 0.05 was considered statistically significant.

4. Results

This study assessed the impact of robot engagement on knowledge acquisition and metabolic control in children with T1DM. We present findings from our analysis of demographic characteristics, knowledge test scores, weekly mean home blood glucose measurements, and HbA1C percentages between the control and intervention groups.

4.1. Participant Characteristics

Table 2 provides a comparative analysis of the demographic variables between the control and intervention groups. Both groups showed similar age distributions across all categories (≤5 years, 6–10 years, >10 years). The control group comprised 40% males and 60% females, while the intervention group had 26.7% males and 73.3% females, with no significant difference in gender distribution between groups. The T1DM duration categories (≤3 months, 3–6 months, 6–12 months, and >12 months) were comparable between groups. No significant differences were observed in the occurrence of symptomatic hypo- or hyperglycemic events or in the frequency of Diabetic Ketoacidosis (DKA) admissions between groups (all $p > 0.05$).

Table 2. Demographic characteristics of participants in the control and intervention groups.

Variable	Control Group (N = 15)	Intervention Group (N = 15)	p-Value
	Age (years)		
≤5	3 (20%)	3 (20%)	

Table 2. *Cont.*

Variable	Control Group (N = 15)	Intervention Group (N = 15)	*p*-Value
6–10	7 (46.7%)	7 (46.7%)	
≥10	5 (33.3%)	5 (33.3%)	
Gender			
Male	6 (40%)	4 (26.7%)	
Female	9 (60%)	11 (73.3%)	
DM duration (months)			
≤3 months	4 (26.7%)	2 (13.3%)	
3–6 months	2(13.3%)	3(20%)	
6–12 months	5 (33.3%)	5 (33.3%)	>0.05
>12 months	4(26.7%)	5 (33.3%)	
Asymptomatic hypoglycemic events			
0	5 (33.3%)	7 (46.7%)	
1	5 (33.3%)	4 (26.7%)	
2	5 (33.3%)	4 (26.7%)	
Symptomatic hypoglycemic events			
0	15 (100%)	14 (93.3%)	
1	0 (0%)	1 (6.7%)	
Admission due to DKA			
0	12 (80%)	14 (93.3%)	
1	3 (20%)	1 (6.7%)	

4.2. Knowledge Acquisition

Knowledge test scores for both groups before and after the intervention are presented in Table 3. The control group's scores ranged from 6 to 10 before this study and 8 to 11 after. The intervention group's scores ranged from 6 to 11 before and 10 to 12 after this study. The percentage changes in scores for the control group ranged from 0.0% to 57.1%, while the intervention group showed changes from 9.1% to 83.3%. Paired *t*-tests showed significant improvements within both groups ($p < 0.05$). An independent *t*-test comparing both groups showed a significant difference ($p < 0.05$), indicating that the overall improvement in test scores differed significantly between the two groups.

Table 3. Knowledge test scores before and after the intervention for control and intervention groups.

Sample No.	Control Group		Percentage Difference	Intervention Group		Percentage Difference	*p*-Value
	Before	After		Before	After		
1	8	9	12.5%	8	11	37.5%	
2	9	9	0.0%	10	12	20.0%	
3	10	11	10.0%	6	10	66.7%	
4	9	10	11.1%	6	11	83.3%	
5	8	8	0.0%	9	10	11.1%	
6	10	10	0.0%	10	11	10.0%	
7	7	11	57.1%	10	12	20.0%	
8	9	10	11.1%	11	12	9.1%	<0.05 *
9	9	10	11.1%	11	12	9.1%	
10	8	9	12.5%	10	11	10.0%	
11	6	8	33.3%	9	11	22.2%	
12	8	10	25.0%	8	11	37.5%	
13	9	9	0.0%	7	10	42.9%	
14	8	10	25.0%	10	12	20.0%	
15	7	9	28.6%	10	12	20.0%	

* Paired *t*-test *p*-values for both groups are less than 0.05.

To provide a more comprehensive analysis of the knowledge test scores, we calculated summary statistics and conducted statistical tests based on the individual scores presented in Table 4, where this table presents a summary of these findings.

Table 4. Summary of knowledge test scores.

Group	Pre Intervention (Mean ± SD)	Post Intervention (Mean ± SD)	*p*-Value (Within Group)
Control	8.33 ± 1.11	9.53 ± 0.99	<0.05 *
Intervention	9.00 ± 1.69	11.27 ± 0.80	<0.05 *

* Paired *t*-test *p*-values for both groups are less than 0.05.

As shown in Table 4, both groups demonstrated significant improvements in their knowledge scores following the intervention. The control group's mean score increased from 8.33 ± 1.11 to 9.53 ± 0.99 ($p < 0.05$, paired *t*-test). The intervention group showed improvement as well, with mean scores increasing from 9.00 ± 1.69 to 11.27 ± 0.80 ($p < 0.05$, paired *t*-test).

To compare the effectiveness of the two educational approaches, an independent *t*-test was conducted to analyze the difference in the improvement between the groups. This test revealed a significant difference ($p < 0.05$), indicating that the overall improvement in test scores differed significantly between the two groups.

4.3. Metabolic Control

4.3.1. Weekly Mean Blood Glucose Levels

Table 5 presents the weekly mean home blood glucose measurements for both groups. In most cases, the average blood glucose levels were lower in the intervention group compared to the control group. All comparisons between groups showed statistically significant differences ($p < 0.05$), with some *p*-values as low as 0.0005.

Table 5. Weekly mean home blood glucose measurements (mg/dL) for control and intervention groups.

Sample	Control Group	Intervention Group	*p*-Value
1	195	178	0.003
2	173	166	0.007
3	204	142	0.002
4	161	134	0.015
5	219	129	0.001
6	185	155	0.020
7	178	111	0.005
8	236	123	0.0005
9	190	137	0.006
10	157	131	0.018
11	212	145	0.004
12	182	130	0.008
13	199	126	0.002
14	169	102	0.005
15	225	170	0.007

To provide a clearer comparison between the two groups, Figure 9 presents the mean weekly blood glucose levels for the control and intervention groups, along with their respective standard deviations. As illustrated, the intervention group demonstrated a substantially lower mean blood glucose level (138.60 ± 21.17 mg/dL) compared to the control group (192.33 ± 24.78 mg/dL). This visual representation underscores the significant difference in glycemic control achieved by the two groups over the study period.

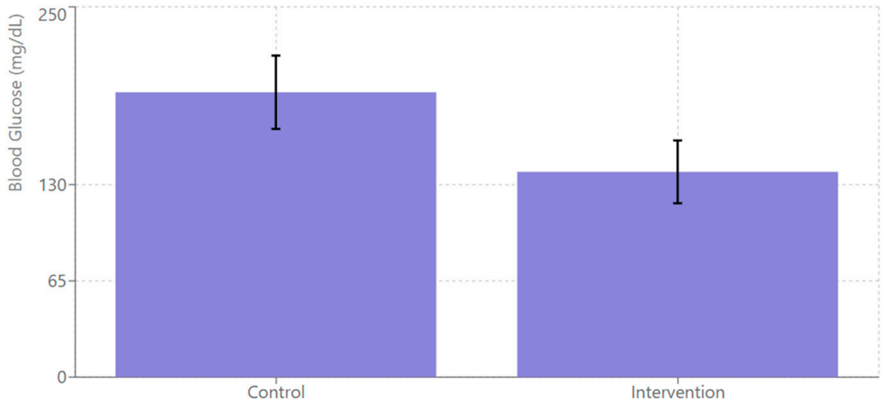

Figure 9. Mean weekly blood glucose levels (mg/dL) for control and intervention groups. Error bars represent standard deviation.

4.3.2. HbA1C Levels

Both groups showed a reduction in HbA1C percentages three months post intervention, as illustrated in Table 6. The control group's mean HbA1C decreased from 9.00 ± 0.50 to 8.25 ± 0.75 (p = 0.04). The intervention group's mean HbA1C decreased from 8.75 ± 0.25 to 7.75 ± 0.25 (p = 0.03). An independent t-test comparing the changes between groups showed a significant difference (p = 0.0330).

Table 6. HbA1C percentages before and three months after the intervention for control and intervention groups.

Time	Control Group (Mean ± SD)	Intervention Group (Mean ± SD)
Before	9.00 ± 0.50	8.75 ± 0.25
Three months after	8.25 ± 0.75 * p-value 0.04	7.75 ± 0.25 *,† p-value 0.03

* Significant reductions within both groups; † greater reduction in intervention group.

To visually represent the changes in HbA1c levels, Figure 10 presents the mean HbA1c percentages before and three months after the intervention for both the control and intervention groups.

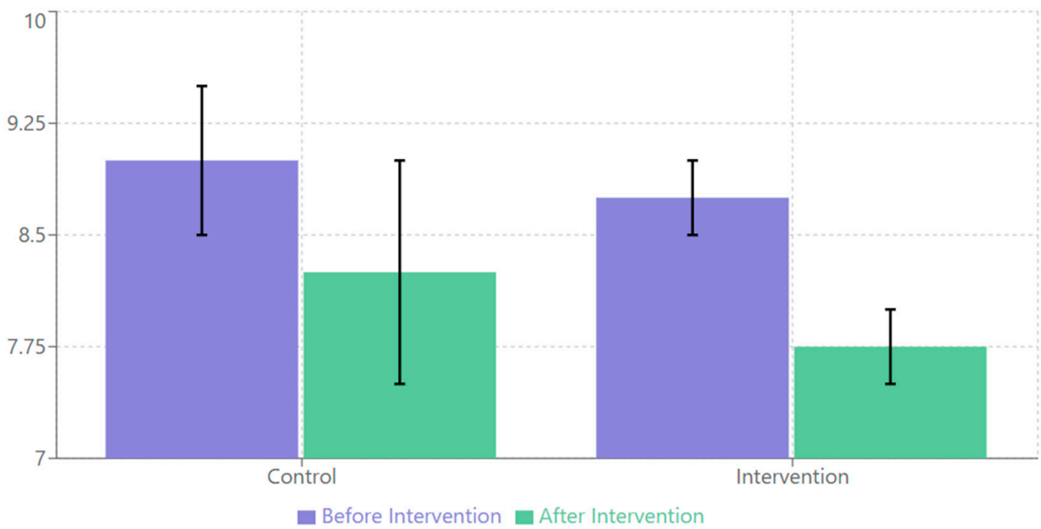

Figure 10. Changes in mean HbA1c levels before and after intervention. Error bars represent standard deviation.

4.4. Participant Engagement

During the intervention, observers noted that children in the robot-assisted group showed higher levels of engagement compared to the control group. Children interacted enthusiastically with the Pepper robot, responding positively to its introductions, handshakes, and playful activities such as dancing and animal mimicry. In contrast, children in the control group typically maintained interest for only the first 3–6 min of each session before showing signs of disengagement.

5. Discussion

5.1. Summary of Key Findings

This study evaluated the impact of robot-assisted education on knowledge acquisition and metabolic control in children with T1DM. Our results demonstrated significant improvements in both the knowledge scores and metabolic control measures in the robot-assisted group compared to the traditional education group.

5.2. Interpretation of Results

As presented earlier in Table 3, the robot-assisted group showed a significantly higher mean increase in the knowledge scores compared to the control group. This greater improvement suggests that robot engagement offers a superior method for educating children with T1DM. The interactive nature of the Pepper robot, including its ability to introduce itself, shake hands, and engage in playful activities, likely contributed to this enhanced learning. This aligns with previous findings that interactive, technology-based interventions can improve health education outcomes [24,25].

The intervention group demonstrated consistently lower weekly mean blood glucose levels compared to the control group, with differences ranging from 7 mg/dL to 113 mg/dL (all $p < 0.05$). Moreover, the intervention group showed a greater reduction in HbA1c (1.00% vs. 0.75% in the control group, $p = 0.0330$). These improvements in both short-term and long-term glycemic control indicators suggest that enhanced knowledge translates to better disease management. This connection between education and clinical outcomes is crucial, as it demonstrates the potential real-world impact of robot-assisted education on T1DM management [26,27].

Observational data indicated that children in the robot-assisted group maintained engagement throughout the 30–40-min sessions, contrasting with the control group where interest waned after 3–6 min. This sustained engagement is particularly noteworthy given the wide age range of participants (5–15 years) and varied disease durations ($\leq$3 months to >12 months). The ability of the robot to capture and maintain attention across these diverse groups suggests its potential adaptability to different developmental stages and experience levels with T1DM [28,29].

5.3. Comparison with Existing Literature

While previous studies have shown the potential of robots in improving the understanding of health conditions [24], our study uniquely demonstrates both educational and clinical benefits in T1DM management. The magnitude of the improvement in HbA1c (1.00%) in our robot-assisted group over just six weeks is particularly noteworthy, comparing favorably with a 6-month telehealth intervention that achieved a 0.5% reduction [30]. This suggests that robot-assisted education may offer accelerated benefits compared to other technology-based interventions.

5.4. Limitations and Future Directions

We believe that several factors may contribute to the observed outcomes. The novelty of interacting with an AI-powered robot, the "Pepper robot", could have increased the initial engagement, though long-term studies are needed to assess if this effect persists. The robot's ability to provide consistent information delivery may have reduced the variability in education quality [31]. Additionally, children might have felt more comfortable asking questions to a robot than a human educator, potentially leading to better understanding.

Our findings suggest that integrating robot-assisted education into T1DM management could significantly enhance care for children. The practical implications include supplementing traditional education, where robots could provide reinforcement between clinic visits. Robot interactions could be tailored based on age, disease duration, and individual learning needs, allowing for personalized interventions. Furthermore, robots could handle routine education tasks, potentially optimizing resources by allowing healthcare providers to focus on more complex aspects of care.

Several limitations should be considered when interpreting our results. Our relatively small sample size (N = 30; 15 per group) and six-week study period limit the generalizability of findings and preclude the assessment of the long-term effects or potential waning of novelty associated with robot interaction. As a single-center study conducted at one clinic in Saudi Arabia, cultural and healthcare system specifics may limit the broader applicability of our results. Furthermore, due to the nature of the intervention, blinding participants to their group assignment was impossible, potentially introducing bias. Lastly, the frequency and style of interactions differed between robot and human educators, which could have influenced the results beyond the simple robot/human distinction.

To address these limitations and expand upon our findings, future research should conduct larger, multi-center, longer-term studies to validate and generalize the results. Incorporating adaptive and personalized robot behaviors to explore sustained engagement over extended periods is crucial, building on the existing literature that suggests engagement levels can vary based on robot interaction personalization [32–34]. Additionally, comparing different robot platforms could identify features that most effectively enhance educational and therapeutic outcomes, as existing studies indicate that variations in robot design can significantly impact user engagement and effectiveness [35].

Future studies should also investigate the specific aspects of robot-assisted education contributing to improved outcomes and explore personalized interventions based on individual patient characteristics. To address the limitation of participant blinding, we propose implementing a crossover design where participants experience both educational approaches (robot-assisted and traditional) in a randomized order, with a washout period between interventions. This design would allow for within-subject comparisons, potentially mitigating biases associated with a lack of blinding and providing insights into individual preferences and responses to different educational approaches.

These strategies will help address the current limitations and advance our understanding of robot-assisted education in pediatric diabetes management, paving the way for more effective and personalized interventions in the future.

6. Conclusions

This study provides promising evidence for the effectiveness of robot-assisted education in improving both knowledge acquisition and metabolic control in children with Type 1 Diabetes Mellitus (T1DM). The intervention group, which interacted with the Pepper robot, showed significant improvements in diabetes knowledge and glycemic control compared to the traditional education group. These findings suggest that robot-assisted education can offer a more engaging and effective approach for managing T1DM in children.

This study makes several novel contributions to the field of robot-assisted diabetes education. It is the first to utilize the advanced features of the Pepper robot specifically for T1DM education in children, combining both educational and clinical outcome measures. Our research uniquely demonstrates the effectiveness of robot-assisted education across a wide age range and in the cultural context of Saudi Arabia. By successfully integrating robot-assisted education into standard care protocols, we provide a practical model for implementing this innovative approach in clinical settings. These findings not only advance our understanding of how social robots can enhance diabetes management in children but also pave the way for more personalized and engaging educational interventions in pediatric chronic disease management.

The cultural context of Saudi Arabia, where interactions with robots are less common, may also have contributed to a novelty effect, enhancing engagement. Therefore, it is essential to conduct similar studies in diverse settings to assess the generalizability of these results. In regions like Japan, where children are more familiar with robots, the outcomes may differ.

Looking forward, advancements in Large Language Models (LLMs) present exciting possibilities for even more personalized and interactive robot-assisted education. Future robots equipped with advanced LLMs could provide more nuanced, adaptive, and culturally sensitive interactions, further enhancing the effectiveness of this approach.

While our study has limitations, including a small sample size and a short study duration, it contributes valuable insights into the potential of robotic systems in pediatric diabetes education. Integrating sophisticated robot-assisted education into existing diabetes care frameworks represents a promising avenue for improving management and long-term health outcomes for children with T1DM. Future research should focus on larger, multi-center studies with longer follow-up periods to validate these findings and explore the long-term benefits of robot-assisted education.

Author Contributions: M.A. and A.M.M. surveyed the recently developed social robot systems for managing type 1 diabetes among children. T.A. and R.S. developed the robot application using Choregraph and Python development environments. L.A.A. and T.A. performed the clinical experiments, whereas F.A. wrote and reviewed this manuscript. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement: An ethical approval for this study was granted by the Ethics Committee of Tabuk University, at Tabuk city Saudi Arabia (No. UT-316-156-2023). The approval included the research protocol data, collection of informed consent forms from participants, and the final report submitted at the end of this study.

Informed Consent Statement: During the routine clinic visits, participants were informed about the study objectives, methodology, risks, and benefits, and if they were willing to be enrolled in this study, they signed the consent form before starting this study. Participants were first requested to give their consent to participate in this study before enrollment. The data of the study participants were kept confidential and coded to preserve the participants' anonymity. They were informed about the study objectives, methodology, risks, and benefits. The investigators were responsible for keeping the participants' privacy and security of the data. Personal information (e.g., name, contact info) was not included in the study data entry software to conserve the participants' privacy. Each subject was assigned a unique identifier code.

Data Availability Statement: In accordance with ethical guidelines and privacy regulations, the data presented in this article are not available for public.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

This appendix includes the list of questions related to demographic and diabetes data.
Demographic and Diabetes Data
What is your age?
Gender?

- Male
- Female

Diabetes duration in year?
Last HbA1c

Insulin treatment

- twice a day injection
- Multiple doses
- Continuous perfusion pump

Mild hypoglycemia (per week)

- None
- Once
- More than once

Severe hypoglycemia that needs hospitalization (past one year)

- None
- Once
- More than once

Admission due to hyperglycemia (past one year)

- None
- Once
- More than once

Parent education, mothers

- Less than high school graduate
- High school graduate
- Bachelor and above Parent education, fathers
- Less than high school graduate
- High school graduate
- Bachelor and above

Knowledge questionnaire
Q1: what is the ideal glucose level range for type 1 diabetes you look for?

a) 60–80 mg/dL
b) 80–120 mg/dL
c) 180–300 mg/dL
d) Not sure

Q2: what is the ideal HbA1C level that should be targeted for to diabetes complication

a) Less than 7.5
b) 7–9
c) 9–10
d) Not sure

Q3: what is about Type 1 diabetes is a disease?

a) Is always life threatening when first diagnosed
b) Could be cured by healthy lifestyle
c) Can be treated by insulin
d) Not sure

Q4: which one of the following is true about type1 diabetes and diet?

a) A diabetic diet should be low in fat, high in fiber, low in added sugar
b) It is ok to eat fried take away food 3 times a week
c) The diet should be free of sugar
d) Not sure

Q5: Why is doing exercise regularly or being physically active good for type 1 diabetes?

a) It can help to control blood sugar
b) It cures type 1 diabetes

c) Not sure

Q6: what should you do if your child gets ill?

a) Check the blood sugar more frequent every 2–4 h
b) Stop giving insulin
c) eat lots of foods
d) Unsure

Q7: Children with type 1 diabetes need to check their eyes, kidney function,

a) Every 6 month
b) Every year
c) 2–3 year
d) Unsure

Q8: which of the following medications is true?

a) If the blood sugar is normal for 2 month stop the insulin because the diabetes is cured
b) Regular medical advice is necessary to adjust the dose and type of insulin
c) No need to worry about your diet if you are taking the insulin
d) Unsure

Q9: If your child has hypoglycemia, you should

a) Immediately take some insulin
b) Rest and wait until she is better
c) Immediately get some sugary foods
d) Unsure

Q10: why do we need to test the blood sugar regularly?

a) To be alert about the patterns of blood sugar level
b) To help making decisions in certain situations such as exercise, illness etc
c) It can make me confident about my child diabetes
d) Unsure

Q11: How often should your child do exercise

a) Once a month for one hour
b) Once a week for one hour
c) Most days for 30 min
d) Unsure

Q12: what you will do if you invited for a party?

a) Feel confident to join while observe my blood sugar and getting my insulin
b) Go to the party, join the food without checking my glucose level
c) Go to the party, join the food without my insulin
d) Do not go

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